AN ABSTRACT OF THE DISSERTATION OF

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Title: Essays on the Interactions between Land Use, Natural Amenity, and Wildfire Risk

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It is essential to study the relationship between environmental features and human land-use activities that can provide a better understanding of human-environment interactions. In a response, this dissertation addresses the human-environment issues from different perspectives in three essays.

The first essay conducts an integrated analysis to investigate the impacts of human activities and environmental features on wildfire occurrence at the Wildland-Urban Interface in a changing climate. We focus on the impacts of land use changes as measured by their density, connectivity, and mix. The conceptual model builds on a theoretical framework developed by Woodward (1987) and Neilson (1995) that characterizes the functioning mechanism of ecosystems. The empirical models identify the key factors that influence wildfires. Hypotheses are tested to demonstrate the spatial heterogeneity of human land-use impacts on wildfires. Results can inform the design of policies that aim to identify community vulnerabilities, reduce wildfire uncertainties,

strengthen firewise community development, and inform future land-use decision making in response to wildfire threats.

The second essay analyzes the impacts of wildfire risk on urban development. It builds on and expands the monocentric-city framework developed by Wu (2006) and Wu (2010) by introducing wildfire risk into this model. We calibrate the model and examine the urban spatial profiles changes under different assumptions of wildfire risks and natural amenities. We find that wildfire risk can take on various aspects of urban spatial profiles at a much broad scale that go beyond the fire-prone areas and affects both households and public decision sectors. Even without inconsistency in fire-zone designation policy, over-development can occur in fire-hazardous area.

The third essay models the role of amenity in interregional migration and spatial distribution of economic activities. Extending the new economic geography model of Helpman (1998) by including locational amenities, we present a multi-market equilibrium framework that includes consumption, production, and trade. Results suggest that the effects of amenities are significantly affected by household preferences, trade barriers, and other regional economic characteristics. This study contributes to the amenity-driven migration literatures and informs the debate about the effect of amenities on interregional migrations and regional economic development.

Essays on the Interactions between Land Use, Natural Amenity and Wildfire Risk

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I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

Wenchao Xu, Author

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CONTRIBUTION OF AUTHORS

Dr. JunJie Wu was involved in the design, analysis, and writing of every chapter.

TABLE OF CONTENTS

Page

TABLE OF CONTENTS (CONTINUED)

Page

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (CONTINUED)

ESSAYS ON THE INTERACTIONS BETWEEN LAND USE, NATURAL AMENITY AND WILDFIRE RISK

CHAPTER 1

1. INTRODUCTION

Recent years have seen an increasing trend in residents and policymakers to recognize and promote the development of sustainable and resilient communities. This trend not only focuses on socio-economic activities such as job creation and public services to achieve a higher “quality of life”, but also takes into consideration various issues regarding human/environment interactions, such as urban congestion, environment pollution, ecosystem degradation, and natural disaster impact.

Southern California is not an exception to this trend. Home to approximately 24 million people as of 2008 (U.S. Census), this region as a whole contains more than half of California's population, and is among the most populous and fast-growing regions in the United States. However, the tendency for continued urban and suburban development faces several constraints including development pressures, wildfires, and climate change, which could jeopardize any attempt at achieving more sustainable societies. As urban areas become increasingly crowded and developable land resources are limited, residents gradually move to amenity-rich suburban areas. Southern California’s Wildland-Urban Interface (WUI) is home to more than six million people, with over 800,000 living in the highest wildfire hazardous areas. Therefore, protecting people, property, and natural resources from wildfire threats is very challenging. In addition, as a drier and warmer climatic pattern is expected to develop in Southern California, pressures on local ecosystems will intensify and increase the possibility of wildfires across this area.

In the meantime, environmental and social injustice continues to be an issue. Historically and geographically, access to remote wilderness areas has been dominated by only a small portion of residents, and the impacts of environmental uncertainties and natural disasters such as wildfires only impact a very few residents and communities. However, the social cost is more than likely to be huge and will be shared by all residents including a large portion of residents and communities with negligible accessibility to these areas have had to bear a very large portion of the wildfire suppression cost and post-fire salvaging expenses. This has led to debates over community development and urban planning, such as how to govern and finance those communities and how to plan for future development. Because land uses are highly diversified in these areas, it is equally important to know which land uses contribute to wildfire mitigation and suppression and reduce ecological and socio-economic impacts of wildfires, and which are vulnerable to or even exacerbate wildfires. It is also important to evaluate whether the current wildfire mitigation approaches such as building code and fuel cleaning have been effective.

Science and social science can contribute to the development of sustainable and resilient communities by providing relevant knowledge regarding human-environment interactions. But current literature provides mixed opinions: some studies tend to attribute the increased wildfires to climate change; others blame this increase on active human activities at the remote wilderness areas. This reflects the fact that communities are understudied and ill-equipped for action in response to natural disasters at the human-environment interface in the climate change arena. Limited or fragmented background knowledge regarding the interactions between humans and the environment will limit our ability to generalize this knowledge and apply it in the future land-use decision making.

This dissertation seeks to provide a better understanding of the human-environment interactions on urban spatial profiles and distribution of economic activities. This dissertation contains three essays, each of which addresses human-environment issues from different perspectives.

The first essay is entitled "Land-Use Change and Wildfire Dynamics at the Wildland-Urban Interface in a Changing Climate". The primary objective of this study is to conduct an integrated analysis to investigate the impacts of human activities and environmental features on wildfires at the Wildland-Urban Interface in a changing climate. It focuses on the impacts of human land-use changes by evaluating their density, connectivity, and mix. It addresses the following research questions: 1) How do human activities, climatic factors, and other environmental features influence wildfire occurrence at the WUI areas? 2) What are the impacts of these factors on wildfires in the post-fire degraded ecosystems? 3) How are human activities associated with human-caused wildfires? Hypothesis tests are conducted to demonstrate the spatial heterogeneity of human land-use impacts on wildfires and disclose which land uses contribute to wildfire mitigation and suppression, and which are vulnerable to or even exacerbate wildfire activities. Results will be useful to identify community vulnerabilities, reduce wildfire uncertainties, and strengthen firewise community development and management in response to wildfire threats in the short term. These findings should therefore enhance the development of sustainable and resilient communities and inform future land-use decision making.

The second essay is entitled "Wildfire Risk and Urban Development Pattern in Fire-Hazardous Area". This study is motivated by the interactions between fire-zoning policy and urban development patterns. Currently in California, there is a system of policies and regulations including the Civil Code Sec. 1103 designed for stopping over-development in the fire-hazardous area. These fire-zoning policies reveal wildfire risks (including average land price, development density, and development area) and require disclosure of risk in property transactions. However, the effectiveness of these policies has been questioned as several empirical literatures found there are inconsistent designations in the fire-hazardous area. While empirical argument seems well understood, there has been little work attempting to address the impacts of fire risk disclosure and the consequences of inconsistent fire-zone designations on urban development patterns. The objective of this study is to develop a model to evaluate the quantitative impacts of fire-zone designation on urban development patterns and thus understand the consequences of inconsistent designation in a spatial setting. The model builds on and expands a theoretical framework by Wu (2006) and Wu (2010) with locational amenities and a public decision sector. We introduce wildfire risk into the model. We then solve for the equilibrium conditions for this economy, which reveal the behaviors of local households and public decision sector as well as urban land-use features. To explore this issue further, we calibrate the model and conduct simulations in Mathematica with parameters regarding the U.S. economy. Sensitivity analysis is then conducted to examine how results are affected by the changes in these assumptions. Simulation results will reveal the urban development patterns with various socio-economic settings regarding wildfire risk, locational amenity, and income mix. This paper also helps us understand the impact of fire-zoning policies on urban development patterns and the consequences of inconsistent designations.

The third essay is entitled "Amenity-Driven Migration and the Spatial Distribution of Economic Activity". This study models the role of natural amenities in influencing interregional migration decisions and the spatial distribution of economic activities. Extending the framework of Helpman (1998) by including locational amenities, it presents a multi-market equilibrium framework that includes consumption, production, and trade. We are interested in answering three major questions. First, under what conditions do locational amenities influence the equilibrium distribution of population? Second, what factors determine the equilibrium distribution of population across regions? Third, what roles do amenities play in interregional migration? The answers to these questions will contribute to the understanding of the role of locational amenities in interregional migrations and inform the debate in the current literature.

This dissertation is organized as follows. Chapters 2, 3, and 4 respectively present the essays introduced above. Each essay includes an introduction, research methods, discussion of results, and conclusions. Finally, Chapter 5 provides an overall summary of conclusions and policy implications.

CHAPTER 2

2. Land-Use Change and Wildfire Dynamics at the Wildland-Urban Interface in a Changing Climate

Abstract

This study conducts an integrated analysis to investigate the impacts of human activities and environmental features on wildfire occurrence at the Wildland Urban Interface in a changing climate focusing on the impacts of land use changes as measured by their density, connectivity, and mix. The conceptual model builds on a theoretical framework developed by Woodward (1987) and Neilson (1995) that characterizes the functioning mechanism of ecosystems. The empirical models identify the key factors that influence wildfires. Hypotheses are tested to demonstrate the spatial heterogeneity of human land-use impacts on wildfires and disclose which land uses contribute to wildfire mitigation and suppression, and which are vulnerable to or even exacerbate wildfire activities. Results can inform the design of policies that aim to identify community vulnerabilities, reduce wildfire uncertainties, strengthen firewise community development, and inform future land-use decision making in response to wildfire threats.

2.1 Introduction

Although the United States is no stranger to any severe natural disaster, the 2007 wildfires will be long remembered for their severity and extent. With 9.32 million acres devoured at a federal cost of nearly $1.8 billion, this fire season is among the most costly ones in recent history (Blazer et al., 2008). Southern California was hard hit, with over 3,000 structures destroyed in the October 2007 outbreak. San Diego County was struck by severe massive wildfires, including the Witch (Creek), Poomacha, Rice, and Harris fires. The Witch and Poomacha fires alone burnt a total of 250,000 acres and destroyed 1,900 structures (CDF-FRAP, 2009), causing insured losses estimated at nearly $1.1 billion (RMS, 2008). [1]

Since the 1990s, persistent droughts in California have brought enormous pressures on local ecosystems. The drought-induced biological and ecological impacts spread so widely that they have caused massive vegetation dieoffs and redistribution, broad-scale mortality of species, and continuous accumulation of fuel biomass. Unfortunately, this situation may not improve any time soon. The majority of climate models used by climatologists in the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) predicted that precipitation is likely to decrease, and intra-annual and summer temperatures are likely to increase in Southern California (IPCC, 2007 and 2007b). These forecasts indicate that droughts will continue to develop with a drier and warmer climate in the long run. As climatic factors play important roles in the dynamics of wildfire regimes, climate change will intensify wildfire uncertainties and more wildfires are likely to occur in years to come.[2]

Besides climate change, growing concerns about human impacts on wildfires at these fire-prone wilderness areas also arise. With high population densities and significant development pressures, California faces some of the most severe challenges in natural disaster management in recent history. As cities become more crowded and developable land resources are increasingly limited in urban areas, affluent residents are moving out to amenity-rich suburban areas. It is evident that many of the newest and fastest growing suburbs in Southern California are located within or around fire-prone wilderness areas. Currently, Southern California's Wildland-Urban Interface is home to more than six million people, with over 800,000 households living in the highest fire-prone areas (CDF-FRAP, 2005). Since urban sprawl is prevalent in these areas and increased human activities may exacerbate wildfire occurrence, protecting people, property, and natural resources from wildfire threats will be extremely challenging.

The combination of high development pressures and climate change in Southern California calls for research to clarify their impacts on wildfires and disclose community vulnerabilities in response to wildfire threats. However, current literature provides mixed results about the effects of climatic and anthropogenic factors on wildfire activities. Some studies attribute the increased wildfire activities more to climate change at both regional and global scales. Swetnam and Betancourt (1990) investigated the fire-Southern Oscillation (SO) relations in the Southwestern United States and found that regional climate effects are implicit in the extreme variability of fire occurrence.[3] They concluded that even with changing vegetation dynamics due to human intervention, the fire-SO linkage could have forecasting value and thus important implications for fire management. Swetnam and Betancourt (1998) found that changes in the strength of interannual wet-dry cycles and drought-fire relations are evident in records.[4] Veblen et al. (2000) examined climatic and human influences on fire regimes in the Colorado Front Range and found strong associations between interannual variability in moisture availability (rather than drought alone) and large fire years. Their study also indicated that warmer and drier spring-summers are strongly associated with years of widespread fire. Westerling et al. (2003) analyzed the regional patterns in western U.S. wildfire regimes in response to climate variability and suggested western wildfire is a process largely governed by climate. Westerling et al. (2006) found that interannual variability in wildfire frequency is strongly associated with regional spring and summer temperature, which is consistent with the findings in Veblen et al. (2000) and Donnegan et al. (2001). More importantly, Westerling et al. (2006) found land-use histories have relatively little effect on fire risks, and fire increases are strongly associated with increased spring and summer temperatures and an earlier spring snowmelt.

In contrast, many other studies blame the wildfire dynamics on increased human activities at the remote fire-prone wilderness areas. Cardille et al. (2001) analyzed the environmental and social factors influencing wildfires in the upper Midwest region of the U.S. and found the increased human accesses and activities (such as road density, housing density, and etc.) tend to be positively associated with both fire occurrence and counts. Sturtevant and Cleland (2007) explored the human and biophysical factors influencing modern fire disturbance in northern Wisconsin and indicated that the likelihood of fire starts is primarily influenced by human activities in Northern Wisconsin. Syphard et al. (2007) discovered that anthropogenic factors explained the most variability in fire frequency in the California fire regimes, suggesting that the spatial development pattern may be an important variable to consider when estimating fire risk. Hammer et al. (2007) examined the housing growth at WUI areas in California, Oregon, and Washington and found that housing growth patterns in this region are exacerbating wildfires.

The inconsistent findings on the impacts of human activities on wildfires may exhibit more than spatial heterogeneity of human environment interactions. Some studies (e.g., Syphard et al., 2007 and Hammer et al. 2007) apparently exclude climatic factors. As a result, active human activities could only demonstrate similar impacts on wildfires as climatic factors. If this is the case, their conclusion might have overstated human impacts and eluded the influence of climate change. Besides, this is at odds with the fact that Wildland-Urban Interface is an essential feature of ecosystems and basic principles of ecosystem sustainability shall apply. Other studies used methods such as Pearson's correlations (e.g., Westerling et al., 2003 and Westerling et al., 2006) that are also debatable. Without considering the functioning mechanisms of ecosystems in a systematic manner, non-functional factors could coincidentally exhibit similar features and show strong correlations with wildfire occurrence as functional factors. In addition, many studies were conducted using aggregated data without considering of the spatial heterogeneity of land-use patterns. Replacing such data with aggregated ones will average out the adverse effects of various human factors and conceal the heterogeneity of land-use impacts on wildfires.

The primary objective of this study is to conduct an integrated analysis to investigate the impacts of human activities and environmental features on wildfires at the Wildland-Urban Interface in a changing climate. It focuses on the highly diverse human land-use patterns and changes and evaluates the impact of density, connectivity, and mix on wildfire occurrence at WUI. It addresses the following research questions: 1) How do human activities, climatic factors, and other environmental features influence wildfire occurrence at the WUI areas? 2) What are the impacts of these factors on wildfires in the post-fire degraded ecosystems? [5] 3) How are human activities associated with human-caused wildfires? Hypothesis tests are conducted to demonstrate the spatial heterogeneity of human land-use impacts on wildfires and disclose which land uses contribute to wildfire mitigation and suppression, and which are vulnerable to or even exacerbate wildfire activities. The estimates will be useful to identify community vulnerabilities, reduce wildfire uncertainties, and strengthen firewise community development and management in response to wildfire threats in the short term. The findings should enhance the development of sustainable and resilient communities and inform future land-use decision making.

This paper is organized as following. A theoretical framework is presented in the next section. Building on the theoretical framework, section 3 specifies the empirical models and describes the key factors and GIS data that are collected in this study. Section 4 discusses the empirical results and investigates the relationship between human activities and wildfires in a changing climate. Section 5 discusses policy implications and avenues for future research.

2.2 The Conceptual Framework

In this study, we develop a conceptual model to understand the interaction between human activities and wildfires and to motivate an empirical analysis. Based on previous literature, wildfire risk ($\pi_{Wildfire}$) is assumed to depend on fuel biomass (B_{Fuel}) and ignition risk (I_g) as follows:

(1) $$\pi_{Wildfire} = f(B_{Fuel}, I_g)$$

In general, ignition risk depends on both natural/environmental factors (NE_{fire}) and anthropogenic factors (A_p).

(2) $$I_g = g(NE_f, A_p)$$

Natural/environmental causes of fire range from weather/climate factors (C_W) (e.g., lightning), soil (S_{soil})/topographic features (T_{topo}) (e.g., sparks from falling rocks and volcanic activity), and vegetation (V_e) (e.g., the spontaneous combustion of plant materials and other organic matter) (Barbour, Burk, & Pitts 1980). Human causes include residential activities (e.g., debris burning and smoking), industrial operation (e.g., vehicle use, equipment use, and power-line), recreational (e.g., campfire), and others (e.g., arson).

By contrast, fuel biomass is much harder to determine. The reason lies in the fact fuel biomass is generated in physiological processes as part of the goods and services provided by ecosystems. Ecosystems are complex, diverse, and made up of multiple elements, in which many agents within are acting in parallel, constantly acting and reacting to what other agents are doing, and macroscopic system properties emerge from interactions among components and may feed back to influence the subsequent development of those interactions (Levin, 1998). As these agents are constantly interacting with each others, both functional and nonfunctional variables are, more or less, internally correlated with each other. Without due regards to wildfire behavior and ecosystems in a systematic manner, nonfunctional variables could be erroneously indentified as functional ones, which lead to misspecification of empirical models and misinterpretation of explanatory variables.

Accordingly, this study assumes that fuel biomass can be determined by the same factors that influence ecosystems. Hence, it considers the underlying ecosystem processes on which the goods and services (including fuel biomass) provided by ecosystems depend. It builds on the theoretical framework developed by Woodward (1987) and Neilson (1995), each of which describes the ecophysiological principles of ecosystems. Woodward (1987) presented a schematic framework that describes the relationships between climate and vegetation. It was proposed that leaf area index and vegetation structure and mass can be predicted from the hydrological budget, and the life form of the vegetation may be predicted from minimum temperature (Woodward, 1987). The aim of this model is to predict the maximum leaf area index (LAI) that could be supported at a site within the constraints of abiotic factors to achieve hydrological and energy balance.[6] This schematic framework can be represented mathematically by the combined equations as follow:

(3)
$$\lambda E = \frac{sR + \rho c_p [e_S(T_a) - e] / r_{aH}}{s + \gamma (r_a + r_S) / r_{aH}}$$
$$\frac{1}{r_S} = \sum_{i=1}^{i=L} \frac{1}{r_{S,i}} \quad (Also,\ \frac{1}{r_a} = \sum_{i=1}^{i=L} \frac{1}{r_{a,i}})$$

where E is the evapotranspiration, λ is the latent heat of evapotranspiration, s is the rate of change of saturation vapor pressure with temperature, R is the net radiant balance of the canopy, ρ is the density of the air, c_p is the specific heat of air, $[e_S(T_a) - e]$ is the difference in water vapor pressure between the ambient air (e) and the air at saturation ($e_S(T_a)$), γ is the psychrometric constant, i is the number of leaf layers, and L is the maximal leaf area index (Monteith, 1973 and 1990). The total of all the stomatal and boundary layer resistances of the individual leaves of the canopy are r_S and r_a respectively. The boundary layer resistance r_{aH} is the boundary layer resistance to sensible heat. The first equation (the Penman-Monteith equation) of the schematic framework in equation (3) describes how the potential evaporation of a site could be affected by generally observed meteorological variables. The second one calculates the total of all the stomatal and boundary layer resistance (r_S and r_a respectively) that changes as canopy layers differ. The stomatal and boundary layer resistance are the key factors that bridges between evapotranspiration and leaf canopies to meet the physiological need, and thus between climate and vegetation.

The theoretical framework implies that the local climate and other environmental characteristics (e.g., vegetation, soil, and topographic features) can have strong influence on evapotranspiration, and thus plant physiology and ecosystem functioning. For example, the boundary layer resistance is strongly influenced by wind speed and leaf size (Gates and Papian, 1971; Grace, 1977). The stomatal resistance depends on various climatic features, in particular irradiance, temperature, vapor pressure deficit, and plant water potential (Jarvis, 1976). More generally, the growth of vegetation is directly related to its ability to intercept solar radiation, which will be converted to carbohydrates (Monteith, 1972 and 1977). The availability of water has a strong influence on leaf area index (Woodward, 1987). And the long term integration of growth processes may be controlled by both temperature and by plant water potential (Tyree and Jarvis, 1982). The geographical range of major physiognomic types of vegetation is dependent on the basis of the annual minimum temperature. During the processes to achieve the hydrological and energy balance, other environmental features exert their influence too. For example, a volume of water will be extracted by plants before the effects of drought occur. This volume is closely dependent on soil structure, soil hydraulic conductivity, and water supply other than directly from precipitation (Woodward, 1987). Some plants may influence water and nutrient dynamics, trophic interactions, or disturbance regime; changes in the abundance of these species will affect the structure and functioning of ecosystems (Chapin et al., 1997). [7]

The model proposed by Woodward (1987) provides a systematic way to predict the geographical distribution of vegetation, whereas prediction errors were admitted.

Woodward (1987) suggests that a more precise model should embody both life-cycle and growth characteristics of the species under investigation. The Mapped Atmosphere-Plant-Soil System (MAPSS) developed by Neilson (1995) is one such model. Similar to the Woodward schematic framework, the MAPSS model combines soil-water balance and plant physiology and predicts the potential vegetation type and leaf area that could be supported at any site within the constraints of abiotic constraints, including water, carbon dioxide (CO2), energy (solar radiation), nutrients, and disturbance regimes (such as wildfires).The MAPSS model focuses mainly on the water side, as water is an essential component in ecosystems, and site water balance is apparently the primary determining factor of vegetation distribution within the conterminous U.S. (Woodward, 1987; Stephenson, 1990, 1998; Neilson et al., 1992). Compared to the Woodward schematic framework, the MAPSS model has a more complicated structure to carry out simulations with and more explicit variables to use. It has been successful for predictions of new vegetation distribution patterns, soil moisture, and runoff patterns in alternative climate at a continental scale (Neilson, 1995).

Beyond the theoretical framework, the impacts of human activities on ecosystems have gained considerable attentions. Although human impacts are not explicitly characterized in the both framework, empirical evidence suggests that human activities not only can exacerbate wildfires, but can exert added influence and disturbances on ecosystems. Like climatic factors, human impacts on ecosystems permeate into various aspects of ecosystems and have some noteworthy features. First, human impacts on ecosystems are complex and ambiguous: they can be beneficial or detrimental, direct or indirect, and long-term or short-term. Second, human impacts exhibit spatial heterogeneity. The highly diverse land-use patterns in the WUI areas will exert different impacts on ecosystems, the outcomes of which will result in disparities across communities environmentally and socioeconomically. Third, human impacts may be subject to change over time. This means that short-term benefits from land-use activities may be contradictory to their long-term objectives. Last, humans not only impact climate and ecosystems, but also actively respond to climatic factors. A changing climate may mean more volatility in human impacts to the remote wilderness area, and thus more uncertainties for both ecosystems and wildfires.

Taking together, this study assumes that fuel biomass depends on both anthropogenic and environmental factors (e.g., climate, vegetation, soil, and topographic characteristics) as:

$$B_{Fuel} = h(C_W,\ V_e,\ S_{soil},\ T_{topo}, A_p) \tag{4}$$

Substitute equation (2) and (4) into (1), we obtain

$$\pi_{Wildfire} = f(C_W,\ V_e,\ S_{soil},\ T_{topo}, A_p) \tag{5}$$

Equation (5) indicated that the factors that influence wildfire risk can be narrowed down to the factors in three major categories: human activities, climate, and other environmental features. In the following section, empirical models will be built based on this characterization.

2.3 The Empirical Specification

As wildfire activities typically depicted with observations showing burned or not-burned, the regression methods for categorical data analysis are adopted. Categorical analysis is a statistical regression tool that predicts the probability of a discrete choice response based on a variety of explanatory variables (McCullagh and Nelder, 1989; Hosmer and Lemeshow, 1989; Collett, 1991; Stokes et al., 2002). It transforms a linear equation that relates a mean response to a vector of explanatory variables through a link function. In our models, the fire occurrence at any given location i in the year t is characterized in general as:

(6) $$y_{i,t} \mid x_{i,t} \sim \text{Bin}(1,\ \pi_{i,t});\ g(\pi_{i,t}) = x'_{i,t}\,\beta \qquad (i = 1,...,3000;\ t = 1990,...,2004),$$

where $\pi_{i,t}$ is the probability that wildfire occurs at location i in the year t. $y_{i,t}$ is a site-specific indicator of wildfire occurrence: $y_{i,t} = 1$ means that location i is burnt by wildfires in the year t, whereas $y_{i,t} = 0$ means the opposite. There are 3,000 sites that are selected by random sampling (see Figure 3), where the observations of y are recorded annually across a 15-year span (from 1990-2004). $x_{i,t}$ is a vector of independent variables and β is a vector of regression parameters to be estimated. g is a canonical link function, which transforms a linear combination of the explanatory variables $x_{i,t}$'s into a nonlinear form.

In response to the three major research questions, three models are specified. Model 1 addresses the first research question, that is, what are the impacts of human land uses, climatic factors, and other environmental features on wildfires at the WUI areas. The empirical model is specified as follows:

$$(7) \qquad y_{i,t} \mid x_{i,t} \sim \text{Bin}(1,\ \pi_{i,t}); \quad g(\pi_{i,t}) = \log\left(-\log\left(1-\pi_{i,t}\right)\right) = x'_{i,t}\,\beta$$

$$(i = 1, \ldots, 3000;\ t = 1990, \ldots, 2004),$$

where $y_{i,t} = 1$ if a wildfire occurred at location i in the year t., $y_{i,t} = 0$ otherwise. The link function takes a complementary log-log form, which fits better for highly unusual events like wildfires (Coles, 2001).[8] In our data sample, 1,165 of 45,000 observations have a burning record ($y = 1$), whereas the others do not ($y = 0$).

Model 2 addresses the second research question, that is, which factors influence wildfire occurrence at the post-fire degraded ecosystems. The empirical model is specified as:

$$(8) \qquad y_{i,t} \mid x_{i,t} \sim \text{Bin}(1,\ \pi_{i,t});\ g(\pi_{i,t}) = \log\left(-\log\left(1-\pi_{i,t}\right)\right) = x'_{i,t}\,\beta$$

$$(i = 1, \ldots, 3000;\ t = 1990, \ldots, 2004),$$

where $y_{i,t} = 1$ if the location i is burnt both in the year t and within a five-year interval prior to the year t, and $y_{i,t} = 0$ if the location i is NOT burnt in the year t, but is burnt within a five-year range prior to the year t. n_t is the total number of the sites that are burnt within a five-year range prior to the year t. The second sample includes 5,446 observations in total and 117 observations have a burning record. [9]

Model 3 addresses the third research question: how human activities can contribute to human-related wildfires. The empirical model is specified as:

(9) $$y_{i,t} \mid x_{i,t} \sim \text{Bin}(1,\ \pi_{i,t});\ g(\pi_{i,t}) = \log\left(\frac{\pi_{i,t}}{1-\pi_{i,t}}\right) = x'_{i,t}\,\beta$$
$$(i = 1, \ldots, n_t;\ t = 1990, \ldots, 2004)$$

$y_{i,t} = 1$ if a wildfire incident is identified as human-related at the location i in the year t and $y_{i,t} = 0$ if not. To get a better estimation, we use a conditional binomial logistic model and stratify the data according to elevation categories. The link function takes a logit form, as the 0's and 1's are roughly balanced. The third sample includes all the aforementioned 1,165 observations with wildfire burning record. And 621 observations are identified as human-caused ($y = 1$) (see Figure 4).

Building on the theoretical framework developed by Woodward (1987) and Neilson (1995), identification of the key factors for the empirical models can be conducted in a simple way: variable selection and GIS data collection are focused on, but not limited to, the water-cycle related variables. This approach is justified by the logic of MAPSS model, which characterizes the ecosystem functioning through the water cycle.[10] Within a complete water cycle, water, carbon, energy, and nutrients work together to support both the physiological needs of plants and organisms and fulfill the functioning of ecosystems. The logic of MAPSS model implies that if factors that are relevant to the water circulation, then they are equally relevant to the functioning mechanism of ecosystems, and thus should be considered in the empirical models.

Accordingly, a comprehensive dataset is developed using ArcGIS and SAS. The dataset integrates the GIS data layers from government agencies at the federal, state, and local levels. These variables can be assorted into six major categories as follow:

1. **Fire history** (1980-2004) contains the fire id, acreage, cause, and other GIS information on an annual basis from the San Diego Graphic Information System (SanGIS) (see Figure 3 and 4).
2. **Vegetation** variables include the vegetation type from CDF-FRAP (see Figure 5) and the Pitch Canker infection zone by the State of California Board of Forestry (BOF) in 1997 from CDF-FRAP.
3. **Soil** variables include the soil series (see Figure 6) from the Soil Survey Geographic Database (SSURGO) of the Natural Resources Conservation Service of U.S. Department of Agriculture (USDA/NRCS), the post-fire erosion class from CDF-FRAP, and the ground water replenishment from the Water Resources of the United States of U.S. Geological Survey (USGS/WRD).
4. **Topological** variables include an elevation dummy variable calculated from the Digital Elevation Model data (see Figure 7) by USGS/EROS, an aggregated slope indicator from SanGIS, and the distance to river calculated using the hydro-geographic data layer (see Figure 8) from SanGIS.
5. **Climatic** variables include the maximum temperature in September from the PRISM Climate Group (PRISM), the minimum precipitations in April and September from PRISM, the mean dew-point in September from PRISM, the atmospheric pressure from the U.S. National Aeronautics and Space Administration

(NASA/SSE), the wind speed from NASA/SSE, and the solar resource from NASA/SSE.

6. **Human activity** variables include the land uses (see Figure 9) from the San Diego Association of Governments (SANDAG) and the road development (see Figure 10) from SanGIS. We calculate the shares of eight major land-use types within each block group at the WUI areas.[11] These shares are used to characterize the mix of land uses.[12] We also calculate the density of all roads and local roads in the same block groups. This not only takes into account of human connectivity to the remote wilderness areas, but also informs land-use density as early literature (e.g., Hammer et al. 2007) suggested that road density is a close proxy for population and development density. The block-group-level land-use features are passed on to any of the 3,000 sites that are located in the corresponding block groups.

The details of the description of variables are shown in Table 1.

Several potential statistical/econometric issues may arise in the estimation of the econometric models, including spatial heterogeneity, spatial dependency (or spatial autocorrelation), regression algorithm, and model fitting. Spatial heterogeneity is referred to as the uneven distribution of elements with regards to composition, structure, function, and impact. Spatial heterogeneity plays a central role in ecological theories and a practical role in population sampling theory (Legendre and Fortin, 1989). In this study, wildfires and their geographical impacts are among the most crucial elements pertaining to spatial heterogeneity. Traditionally, wildfires are often treated as on an incident scheme in the current literature. Many studies use aggregate data to analyze the factors influencing wildfire occurrence. Such approaches could potentially average out the spatially heterogeneous features of explanatory variables. Besides, as extreme events, wildfires are usually characterized with a very small probability of occurrence, although wildfire incidents have been seen on the rise in recent years. Thus, using the traditional scheme may result in a very small data sample and hinder this study from fully exploiting the information that is stored in the GIS data layers. Therefore, this study adopts random sampling scheme, which means that sites are chosen independently and identically over space (Cressie, 1991). Specifically, 3,000 sampling sites are randomly selected within the San Diego WUI area using ArcGIS 9.3 (also see Figure 4).[13] The observations of fire incidents at the selected locations are recorded on an annual basis for 15 consecutive years from 1990 to 2004.

Spatial dependency (spatial autocorrelation) refers to the pattern in which neighboring sites are more likely to demonstrate similar characteristics than by chance alone (Fortin et al., 2002). It can decrease the precision of the estimates and reduce the reliability of hypotheses testing, as the estimates of the variance of the estimators are generally biased (Anselin, 1988; Legendre and Fortin, 1989; Cressie, 1991; Anselin and Florax, 1995; Goovaerts, 1997; Dubin, 1998). There are several approaches that have been developed to control spatial dependency in a discrete choice framework. One approach is to model the process itself and requires the use of a spatial weight matrix W (Anselin, 1988; Anselin and Florax, 1995). However, this approach does not fit well in this study: a weight matrix with 45,000 by 45,000 elements will inevitably increase the computation intensity. Besides, the choice of weighting scheme for W is known to significantly influence the estimation of spatial correlation coefficient (Durbin, 1998). Another approach is spatial sampling, which relies on selecting a noncontiguous subset of observations to draw inferences, and thus requires a large initial data set with sufficient variation to offset the loss of information and inefficiency (Carrión-Flores and Irwin, 2004). Considering the GIS data and the computational difficulties involving, the random sampling is considered the main scheme to correct spatial dependency. Nevertheless, we should be alerted that random sampling scheme will not remove true or induced spatial autocorrelation (Fortin et al, 2002). This is because there is an underlying spatial pattern in the distributions of organisms and their environment, and thus spatial autocorrelation is frequently encountered in ecological data (Legendre and Fortin, 1989). Besides random sampling scheme, we conduct spatial interpolations (including Kriging). Kriging is an optimal interpolation based on regression against observed values of surrounding data points, weighted according to spatial covariance values (Cressie, 1991; Goovaerts, 1997). Different from the spatial weight matrix method in which the process generating the errors is modeled (Anselin, 1988; Anselin and Florax, 1995), Kriging assumes a functional form for the covariance structure (Dubin, 1998). But the Kriging interpolation approach is only applied to the low-resolution maps in ArcGIS 9.3, but not to all the variables in the dataset.[14] As a result, we should be alerted that spatial dependency (spatial autocorrelation) is not completely resolved in this study.

The parameters in the three models are obtained by using Maximum Likelihood Estimation via the Newton-Raphson algorithm in the Logistic procedures in SAS 9.2. As some of our explanatory variables are continuous, the Hosmer-Lemeshow test and the residual chi-square (score) test are among the strategies to evaluate model fitting (Stokes et al., 2000). The Hosmer-Lemeshow test places observations into k deciles based on the model-predicted probabilities, then computes a Pearson chi-square test based on the observed and expected number of subjects in the deciles (Hosmer and Lemeshow, 1989; Stokes et al., 2000). The statistic is compared to a chi-square distribution with $k-2$ degrees of freedom: the higher the p-value, the better the model fitting.[15] When the Hosmer-Lemeshow test is not feasible (e.g., in the conditional logit model), the residual chi-square (score) test statistic is examined. This criterion evaluates the extent to which the residuals from the model are linearly associated with other potential explanatory variables: if there is an association, this is an indication that these variables should also be included in the model (Stokes et al., 2000). This criterion is in combination with the backward elimination, another model-building strategy. We specify the significance level of the Wald chi-square for a variable to stay in the model. If the effect cannot meet the significance level, this strategy removes variables from the model one at a time until the residual chi-square becomes significant (SAS, 2009). The test of model-fitting and application of model-building strategy is conducted in SAS 9.2. The estimates are also cross-validated with science and social science literature, which are discussed in the following section.

2.4 Results

We begin our empirical inquiry by examining the three data samples respectively. All analyses are carried out in SAS 9.2. The parameters estimated are summarized in 2.2, 2.3, and 2.4. Test statistics are also reported to evaluate variable significance and model fitting. Four major hypotheses are tested:

1) Fire mitigation and suppression approaches (e.g., building code and fuel cleaning) adopted on some land uses have been effective in reducing wildfire impacts.

2) Human accessibility and low density development in the remote wilderness areas increase wildfire risk.

3) Seasonal human activities may increase wildfire risk, which may cancel out the effectiveness of fire mitigation and suppression approaches.

4) Human activities reduce wildfire occurrence in general but contribute to human-caused wildfires.

(Tables 2.2 – 2.4)

Table 2.2 presents the results of the estimated relationship between various factors and wildfires in the WUI areas in San Diego County, CA. The Hosmer-Lemeshow test statistic suggests that the first model has an adequate fit. The findings are used to address the first research question: how do land uses, climatic factors, and other environmental features influence the wildfire occurrence at the WUI areas? Overall, our estimates are consistent with our expectation based on both theoretical and conceptual framework.

First, the estimates highlight the effects of environmental factors (including vegetation, soil, and topographic features) on wildfire activities. Vegetation type plays a critical role in influencing wildfire occurrence. Particularly, shrub lands are more prone to wildfires than landscapes covered with all other major types of vegetation, including grass, conifer, and hardwood. Consistent with the current literature, this finding raises safety concerns, again, for both land-use and other human activities at these areas. Forestry health condition is highly relevant to wildfire occurrence, as the sites located in the pitch canker infection zone have higher possibility of wildfire outbreaks. Soils are also important in wildfire analysis, whilst spatial heterogeneity in the relationship between different soils and wildfires are evident as well.[16] Of all the soil series found at the selected sites, the soil series of MUKEY 660448, 660448, and six others (see Table 2.2) are seen positively correlated with wildfire risk compared to the reference group. [17] In contrast, the sites with the soil series of MUKEY 660468 and 661097 are less likely to be burnt. The distance to the closest water body is negatively associated with wildfire occurrences: the closer a site is to a river, the more wildfire incidents are. Similarly, elevation is also seen to be negatively associated with wildfire occurrences. Everything else equal, our estimate suggests that those sites located within the range of 2 km and 6 km, as a matter of fact, are less likely to be burnt by wildfires. This could be attributed to the lower levels of temperature, precipitation, and vegetation coverage in the higher elevation area, although active human activities and few fire-suppression means could contribute to wildfire dynamics in these areas.

Second, our estimates also suggest that the roles of climatic factors in wildfire activities are significant, with which more complicated mechanisms could be involved. As vegetation growth is facilitated by increased level of precipitation in growing seasons, fuel biomass may accumulate as well. Higher precipitation levels in early spring (April) and late summer (September) are more likely to increase wildfire risk.[18] Higher solar radiation also contributes to wildfire occurrence, but its effects vary spatially: higher-slope locations with higher level of solar radiation are more likely to be burnt, whereas wildfire at the sites with higher post-fire erosion potentials are less likely to occur. Higher temperature in late summer (September) increases wildfire risk too, but its role in influencing wildfires is fundamentally different from those of precipitations. Its impacts are mainly on the fuel biomass side, as high temperature can increase evapotranspiration, decrease soil moisture, and convert more vegetation into fuel stock. Dew-point in September seems to do the opposite, which is negatively correlated with wildfire occurrences. [19] As an indicator for humidity level, higher level of dew-point in late summer can hinder wildfire from spreading.[20] Higher wind speed can facilitate wildfire spread. Atmospheric pressure is among the most influential one of all factors, a lower level of which greatly increases the possibility of wildfire ignition and spreading. As the Santa Ana winds in the late summer blow from the high-pressure area around Nevada to the low-pressure area around the Southern California coast, this estimate implies that the prevailing winds in the late summer could be a contributing factor to the wildfire dynamics.

Third, the estimates suggest strong correlations between human land-use changes and wildfire dynamics at these areas. And the changes in the mix, density, and connectivity of various land uses suggest the spatial heterogeneity in various land-use patterns can exert various impacts on wildfire occurrence. For example, raw correlations show that the increases on the land uses for residential development and industrial operation are negatively associated with the wildfire activities, given that the shares of land uses for commercial purpose, transportation facilities, and public facilities (government offices, public services, hospitals, schools, and etc.) remain unchanged. This estimate may run counter to many people's expectation. Although most people may expect the opposite estimation, this finding may, simply, reflect the *status quo* that strict fuel mitigation approaches (e.g., fuel cleaning and building codes), zoning policies, and wildfire suppression efforts effectively control wildfire spread in the Southern California's wilderness areas. Everything else equal, area with higher land-use portion of open space easement and agriculture purpose is, to the opposite, more susceptible to wildfires. This is consistent with the fact that fuel biomass associated with open space easement and agriculture is usually high. Besides, recreational activities in the wilderness areas contribute to wildfire risk as well. Similarly, the increase on the land left vacant and under-construction is positively correlated with wildfire activities; negligence of wildfire mitigation and insufficient management of fire mitigation and suppression should be blamed on. The results also disclose the vulnerability of local communities, as the block group is small enough and the increased wildfire activities that could be induced by land-use changes will cause direct consequences for residents and business that are located within these areas.

Although human access to wilderness areas is often blamed for wildfire dynamics, our estimates regarding the density and connectivity of land uses reveal that this preconception is, at least in part, inaccurate. In general, the density of major roads to the wilderness area is negatively correlated with wildfire occurrence, which suggests that human connectivity to the wilderness area decreases wildfire risk. In this case, human access exhibit two different impacts on wildfires: although it increases the possibility of wildfire ignition, it also facilitates transportation of fire suppression facilities and resources in an effort to reduce burnt areas, the latter of which apparently dominates. In the remote wilderness area, local roads gradually become the dominant road type. They provide more accessibility to remote wilderness areas, but their lower function quality may hinder fire suppression efforts. As road density is a close approximation for population density, it implies that low-density development can be vulnerable or even exacerbate wildfires in the remote wilderness areas.

Last, our results indicate that human actively responds to climatic factors as the interaction between human and climate performs surprisingly well. Human are known to respond to climatic factors in very active ways. For example, residential development may be active in the areas with amenable climates, while suitable climatic factors that help to promote productivity and lower cost for agricultural and horticultural production. [21] We found the interaction between residential land use and the climate indicator (i.e., NDP09) is positively correlated with wildfire occurrences. [22] This echoes the concern of the residential development for vacation purposes with regards to fire mitigation and suppression issues: these residential developments are only occupied seasonally and lack of fire management could create serious problems. Similarly, the interaction between industrial land use and NDP is positively correlated with wildfire occurrences. By contrast, the interactions between other land uses (i.e., open space easement, agriculture, vacant land, and under-construction land) and climate indicators show negative correlations with wildfire activities, as the forest management and fire suppression effectively reduce wildfire ignition or spreading during fire seasons. As the fact that the change of land uses is evaluated annually and the climate indicators are seasonal ones, it could be inferred from our results that human impacts on wildfire occurrence also exhibit seasonal features, which could be different from the annual ones.

The next research question to be addressed is: How do the aforementioned factors contribute to wildfires in the post-fire degraded ecosystems. These results are displayed in Table 2.3. The variables are selected by using the backward elimination by setting the significance level at 0.30, at which the least significant effect that does not meet for staying in the model is removed. Both the Hosmer-Lemeshow test statistic and the Residual Chi-square (Score) test statistic suggest the second model has an adequate fit. Surprisingly, the fitted model contains fewer climatic variables than Model 1, which implies that climatic factors may exert fewer impacts on the post-fire degraded ecosystems. This finding is, in fact, consistent with the current literature that wildfires burn off organic materials and then condense on soil particles causing them to become water repellent (Debano, 1981 & 2000; Benavides-Solorio and MacDonald, 2001; Letey, 2001), which disrupt the site water balance and the water circulation. The literature regarding the fire-induced soil water-repellency explains why the soil variables are still relevant in studying wildfires and the impacts of other environmental features turn out to be less significant. Among the environmental factors, atmospheric pressure is still a strong factor that influences wildfire risk, which indicates how the prevailing winds contribute to wildfire spread. Sites located within the Pitch Canker infection zone or located in the area with soil types of MUKEY 660457, 660458, 660460, 660477, and 661097 are also likely to be burnt by wildfires.[23] By contrast, human land-use activities are still seen significant correlations with wildfire occurrence with the same signs as those in Table 2.2. For example, increased land use for residential development and industrial operation may reduce wildfire risk, whereas increase land use for open space & parks, agriculture, and vacant land may do the opposite, given that the shares of land uses for commercial purpose, transportation facilities, and public facilities (government offices, public services, hospitals, schools, and etc.) remain unchanged. Similar to Table 2.2, the results in Table 2.3 also exhibit seasonal features of human impacts on wildfire. Spatial heterogeneity is a concern as well: the impacts of some land-use patterns (e.g., industrial operation, open space & park, and local roads) seem to be insignificant, which could be attributed to lack of enough observations rather than irrelevancy.

The last research question to be addressed is: How human land use activities associated with human-related wildfires. We focused on the difference in the roles of human activities between human-related wildfires and wildfires of all causes. [24] Of all the 1,165 observations at the 3,000 selected locations during 1990-2004, 621 are identifiable as human-related and 544 are not.[25] Examination of these observations not only identifies the most relevant contributing factors in human-caused wildfires, but helps to disclose the difference in the roles of human factors between human-related and non-human-related wildfires. These results are displayed in Table 2.4. [26] The variables are selected by using the backward elimination by setting the significance level at 0.30, at which the least significant effect that does not meet for staying in the model is removed. The Residual Chi-square test statistic suggests the model has an adequate fit.

Compared to the estimates in Tables 2.2 and 2.3, there are two notable differences. First, the increase on the share of industrial land use increases human-related wildfire risk, whilst the increase on the share of residential land use decreases human-related wildfire risk. However, another fitted model that examines a sample of human-related wildfire occurrence provides estimates that still support the conclusions made for Table 2.2.[27] The seemingly contradictory results require further investigation of the land-use features of the regions (block-groups) with fire-burnt sites. A close examination of these samples reveals that compared to the regions (block-groups) without fire-burn history, industrial land use in the regions (block-groups) with fire-burn history exhibit a much lower share of industrial land use (0.00184 with maximum 0.1019 in the ever-burnt regions vs. 0.0125 with maximum 0.8845 in the non-burnt regions), whereas the difference in the share of residential land use between them is much smaller (0.0937 with maximum 0.8491 in the ever-burnt regions vs. 0.1375 with maximum 0.9229 in the non-burnt regions). Although fire mitigation and suppression efforts by human activities on the industrial land use can effectively control wildfire spread in general, industrial operation may, on the other hand, increase the chance of human-related fire ignition. And this is also consistent with the fact that human-related causes such as vehicle use, equipment use, and power-line, are among the leading ones of all wildfire causes at the site level.

Second, this examination also reveals the differences in the effects of other features, such as the road density and elevation. The share of local road grows to an average of 0.8309 from 0.7842 with a much lower density (8.0356 vs. 12.4491) in the ever-burnt areas compared with the non-burnt areas. The road density feature explains the other major differences in the impact of human activities on wildfires compared to the estimates in Tables 2.2 and 2.3. Local roads with reduced functions may only contribute to human activities to the remote wilderness areas and exacerbate human-related wildfires, and could hinder fire suppression efforts when fire occurs. Taken together, it could be inferred by combined results in Tables 2.2-2.4 that human activities in the wilderness areas do exacerbate human-caused wildfire activities, which cancel out human efforts in wildfire mitigation and suppression. The examination also indicates that the ever-burnt areas are located where elevation is at 2 km or higher. But this does not necessarily mean that these areas are more prone to human-related wildfires or even wildfires in general, as wildfire risk in these areas can be interpreted by various other environmental and anthropogenic factors. However, this justifies the usage of elevation dummy variables in our empirical analysis.

In sum, our results demonstrate how human activities, climate, and other environmental features influence wildfires at the WUI areas. Our findings confirm previous studies that a changing climate in Southern California, projected as a drier and warmer climate, will exert more pressures on the wildfire activities in WUI areas. Our estimates also imply that human activities and accessibilities in the fire-prone areas, evaluated by various land-use patterns and changes, have very complicated relationships with both ecosystems and wildfire activities and exhibit great spatial heterogeneity. Hypotheses tests suggest that the fire mitigation and suppression approaches (e.g., building code and fuel cleaning) adopted on some land uses have been effective in reducing wildfire impacts. And human connectivity to the remote wilderness areas, in general, reduces wildfire burnt areas. By contrast, the land uses in the low-density areas are vulnerable to or even exacerbate wildfires. Seasonal human activities may increase wildfire risk, which may cancel out the effectiveness of fire mitigation and suppression approaches. And human activities reduce wildfire occurrence in general but contribute to human-caused wildfire.

2.5 Conclusion

Development of sustainable and resilient communities has received a great deal of attentions from the general public and policymakers. This idea not only focuses on socio-economic activities such as job creation and public services to achieve a higher "quality of life", but also takes into consideration various issues regarding human-environment interactions, such as urban congestion, environment pollution, ecosystem degradation, and natural disaster impact. Southern California is not an exception. Home to approximately 24 million people as of 2008 (U.S. Census), this region as a whole has more than half of California's population, and is among the most populous and fast-growing regions in the United States. However, the tendency for continued urban and suburban development faces several constraints including development pressures, wildfires, and climate change, which could jeopardize any attempt at achieving more sustainable societies.

Development of sustainable and resilient communities requires knowledge regarding human environmental interactions. This study seeks to provide a better understanding of human-environment interactions. It conducts an integrated analysis by investigating the impacts of human activities, climate, and other environmental factors on the wildfire activities at the WUI areas. This study builds on the theoretical framework developed by Woodward (1987) and Neilson (1995) to characterize the ecosystem functions and services through the water circulation. The empirical models focus on the impacts of land-use changes and identify the key factors that influence both ecosystems and wildfires. By examining the data samples collected from WUI area of San Diego County, CA, this study reveals a very complicated picture of how these factors contribute the wildfire activities at the WUI area in a changing climate. The results suggest that the fire mitigation and suppression approaches adopted have been effective in reducing wildfire impacts. Particularly, human activities in the low-density areas are more vulnerable to wildfires and may increase wildfire risk in the remote wilderness areas than elsewhere, although human connectivity to these areas, in general, reduces wildfire risk. Seasonal human activities may increase wildfire risk, which may cancel out the effectiveness of fire mitigation and suppression approaches. Human activities reduce wildfire occurrence in general but contribute to human-caused wildfire. In sum, spatial heterogeneity in human impacts on wildfires is evident and deserves further investigation.

These results help to identify community vulnerabilities, reduce wildfire uncertainties, and strengthen firewise community development in response to wildfire threats in the short term. The findings should enhance the development of sustainable and resilient communities and inform future land-use decision making. Nevertheless, some of the simplifying features of the model should be kept in mind when we interpret the above results. First, we only assume that land-use activities impact wildfire occurrence, but not the other way around. Otherwise, the endogeneity issue may arise, and thus could potentially invalid the specification of the empirical models in this study.[28] Second, we assume that fuel biomass will not accumulate over years at the site level, given the fact that property owners have the responsibility of fuel cleaning at the fire-prone area. This limits the possibility of extending the empirical model within a temporal dynamic context.

This study addresses the importance of using multi-disciplinary knowledge in future studies to investigate human-environment interactions, which can entail a deeper level and a broader scope. It suggests that future studies should focus on the community vulnerabilities in response to natural disasters. Future research avenues should include both building on theoretical framework that can systematically specify the functioning mechanism of systems and extending both spatial and temporal relations into both the theoretical framework and statistical techniques.

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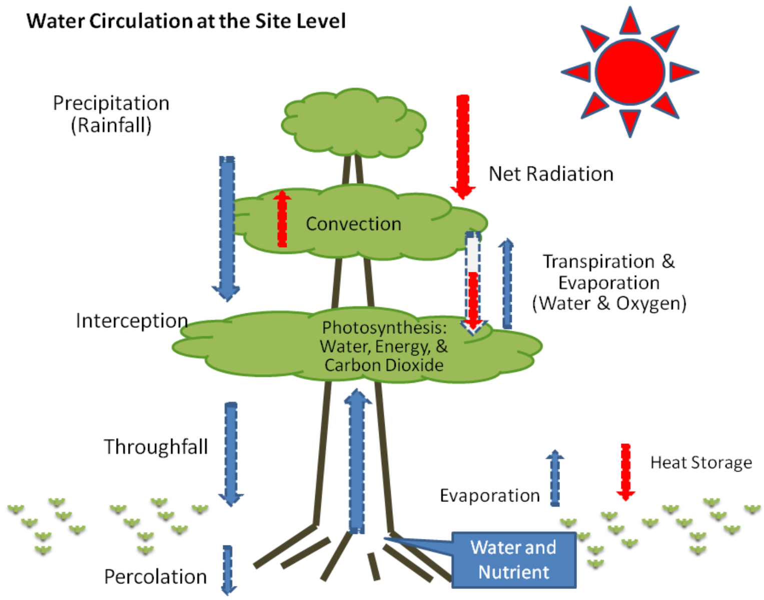

Figure 2.1 The Water Cycle at the Site Level

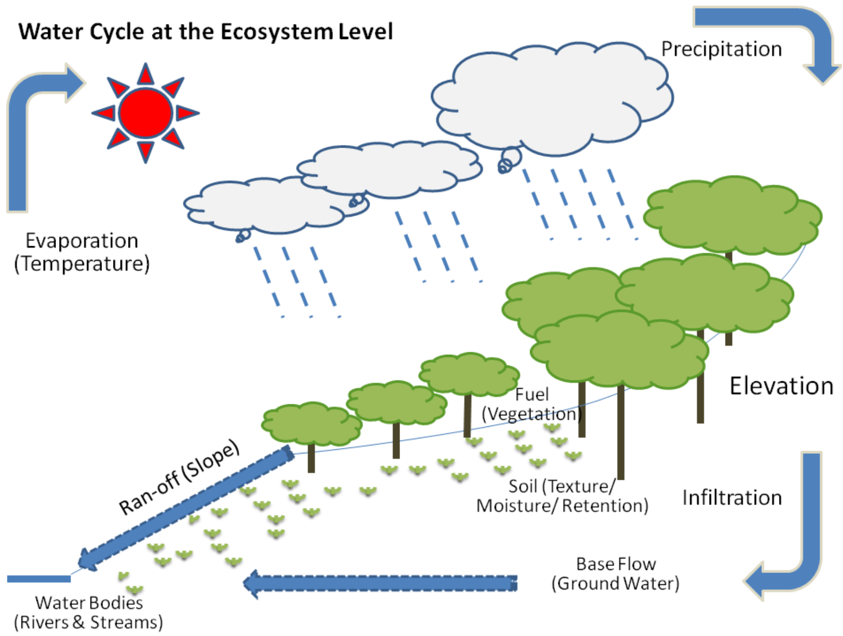

Figure 2.2 The Water Cycle at the Ecosystem Level

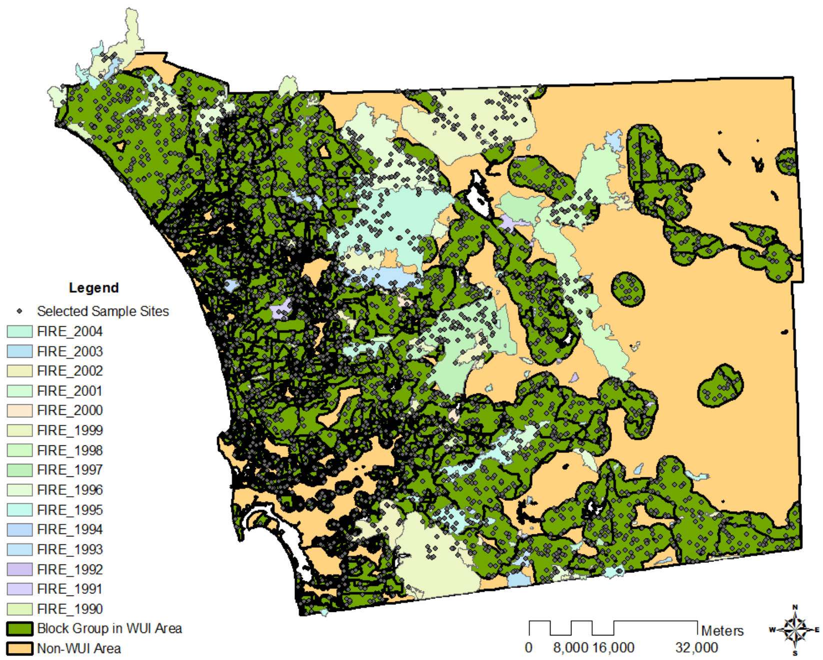

Figure 2.3 Fire History in the WUI Area of San Diego County

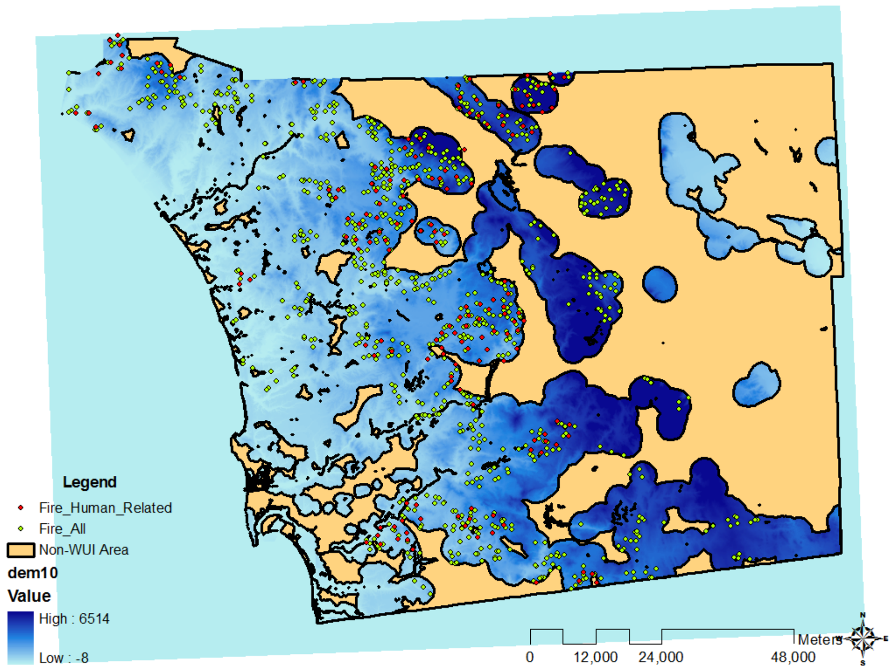

Figure 2.4 Pointwise Records of Human-related Fire in San Diego County

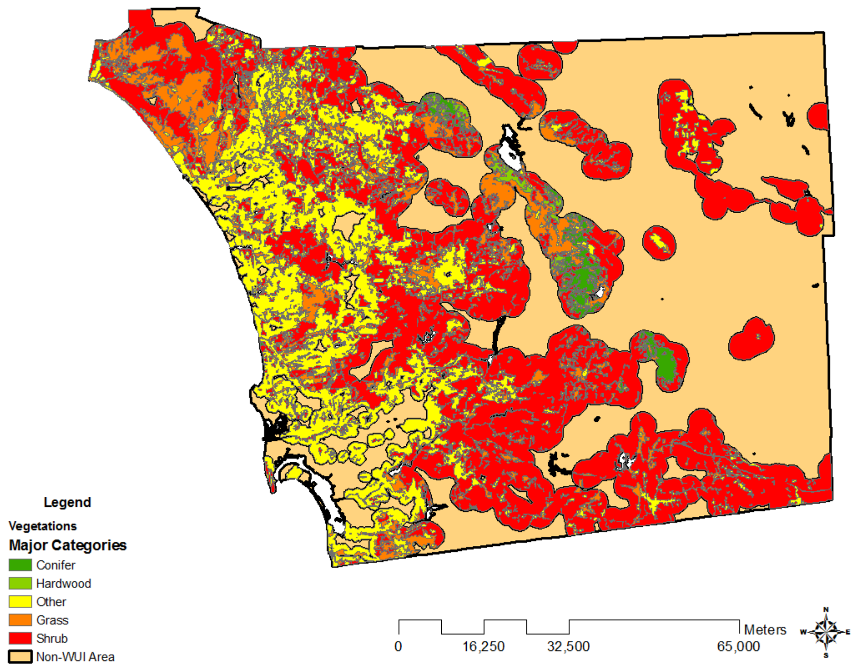

Figure 2.5 Distribution of Major Vegetation Types in San Diego County

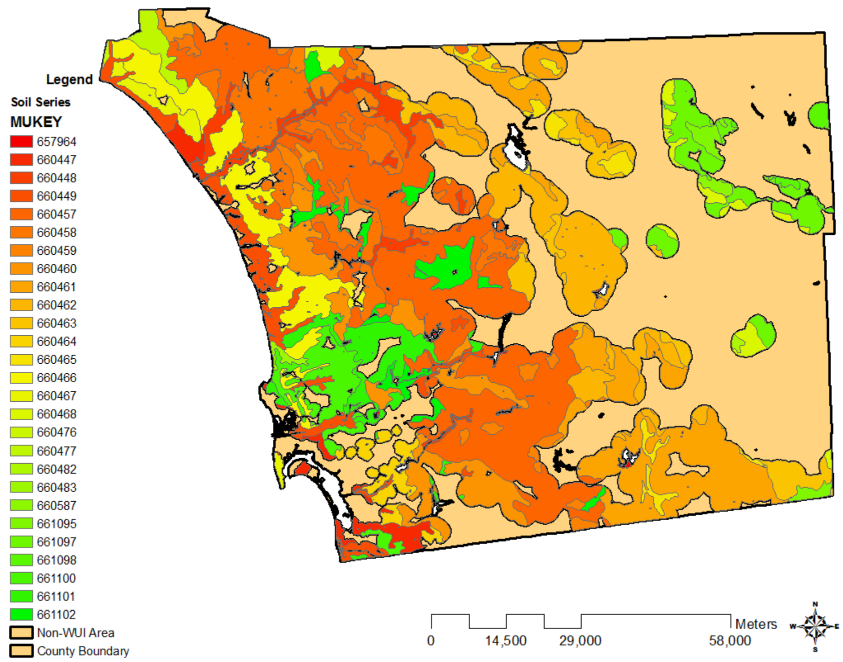

Figure 2.6 Soil Series in San Diego County

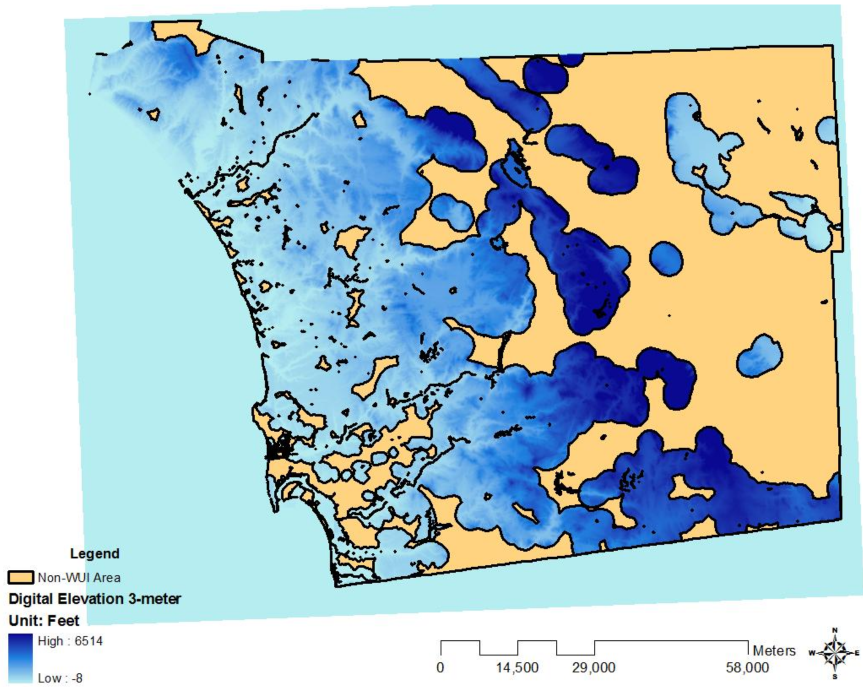

Figure 2.7 Elevation in San Diego County

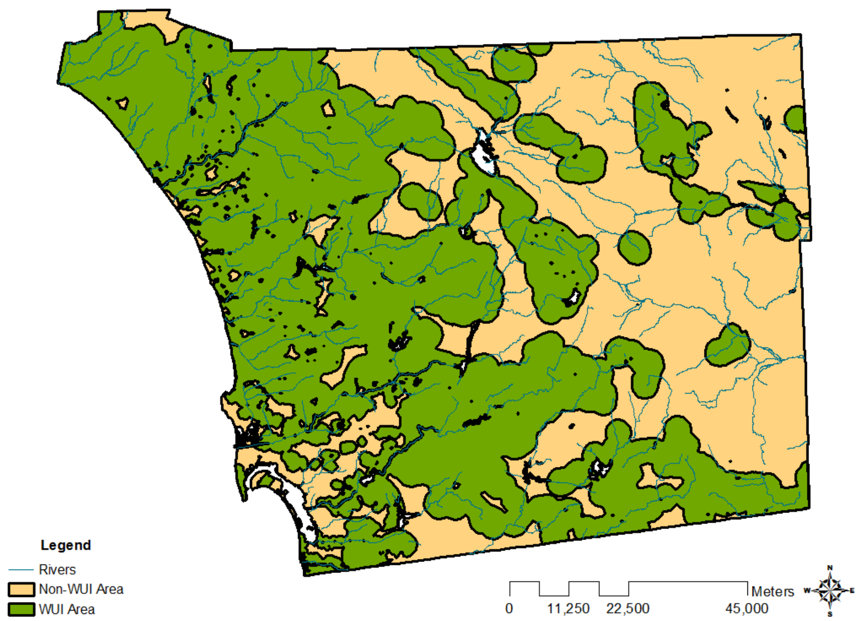

Figure 2.8 Major Rivers in San Diego County

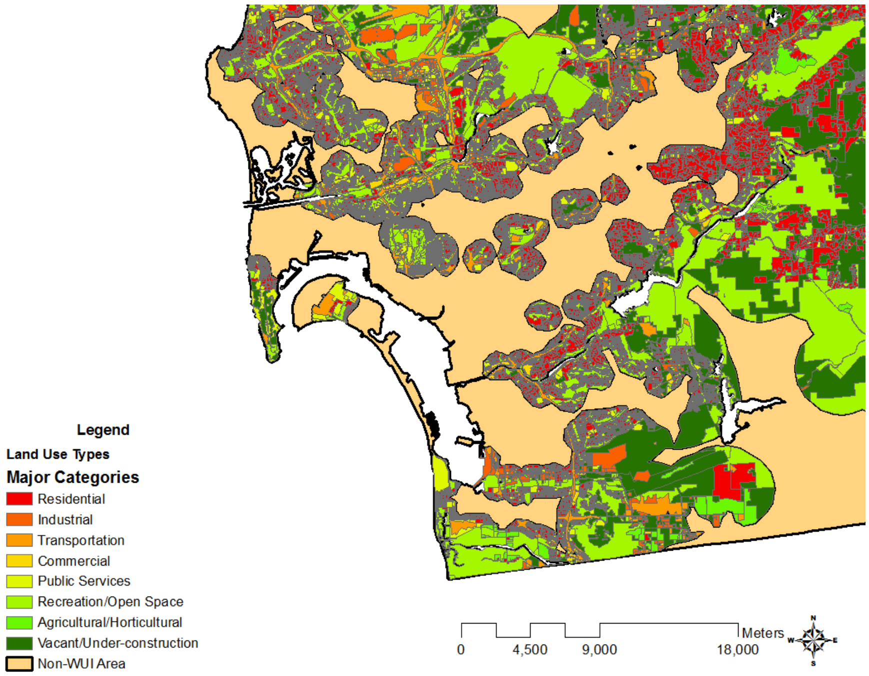

Figure 2.9 Land-use Patterns in San Diego County as of 2004

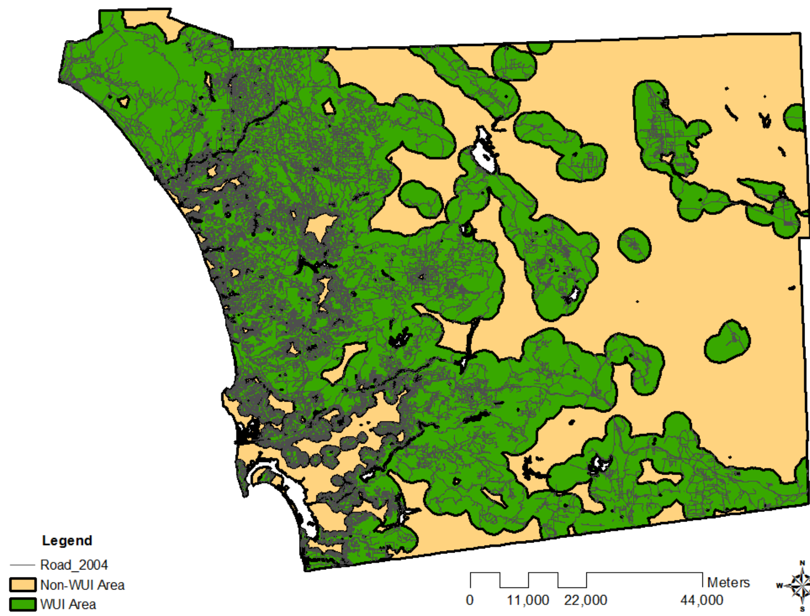

Figure 2.10 Road Distribution in San Diego County as of 2004

Table 2.1 Description of Variables

Variables	GIS Data Layer	GIS Data Source	Unit	Resolution	Description	Dummy
Fire History						
Annual Fire Record	County GIS Layer of Fire	SanGIS	-	1:40,000-scale	Calculated	N/A
Vegetation						
Vegetation Type - Shrub	Statewide GIS Layer of Fire Rotation for Burnable Lands	CDF-FRAP	-	30-meter	2006-edition	Yes
Pitch Canker Infection Zone	Pitch Canker Infection Zone	CDF-FRAP	-	1:100,000-scale	1997-designation	Yes
Soil						
Soil Series (MUKEY 660448, MUKEY 660449, MUKEY 660457, and etc.)	Soil Survey Geographic Database (SSURGO)	USDA/NRCS	-	30-meter	-	Yes
Ground Water Recharge	Ground Water Recharge	USGS/WRD	-	1-km	-	No
Soil Erosion (Class 2)	Post-fire Erosion Class	CDF-FRAP	-	90-meter	2004-version	Yes
Topographic Features						
Slope (Higher than 25%)	Aggregated Slope Layer	SanGIS	-	1-feet	-	Yes
Elevation	National Elevation Dataset	USGS/EROS	-	3-meter	-	Yes
Distance to River	All Rivers Layer	SanGIS	km	1-km	Calculated	No
Climate						
Precipitation in Apr.	Precipitation in Apr.	PRISM	cm	4-km	Monthly	No
Precipitation in Sept.	Precipitation in Sept.	PRISM	cm	4-km	Monthly	No
Temperature in Sept.	Temperature in Sept.	PRISM	Celsius	4-km	Monthly	No
Dew point in Sept.	Dew point in Sept.	PRISM	Celsius	4-km	Monthly	No
Temp-Minus-Dewpoint in Sept. (NDP09)	-	-	Celsius	-	Calculated	No
Atmospheric Pressure in Sept.	Atmospheric Pressure in Sept.	NASA/SSE	Kpa	1-degree	Monthly& Annual based on 22-year average	No
Wind Speed in Sept.	Wind Speed in September	NASA/SSE	mpm	1-degree	Monthly& Annual based on 10-year average	No
Solar Radiation in Apr.	Annual Solar Radiation	NASA/SSE	kw/m2	1-degree	Monthly& Annual based on 22-year average	No
Land Uses						
Land-use Patterns (Residential Development, Industrial Operation, Open Space & Parks, Agriculture, and Vacant/Under-construction)	Land-use Layer in 1990, 1995, 2000, and 2004	SANDAG	percentage point	-	Calculated	No
Road Density (Major Roads and Local Roads)	Road Layer	SanGIS	mile/acre	-	Annual /Calculated	No

Table 2.2 Human land Uses, Climatic Factors, and Other Environmental Features on Wildfires at Wildland-Urban Interface

Variables	Parameter Estimated	Standard Error	Chi-square	Significance	Description
Constant	168.500	21.440	61.764	***	
Vegetation					
Vegetation Type - Shrub	0.148	0.038	14.986	***	
Pitch Canker Infection Zone	0.357	0.065	29.812	***	
Soil					
MUKEY 660448	0.570	0.076	56.330	***	
MUKEY 660449	0.693	0.130	28.234	***	
MUKEY 660457	0.514	0.050	106.046	***	
MUKEY 660458	0.442	0.080	30.695	***	
MUKEY 660460	0.703	0.076	85.736	***	
MUKEY 660463	0.321	0.071	20.722	***	
MUKEY 660464	0.941	0.217	18.785	***	
MUKEY 660468	-0.540	0.265	4.140	**	
MUKEY 660477	0.604	0.142	18.098	***	
MUKEY 661097	-0.509	0.226	5.059	**	
Ground Water Recharge	-0.049	0.011	18.980	***	
Soil Erosion (Class 2)	-	-	-	-	#
Topographic Features					
Slope (Higher than 25%)	-	-	-	-	#
Elevation (Higher than 2km and lower than 6km)	-0.199	0.054	13.656	***	
Distance to River	-0.029	0.010	9.192	***	
Climate					
Precipitation in Apr.	0.007	0.001	28.338	***	
Precipitation in Sept.	0.016	0.003	30.231	***	
Temperature in Sept.	0.236	0.046	26.821	***	
Dew point in Sept.	-0.347	0.044	62.450	***	
Temp-Minus-Dewpoint in Sept. (NDP09)	-	-	-	-	#
Atmospheric Pressure in Sept.	-2.295	0.316	52.911	***	
Wind Speed in Sept.	0.178	0.037	23.289	***	
Solar Radiation in Apr.	-	-	-	-	#
Land Uses					
Residential Development	-0.083	0.020	17.583	***	
Industrial Operation	-0.783	0.270	8.392	***	
Open Space & Parks	0.066	0.009	51.086	***	
Agriculture	0.198	0.038	27.410	***	
Vacant/Under-construction	0.055	0.009	36.195	***	
Road Density (Major)	-0.082	0.022	13.794	***	
Road Density (Local)	0.008	0.008	0.994		
Interaction Terms					
Solar Radiation 04*Slope	0.012	0.005	5.189	**	
Solar Radiation 04*Soil Erosion	-0.011	0.005	4.250	**	
NDP09*Residential Development	0.003	0.001	10.504	***	
NDP09*Industrial Operation	0.036	0.014	6.531	***	
NDP09*Open Space & Parks	-0.004	0.001	50.924	***	
Temperature in Sept.*Agriculture	-0.007	0.001	29.689	***	
NDP09*Vacant/Under-construction	-0.003	0.000	48.615	***	

The Hosmer-Lemeshow test statistic is 6.5605 with the degree of freedom at 8 and p-value of 0.5847.
* $p<0.10$, ** $p<0.05$, *** $p<0.01$
# Not Used Sperately

Table 2.3 Human Land Uses, Climatic Factors, and Other Environmental Characteristics on Wildfires at Post-fire Degraded Ecosystems

Variables	Parameter Estimated	Standard Error	Chi-square	Significance	Description
Constant	84.673	30.735	7.590	***	
Vegetation					
Pitch Canker Infection Zone	0.475	0.208	5.218	**	
Soil					
MUKEY 660457	0.203	0.109	3.462	*	
MUKEY 660458	0.408	0.192	4.519	**	
MUKEY 660460	0.711	0.186	14.555	***	
MUKEY 660477	0.499	0.227	4.848	**	
MUKEY 661097	1.238	0.430	8.304	***	
Ground Water Recharge	0.102	0.024	17.724	***	
Soil Erosion (Class 2)	-	-	-	-	#
Topographic Features					
Slope (Higher than 25%)	-	-	-	-	#
Elevation (Higher than 2km and lower than	-0.195	0.109	3.209	*	
Climate					
Precipitation in Sept.	0.012	0.006	3.963	**	
Temp-Minus-Dewpoint in Sept. (NDP09)	-	-	-	-	#
Atmospheric Pressure in Sept.	-0.896	0.318	7.950	***	
Solar Radiation in Apr.	-	-	-	-	#
Land Uses					
Residential Development	-0.234	0.079	8.783	***	
Industrial Operation	-1.945	1.235	2.482		
Open Space & Parks	0.031	0.024	1.692		
Vacant/Under-construction	0.200	0.094	4.519	**	
Road Density (Major)	-0.176	0.099	3.190	*	
Interaction Terms					
Solar Radiation 04*Slope	0.018	0.013	1.890		
NDP09*Residential Development	0.010	0.004	7.250	***	
NDP09*Industrial Operation	0.100	0.057	3.092	*	
NDP09*Open Space & Parks	-0.002	0.001	1.819		
Temperature in Sept.*Agriculture	-0.006	0.003	4.191	**	
NDP09*Vacant/Under-construction	0.000	0.000	1.211		

The Hosmer-Lemeshow test statistic is 5.5458 with the degree of freedom at 8 and p-value of 0.6980.

* $p<0.10$, ** $p<0.05$, *** $p<0.01$

Not Used Sperately

Table 2.4 Human Land Uses, Climatic Factors, and Other Environmental Factors on Human-related Wildfires

Variables	Parameter Estimated	Standard Error	Chi-square	Significance	Description
Vegetation					
Pitch Canker Infection Zone	-0.219	0.167	1.731		
Soil					
MUKEY 660448	-0.243	0.171	2.023		
MUKEY 660449	1.726	0.398	18.783	***	
MUKEY 660457	-0.306	0.115	7.073	***	
MUKEY 660458	-0.448	0.198	5.096	**	
MUKEY 660460	0.316	0.187	2.846	*	
MUKEY 660463	-0.361	0.177	4.173	**	
MUKEY 660464	4.121	3.998	1.062		
MUKEY 660477	0.800	0.371	4.653	**	
Topographic Features					
Slope (Higher than 25%)	-	-	-	-	#
Distance to River	0.099	0.023	17.890	***	
Climate					
Precipitation in Apr.	0.013	0.003	15.186	***	
Precipitation in Sept.	0.041	0.010	17.984	***	
Temperature in Sept.	0.295	0.087	11.360	***	
Dew point in Sept.	0.456	0.097	22.342	***	
Temp-Minus-Dewpoint in Sept. (NDP09)	-	-	-	-	#
Atmospheric Pressure in Sept.	0.563	0.162	12.050	***	
Wind Speed in Sept.	-0.247	0.053	21.885	***	
Solar Radiation in Apr.	-	-	-	-	#
Land Uses					
Residential Development	-0.136	0.047	8.447	***	
Industrial Operation	2.375	0.817	8.456	***	
Vacant/Under-construction	-0.079	0.022	13.146	***	
Road Density	0.030	0.016	3.753	*	
Interaction Terms					
Solar Radiation 04*Slope	0.029	0.012	5.981	**	
NDP09*Residential Development	0.009	0.002	15.466	***	
NDP09*Industrial Operation	-0.120	0.043	7.941	***	
NDP09*Open Space & Parks	0.001	0.000	15.187	***	
Temperature in Sept.*Agriculture	0.001	0.000	8.539	***	
NDP09*Vacant/Under-construction	0.005	0.001	15.440	***	

The Risidual Chi-square test statistic is 3.6127 with the degree of freedom at 8 and p-value of 0.8903.
* $p<0.10$, ** $p<0.05$, *** $p<0.01$
# Not Used Sperately

Endnotes

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[1] CDF-FRAP is the Fire and Resource Assessment Program of California Department of Forestry and Fire Protection. RMS, Risk Management Solutions Inc., is a California-based company that specializes in estimating potential losses from natural disasters and terrorist attacks.

[2] The relevant literature regarding climate change, human activities, and wildfires can be found in Swetnam and Betancourt (1990) and (1998), Lenihan et al. (2003), Westerling et al. (2003), Fried et al. (2004), Westerling et al. (2006), Bachelet et al. (20007), Lenihan et al. (2008), Westerling and Bryant (2008), and others.

[3] Southern Oscillation (OS) is the atmospheric component of El Niño. It is measured by calculating the differences in air pressure anomaly between Tahiti and Darwin, Australia. See *The ENSO Cycle* at the Climate Prediction Center (CPC), National Weather Service (NWS) of NOAA (http://www.cpc.noaa.gov/products/analysis_monitoring/ensocycle/enso_cycle.shtml).

[4] PDSI, a measure of drought condition, represents accumulated precipitation anomalies and to a very small extent temperature anomalies.

[5] A degraded ecosystem is referred to as the one that was burnt by recent wildfires. Soil water-repellency and the resulting soil erosion could be serious post-fire problems in these areas (DeBano, L.F., 1981 and 2000; Benavides-Solorio and MacDonald, 2001).

[6] In general, the leaf area index (L.A.I.) can be seen as a measure of the number of leaf layers.

[7] Disturbance regime is referred to as various modes of widespread floral replacement, e.g., flood, wildfire, insect, pathogen, wind, or a combination thereof.

[8] Our results also confirm that the parameters estimated with the logit link function show similar signs but lower significance levels.

[9] For example, suppose the current year is 1990, the wildfire records from 1986-1989 at a single location are checked. If any burning is recorded from 1986-1989, $y_{t-5} = 1$ and this location will be chosen.

[10] For example, the water circulates at site level to satisfy the physiological needs of vegetations (as shown in Figure 1). Outside any single plant, water circulates in ecosystems (as shown in Figure 2), as plants compete for water and space.

[11] We use the block-group GIS layer was compiled by CDF, which may be different from the block-group GIS layer defined by the Census 2000 of the U.S. Census Bureau. There are 2,597 block groups in San Diego County, CA (2,203 in WUI areas). Besides non-WUI areas, we also removed all water bodies. 3,000 sites are randomly sampled, which are located in 592 block groups out of all 2,203. The GIS layer was compiled by CDF, which is slightly different from the boundaries of the block groups defined by the Census 2000 of the U.S. Census Bureau. Besides non-WUI areas, we also removed all water bodies.

[12] For the year that the survey was not conducted, this land-use feature is constructed by interpolation of missing values in time series in SAS 9.2.

[13] The 3,000 randomly selected sites are located in 592 block groups out of all 2,203. For the 592 concerning block groups, one block group contains at least 1 site and at most 180, depending on its acreage. The minimum distance from one point to its nearest neighbor is 32.50 meters, and could reach up to 4,359.50 meters. The average of the minimum distance is 758.48 meters. These sites are small circles with an 800-meter radius.

[14] The maps regarding atmosphere, wind speed, and solar radiation are among the low-resolution ones from NASA/SSE. The precipitation, temperature, and dew-point data from PRISM Climate Group that are provided in the grid format with distance and clustering already incorporated in the RPISM model. For simplicity reason, these data are interpolated by the bilinear interpolation approach, which is the default setup in ArcGIS 9.3 in terms of the PRISM user manual. (http://www.prism.oregonstate.edu/pub/prism/spatial_analysis.html, accessed Dec. 04, 2009)

[15] The Hosmer-Lemeshow test statistic may have low power for detecting departure from goodness of fit. See Stokes et al. (2000) for more discussion.

[16] There are concerns over the correlation between soils and vegetation types. According to the theoretical framework, this should not be problematic, as vegetation type is primarily determined by the lowest annual temperature (Woodward, 1987).

[17] The reference group contains the soil series of MUKEY 657964, 660447, 660459, 660461, 660462, 660465, 660466, 660467, 660476, 660482, 660483, 660587, 661095, 661098, 661100, 661101, and 661102.

[18] It is worth noting that the temperature in April (early spring) is not included in our analysis. This is seemingly at odds with previous research (e.g., Westerling et al, 2006), which addressed the importance of including the temperature in early spring in wildfire analysis. Conversely, the effects of the temperature in April can be explained by other factors. For example, we found the temperature in April is strongly correlated

($\rho_{Pearson} = -0.6175$ with $p-value < 0.0001$) with the precipitation level in April. This implies that a lower precipitation level in April mean a spring to be both drier and warmer. Exclusion of the temperature in April will alleviate multicollinearity and improve overall model fitting. Taken together, the conclusion still can be inferred from our empirical evidence that a drier, warmer, and windier climate may contribute to more wildfire incidents in the WUI areas.

[19] Dew-point is the temperature to which a given parcel of air must be cooled, at constant barometric pressure, for water vapor to condense into water.

[20] The reference group includes erosion levels of 0, 1, and 3.

[21] To construct the interactions between human activities and climate, we create one variable named NPD09 and multiply it with the land-use variables. With a simple transformation, the relative humidity (RH) can be expressed as $RH = 100 - 5(T - T_d)$, with T is the temperature and T_d the dew-point. The relative humidity, a dew-point pressure, is an important indicator of a comfortable level. The variable we construct here is analogous to the negative value of the relative humidity or the dew-point pressure, and we name it NDP09 in our model.

[22] Urban literature suggests people tend to move to area with levels of locational amenities, either temporarily or permanently. In California, seasonal lodging in these area increase human access to these areas.

[23] The reference group contains the soil series of MUKEY 657964, 660447, 660448, 660449, 660459, 660461, 660462, 660465, 660466, 660467 , 660468, 661101, and 661102.

[24] The wildfire incidents (1911-2007) in San Diego County can be assorted into three major categories: one is nature-caused wildfire, mainly by lightning (59 incidents); another is human-related (or –caused) wildfires, and the causes include arson, campfires, power-line, vehicle, equipment use, smoking and miscellaneous causes (860 incidents in total); while the causes of the rest ones are unidentified. This is based on the wildfire history in San Diego County from 1911 to 2007 by SanGIS.

[25] It is worth noting that the wildfires with unknown caused may be identified as human-caused wildfire as well. However, without being provided with any further relevant information, we prefer to keep all the observations and assess the consistency of our estimates in logic.

[26] The reference group contains the soil series of MUKEY 657964, 660459, 660461, 660462, 660465, 660466, 660467, 660468, 660476, 661097, 661101, and 661102.

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[27] The sample includes all the variables in Table 3.2. The only difference is the independent variable: only human-related wildfire burning is recorded instead of all types of wildfires.

[28] Notwithstanding, residents may not be fully aware of wildfire risks and the cognitive process may require time and efforts to take shape. Considering our observations are obtained within a very short period, the possibility of the endogeneity issue might be really small.

CHAPTER 3

3. Wildfire Risk and Urban Development Pattern in Fire-Hazardous Area

Abstract

California is currently implementing a system of codes and regulations, including the Civil Code Sec. 1103 to govern natural hazard disclosure and management. However, the effectiveness of Sec 1103 for stopping over-development in the fire-hazardous areas has been questioned due to the inconsistent fire-zone designation at the Local Responsibility Area (LRA). This study analyzes the impacts of wildfire risk on urban development by introducing wildfire risk to a classic urban economics model with locational amenities and a public decision sector to characterize the behaviors of risk-averse local households and government. We calibrate the model and examine the urban spatial profiles changes under different assumptions of wildfire risks and natural amenities. We find that wildfire risk can take on various aspects of urban spatial profiles at a much broad scale that go beyond the fire-prone areas and affects both households and public decision sectors. Even without inconsistency in the fire-zone designation policy, over-development can occur in the fire-hazardous area.

3.1 Introduction

Among the most populous and fast-growing regions in the United States, Southern California faces one of the most challenging constraints for continued urban and suburban development. With high development pressures, congestion costs, and pollution levels in urban areas, affluent Americans are increasingly moving to the amenity-rich suburban areas, which include the fire-prone human-environment interface. Southern California's Wildland-Urban Interface (WUI) is home to more than six million people, with over 800,000 living in the highest wildfire hazardous zones. However, this development trend also gives rise to serious ecological and socio-economic problems. Besides habitat loss and fragmentation (Theobald et al., 1997), and biodiversity decline (Soulé, 1991; Mckinney, 2002), human-caused wildfires in these areas are quite common (Hammer et al., 2007), and protection of structures from wildfires is most challenging (Cohen, 2000; Winter and Fried, 2001; Haight et al., 2004). This, in turn, impacts on residential development patterns as well. During the 2007 fire season, at least half a million people from 346,000 homes were forced to evacuate, and over 3,000 homes and buildings were left in ruins, with estimated insured losses up to $2.5 billion (Burned Area Emergency Response, B.A.E.R.).

The increasing tension between the needs for urban and suburban development and the increased wildfire activities within human-environment domain has led the California State legislature to enact rulings and regulations as continued efforts with the aim of protecting people, property, and natural resources from wildfire threats and reducing wildfire suppression cost. California Civil Code Sec. 1103 is one mile-stone effort, which was passed in 1998 after the 1991 Oakland Hills Fire. It has two major components: First, it stipulates the disclosure responsibility for the seller and realtor, who need to complete a Natural Hazard Disclosure Statement indicating whether the property in question is located in statutory wildfire, flood, and seismic–hazard zones. In particular, sellers are required to disclose if their property is in a Very High Fire Hazard Severity Zone. Second, it also mandates the responsibilities of government agencies at the state and local levels. For example, California Public Resources Code Sec. 4201 requires state government agency, California Department of Forestry and Fire Protection (CDF), to provide the classification of lands within state responsibility areas (SRA) in accordance with the severity of wildfires. California Government Code 51178 requires CDF to identify very high fire severity zones (VHFHSZ) within the local responsibility areas (LRA) and transmit this information to local agencies. Local agencies shall take proper actions and make the information available for public review.

This has motivated several researchers to investigate the impacts of fire risk disclosure and the consequences of inconsistent fire-zone designations. A noteworthy study is conducted by Troy and Romm (2004), who used a hedonic method to assess the 1998 California Natural Hazard Disclosure Law. Their empirical results suggest that housing values depreciated by 5.1% after a major fire storm nearby. By contrast, fire-zone homes near recent fires are worth 3% more than comparable non-fire-zone homes and fire-zone homes not near recent fires were worth 8% more, although Sec. 1103 is already in effect. This implies that California Natural Hazard Disclosure Law may have no effect to stop the over-development in fire-hazardous areas (Troy and Romm, 2004 and 2006). Although the findings may sound contradictory, similarly evidence is also discovered by other studies with regards to risk disclosure and urban development patterns. For example, in a case study to examine the effects of a wildland fire rating that was available to the public at Colorado Springs, CO, Donovan et al. (2007) found that fire risk and housing price are positively related before the information is released, but not afterwards. There are many factors that could cause the over-development in the fire-hazardous areas, including households' perception and cognition of wildfire risk and preferences for locational and social amenities, as well as the fallacy and inadequacy of institutional incentive structures. Troy and Romm (2007) suggest that inconsistent designations are accountable for overdevelopment in the wildfire hazardous area at Local Responsibility Areas, whereas homeowners' preference for locational amenities may also lead them to dismiss or underestimate wildfire hazard. While the empirical argument above seems well understood, there has been little work attempting to address the impacts of fire risk disclosure and the consequences of inconsistent fire-zone designations on urban development patterns within a theoretical framework. Without such a framework, the impacts of fire risk disclosure on urban development patterns may be blurred by other socio-economic factors such as natural amenities, post-fire assistance, insurance, or other land-use policies, since these factors may jointly affect the urban development patterns.

The objective of this study is to develop a model to evaluate the quantative impacts of fire-zone designation on urban development patterns (including average land price, development density, and development area) and understand the consequences of inconsistent designation in a spatial setting. The model builds on and expands the monocentric-city framework developed by Wu (2006) and Wu (2010) by introducing wildfire risk to the model. In this framework, households decide where to reside and how much of their expenditure be allocated to housing (land), and the public decision sector determines the local property tax rate and the provision of public services. We solve for the equilibrium conditions for this economy, which reveals urban land-use features such as income mix and community development boundaries. The model incorporates three major components that we consider essential to analyze the interaction between wildfire risk and urban development patterns. First, there is substantial heterogeneity in income, preferences for variety, and perception of fire risk across households. Second, land development is driven by profit. Third, public service is provided at the local level, and likewise funding for public services is largely determined at this level.

We calibrate the model and conduct simulations in Mathematica with parameters found in statistics, surveys, and empirical works regarding U.S. economy. The results demonstrate how urban development patterns in various socio-economic settings regarding wildfire risk, locational amenity, and income mix. We focus on the development patterns within the fire-hazardous area, whilst the development pattern in the non-fire-hazardous area will also be examined. The consequences of inconsistent designation are discussed by comparing the benchmark level for a consistent fire-zone mapping and the contrast level for an inconsistent one. Sensitivity analysis is conducted to examine how results are affected by changes in these assumptions.

This paper is organized as following: Section 2 describes the theoretical model and the equilibrium conditions. Section 3 analyzes the impacts of wildfire risk on the level of public services and property values. Section 4 calibrates the models that are used for simulations. Section 5 discusses the impacts of fire risk disclosure on urban development patterns and the consequences of inconsistent fire-zone designations. Section 6 concludes.

3.2 The Model

Our analysis begins with a simple open city model that includes only one circular metropolitan city. The urban landscape is shown in Figure 3.1. The residential development expands outwards from the center of the city (CDB). The distances to the CBD on a circle with a radius x are the same due to the symmetric property of cycles. The dotted line indicates the urban development boundary (r_c). The area between the solid line (the lower boundary, i.e. r_{fl}) and the dash line (the upper boundary, i.e. r_{fh}) with the width w_f is designated as fire-hazardous area by state government agencies. The probability of wildfire occurrence (π) is uniform across the fire-hazardous area. This area is also characterized with higher levels of natural amenity.

(Figure 3.1)

The micro level decisions

The production of non-housing goods and services are produced in the center of the city (CBD), whereas wage, price of private goods, and unit commuting cost are all exogenous. The economy is populated by individual households who have identical preferences in each income group. All decisions are made by individual households choose residential locations and consumption bundles to maximize an expected utility. Assuming their utility takes the von Neumann-Morgenstern expected utility form, this can be expressed as:

(1) $$E(u) = (1 - E(\pi))u_0(z, h, g, a) + E(\pi)u_1,$$

where π is the stated probability of wildfire occurrence by the government agency, z is consumption of a private good, h is consumption of housing (land), g is consumption of public services, a is consumption of locational amenities, u_1 is the utility level when wildfire breaks out and is fixed, u_0 is the utility level when fire does not break out and is given, and E is an expectation operator. $u_0(\cdot)$ is continuous, quasi-concave, and twice differentiable. [1] Thus, $E(\pi)$ (or π_e) is the probability of wildfire occurrence perceived by households, which is also assumed to be uniform across the fire-prone area, but might be different from π.

Individual households choose a location in the urban area, from which they commute x miles to work with the unit transportation cost at t . The urban features are characterized by net-of-tax housing prices (p), property tax rates on housing (land) expenditures (τ), levels of public services (g), and locational amenities (a). The level of public service (g) is identical for each household and solely funded by the proceeds of local property tax that is levied on the housing value (ph). The level of locational amenity is exogenously determined and can be freely enjoyed, whereas the further away from its source, the lower the level received by households. A household's budget constraint is

(2) $$(1+\tau)ph + z + tx \le y ,$$

where y is households' annual income. The locational amenity level that is received by households at x takes the following form:

(3) $$a = \begin{cases} a_0 & x \le r_{fl} \ \ or \ \ x \ge r_{fh} \\ a_0 + a_1 \, \mathrm{e}^{-\delta|x-c_A|} & r_{fl} \le x \le r_{fh} \end{cases} ,$$

where a_0 is the benchmark level of locational amenity in this city, a_1 is the additional amenity obtained from living in the fire-prone area, c_A is the geographic center of the amenity source such as stream, lake, or forest, and δ is a inverse-distance parameter that determines how fast amenity levels decrease from c_A . a_0 , a_1 , and δ are exogenous.

Regarding wildfire risk, households can be assorted into two groups: residents inside the designated fire-zone ($j=1$) and residents outside of the fire-zone ($j=0$). Since wildfire is very unlikely to occur outside the designated fire-zone, the expected utility of residents who live outside fire-prone area(s) can be reduced to

(4) $$E_{j=0}(u) = u_0(\cdot) .$$

And the expected utility of residents within the fire-prone area(s) takes the same form as equation (1):

(5) $$E_{j=1}(u) = E(\pi)u_1 + (1-E(\pi))u_0(\cdot) .$$

Note that from individual household's perspective, the city is characterized by the pair (τ, g) . Thus, an individual household with income y facing (τ, g) has an indirect utility function V defined by:

(6) $$\bar{V} = \max_{z,h}[(1-E(\pi))u_0(z,h,g,a) + E(\pi)u_1]$$
$$\text{s.t. } (1+\tau)ph + z + tx \le y,\ z \ge 0, h \ge 0, \tau \ge 0, g \ge 0.$$

The optimal consumption of private goods (z^*), housing expenditures (h^*), and land price (p^*) can be obtained by solving households' utility maximization problem.

For preferences we assume u_0 takes the Cobb-Douglas form as:

(7) $$u_0 = h^{\alpha} z^{1-\alpha} a^{\gamma} g^{\mu} ,$$

where $0<\alpha<1$, $\gamma>0$, $\mu>0$, and $\alpha>\mu$. The assumption $\alpha>\mu$ ensures that some public services are provided even there is no scale economy in the provision of public services. u_1 is assumed to comes from government assistance and insurance claim, which is fixed (i.e., $u_1=v_1=\overline{S}$).

Solving the utility maximization problem yields the optimal demand of housing (h^*) and non-housing goods (z^*) respectively, we obtain:

$$h^*=\frac{\alpha(y-tx)}{(1+\tau)p^*(x)},\ z^*=(1-\alpha)(y-tx)\,. \tag{8}$$

Substituting (8) to equation (7), the indirect utility level (v_0) and optimal land price ($p^*(x)$) offered by households are obtained as:

$$v_0=\frac{\alpha^\alpha(1-\alpha)^{1-\alpha}(y-tx)a^\gamma g^\mu}{(1+\tau)^\alpha p^*(x)^\alpha}\,, \tag{9}$$

$$p^*(x)=\frac{\left(\alpha^\alpha(1-\alpha)^{1-\alpha}\right)^{\frac{1}{\alpha}}(y-tx)^{\frac{1}{\alpha}}a^{\frac{\gamma}{\alpha}}g^{\frac{\mu}{\alpha}}}{(1+\tau)v_0^{\frac{1}{\alpha}}}\,. \tag{10}$$

Notice that both π_e and v_0 are exogenously determined. From equation (6), we can obtain:

$$v_0=(\overline{V}-v_1\pi_e)\big/(1-\pi_e)\,, \tag{11}$$

where v_0 denotes the optimal utility level when fire does not occur(i.e., $v_0 = \max_{z,h}[u_0(z,h,g,a)]$). Substitute equation (11) and $v_1 = \overline{S}$ into equation (10), we obtain:

$$p^*(x) = \frac{\left(\alpha^{\alpha}(1-\alpha)^{1-\alpha}\right)^{\frac{1}{\alpha}}(1-\pi_e)^{\frac{1}{\alpha}}(y-tx)^{\frac{1}{\alpha}}a^{\frac{\gamma}{\alpha}}g^{\frac{\mu}{\alpha}}}{(1+\tau)(\overline{V}-\pi_e\overline{S})^{\frac{1}{\alpha}}} \tag{12}$$

Equation (12) highlights the impacts of fire-zone designation on urban development patterns. First, optimal land price reflects the perceived fire risk (π_e) instead of the stated one (π_s) by government agencies, although the perceived fire risk can be influenced by the stated one as the fire-zone designation can be very informative regarding wildfire risk. The difference between the perceived fire risk and the stated one may determine to which degree wildfire risk can be capitalized in the land price. As suggested by land conversion criterion (i.e., $p^{**}(x) = \max[p^*(x), p_{ag}]$), land price and land-use pattern are closely connected. Taken together, if the perceived wildfire risk is lower than the stated one (i.e., $\pi_e < \pi_s$), then more land will be developed for residential purpose than they should be and over-development emerges in the fire-hazardous area. Otherwise, there will be less land to be developed and under-development will be seen in this area. Second, land price outside the fire-prone area will also be affected by perceived wildfire risk within the fire-prone area. The connection lies in the level of public services, which affects the land price across the urban area. Consequently, this also means that the land-use patterns and community features outside the fire-hazardous area will be impacted by the perceived wildfire risk in indirect ways.

The local public sector decisions

Next, we turn to the characterization of the local tax rate. In this model, a public decision sector in this economy determines the level of public services and the level of proportional tax rate. The local budget is comprised of two components: total revenue (TR) and total cost (TC). The total revenue comes from the proceeds of the local property tax that is levied on the total value of housing expenditures (TLV). That is, $TR = \tau \cdot TLV$. The total cost is only associated with the provision of public services. And it is assumed that the objective of the public decision sector is to maximize the total tax base (i.e., the total land value denoted as TLV), whilst keeping the budget balanced

$$\begin{aligned} &\max_{(\tau,g)}[TLV] = \int_{x\in\aleph} 2\text{Pi}\cdot p^*(x)dx \\ &\text{s.t.}\quad TC \le TR \end{aligned}, \tag{13}$$

where $\aleph$ is the domain of land development and $p^*(x)$ is the optimal price for residential land use.

Following Borcherding and Deacon (1972), we assume that the cost of public services takes the form as:

$$TC = gN^{\lambda}, \tag{14}$$

where λ is the economy of scale parameter and $\lambda \in (0,1]$: providing public services to a larger group of residents is more efficient than that to a smaller group. N is the total number of households in the city

(15) $$N = \int_{x \in \aleph} \frac{2\text{Pi} \cdot x}{h} dx = \int_{x \in \aleph} \frac{2\text{Pi} \cdot (1+\tau)}{\alpha} \frac{p^*(x)x}{y - tx} dx .$$

We assume the total revenue that finances the public services is defined as:

(16) $$TR = \tau \cdot \int_{x \in \aleph} 2\text{Pi} \cdot p^*(x) x dx ,$$

where $\aleph$ defines the domains of residential development and Pi is the mathematical constant of the ratio of any circle's circumference of its diameter in Euclidean space.

The last relationships that need to be specified are neighborhood development boundary (x_0), urban development boundary (r_c), and tax burden, as the economy reaches equilibrium. A neighborhood development boundary (x_0) is a price-indifference locus, where the prices offered by both income groups equal (e.g., $p_h(x_0) = p_l(x_0)$ in a two-neighborhood scenario), if income mix exists. Similarly, an urban development boundary (r_c) is defined as the locus where the land price equals land reservation price (e.g., $p(r_c) = p_{ag}$). For tax revenue we specify three indicators, the share of the total residents in the fire-zone (η_c), the share of the total tax revenue from residents in the fire-zone (η_r), and the relative tax revenue for residents in the fire-zone compared with average level (β_R), defined respectively as

(17) $$\eta_c = \frac{N_{j=1}}{N} = \frac{1}{N} \int_{x \in \aleph_{j=1}} \frac{2\mathrm{Pi}x}{h_{j=1}} dx\,,\ \eta_r = \frac{TR_{j=1}}{TR} = \frac{1}{TR} \int_{x \in \aleph_{j=1}} 2\mathrm{Pi}\,\tau\, p_{j=1}(x) x dx\,,$$

$$\beta_R = \frac{TR_{j=1}}{N_{j=1}} \Big/ \frac{TR}{N} = \frac{\eta_r}{\eta_c}\,.$$

The relative tax revenue (β_R) stands for the ratio of tax revenue per household in the fire-zone to the average level in the city.

At equilibrium, three characteristics characterize this economy. First, households choose their location and have no intention to move.[2] Second, land owners will allocate the land to achieve the highest possible land value (i.e., $p^{**}(x) = \max[p^*(x), p_{ag}]$ with p_{ag} land reservation price). Third, the tax base is optimized and the budget of the local government is strictly balanced.

3.3 Analysis of the Impacts of Wildfire Risk on Urban Development Patterns

In this section, we examine how wildfire risk perceived by residents affects the level of public services and urban development patterns both inside and outside the fire-hazardous area.

The impacts of fire risk on public service levels

In our model, we analyze the a fire-zone designation policy that may lead to changes in three major factors and thus influence household's perception of wildfire risks: wildfire occurrence (π_e), fire-hazardous area (w_f), and post-fire assistance ($\overline{S}$). We first consider the case that there is only one income group living in the city (Propositions 1 and 2) and then consider the more general case (Proposition 3).

Following Wu (2010), if households have identical preferences over the consumption bundles, the optimization of the total land value is equivalent to the maximization of $(1+\tau)^{-1} g^{\frac{\mu}{\alpha}}$ subject to the same constraint. As a result, a fixed tax rate of $\tau = \mu[\alpha + (1-\lambda)\mu]^{-1}$ is obtained, and reduces the optimization problem further to the optimization of public services to the same budget constraint. Hence, g represents the interests of the local governments and can characterize their behaviors. [3] Using this result, we can obtain the following propositions:

Proposition 1: If $\beta_R > \lambda$, higher wildfire risk (π_e) or lower level of post-fire assistance ($\overline{S}$) decreases the level of public services (i.e., $\frac{\partial g}{\partial \pi_e} < 0$, $\frac{\partial g}{\partial \overline{S}} > 0$); otherwise, the effect is reversed. (Proof: see the Appendix.)

Proposition 1 indicates that an increase on wildfire risk and post-fire assistance has an ambiguous effect on the level of public services. Thus it is not possible to state whether in equilibrium the level of public services will be higher or lower than that in a benchmark scenario. This follows from the fact that how an increase in wildfire risk and post-fire assistance can change the relative tax revenue for residents in the fire-zone compared with average level (β_R). That is, for example, if the increase in wildfire risk leads to the situation that the total tax revenue decreases faster than the total cost does, the level of public services will be lowered.

Proposition 2: Given a fixed lower boundary of the fire-zone (r_{fl}), and suppose there is no undeveloped area in fire-hazardous area. If $\beta_{R2} = \frac{\tau p(r_{fl} + w_f)h}{TR/N} > \lambda$, then the decrease in the size of the designated fire-zone (w_f) increases the level of public services (e.g., $\frac{\partial g}{\partial w_f} < 0$); otherwise, the effect is reversed. (Proof: Analogous to the proof of Proposition 1, and therefore it is omitted.)

Proposition 2 delivers similar information compared with Proposition 1: an increase in the fire-hazardous area has an ambiguous effect on the level of public services, and therefore it is impossible to determine whether in equilibrium the level of public services will be higher or lower. This is determined by how the change in the fire-hazardous area can change β_{R2} , an indicator of tax revenue for residents living at the upper boundary compared with the average level in the city. However, it is worth noting that the above conclusion is base on the assumption that there is no vacant land in the fire-prone area. Otherwise, the results may be invalid.[4]

Proposition 3: Suppose residents belong to either the low-income group (with a subscript l) or the high-income group (with a subscript h). If $\beta_{R3} = \frac{(\omega_l \eta_{l,r} + \omega_h \eta_{h,r})}{(\omega_l \eta_{l,c} + \omega_h \eta_{h,c})} > \lambda$, then higher fire risk (π_e) decreases the level of public services (e.g., $\frac{\partial g}{\partial \pi_e} < 0$); otherwise, the effect is reversed. Similarly, if $\beta'_{R3} = \frac{(\omega'_l \eta_{l,r} + \omega'_h \eta_{h,r})}{(\omega'_l \eta_{l,c} + \omega'_h \eta_{h,c})} > \lambda$, higher post-fire assistance ($\bar{S}$) increases the level of public services (e.g., $\frac{\partial g}{\partial \bar{S}} > 0$); otherwise, the effect is reversed. [5] (Proof: see the Appendix.)

Extending from the results in Proposition 1, Proposition 3 indicates that our argument is still valid that an increase on wildfire risk and post-fire assistance has an ambiguous effect on the level of public services. It follows that it is critical for the local public decision sector to find out how the fire-zone designation policy can influence the relative revenue of residents living within the fire-zone compared with the average level in the city. Nonetheless, we should note that the signs of $\beta_{R3} - \lambda$ and $\beta'_{R3} - \lambda$ can be different, which implies that it is possible to have $\frac{\partial g}{\partial \pi_e} > 0$ and $\frac{\partial g}{\partial \bar{S}} > 0$ at the same time.

The results in all three propositions indicate that an increase in fire-related risk (including the probability of wildfire occurrence, fire-hazardous range, and post-fire assistance) has an ambiguous effect on the level of public services. The effects of the change in fire risk are dependent on some precondition regarding the composition of the residents and of the tax revenue and of the cost of public services. Proposition 1 and Proposition 2 imply that if households have misperceptions of wildfire risk or delusions of post-fire assistance, the level of public services could be quite different from the level that it should be. And the higher the level of misperception in wildfire risk, the bigger the difference in an optimal level of public services. The results in Proposition 3 indicate that the conclusions in Proposition 1 can be generalized in the presence of income mix with refined conditions.

The impacts of fire risk on property values

To understand behaviors of local residents, it is necessary to investigate the relationship between the perceived fire risk and property values. It is clear that without collecting local property tax and providing public services, land prices outside the designated fire-zone will not change at all. By contrast, if local property tax is levied to finance public services, households outside the fire-zone will also be affected by fire-zone designations.

First, we focus on the wildfire risk impacts on land prices inside the fire-zone ($p^*_{j=1}(x)$). Suppose all identical residents are from one income-group. If $\beta_R > \lambda$ and

$\beta_{R2} > \lambda$, $\frac{\partial g}{\partial \pi_e} < 0$, $\frac{\partial g}{\partial \overline{S}} > 0$, and $\frac{\partial g}{\partial w_f} < 0$ from Propositions 1 and 2. Differentiating (12), we obtain:

(18) $$\frac{\partial p^*_{j=1}(x)}{\partial \pi_e} < 0 \ , \ \frac{\partial p^*_{j=1}(x)}{\partial \overline{S}} > 0 \ , \ \frac{\partial p^*_{j=1}(x)}{\partial w_f} < 0 \ .$$

However, if $\beta_R < \lambda$ and $\beta_{R2} < \lambda$, $\frac{\partial p^*_{j=1}(x)}{\partial w_f} > 0$ still holds if there is no undeveloped land in the fire-hazardous area. But the signs of $\frac{\partial p^*_{j=1}(x)}{\partial \pi_e}$ and $\frac{\partial p^*_{j=1}(x)}{\partial \overline{S}}$ are generally undetermined.

Next, consider the wildfire risk impacts on land prices outside the fire-zone ($p^*_{j=0}(x)$). If $\beta_R > \lambda$ and $\beta_{R2} > \lambda$, from Propositions 1 and 2, $\frac{\partial g}{\partial \pi_e} < 0$, $\frac{\partial g}{\partial \overline{S}} > 0$, and $\frac{\partial g}{\partial w_f} < 0$. Differentiating (12), we obtain:

(19) $$\frac{\partial p^*_{j=0}(x)}{\partial \pi_e} < 0, \quad \frac{\partial p^*_{j=0}(x)}{\partial \overline{S}} > 0, \quad \frac{\partial p^*_{j=0}(x)}{\partial w_f} < 0.$$

Conversely, if $\beta_R < \lambda$ and $\beta_{R2} < \lambda$, $\frac{\partial p^*_{j=0}(x)}{\partial \pi_e} > 0$, $\frac{\partial p^*_{j=0}(x)}{\partial \overline{S}} < 0$, and $\frac{\partial p^*_{j=0}(x)}{\partial w_f} > 0$. These results suggest that the fire-zone designation and the perceived wildfire risk affect land values both inside and outside the fire-hazardous area, and thus they can increase or decrease property values. The greater the difference between perceived fire risk and stated one, the larger the distortions in property values, land-use patterns, and the development areas. As the land rent represents household's behaviors, it may, in part, explains why some residents may act collectively to challenge the fire-zone designation even thought their properties are not located within the designated fire-hazardous areas. Other factors (such as locational amenities) can also lead to the change in the composition of households living inside and outside the fire-prone areas, and thus can impact the property value and urban development patterns across the city.

3.4 Parameterization for Simulations

We set parameter values such that households' preferences and urban features match important observations in metropolitan cities for the U.S. economy. In particular, we carefully choose the values of the exogenous parameters, including income levels, aggregated expenditure shares (preferences), transportation cost, and land reservation price. Our sources of data include U.S. Census Bureau (USCB), Bureau of Labor Statistics (USDL/BLS), California State Government, San Diego County, and San Diego City.

There are four major expenditures in the conceptual model: private good, housing (land), public service level, and transportation cost. The ratio of annual housing expenditure to average annual expenditures is 0.40 in 2001-2002.[6] Considering that land usually accounts for around 25% of a real property value (Epple and Romer, 1991), we set households' preference for housing (land) at 0.125. The ratio of annual expenditure in utilities, fuels, and public services to average annual expenditures is 0.0562 in the same period. Excluding utilities and fuels, we set the preference for public services at 0.015. [7] The ratio of annual expenditure in transportation to average annual expenditures is 0.1833 in the same period. Housing survey reveals that the median household's income is $49,868 in 2002.[8] We set the income of high-income households at $75,000 annually, which lies within the fifth quintile in accordance to the block level household's income statistics in the San Diego County from the U.S. Census 2000. Similarly, we set the income of low-income households at $35,000 annually, which lies within the third quintile. [9] Assuming that high-income households have higher opportunity cost than low-income households, we set the annual commuting cost at $1,500 per mile for high-income households and $1,000 per mile for low-income households. Lack of knowledge about households' preference for natural amenities, its value is set at 0.125. The parameters that describe wildfire risk are set considering the wildfire history in San Diego County.[10] Land reservation price is estimated at $1,000 per acre, close to the U.S. average farm real estate value in 2000 by the National Agricultural Statistics Service Information (USDA/NASS). The parameters values used in simulations are shown in Table 3.1.

The simulation results are shown in Tables 3.2 and 3.3, which will be discussed in the following section. Sensitivity analysis is also conducted to test the effect of parameter values on simulation results. All simulations are conducted using Mathematica 6.2.

3.5 Results and Discussion

(Table 3.2)

Table 3.2 presents the simulated urban development patterns with only high-income households living in the city. Our discussion focuses on total value of developed land, housing prices, development densities, lot sizes, government service levels, and property tax per household, which are placed in the first column. We examine the effects of wildfire risk (fire occurrence probability and fire-hazardous area) and locational amenities (amenity levels and geographic location). The value of the exogenous parameters chosen such that $\alpha > \mu$, $\beta_R > \lambda$, and $\beta_{R2} > \lambda$. Thus, it is expected that higher wildfire risk will reduce the level of public services and property values. To simplifying the analysis, the post-fire assistance is set as $\bar{S} = 0$, which implies that households cannot depend on external assistance when wildfire breaks out.

The results in the 2nd column present the urban development features without any fire risk, which sets the bench mark value for comparison with results in other scenarios. In the benchmark scenario, the total land value is at $2,970 million. The radius of the urban boundary is 17.216 mile. The average land price in the city is $4,983/acre. In the benchmark scenario, the land value around the city center is at $23,644/acre. There are 426,519 households living in the city with an average lot size of 1.4 acre. Average tax payment per household of housing value is $851 with the local property tax rate at

12.22%, which is about 3% considering that land accounts for 25% of the total housing value.

First, we consider how fire occurrence/burning risk could impact urban development patterns. The fire-hazardous area is located between 10 and 12-mile away from the city center. We examine three wildfire annual occurrence probabilities at 0.05, 0.1, and 0.2, which means wildfire may rotate in every 20, 10, and 5 years. As expected, land prices decrease with increased wildfire burning risk as perceived by households. Hence, both the total land value in the city and the size of the city decrease. With less available tax base, the level of public services is lower whereas the tax burden for each households is higher. The situation within the fire-hazardous area is even worse: the average land price drops at an increasing rate as the probability of wildfire occurrence increases. In particular, when wildfire occurs every 5 years on average, no residential development can be found in the fire hazardous area. This also explains why both the average land price and development density in the city increase on this occasion.

The effect of wildfire risk is illustrated in Figure 3.2, where the horizontal line indicates the distance to work at the city center and the vertical line indicates the land price. The land reservation price is uniform across the city. The dashed line represents the land price without perceived fire risk, whilst the solid line represents the land price with perceived fire risk. As depicted in Figure 3.2, land prices both inside and outside the fire-prone area decrease. Land prices within the fire-prone areas decrease faster than outside the zone. This is because the households within the fire-prone area are under direct wildfire threats, which are directly reflected in the land prices. By contrast, households outside the fire-prone area are affected because of the change in the level of public services. Consequently, the total development area decreases.

Second, we consider the impact of fire-hazardous area on urban spatial profile. We assume that the annual wildfire occurrence probability is 0.10 or wildfire may rotate in every 10 years. The lower boundary of fire-prone area is fixed at 10 miles from city center, but the upper boundary varies. We examine three scenarios with the upper boundary at 12, 14, and 16 miles. Similar to the previous scenarios, as households perceive that wildfire burning risk spread geographically, their intension to offer the same bid is lowered , and thus the total land value in the city decreases compared to the benchmark scenario. However, we do see that there are improvements on average land price, residential development density, city size, and public services in the scenario with a 6-mile width fire-hazardous area, which seems somewhat contradictory. The reason is that residential development may not follow the increase of fire-hazardous area. This means that the increase on the fire-hazardous area drives more residential development out. In this occasion, using fewer local funds to provide public services to even fewer residents, the level of public services improves and land prices in non-fire-hazardous area increase.

Next, we investigate how additional amenities obtained from living in the zone influence urban development patterns. In the 3rd, 4th, and 5th columns of Table 3.2 (Continued), we assume that the annual wildfire occurrence probability is 0.10 or wildfire may rotate in every 10 years. We also assume that the location of fire-hazardous area is fixed in between 10 and 12-mile away from the city center. We further assume that the center of the fire-hazardous area has some aesthetic values which generate natural amenities as perceived by local households (a_1 is arbitrarily set at 1, 2, and 3.). Compared with the results in the second column for the bench mark scenario and the fourth column for the uniform amenity scenario, the results clearly demonstrate how amenities in the fire-hazardous area influence households' willingness to pay for land and the urban development patterns transform accordingly. With the increase of locational amenity levels in the fire-prone area, households are willing to pay a higher price to live in the amenity-rich area. This attracts more households moving in from other area that are outside this city. With the increase in urban development pressures, average land price increases and so does the total land value, whilst the average lot size decreases. Higher locational amenities also bring other benefits to the city, and the most significant ones (and perhaps favorable for households) are the higher public services levels and lower property tax. However, this does raise concerns over the development patterns in the fire-hazardous areas. With increasing inflow of households to live within and higher property values, high casualties and property damages are inevitable when wildfire strike this area.

Figure 3.3 illustrates this. The layout of Figure 3.3 follows that of Figure 3.2, except that we assume that natural amenity is located inside the fire-prone area and its locational value decreases as the distance to its center increases. Similar to Figure 3.2, land prices both inside and outside the fire-prone area decrease and so does the total development area. Different from Figure 3.2, the higher amenities in the fire-hazardous area attracts more households from other regions, which raise housing prices both inside and outside the fire-prone area and the total development area.

Fourth, our simulations results also suggest that the geographic locations of natural amenity source may also influence the development pattern across the region. In the 6th, 7th, and 8th columns of Table 3.2 (Continued), we assume that the annual wildfire occurrence probability is still 0.10 and the location of fire-hazardous area is fixed in between 10 and 12-mile away from the city center. We continue to assume that the natural amenity level at its center is within the fire-hazardous area (a_1 is set at 0.5), but let the center vary (with its distance from the city center valued at 10, 11, and 12 miles). In general, the results are quite like what we have seen for the results in the 3rd, 4th, and 5th columns of Table 3.2 (Continued). Compared to the benchmark scenario, locational amenities will increase total land value, average land price, and development density, improve the level of public services, and lower property tax burdens. Besides, the results suggest that the further away from the city center the center of the locational amenities, the fewer impacts the natural amenities will influence the spatial profiles of the city.

In the previous discussion, the results in Table 3.2 demonstrate how wildfire risk (fire occurrence probability and fire-hazardous area) in combination of locational amenities (amenity levels and geographic location) influences urban development patterns with households from one income-group. We are also interested to know if the above results still hold when multiple income groups live in the city and how the perceived fire risk can, in turn, change the composition of households in terms of income groups. We continue to use the setups as we stated earlier for Table 3.3.

(Table 3.3)

The 2nd column of Table 3.3 present the benchmark urban development features when two income groups live in the city, where there is no perceived wildfire risk. As indicated, the total land value is at $4,380 million. The furthest land that is used in residential development is located 16.96 mile away from the geographic center of the city. The average land price in the low-income neighborhood is $15,114/acre and that in the high-income neighborhood is $2,017/acre. The land value around the city center with a 2-mile radius is averaged at $57,164/acre. There are 1,130,250 low-income households and 110,581 high-income households living in the city. Compared with the scenarios in Table 3.2, this city demonstrates higher development pressures as the land price is much higher and the average lot size per household is much smaller. The local property tax rate is still at 12.22% and the average tax payment per household is $431, which is much lower than its counterpart in Table 3.2. The reason of the differences above lies in the income gaps between the two income groups: with limited income, low-income households can only afford a smaller housing unit, which can only generates less property tax revenue and leads to poorer level of public services.

In general, the results in Table 3.3 are quite similar to those in Table 3.2, which confirm the results at equilibriums that we obtained for the conceptual models. The increase on fire occurrence probability reduces households' willingness to pay. And thus, it decreases the total land value, lowers the average land price and development density. The tax burden per household is lowered and so is the level of public services. The increase of fire-hazardous area also reduces households' willingness to pay. And more importantly, it reduces the total development area, as undeveloped area shows in the fire-hazardous area. Higher levels of locational amenities attract households from outside of the city. Although a city with a higher level of public services and lower tax burden is more preferred, in general, by households, this may lead to over-development in the fire-hazardous area when wildfire risk is either overlooked or underestimated by households. Also, the farther away the amenity source is from the center of the city, the smaller the impacts of locational amenity on urban development patterns is. Different from the results in the 6th, 7th, and 8th columns of Table 3.2, the results in the same columns of Table 3.3 show that both the level of public services and the total residential development in non-fire-hazardous area decrease. This lies in the reason that although both local tax revenue and residents decline, local tax revenue declines faster than residents (particularly the high-income households).

Nonetheless, there are a few contrasting results in Table 3.3 that we would like to mention. First, households from different income-groups are impacted differently in terms of land prices, densities, tax burden, and public services levels, although they are assumed to have the same preferences over private goods, housing (land), public services, and locational amenities. The heterogeneity in income may be the key. The differences in these impacts may reflect their perspectives towards fire risk. Second, wildfire risk in combination of locational amenity will also change the composition of households from different income groups in the city, particularly in the fire hazardous area. For example, in Table 3.3, we see the ratio between the low and high-income households decreases rapidly, which implies more low-income households leaving the fire-prone area after weighting between locational amenity, wildfire risk, and quality of life.

Our simulations are conducted using parameters found in statistics, survey, and empirical work. Because there are variations in the estimation of the parameters, it is necessary to test how the results discussed above may change with alternative parameter values. The simulations are conducted by recalibrating the models with different parameter values. To focus on the discussion, we only consider alternative values of the preferences for private goods, housing, and public services and the scale of economy. The results, in general, are as we have expected in our earlier discussion. Changing the values of these parameters does not change any of the qualitative results: the results either demonstrate similar patterns as shown in Tables 3.2 and 3.3 as $\alpha > \mu$, $\beta_R > \lambda$, and $\beta_{R2} > \lambda$, or the opposite patterns when, for example, $\alpha > \mu$, $\beta_R < \lambda$, and $\beta_{R2} < \lambda$. These results are not reported in this discussion.

In sum, the simulated urban spatial profiles shown in Tables 3.2 and 3.3 suggest that wildfire risk in combination of locational amenities can greatly impact the urban land-use patterns and community characteristics. The impacts take on various aspects of community features and urban development patterns, including land price, development density, public services, tax burdens, population, and income mix. The impacts can be widespread: residents both inside and outside the fire-prone area could both be affected by wildfires, which influence land-use patterns and community profiles across the urban area. As there is substantial heterogeneity of income in households, wildfire risk can influence multiple income groups in different ways and thus change their proportion in the total number of residents in the city.

The simulation results have policy implications. First, perception (or misperception) of wildfire risks by households may be cause of over-development in fire-prone areas. Wildfires are characterized by complicated behaviors and high uncertainties with a very small probability to occur. Consequently, wildfire risk perceived by residents may be limited by their knowledge or underestimated or even omitted due to other factors, including locational amenities, post-fire assistance, and insurance coverage, although the stated wildfire risk may have signaling effects. As the perceived wildfire risk of residents may be quite different from the stated one by the government agencies, a divergence from policymaker's expected development patterns is highly anticipated even without any inconsistency in the fire-zone designation policy. Second, policy analysis in a spatial setting will help to evaluate the impacts on residents and local communities. Our results suggest that residents outside the fire-prone area will also be impacted by the fire-zone designation policy. As a result, some residents outside fire-prone areas may not support the fire-zone designation policy. Last, the fire-zone designation policy should consider the impacts on local communities, as this policy may make state interests at odds with local interests. Without systematic policies that help alleviate the policy impacts on local residents from different income-groups and public decision sectors, if there is any institutional inconsistency in the fire-zoning policy that local residents and public decision sector could take advantage of, the designation of fire-zone will be challenged or even repealed at the local level.

3.6 Concluding Remark

This study demonstrates that spatial considerations are an important element in assessing a fire-zone designation policy and urban spatial transformation. The analysis expanded a classic urban economics model by introducing wildfire risk, locational and social amenities, and a public decision sector and characterized the behaviors of risk-averse local households and government. We conducted simulations and calibrated the model to the data of U.S. metropolitan area. We used the simulated urban spatial profiles changes to investigate the impacts of wildfire risk on urban land-use patterns and community characteristics and evaluate the consequences of inconsistent fire-zone designation policy.

Our findings indicate that fire-zone designation policy that signals wildfire risks could greatly impact the urban land-use patterns and community characteristics. The impacts take on various aspects, including land price, development density, number of households, public services, and tax burdens. The influences of the fire-zone policy are not only within the fire-prone area, but can reach out to the non-fire-zone area. This policy will not impact different income-groups in the same way, and thus the composition of residents from different income-groups is affected as well. With limited knowledge in wildfire risk and high preferences to natural amenities, local residents and the public decision sector may challenge the fire-zoning designation and underestimate wildfire risk. If this were the case, over-development in the fire-hazardous area will be an issue that may be quite challenging for wildfire suppression and rescue in the future.

Nevertheless, some of the simplifying features of the model should be kept in mind when interpreting the results. First, we assume that all households have identical preferences over private good, housing (land), public services level, and locational amenity. This assumption further simplifies the derivation of the local property tax rate. However, if preference heterogeneity is present, the local tax rate may vary in a response to the change in the composition of households from different income groups.[11] Second, we use a Cobb-Douglas utility function to describe households' preferences. Our guiding principle is that the specification of functional forms is commonly used in quantative analyses. Although there are other options, there is little evidence that one functional form is better than other alternatives. Third, this study considers the post-fire assistance and insurance, but did not relate it to property value and discuss specifically how this may change the behavior of local residents. In particular, if there is an institutional failure, affordable insurance, paradoxically, attracts residents to live in the fire-prone area. Future work should focus on how to incorporate these factors can influence the assessment of fire-zone designation policy such as Sec. 1103. Policymakers should consider the spatial transformation of urban and community characteristics after implementing the fire-zone designation policy and make subsequent measures to facilitate policy implementation while alleviating impacts on local residents and public decision sectors.

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3.8 Appendix

Proof of Proposition 1

Suppose the city has a perceived fire-prone area that is located between r_{fl} and r_{fh} with a w_f -mile width. Following Wu (2010), we substitute $\tau = \mu[\alpha + (1-\lambda)\mu]^{-1}$ to TC and TR and obtain:

$$TC = g^{\frac{\mu\lambda}{\alpha}+1}(\int_{j=0} \delta\theta_0 (y-tx)^{\frac{1}{\alpha}-1} xdx + \int_{j=1} \delta\theta_1 (y-tx)^{\frac{1}{\alpha}-1} xdx)^{\lambda},$$

$$TR = g^{\frac{\mu}{\alpha}}(\int_{j=0} \varepsilon\theta_0 (y-tx)^{\frac{1}{\alpha}} xdx + \int_{j=1} \varepsilon\theta_1 (y-tx)^{\frac{1}{\alpha}} xdx)^{\lambda},$$

where $\theta_1 = (1-\pi_e)^{\frac{1}{\alpha}} (\overline{V} - \pi_e \overline{S})^{-\frac{1}{\alpha}}$, $\theta_0 = (\overline{V})^{-\frac{1}{\alpha}}$, $\delta = \dfrac{2\text{Pi}\left[\alpha^{\alpha}(1-\alpha)^{1-\alpha}\right]^{\frac{1}{\alpha}}}{\alpha}$ and

$\varepsilon = 2\text{Pi}\left[\alpha^{\alpha}(1-\alpha)^{1-\alpha}\right]^{\frac{1}{\alpha}}$. (The '0' in the subscript means $j=0$ and the '1' in the subscript means $j=1$.)

Let $C_0 = \int_{j=0} \delta (y-tx)^{\frac{1}{\alpha}-1} xdx$, $C_1 = \int_{j=1} \delta (y-tx)^{\frac{1}{\alpha}-1} xdx$, $R_0 = \int_{j=0} \varepsilon (y-tx)^{\frac{1}{\alpha}} xdx$,

$R_1 = \int_{j=1} \varepsilon\theta_1 (y-tx)^{\frac{1}{\alpha}} xdx$.

Accordingly, $TC = g^{\frac{\mu\lambda}{\alpha}+1}(\theta_0 C_0 + \theta_1 C_1)^{\lambda}$ and $TR = \frac{\tau}{(1+\tau)} g^{\frac{\mu}{\alpha}}(\theta_0 R_0 + \theta_1 R_1)$.

Additionally, The first order conditions of θ_1 with respect to the change in parameters of π_e and $\bar{S}$ can be derived as:

$$\frac{\partial\theta_1}{\partial\pi_e} = \frac{1}{\alpha}\theta_1^{\frac{1}{\alpha}-1}\frac{(-1)(\bar{V}-\pi_e\bar{S})-(-\bar{S})(1-\pi_e)}{(\bar{V}_i-\pi_e\bar{S})^2} = -\frac{1}{\alpha}\theta_1^{\frac{1}{\alpha}-1}\frac{(\bar{V}-\bar{S})}{(\bar{V}-\pi_e\bar{S})^2} < 0,$$

$$\frac{\partial\theta_1}{\partial\bar{S}} = -\frac{1}{\alpha}\theta_1^{\frac{1}{\alpha}-1}\frac{(1-\pi_e)}{(\bar{V}-\pi_e\bar{S})^2}(-\pi_e) = \frac{1}{\alpha}\theta_1^{\frac{1}{\alpha}-1}\frac{(1-\pi_e)}{(\bar{V}-\pi_e\bar{S})^2}\pi_e > 0.$$

Let $F = TC - TR = 0$. We obtain the first order condition with respect to g and π_e respectively as:

$$\frac{\partial F}{\partial g} = (\frac{\mu\lambda}{\alpha}+1)g^{\frac{\mu\lambda}{\alpha}+1}(\theta_0 C_0+\theta_1 C_1)^{\lambda} g^{-1} - \frac{\tau}{(1+\tau)} g^{\frac{\mu}{\alpha}}(\theta_0 R_0+\theta_1 R_1)\frac{\mu}{\alpha} g^{-1},$$

$$\frac{\partial F}{\partial\pi_e} = g^{\frac{\mu\lambda}{\alpha}+1}(\theta_0 C_0+\theta_1 C_1)^{\lambda-1}\lambda(\frac{\partial\theta_1}{\partial\pi_e}C_1) - \frac{\tau}{(1+\tau)} g^{\frac{\mu}{\alpha}}(\frac{\partial\theta_1}{\partial\pi_e}R_1).$$

Let $\eta_r = \frac{\theta_1 R_1}{\theta_0 R_0+\theta_1 R_1}$ and $\eta_c = \frac{\theta_1 C_1}{\theta_0 C_0+\theta_1 C_1}$. We substitute η_r, η_c, and $\frac{\partial\theta_1}{\partial\pi_e}$ into $\frac{\partial F}{\partial\pi_e}$ and obtain: $\frac{\partial F}{\partial\pi_e} = \frac{-TR\cdot\eta_c}{\alpha(1-\pi_e)}\left[\frac{(\bar{V}-\bar{S})}{(\bar{V}-\pi_e\bar{S})}(\lambda-\frac{\eta_r}{\eta_c})\right]$.

Similarly, $\frac{\partial F}{\partial\bar{S}} = \frac{\pi_e}{\alpha}TR\left[\frac{(\lambda\eta_c-\eta_r)}{(\bar{V}-\pi_e\bar{S})}\right] = \frac{\pi_e TR\cdot\eta_c}{\alpha(\bar{V}-\pi_e\bar{S})}(\lambda-\frac{\eta_r}{\eta_c})$.

Apply the Envelope Theorem and let $\beta_R = \frac{\eta_r}{\eta_c}$. The above two equations can be transformed as:

$$\frac{\partial g}{\partial \pi_e} = -\frac{\partial F/\partial \pi_e}{\partial F/\partial g} = -\frac{\tau g \eta_c (\overline{V} - \overline{S})}{\mu(1-\pi_e)(\overline{V} - \pi_e \overline{S})}(\beta_R - \lambda),$$

$$\frac{\partial g}{\partial \overline{S}} = -\frac{\partial F/\partial \overline{S}}{\partial F/\partial g} = \frac{\pi_e \tau g \eta_c}{\mu(\overline{V} - \pi_e \overline{S})}(\beta_R - \lambda) \; .$$

(QED)

Proof of Proposition 3

The proof here only considers the situation that income mix also exists in the fire-zone designation, which means both low- and high-income households live in the fire-prone area. Proofs in other scenarios can be conducted analogously.

Suppose the city has a perceived fire-prone area that is located between r_{fl} and r_{fh} with a w_f -mile width. Following Wu (2010), we substitute $\tau = \mu[\alpha + (1-\lambda)\mu]^{-1}$ to TC and TR and obtain:

$$TC = g^{\frac{\mu\lambda}{\alpha}+1}\Big(\int_{j=0,l} \delta\theta_0 (y-tx)^{\frac{1}{\alpha}-1} xdx + \int_{j=0,h} \delta\theta_0 (y-tx)^{\frac{1}{\alpha}-1} xdx$$
$$+ \int_{j=1,l} \delta\theta_1 (y-tx)^{\frac{1}{\alpha}-1} xdx + \int_{j=1,h} \delta\theta_1 (y-tx)^{\frac{1}{\alpha}-1} xdx\Big)^{\lambda} ,$$

$$TR = g^{\frac{\mu}{\alpha}}\Big(\int_{j=0,l} \varepsilon\theta_0 (y-tx)^{\frac{1}{\alpha}} xdx + \int_{j=0,h} \varepsilon\theta_0 (y-tx)^{\frac{1}{\alpha}} xdx + \int_{j=1,l} \varepsilon\theta_1 (y-tx)^{\frac{1}{\alpha}} xdx + \int_{j=1,h} \varepsilon\theta_1 (y-tx)^{\frac{1}{\alpha}} xdx\Big)^{\lambda},$$

where $\theta_{1,l} = (1-\pi_e)^{\frac{1}{\alpha}} (\overline{V}_l - \pi_e \overline{S}_l)^{-\frac{1}{\alpha}}, \theta_{1,h} = (1-\pi_e)^{\frac{1}{\alpha}} (\overline{V}_h - \pi_e \overline{S}_h)^{-\frac{1}{\alpha}}$, $\theta_{0,l} = (\overline{V}_l)^{-\frac{1}{\alpha}}$,

$\theta_{0,h} = (\overline{V}_h)^{-\frac{1}{\alpha}}$, $\delta = \dfrac{2\text{Pi}\left[\alpha^{\alpha}(1-\alpha)^{1-\alpha}\right]^{\frac{1}{\alpha}}}{\alpha}$ and $\varepsilon = 2\text{Pi}\left[\alpha^{\alpha}(1-\alpha)^{1-\alpha}\right]^{\frac{1}{\alpha}}$.

Let $C_{0,l} = \int_{j=0,l} \delta(y-tx)^{\frac{1}{\alpha}-1} xdx$, $C_{1,l} = \int_{j=1,l} \delta(y-tx)^{\frac{1}{\alpha}-1} xdx$, $C_{0,h} = \int_{j=0,h} \delta(y-tx)^{\frac{1}{\alpha}-1} xdx$,

$C_{1,h} = \int_{j=1,h} \delta(y-tx)^{\frac{1}{\alpha}-1} xdx$, $R_{0,l} = \int_{j=0,l} \varepsilon(y-tx)^{\frac{1}{\alpha}} xdx$, $R_{1,l} = \int_{j=1,l} \varepsilon\theta_1(y-tx)^{\frac{1}{\alpha}} xdx$,

$R_{0,h} = \int_{j=0,h} \varepsilon(y-tx)^{\frac{1}{\alpha}} xdx$, and $R_{1,h} = \int_{j=1,h} \varepsilon\theta_1(y-tx)^{\frac{1}{\alpha}} xdx$.

Thus, we obtain $TC = g^{\frac{\mu\lambda}{\alpha}+1}(\theta_{l,0}C_{l,0} + \theta_{h,0}C_{h,0} + \theta_{l,1}C_{l,1} + \theta_{h,1}C_{h,1})^{\lambda}$ and

$$TR = \frac{\tau}{(1+\tau)} g^{\frac{\mu}{\alpha}} (\theta_{l,0}R_{l,0} + \theta_{h,0}R_{h,0} + \theta_{l,1}R_{l,1} + \theta_{h,1}R_{h,1})$$

Similarly, we can obtain the first order conditions of $\theta_{i,1}$ with respect to π_e and $\overline{S}_i$ as:

$$\frac{\partial\theta_{i,1}}{\partial\pi_e} = \frac{1}{\alpha}\theta_{i,1}^{\frac{1}{\alpha}-1} \frac{(-1)(\overline{V}_i - \pi_e\overline{S}_i) - (-\overline{S}_i)(1-\pi_e)}{(\overline{V}_i - \pi_e\overline{S}_i)^2} = -\frac{1}{\alpha}\theta_{i,1}^{\frac{1}{\alpha}-1} \frac{(\overline{V}_i - \overline{S}_i)}{(\overline{V}_i - \pi_e\overline{S}_i)^2} < 0,$$

$$\frac{\partial \theta_{i,1}}{\partial \overline{S}_i} = -\frac{1}{\alpha}\theta_{i,1}^{\frac{1}{\alpha}-1}\frac{(1-\pi_e)}{(\overline{V}_i - \pi_e \overline{S}_i)^2}(-\pi_e) = \frac{1}{\alpha}\theta_{i,1}^{\frac{1}{\alpha}-1}\frac{(1-\pi_e)}{(\overline{V}_i - \pi_e \overline{S}_i)^2}\pi_e > 0 .$$

Denote $\overline{\theta_0 C_0} = \theta_{l,0}C_{l,0} + \theta_{h,0}C_{h,0}$, $\overline{\theta_0 R_0} = \theta_{l,0}R_{l,0} + \theta_{h,0}R_{h,0}$, $\overline{\theta_1 C_1} = \theta_{l,1}C_{l,1} + \theta_{h,1}C_{h,1}$, and $\overline{\theta_1 R_1} = \theta_{l,1}R_{l,1} + \theta_{h,1}R_{h,1}$. Let $F = TC - TR = 0$ and the first order conditions with respect to g and π_e can be obtained as:

$$\frac{\partial F}{\partial g} = (\frac{\mu\lambda}{\alpha}+1)g^{\frac{\mu\lambda}{\alpha}}(\overline{\theta_0 C_0} + \overline{\theta_1 C_1})^{\lambda} - \frac{\tau}{(1+\tau)}g^{\frac{\mu}{\alpha}}(\overline{\theta_0 R_0} + \overline{\theta_1 R_1})\frac{\mu}{\alpha}g^{-1} = \frac{\mu}{\alpha}\tau^{-1}g^{-1}TR > 0 ,$$

$$\frac{\partial F}{\partial \pi_e} = TR(\overline{\theta_0 C_0} + \overline{\theta_1 C_1})^{-1}\lambda(\frac{\partial \theta_{l,1}}{\partial \pi_e}C_{l,1} + \frac{\partial \theta_{h,1}}{\partial \pi_e}C_{h,1}) - TR(\overline{\theta_0 R_0} + \overline{\theta_1 R_1})^{-1}(\frac{\partial \theta_{l,1}}{\partial \pi_e}R_{l,1} + \frac{\partial \theta_{h,1}}{\partial \pi_e}R_{h,1}) .$$

Let $\eta_{l,c} = \frac{\theta_{l,1}C_{l,1}}{(\overline{\theta_0 C_0} + \overline{\theta_1 C_1})}$, $\eta_{l,r} = \frac{\theta_{l,1}R_{l,1}}{(\overline{\theta_0 R_0} + \overline{\theta_1 R_1})}$, $\eta_{h,c} = \frac{\theta_{h,1}C_{h,1}}{(\overline{\theta_0 C_0} + \overline{\theta_1 C_1})}$, $\eta_{h,r} = \frac{\theta_{h,1}R_{h,1}}{(\overline{\theta_0 R_0} + \overline{\theta_1 R_1})}$,

$$\frac{\partial F}{\partial \pi_e} = TR\left[\lambda(\frac{1}{\theta_{l,1}}\frac{\partial \theta_{l,1}}{\partial \pi_e}\eta_{l,c} + \frac{1}{\theta_{h,1}}\frac{\partial \theta_{h,1}}{\partial \pi_e}\eta_{h,c}) - (\frac{1}{\theta_{l,1}}\frac{\partial \theta_{l,1}}{\partial \pi_e}\eta_{l,r} + \frac{1}{\theta_{h,1}}\frac{\partial \theta_{h,1}}{\partial \pi_e}\eta_{h,r})\right].$$

Let $\omega_l = \frac{(\overline{V}_l - \overline{S}_l)}{(\overline{V}_l - \pi_e \overline{S}_l)}$ and $\omega_h = \frac{(\overline{V}_h - \overline{S}_h)}{(\overline{V}_h - \pi_e \overline{S}_h)}$. Substitute ω_l , ω_h , and $\frac{\partial \theta_{i,1}}{\partial \pi_e}$ to $\frac{\partial F}{\partial \pi_e}$

$$\frac{\partial F}{\partial \pi_e} = \frac{-1}{\alpha(1-\pi_e)}TR(\omega_l \eta_{l,c} + \omega_h \eta_{h,c})\left[\lambda - \frac{(\omega_l \eta_{l,r} + \omega_h \eta_{h,r})}{(\omega_l \eta_{l,c} + \omega_h \eta_{h,c})}\right].$$

The first order condition of F with respect to $\overline{S}$ can be obtained as:

$$\frac{\partial F}{\partial \overline{S}} = TR\left[\frac{1}{\theta_{l,1}}\frac{\partial \theta_{l,1}}{\partial \overline{S}}(\lambda\eta_{l,c} - \eta_{l,r}) + \frac{1}{\theta_{h,1}}\frac{\partial \theta_{h,1}}{\partial \overline{S}}(\lambda\eta_{h,c} - \eta_{h,r})\right].$$

Note that if $\overline{S}_l \neq \overline{S}_h$, we can directly apply chain rule and show that the impacts on different income groups only depends on its proportion. For simplification purpose, we impose the assumption of $\overline{S}_l = \overline{S}_h = \overline{S}$.

Let $\omega_l' = \frac{1}{(\overline{V}_l - \pi_e \overline{S})}$ and $\omega_h' = \frac{1}{(\overline{V}_h - \pi_e \overline{S})}$. Substitute ω_l' , ω_h', and $\frac{\partial \theta_{i,1}}{\partial \overline{S}}$ to $\frac{\partial F}{\partial \overline{S}}$

$$\frac{\partial F}{\partial \overline{S}} = \frac{\pi}{\alpha} TR(\omega_l'\eta_{l,c} + \omega_h'\eta_{h,c})\left[\lambda - \frac{(\omega_l'\eta_{l,r} + \omega_h'\eta_{h,r})}{(\omega_l'\eta_{l,c} + \omega_h'\eta_{h,c})}\right].$$

Apply the Envelope Theorem

$$\frac{\partial g}{\partial \pi_e} = -\frac{\partial F/\partial \pi_e}{\partial F/\partial g} = -\frac{\tau g(\omega_l'\eta_{l,c} + \omega_h'\eta_{h,c})}{\mu(1-\pi_e)}\left[\frac{(\omega_l'\eta_{l,r} + \omega_h'\eta_{h,r})}{(\omega_l'\eta_{l,c} + \omega_h'\eta_{h,c})} - \lambda\right].$$

Similarly,

$$\frac{\partial g}{\partial \overline{S}} = -\frac{\partial F/\partial \overline{S}}{\partial F/\partial g} = \frac{\pi_e \tau g}{\mu TR} TR(\omega_l'\eta_{l,c} + \omega_h'\eta_{h,c})\left[\frac{(\omega_l'\eta_{l,r} + \omega_h'\eta_{h,r})}{(\omega_l'\eta_{l,r} + \omega_h'\eta_{h,r})} - \lambda\right].$$

In particular, when $\overline{S} = 0$, then $\omega_l = \omega_h = 1$; the above results will be reduced to that in Proposition 1.

(QED)

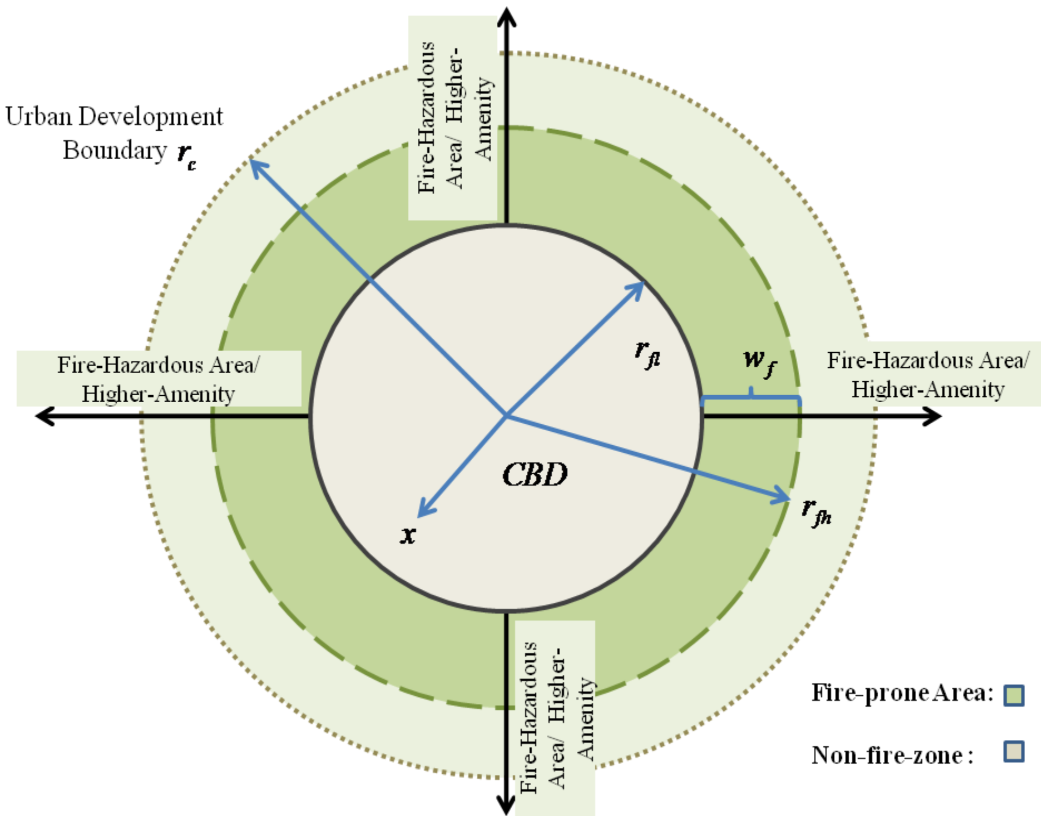

Figure 3.1 Urban Landscape

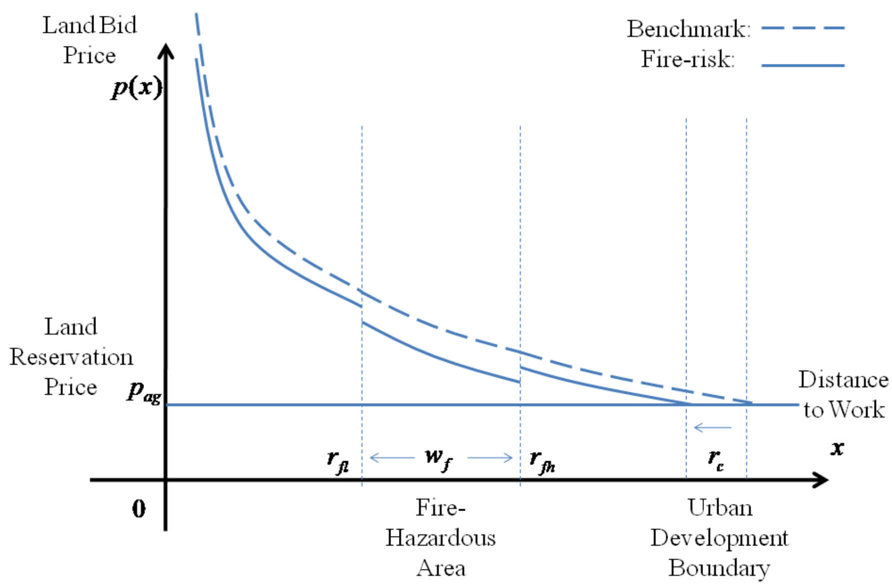

Figure 3.2 Optimal Land Price with Wildfire Risks and Uniform Natural Amenity Level

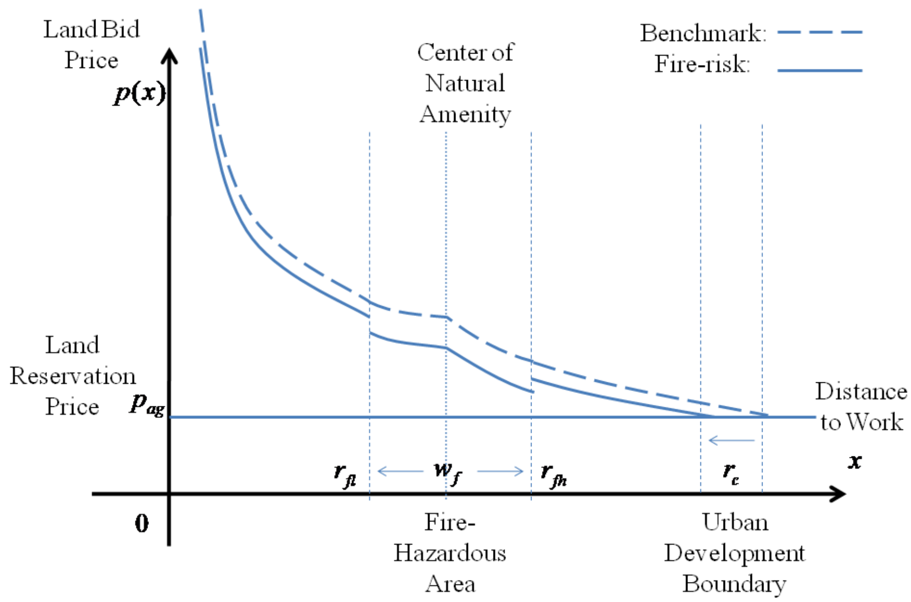

Figure 3.3 Optimal Land Price with Wildfire Risks and Heterogeneous Natural Amenity Levels

Table 3.1 Exogenous Parameter Values for Simulations

Parameters of Interest	**Denotation**	**Value**
Households Characteristics		
Income (Low-income Household)	y_l	35,000
Income (High-income Household)	y_h	75,000
Expected Utility (Low-income Household)	$\overline{V}_l$	2,920
Expected Utility (High-income Household)	$\overline{V}_h$	7,123
Post-fire Assistance (for Low-income Household)	$\overline{S}_l$	0
Post-fire Assistance (for High-income Household)	$\overline{S}_h$	0
Unit Commuting Cost (Low-income Household)	t_l	1,000
Unit Commuting Cost (High-income Household)	t_h	1,500
Preference for Housing (Low-income Household)	α_l	0.125
Preference for Housing (High-income Household)	α_h	0.125
Preference for Public Services (Low-income Household)	μ_l	0.015
Preference for Public Services (High-income Household)	μ_h	0.015
Preference for Natural Amenities (Low-income Household)	γ_l	0.125
Preference for Natural Amenities (High-income Household)	γ_h	0.125
Urban Community Characteristics		
Economy of Scale (Public Services)	λ	0.85
Land Reservation Price	p_{ag}	1,000
Fire Risk and Natural Amenities Features		
Amenities Function Parameters	a_1	1/2/3
Amenities Function Parameters	δ	0.5
Amenities Function Parameters	w_A	1.0
Fire-zone Area (Width)	w_f	2/3/4
Wildfire Occurrence Probability	π_e	0.05/0.1/0.2

Table 3.2 Wildfire Risks and Urban Development Patterns (One Income Group)

Community Characteristics	Baseline	Fire Occurrence Probability			Fize-Hazardous Area: Width		
		0.05	0.1	0.2	2-mile	4-mile	6-mile
City							
Total Land Value (Million Dollars)	2,970	2,849	2,765	2,611	2,765	2,585	2,382
Community Development Boundary (Miles)	17.216	17.214	17.213	17.211	17.213	17.212	17.213
Average Land Price ($/Acre)	4,983	4,782	4,642	5,149	4,642	4,521	5,278
Average Land Price Around CBD ($/Acre)	23,644	23,634	23,626	23,612	23,626	23,620	23,628
Number of Households	426,519	407,996	395,185	371,530	395,185	365,967	331,292
Lot Size (Acre/ Household)	1.40	1.46	1.51	1.36	1.51	1.56	1.36
Density (Units/Square Miles)	458	438	425	469	425	410	470
Quality of Public Service (Index)	5,948	5,925	5,909	5,880	5,909	5,897	5,913
Average Property Tax Payment ($/Household)	851	853	855	859	855	863	879
Property Tax Rate	12.22%	12.22%	12.22%	12.22%	12.22%	12.22%	12.22%
Fire-zone							
Start Location (Mile)	-	10.00	10.00	10.00	10.00	10.00	10.00
End Location (Mile)	-	12.00	12.00	12.00	12.00	14.00	16.00
Width (Mile)	-	2.00	2.00	2.00	2.00	4.00	6.00
Community Development Boundary (Miles)	-	12.00	12.00	10.00	12.00	13.57	13.57
Total Development (Acre)	-	88,467	88,467	-	88,467	169,119	169,204
Average Residential Land Price ($/Acre)	-	2,109	1,369	-	1,725	1,468	1,468
Number of Households	-	111,073	23,403	-	23,403	38,778	38,806
Average Lot Size in Fire-zone (Acre/ Household)	-	2.45	3.78	-	3.78	4.36	4.36
Development Density (Units/Square Miles)	-	261	169	-	169	147	147
Indicator (β_R)	-	0.934	0.932	-	0.932	0.906	0.890

Table 3.2 Wildfire Risks and Urban Development Patterns (One Income Group) (Continued)

Community Characteristics	Baseline	Natural Amenity: Level			Natural Amenity: Geographic Location		
		1	2	3	10-mile	11-mile	12-mile
City							
Total Land Value (Million Dollars)	2,970	3,317	3,868	4,420	3,088	3,041	3,025
Community Development Boundary (Miles)	17.216	17.387	17.531	17.655	17.273	17.304	17.355
Average Land Price ($/Acre)	4,983	5,457	6,260	7,054	5,148	5,051	4,995
Average Land Price Around CBD ($/Acre)	23,644	23,870	24,110	24,346	23,822	23,749	23,703
Number of Households	426,519	478,666	562,133	645,646	442,848	436,933	435,597
Lot Size (Acre/ Household)	1.40	1.27	1.10	0.97	1.35	1.38	1.39
Density (Units/Square Miles)	458	504	582	659	472	464	460
Quality of Public Service (Index)	5,948	6,022	6,126	6,224	5,990	5,967	5,950
Average Property Tax Payment ($/Household)	851	847	841	837	852	851	849
Property Tax Rate	12.22%	12.22%	12.22%	12.22%	12.22%	12.22%	12.22%
Fire-zone							
Start Location (Mile)	-	10.00	10.00	10.00	10.00	10.00	10.00
End Location (Mile)	-	12.00	12.00	12.00	12.00	12.00	12.00
Width (Mile)	-	2.00	2.00	2.00	2.00	2.00	2.00
Community Development Boundary (Miles)	-	12.00	12.00	12.00	12.00	12.00	12.00
Total Development (Acre)	-	88,467	88,467	88,467	88,467	88,467	88,467
Average Residential Land Price ($/Acre)	-	3,090	4,459	5,834	2,284	2,407	2,262
Number of Households	-	41,916	60,500	79,148	30,957	32,650	30,717
Average Lot Size in Fire-zone (Acre/ Household)	-	2.11	1.46	1.12	2.86	2.71	2.88
Development Density (Units/Square Miles)	-	303	438	573	224	236	222
Indicator (β_R)	-	0.941	0.948	0.952	0.936	0.937	0.938

Table 3.3 Wildfire Risks and Urban Development Patterns (Mixed Income Groups)

Community Characteristics	Baseline	Fire Occurrence Probability			Fize-Hazardous Area: Width		
		0.05	0.1	0.2	2-mile	4-mile	6-mile
City							
Total Land Value (Million Dollars)	4,380	4,261	4,178	4,026	4,178	3,982	3,777
Community Development Boundary (Miles)	16.960	16.958	16.956	16.950	16.956	16.944	16.931
Average Land Price ($/Acre)							
Low-income group	15,114	14,835	14,642	14,412	14,642	14,600	14,556
High-income group	2,017	1,865	1,760	2,007	1,760	1,368	1,214
Around CBD	57,164	57,131	57,108	57,029	57,108	56,944	56,771
Number of Households							
Low-income group	1,130,250	1,105,330	1,088,090	1,055,600	1,088,090	1,084,970	1,081,660
High-income group	110,581	102,672	97,201	82,350	97,201	66,965	33,957
Lot Size (Acre/ Household)							
Low-income group	0.22	0.22	0.23	0.23	0.23	0.23	0.23
High-income group	3.01	3.24	3.42	2.96	3.42	4.36	5.00
Density (Units/Square Miles)							
Low-income group	2,948	3,522	2,838	2,753	2,838	2,830	2,821
High-income group	213	197	187	216	187	147	128
Quality of Public Service (Index)	3,539	3,510	3,510	3,470	3,510	3,427	3,341
Average Property Tax Payment ($/Household)	431	431	431	428	431	422	414
Property Tax Rate	12.22%	12.22%	12.22%	12.22%	12.22%	12.22%	12.22%
Fire-zone							
Start Location (Mile)	-	10.00	10.00	10.00	10.00	10.00	10.00
End Location (Mile)	-	12.00	12.00	12.00	12.00	14.00	16.00
Width (Mile)	-	2.00	2.00	2.00	2.00	4.00	6.00
Community Development Boundary in Fire-zone (Miles)	-	12.00	12.00	10.00	12.00	13.27	13.26
Total Development Acre	-	88,467	88,467	-	88,467	153,050	169,204
Average Residential Land Price in Fire-zone ($/Acre)	-	2,595	1,683	-	1,683	1,454	1,452
Number of Households in Fire-zone	-	63,244	41,020	-	41,020	52,769	52,487
Low and High-income Mix Ratio	-	3.1050	3.1050	-	3.1050	1.4172	1.4251
Average Lot Size (Acre/ Household)	-	1.40	2.16	-	2.16	2.90	2.90
Density (Units/ Square Miles)	-	458	297	-	297	221	221
Indicator (β_R)	-	1.029	1.030	-	1.030	1.220	1.244

Table 3.3 Wildfire Risks and Urban Development Patterns (Mixed Income Groups) (Continued)

Community Characteristics	Baseline	Natural Amenity: Level			Natural Amenity: Geographic Location		
		1	2	3	10-mile	11-mile	12-mile
City							
Total Land Value (Million Dollars)	4,380	4,817	5,455	6,094	4,574	4,498	4,465
Community Development Boundary (Miles)	16.960	17.153	17.312	17.447	17.021	17.060	17.121
Average Land Price ($/Acre)							
Low-income group	15,114	16,431	18,222	20,017	16,007	15,536	15,203
High-income group	2,017	2,269	2,755	3,224	1,918	2,018	2,135
Around CBD	57,164	57,718	58,309	58,887	57,535	57,416	57,365
Number of Households							
Low-income group	1,130,250	1,235,190	1,382,560	1,530,220	1,199,700	1,161,620	1,134,060
High-income group	110,581	129,719	162,013	194,185	107,102	113,500	121,532
Lot Size (Acre/ Household)							
Low-income group	0.22	0.20	0.18	0.16	0.20	0.21	0.22
High-income group	3.01	2.67	2.21	1.89	3.15	2.99	2.83
Density (Units/Square Miles)							
Low-income group	2,948	3,222	3,606	3,991	3,129	3,030	2,958
High-income group	213	240	290	339	203	214	226
Quality of Public Service (Index)	3,539	3,589	3,659	3,722	3,536	3,551	3,571
Average Property Tax Payment ($/Household)	431	431	421	432	428	431	435
Property Tax Rate	12.22%	12.22%	12.22%	12.22%	12.22%	12.22%	12.22%
Fire-zone							
Start Location (Mile)	-	10.00	10.00	10.00	10.00	10.00	10.00
End Location (Mile)	-	12.00	12.00	12.00	12.00	12.00	12.00
Width (Mile)	-	2.00	2.00	2.00	2.00	2.00	2.00
Community Development Boundary in Fire-zone (Miles)	-	12.00	12.00	12.00	12.00	12.00	12.00
Total Development Acre	-	88,467	88,467	88,467	88,467	88,467	88,467
Average Residential Land Price in Fire-zone ($/Acre)	-	3,012	4,346	5,685	2,234	2,347	2,204
Number of Households in Fire-zone	-	73,494	106,104	138,828	55,616	57,239	52,523
Low and High-income Mix Ratio	-	3.0825	3.0704	3.0624	3.4973	3.1152	2.7566
Average Lot Size (Acre/ Household)	-	1.20	0.83	0.64	1.59	1.55	1.68
Density (Units/ Square Miles)	-	532	768	1,004	402	414	380
Indicator (β_R)	-	1.027	1.026	1.025	1.015	1.028	1.044

Endnotes

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[1] By definition, $u_{1,k} \ll u_{0,k}$: this rules out the possibility that somebody may benefit from wildfires.

[2] This also implies that if income mix exists, the residents in one community of a single income group do not have any intension to move, which constitutes a community development boundary for that income group.

[3] The results will hold if income mix exists with identical-preference households. The results may not hold if natural amenity level is endogenously affected or residents with income mix have heterogeneous preferences. See Wu et al. (2009) for the details of assumptions and proofs. The simulations are conducted in accordance to equation (6).

[4] See results in the 6th, 7th, and 8th columns of Tables 3.2 and 3.3 for more details.

[5] β_{R3} can be seen as the relative tax burden for residents in the fire-zone β_R weighted by the proportion of the number of households. ω_i is denoted as the fire occurrence elasticity (π_e) of the risk measure function $\theta_{i,1}$ for income group i, with $\theta_{i,1} = \left[\frac{(1-\pi_e)}{(\overline{V}_i - \pi_e \overline{S})} \right]^{1/\alpha}$. Also note that the weights (ω_i / ω_j and ω_i' / ω_j') are different if $\overline{S} > 0$; if $\overline{S} = 0$, both β_{R3} and β_{R3}' equal β_R. See proof in the Appendix for more details.

[6] This number is calculated based on the average annual expenditures and characteristics in San Diego Metropolitan Statistical Area (MSA), Consumer Expenditure Survey conducted by the Bureau of Labor Statistics.

[7] This is based on the calculation with data taken from the 2002 American Housing Survey data chart for occupied housing units for the San Diego Metropolitan Area of U.S. Census Bureau.

[8] The data is taken from the 2002 American Housing Survey data chart for occupied housing units for the San Diego Metropolitan Area of U.S. Census Bureau.

[9]This is equivalent to households with income less than or equal to $75,000/year, which account for around 84.27% of households in the San Diego County. This is equivalent to households with income less than or equal to $35,000/year, which account for around 42.36% of households in the San Diego County.

[10] The data are taken from the Fire Burn History GIS layer from San Diego Geographic Information System (SanGIS).

[11] See Wu (2010) for details and proofs.

CHAPTER 4

4. Amenity-Driven Migration and the Spatial Distribution of Economic Activity

Abstract

This study models the role of amenity in interregional migration and spatial distribution of economic activities. Extending the framework of Helpman (1998) by including locational amenities, it presents a multi-market equilibrium framework that includes consumption, production, and trade. Results suggest that the effects of amenities are significantly affected by household preferences, trade barriers, and other regional economic characteristics. When there are few trade barriers between regions, amenities is a major determinant of the spatial distribution of population and economic activities; however, when trade barriers exist, the effects of amenities will be strongly affected by household preferences. This means that if the preference for residential space is relatively low compared with the preference for varieties and amenities, a large city will likely emerge and amenities have little effect on interregional migration. Otherwise, a dispersed distribution pattern of population will emerge and amenities have larger impacts on the spatial distribution of economic activities. This study contributes to the amenity-driven migration literatures and informs the debate about the effect of amenities on interregional migrations and regional economic development.

4.1 Introduction

Americans are known to be one of the most mobile people in the world. Their migration patterns have been always on the change: these changes are reflected not only in interregional migration, as Americans were seen moving around the Country throughout history, but also in intraurban migration, as they move from the center of the city to the suburban areas in recent decades (Frey, 2009). These changing patterns not only created the unique landscape and culture in the United States, but also created many issues that await research in regional science and urban economics.

In recent years, amenity-driven migration has attracted much attention. There have been many studies showing that residential developments are expanding rapidly into amenity-rich areas. As a matter of fact, the effects of locational amenities on intraurban and interregional migration have been long recognized and systematically studied in abundant literatures from various perspectives.[1] Rosen (1979) and Roback (1982) provided a theoretical framework to understand locational amenities and migration decisions. In their frameworks, individuals are mobile enough to eliminate utility differences across space in pursuit of higher quality of life in a long-term equilibrium. Applying this framework to housing market and non-traded goods, Roback (1982) provided empirical evidence that regional wage differences can be explained largely by local attributes. Linneman and Graves (1983) used a multinomial logit model to reveal that both housing demand and more traditional job search motivation significantly influence migration decisions. Graves and Waldman (1991) showed that the general multimarket amenity compensation model presents a more accurate picture of the spatial equilibrium mechanism than the competing hypothesis that amenities are priced separately into either the land or the labor market. Treyz et al. (1993) estimated a net migration model by using time series data for 51 regions over the period 1971-1988. Their results revealed that the dynamic response of net migration is significantly related to stock equilibrium changes induced by amenity differentials, relative employment opportunities, relative real wages, and industry composition.

The effects of locational amenities are recognized to be complicated and pervasive in different aspects of economies in regional science and urban studies literatures. First, locational amenities take various forms. For example, forests, lakes, beaches, and other natural and geographic features are generally used to evaluate locational amenities in intraurban migration (Johnson and Beale, 1994; Radeloff et al., 2005; Radeloff et al., 2000; Rasker and Hanson, 2000). Climatic factors and environmental qualities are also popular standards to evaluate locational amenities for interregional migration literatures. Glaeser and Shapiro (2005) found out that weather is significantly associated with city population growth, which might suggest that the weather is one likely observable source of exogenous variation in the demand for particular locales. A more recent study by Banzhaf and Walsh (2008) provided strong empirical support for the notion that households "vote with their feet" for environmental quality.

Second, locational amenities affect the migration decisions of various age-, skill-, and race-groups, and thus influence regional productivity and firm location choices. Adamson et al. (2004) suggested that urban amenities affect skilled workers' location choices. Chen and Rosenthal (2008) analyzed individual level migration decisions and found that young, highly educated households tend to move towards places with higher quality business environment, whereas couples near retirement tend to move towards places with highly valued consumer amenities.

Third, by influencing residential locations choices, location amenities also affect public services, and thus shape urban and suburban spatial profiles and development patterns. Brueckner et al. (1999) presented an amenity-based theory of location and showed that the relative location of different income groups depends on the spatial pattern of amenities in a city. Wu (2006) developed an economic model to explore the causes of fragmentation in land development and found that spatial heterogeneity of amenities is a major determinant of development patterns and community profiles. Wu et al. (2009) investigated locational amenities from open space conservation and its impacts on community characteristics.

Last, by affecting both consumption and production, locational amenities are also found to be closely associated with economic growth and regional development. Black and Henderson (1999) found non-coastal cities with poorer climate grow more slowly. They also suggested that agglomeration is promoted by coastal location, good climate, and high market potential. Rappaport and Sachs (2003) studied U.S. economic activity and suggested that the investigation of coastal concentration should focus primarily on factors from both the productivity side and the quality of life aspect. Glaeser et al. (2004) showed that housing supply plays a part in mediating urban growth, and that differences in the regulatory environment across space affect how cities respond to increases in productivity.

In spite of the increasing number of studies that address the role of locational amenities in interregional migration, the importance of locational amenities has also been questioned. The issue centers around the prolonged debate over “people follow jobs” or “jobs follow people”. Greenwood and Hunt (1989) argued that job and wages are considerably more important than location-specific amenities in explaining net metropolitan migration of employed persons. Greenwood et al. (1991) suggest that disequilibrium in migration may lead to biased estimates of amenity valuations and, in general, to biased valuations of the entire bundle of the location-specific characteristics associated with each region, if regional markets do not tend to clear quickly on a continuous basis. Hunt (1993) questioned the efficacy of including locational amenities in interregional migration studies, and claimed that it does little to correct wrong signs or increase the significance of correctly signed coefficients on the economic opportunities. Besides, current literatures that heavily emphasize the effects of locational amenities on migration cannot explain the heterogeneity in regional development. On one hand, regions with high locational amenities continue to grow, while regions with disamenities are on the wane. On the other hand, regions with high disamenities continue to thrive, whereas high-locational-amenity places are left completely undeveloped. And the recession in the early 21st century made it even harder for people to readily accept as true the importance of locational amenities in interregional migration. Florida, which was once the top draw for Americans in search of work and warmer climates, lost more than 31,179 residents as of July 1, 2009 according to a Brookings report (Fey, 2009). As people move in search of jobs in the current economic crises, evidence grows that job opportunities are more important than locational amenities in interregional migrations. However, generally speaking, current studies seem to omit the difference between intraurban migration and interregional migration. Also, current literatures did not provide a multi-market-equilibrium framework that characterizes various economic activities both within regions and across regions. Accordingly, there is great need to develop such a model that could incorporate factors that influence quality of life and job opportunity on household's migration decision in one analysis.

The objective of this study is to develop a model to address the roles of locational amenities in interregional migration. We extended the framework of Helpman (1998) by including locational amenities. We are interested in answering three major questions. First, under what conditions do locational amenities influence the equilibrium distribution of population? Second, what factors determine the equilibrium distribution of population across regions? Third, what roles do amenities play in interregional migration? The answers to these questions will contribute to the understanding the role of locational amenities in interregional migrations.

The paper is organized as follows. In the next section, we present the model to study amenity-driven migration and the spatial distribution of population. In the third section, we conduct simulation analyses, and discuss results under different scenarios. In the last section, we summarize the main results and suggest avenues for future research.

4.2 The Model

In 1991, Krugman published a path-breaking paper to investigate the heterogeneity in regional structure and economic development. As Krugman (1991) perceived, his model is a variant on the monopolistic competition framework initially proposed by Dixit and Stiglitz (1977). Krugman's general equilibrium framework has two groups of participating agents: individual households and firms. Individual households maximize their utility by way of consumption subject to their income. Firms hire labor, produce goods, and maximize their profits. This general equilibrium framework also incorporates two sectors: agricultural and manufacturing. The two sectors differ in the way of how products are traded and how demands are generated. When regional economies reach equilibriums in multi-markets (e.g., the supply and demand of tradable goods, the supply and demand of labor, and the income and expenditure of representative households) simultaneously, the equilibrium distribution of population in space is determined.

By contrast, Helpman (1989) proposed an alternative model. In Helpman's framework, the agricultural sector is replaced by an immobile housing sector. It is also assumed that the gross income generated from the housing sector, the land rent, is distributed among regions in proportion to the number of residents. This assumption takes the place of Krugman's that the income from the agricultural sector is spent entirely in that region. These changes in setups not only emphasize the role of housing consumptions in interregional migration, but produce results different from Krugman's. This study builds upon Helpman's framework. In what follows, we explain in detail how we modify Helpman's framework, and how equilibrium conditions in multimarkets can be derived.

4.2.1 The micro level decisions

Consider an economy with two regions. Region k ($k = 1,\ 2$) has N_k households and n_k monopolistic competitive firms. Household i ($i = 1, ..., N_k$) earns incomes ($E_{i,k}$) and chooses a consumption bundle, containing tradable commodities and housing, to maximize utility. Each firm j ($j = 1, ..., n_k$) hires labor and produces one unique variety. The commodity can be traded across regions at an iceberg transport cost τ. Labor cost on the production side is transformed into household's income source on the consumption side.

From the consumption side, households maximize utility subject to their earned income. Their utility comes from two main sources: tradable goods (manufactured varieties) and non-tradable goods (housing). Housing consumption is comprised of three major elements: land, structure, and locational amenities. Housing main structure is made up of commodities that can be traded across regions, whereas land and locational amenities are non-tradable. The total amount of developable lands is fixed in each region.

Formally, household i's utility maximization problem can be expressed as

$$\text{(1)} \qquad \begin{aligned} &\max u_{i,k} \equiv \left(A_k^{\theta} l_{i,k}^{\ 1-\theta}\right)^{\gamma} \left\{ \left[\sum_{j=1}^{n_1} x_{i,j,k}^{\alpha} + \sum_{j=1}^{n_{-k}} x_{i,j,-k}^{\alpha} \right]^{1/\alpha} \right\}^{1-\gamma} \\ &s.t. \quad p_l l_{i,k} + \sum_{j=1}^{n_k} p_{j,k} x_{i,j,k} + \sum_{j=1}^{n_{-k}} \left(\tau p_{-k}\right) x_{i,j,-k} \le E_{i,k} \qquad (k = 1,\ 2) \end{aligned}$$

A_k is the level of locational amenity in region k, and can be freely enjoyed by all residents living in the region. $l_{i,k}$ is the amount of land consumed by household i in region k, at a cost p_l per unit. $l_{i,k}$ is assumed to be the same for all households living in a region (e.g., $l_{i,k} \equiv L_k / N_k$). For household i, $x_{i,j,k}$ is the demand for tradable good that produced locally, and $x_{i,j,-k}$ is imported from other regions at the iceberg transport cost τ.[2] γ represents households' preference for housing relative to the consumption bundles of tradable goods, and θ represents households' reference for locational amenities relative to housing. All households have the same preferences. This setup implies a constant elasticity of substitution (ε) between the tradable goods with $\varepsilon = 1/(1-\alpha)$ and $0 < \alpha < 1$.[3] Migration between different regions is costless.

Solving this utility maximization problem, we obtain two important results. First, this maximization problem determines the optimal allocation of households' income between the tradable and non-tradable goods: [4]

(2) $$p_l l_k = (1-\theta)\gamma \frac{E_k}{(1-\theta\gamma)}; \quad \sum_{1}^{n_k} p_{j,k} x_{j,k} + \sum_{1}^{n_{-k}} \left(\tau p_{j,-k}\right) x_{j,-k} = (1-\gamma)\frac{E_k}{(1-\theta\gamma)}$$

Second, from the maximization problem, we can derive the demand for locally-produced goods ($x_{j,k}$) and imported goods ($x_{j,-k}$) as functions of prices ($p_{j,k}$ and $p_{j,-k}$), iceberg transport cost (τ), and the total expenditures in region k (E_k):

(3)

$$x_{j,k} = \frac{(1-\gamma)\, p_{j,k}^{\frac{1}{\alpha-1}} E_k}{(1-\theta\gamma)\left[\sum_{1}^{n_k} p_{j,k}^{\frac{\alpha}{\alpha-1}} + \sum_{1}^{n_{-k}} \left(\tau p_{j,-k}\right)^{\frac{\alpha}{\alpha-1}}\right]}$$

$$x_{j,-k} = \frac{(1-\gamma)\left(\tau p_{j,-k}\right)^{\frac{1}{\alpha-1}} E_k}{(1-\theta\gamma)\left[\sum_{1}^{n_k} p_{j,k}^{\frac{\alpha}{\alpha-1}} + \sum_{1}^{n_{-k}} \left(\tau p_{j,-k}\right)^{\frac{\alpha}{\alpha-1}}\right]}$$

Following Helpman, we assume that it takes $a + x_{j,k}$ units of labor to produce $x_{j,k}$ units of output. Thus, the labor demand of each firm is $lr_{j,k} = a + x_{j,k}$, where a is a fixed cost associated with labor inputs, which is assumed to be the same for all regions. Wage rate, w_k, or the marginal cost of producing the tradable good $x_{j,k}$, is assumed to be the same within each region.

The solution of profit maximization of each monopolistic competitive firm j gives the price set by the function $p_{j,k} = \frac{1}{\alpha} w_k$. In addition, free entry in the production market for individual firm implies

(4) $$p_{j,k} x_{j,k} = \left(a + x_{j,k}\right) w_k \Rightarrow x_{j,k} = \frac{\alpha a}{1-\alpha} = x_k$$

This suggests that all firms in region k produce the same amount of output and thus set the same price for all products:

(5) $$p_{j,k} = \left(\frac{a + x_k}{x_k}\right) w_k = p_k$$

4.2.2. Labor market equilibrium and the number of variety

The total labor demand in region k equals $(a+x_k)n_k$ with n_k the number of varieties produced in this region. The total labor supply equals the number of households living in this region (N_k). When the labor market is cleared, the number of variety (n_k) is determined as

(6) $$n_k = \frac{1-\alpha}{a} N_k$$

The labor market equilibrium can be use to evaluate labor demand (job opportunities), which is essential component in Helpman's framework.

4.2.3. Households' income and expenditure

Each household has two sources of income: the wage income and the income from land rent. By assumption, collected land rent is distributed equally among households living in the region. The total amount of land rent collected in the two regions equals the total amount of household income spent on land $\frac{(1-\theta)\gamma}{(1-\gamma)}\left(w_k N_k + w_{-k} N_{-k}\right)$. Thus, region k 's total income I_k equals

(7) $$I_k = w_k N_k + \frac{N_k}{N}\frac{(1-\theta)\gamma}{(1-\gamma)}\left(w_k N_k + w_{-k} N_{-k}\right), \quad k = 1,\ 2.$$

4.2.4. The relative prices between the two regions

For each tradable good produced in region 1, the supply is $x_{1,s} = \frac{\alpha a}{1-\alpha}$. The total demand for a tradable good produced in region 1 equals:

(8) $$x_{1,d} = \frac{p_1^{1-\varepsilon}}{n_1 p_1^{1-\varepsilon} + n_2(\tau p_2)^{1-\varepsilon}} \frac{(1-\gamma)E_1}{(1-\theta\gamma)p_1} + \frac{(\tau p_1)^{1-\varepsilon}}{n_1(\tau p_1)^{1-\varepsilon} + n_2 p_2^{1-\varepsilon}} \frac{(1-\gamma)E_2}{(1-\theta\gamma)p_1}$$

$\frac{p_1^{1-\varepsilon}}{n_1 p_1^{1-\varepsilon} + n_2(\tau p_2)^{1-\varepsilon}}$ is the share of the total expenditure of region 1 spent on the good produced in region 1, and $\frac{(\tau p_1)^{1-\varepsilon}}{n_1(\tau p_1)^{1-\varepsilon} + n_2 p_2^{1-\varepsilon}}$ is the share of the total expenditure of region 2 spent on the good produced in region 1.

Let q be the ratio of prices of the tradable good in the two regions (i.e. $q \equiv p_1/p_2 = w_1/w_2$), and let f be the share of total population in the economy living in region 1 (i.e., $f \equiv N_1/N$). The equilibrium condition for the commodity market (i.e., $x_{1,d} = x_{1,s}$) implies the following condition

(9) $$\begin{aligned} 1-\theta\gamma = & \frac{fq^{-\varepsilon}}{fq^{1-\varepsilon} + (1-f)\tau^{1-\varepsilon}} \left\{(1-\gamma)q + \gamma(1-\theta)\left[qf + (1-f)\right]\right\} \\ & + \frac{(1-f)\tau^{1-\varepsilon}q^{-\varepsilon}}{f\tau^{1-\varepsilon}q^{1-\varepsilon} + (1-f)} \left\{(1-\gamma) + \gamma(1-\theta)\left[qf + (1-f)\right]\right\} \end{aligned}$$

This result is quite similar to that of Helpman (1998). There are two important implications. First, given the household's preferences, the relative price is a function of the distribution of the population between the two regions. Second, the change in the preference of locational amenities leads to adjustment in both the relative price and the distribution of total population between the two regions.

4.2.5. Relative utilities and the condition for spatial equilibrium

Using the price index of tradable products, the utility level of each household in region k can be derived as

(10) $$u_k = \left[A_k^{\theta} (\frac{H_k}{N_k})^{1-\theta} \right]^{\gamma} \left[\frac{(1-\gamma)E_k}{(1-\gamma\theta)N_k P_{dk}} \right]^{1-\gamma}$$

where $P_{dk} \equiv \left[n_k p_k^{1-\varepsilon} + n_{-k} \left(\tau p_{-k} \right)^{1-\varepsilon} \right]^{1/(1-\varepsilon)}$ is the price index in region k. Substituting E_k and P_{dk} into equation (10) gives

(11) $$u_k = C_0 A_k^{\theta\gamma} H_k^{(1-\theta)\gamma} f_k^{-(1-\theta)\gamma} \left[\frac{(1-\gamma)q_k + \gamma\left(qf_k + f_{-k}\right)}{\left[f_k q_k^{1-\varepsilon} + f_{-k}\tau^{1-\varepsilon} \right]^{1/(1-\varepsilon)}} \right]^{1-\gamma} N^{\frac{(1-\gamma\varepsilon)}{(\varepsilon-1)}+\theta\gamma}$$

with $C_0 = \left[\alpha \left(\frac{a}{1-\alpha} \right)^{1/(1-\varepsilon)} \frac{1}{(1-\gamma\theta)} \right]^{1-\gamma}$.

Using equation (11), the ratio of utility for households living in regions 1 and 2 ($v_{1,2}$) can be derived as

(12) $$v_{1,2} = \left(\frac{A_1}{A_2} \right)^{\theta\gamma} \left(\frac{H_1}{H_2} \right)^{(1-\theta)\gamma} \left(\frac{1-f}{f} \right)^{(1-\theta)\gamma} \left[\frac{(1-\gamma)q + \gamma\left(qf + 1 - f\right)}{(1-\gamma) + \gamma\left(qf + 1 - f\right)} \right]^{1-\gamma} \left[\frac{\left(1-f\right) + f\left(\tau q\right)^{1-\varepsilon}}{fq^{1-\varepsilon} + \left(1-f\right)\tau^{1-\varepsilon}} \right]^{\frac{(1-\gamma)}{(1-\varepsilon)}}$$

Equation (12) states that a distribution of population between the two regions is a spatial equilibrium if no one has incentives to move. If $v_{1,2} > 1$, some households in region 2 would move to region 1; and vice versa. So, in equilibrium, $v_{1,2} = 1$. Equation (12) also implies that agglomeration configurates where all households living in one region cannot be a spatial equilibrium. This is because if *f*=1, some households in region 1 would move to region 2 because $v_{1,2} = 0$; likewise, if *f*=0, some households in region 2 would move to region 1 because $v_{1,2} \to \infty$.

In the next section, we will expand our discussion of equilibrium conditions with consideration of different scenarios and reveal the effects of locational amenities on interregional migrations.

4.3 Equilibrium Distribution of Population

Equation (12) indicates that transport cost influences the equilibrium distribution of population and economic activity between the two regions. Transport cost changes the relative price of locally vs. non-locally manufactured products, which in turn affects households' consumption bundles. The adjustment in consumption bundles has a ripple effect on firms' operation, including adjustments in the production of manufactured products and demand for labor. The iceberg transport cost can be viewed not only as a trade barrier that determines the accessibility of local markets between regions, but also as an indicator to evaluate how regions are connected through economic activities, such as consumption, production, and trade. In this section, we examine how transport costs affect the equilibrium distribution of population between the two regions.

4.3.1. No trade barrier to access local markets

When there is no transport cost ($\tau \to 1$), competition causes the price of tradable goods to be equal across regions (i.e., $q \to 1$). Substituting these conditions into equation (12), we get

(13) $$v_{1,2} = \left(\frac{A_1}{A_2}\right)^{\theta\gamma} \left(\frac{H_1}{H_2}\right)^{(1-\theta)\gamma} \left(\frac{1}{f} - 1\right)^{(1-\theta)\gamma}.$$

Equation (13) indicates that the level of utility in region 1 relative to that in region 2 decreases as more people move to region 1 (i.e., as f increases). Setting $v_{1,2} = 1$, the equilibrium distribution of population between the two regions can be derived as

(14) $$f^* = \frac{1}{1 + \left|\left(\frac{A_2}{A_1}\right)^{\frac{\theta}{(1-\theta)}} \left(\frac{H_2}{H_1}\right)\right|}.$$

$f = f^*$ is a stable solution, which could be verified by imposing an extra disturbance, for example, that attracts households to region 1. This would decrease the relative utility level in region 1, which, in turn, causes out-migration. The equilibrium is regained as $f = f^*$. From equation (14), it is easy to verify that if the two regions have the same level of developable lands and the same level of locational amenities (e.g., $H_1 = H_2$ and

$A_1 = A_2$), $f^* = 0.5$, that is, the symmetric distribution of population between the two regions is the equilibrium. If the two regions have the same amount of developable lands but different amenity levels (e.g., $H_1 = H_2$ and $A_1 \neq A_2$), the regions with a higher level of locational amenities has a larger population. Besides $f = f^*$, it is easy to verify that either $f \to 0$ or $f \to 1$ is not a stable solution.

Graphically, the relationship between $v_{1,2}$ and f for the two-region case is shown in Figure 4.1. The vertical axis stands for the relative utility level between the two regions ($v_{1,2}$). The horizontal line represents the share of population living in region 1 (f). The solid line is the relative utility curve with the locational amenity level of region 1 at $A_1 = 1.2$. The dotted line suggests a higher locational amenity level in region 1 ($A_1 = 1.5$). With higher locational amenities, the relative utility curve was shifted upward, which results in a larger f^*_{high} compared to f^*_{low}. Figure 4.1 suggests that locational amenities affect the equilibrium distribution of population between the two regions. As expected, regions with a higher locational amenity level attract more households, produce more varieties of tradable goods, and create more job opportunities.

(Figure 4.1)

4.3.2. Trade barrier to access local markets

When τ is greater than 1, equation (9) exhibits a highly non-linear relationship between the relative price (q) and the share of population living in region 1 (f). Following Helpman, equation (11) indicates the utility level in each region is proportional to $N^{\frac{(1-\gamma\varepsilon)}{(\varepsilon-1)}+\theta\gamma}$ and welfare rises with population size if and only if $\frac{(1-\gamma\varepsilon)}{(\varepsilon-1)}+\theta\gamma>0$.

Let $R(\gamma,\alpha,\theta)\equiv\frac{(1-\gamma\varepsilon)}{(\varepsilon-1)}+\theta\gamma$. We substitute $\varepsilon=1/(1-\alpha)$ to $\frac{(1-\gamma\varepsilon)}{(\varepsilon-1)}+\theta\gamma$. It follows

(15) $$R(\gamma,\alpha,\theta)=\left(1-\gamma\right)(\frac{1}{\alpha}-1)-(1-\theta)\gamma$$

Note that $\frac{\partial R}{\partial\gamma}<0$, $\frac{\partial R}{\partial\alpha}<0$, and $\frac{\partial R}{\partial\theta}>0$. These results suggest that condition $\frac{(1-\gamma\varepsilon)}{(\varepsilon-1)}+\theta\gamma>0$ is more likely to hold if the preference for housing is low or the preference for varieties and locational amenities is high. Under these conditions, welfare rises with population size and a large city will emerge. In this event, a large population increases the variety of tradable commodities, reduces transport cost, and provides more hiring opportunities. On the contrary, the condition $\frac{(1-\gamma\varepsilon)}{(\varepsilon-1)}+\theta\gamma<0$ is more likely to hold if the preference for housing is high and the preference for varieties and locational amenities is low. Under these circumstances, welfare falls with population increases and a dispersed distribution pattern of population will emerge. In this case, a large consumption of residential land and high level of amenities induce people to move out of congested areas, reduce the cost of living, and provide more varieties to less-congested area.

The corresponding figures (Figures 2.a and 2.b) generated from our simulation analyses are consistent with the argument above. Figure 4.2.a shows one case for $\frac{(1-\gamma\varepsilon)}{(\varepsilon-1)}+\theta\gamma>0$. The parameter values used in this simulation are $\theta=0.3$, $\varepsilon=2$, $\gamma=0.4$, and $\tau=6.0$. We assume that both regions have the same housing stock ($H_1=H_2=1$), but different locational amenity levels ($A_1\neq A_2$). In Figure 4.2.a, there are three equilibrium solutions for f that could be derived by $v_{12}=1$. But the one in the middle, f_2^*, is unstable, whereas both f_1^* and f_3^* are stable. This can be verified by the fact that the system will bring the distribution back to f_1^* and f_3^* if an external shock causes some households to move between the two regions. Suppose the initial equilibrium is $f=f_1^*$ and an external shock causes some households to move from region 1 to region 2. This would increase the relative utility level in region 1, which, in turn, would cause some households to move from region 2 to region 1. The equilibrium is regained at $f=f_1^*$.

Figure 4.2.a also shows the effects of locational amenities on interregional distribution of population, as the dotted line indicates an increase in the amenity level in region 1 and more residents will choose to live in this region. However, the effects of locational amenities on the distribution of population are greatly overshadowed by the agglomeration effects that constitute the main force to influence the distribution of

population and economic activities. Thus, the region with lower amenities could have a larger population.

(Figure 4.2.a)

Figure 4.2.b shows one case of $\frac{(1-\gamma\varepsilon)}{(\varepsilon-1)}+\theta\gamma<0$. The parameter values are set up as $\theta=0.3$, $\varepsilon=2$, $\gamma=0.7$, and $\tau=6.0$. We also assume that both regions have the same housing stock ($H_1=H_2=1$), but different locational amenity levels ($A_1 \neq A_2$). In Figure 4.2.b, there is one equilibrium solutions for f that could be derived by $v_{12}=1$. Households' preference for housing is high, so that $\frac{(1-\gamma\varepsilon)}{(\varepsilon-1)}+\theta\gamma<0$. In this case, the utility level declines with increases in population in each region. In contrast to Figure 4.2.a, there is one stable equilibrium solution ($f = f^*$). It is important to note that in this situation, amenities play a more decisive role in shaping the spatial distribution of population and economic activity. Besides land, locational amenities induce households to move out of the congested area to enjoy locational amenities and save living cost. In contrast to the case in Figure 4.2.a, amenities play a more conspicuous role; the spatial distribution of population is more responsive to changes in amenities.

(Figure 4.2.b)

Finally, consider the case when the transport cost is prohibitive (i.e., $\tau\to\infty$). This simply means that trade between two regions may be impossible. Take the limit of equation (9) on both sides as τ approaches ∞ and we can get $q \to 1$.[5] Substitute $q \to 1$ and $\tau \to \infty$ to equation (12), and the relative utility function is reduced to

$$(16) \qquad v_{12} = \left(\frac{A_1}{A_2}\right)^{\gamma\theta} \left(\frac{H_1}{H_2}\right)^{\gamma(1-\theta)} \left(\frac{f}{1-f}\right)^{\frac{(1-\gamma\varepsilon)}{(\varepsilon-1)}+\gamma\theta}$$

In equilibrium, $v_{1,2} = 1$. Using equation (13), the equilibrium distribution of population between the two regions can be derived as

$$(17) \qquad f^* = \frac{1}{1+\left|\left(\frac{A_1}{A_2}\right)^{\frac{\gamma\theta}{R(\cdot)}} \left(\frac{H_1}{H_2}\right)^{\frac{\gamma(1-\theta)}{R(\cdot)}}\right|}$$

Equation (17) suggests that if $\frac{(1-\gamma\varepsilon)}{(\varepsilon-1)} + \gamma\theta > 0$, then the relative welfare, v_{12} , improves with the increase in the share of population in region 1 and a larger city will emerge. Other things being equal, the region with higher amenities has a smaller population in equilibrium. In this case, the region with lower amenities enjoyed more varieties of manufactured goods. This equilibrium is unstable, however. A small derivation from this equilibrium would lead to an agglomerated configuration, that is, all households live in one region. The agglomerated configuration where all households live in the high-amenity region is socially optimal, although the other agglomerated configuration where all households live in the low-amenity region is also stable. On the other hand, if

$\frac{(1-\gamma\varepsilon)}{(\varepsilon-1)}+\gamma\theta<0$, then the relative welfare, v_{12} , declines as the share of population in region 1 increases and the equilibrium given by (17) is stable.

Figure 4.3.a and Figure 4.3.b confirm the results above. Figure 4.3.a shows the case of $\frac{(1-\gamma\varepsilon)}{(\varepsilon-1)}+\theta\gamma>0$. The parameter values are set up as $\theta=0.3$, $\varepsilon=2$, $\gamma=0.4$, and $\tau\rightarrow\infty$. In this situation, $f = f^*$ is unstable. As in Figure 4.2.a, the agglomeration effect from producing more varieties is the main factor influence the spatial distribution of population and economic activities, locational amenities play only limited role in interregional migrations. Figure 4.3.b shows the case of $\frac{(1-\gamma\varepsilon)}{(\varepsilon-1)}+\gamma\theta<0$ with the setup of parameter values as $\theta=0.3$, $\varepsilon=2$, $\gamma=0.7$, and $\tau\rightarrow\infty$. In this instance, there is one stable equilibrium solution $f = f^*$. Other things being equal, the region with higher level of amenities has a larger population, and migration is highly responsive to changes in amenities. This implies that locational amenities play an active role in influencing household's location choice, firm's productivity, and the distribution of economic activities between the two regions.

(Figures 4.3.a and 4.3.b)

In sum, the effect of locational amenities on the spatial distribution of population and economic activities depends on regional economic characteristics, household preferences and trade barriers. When there is no trade barrier to access local markets, a more dispersed spatial pattern may arise, and regions with higher locational amenities attract more households. When there is a trade barrier to access local markets, the role of locational amenities on interregional migration depends on household preferences. When the preference for residential space is relatively low compared with the preference for locational amenities and varieties of manufactured goods (i.e., $\frac{(1-\gamma\varepsilon)}{(\varepsilon-1)}+\theta\gamma>0$), an agglomerated configuration of population emerges. In this case, agglomeration to produce more varieties is the main factor shaping the spatial distribution of population and economic activities, whereas the locational amenities play only a limited role. In contrast, if the preference for residential space is relative high compared with the preference for varieties and locational amenities (so that $\frac{(1-\gamma\varepsilon)}{(\varepsilon-1)}+\theta\gamma<0$), a dispersed pattern of population emerges. In this case, amenities play an important role in shaping the spatial distribution of population and economic activities.

4.4 Discussion and Conclusion

The new economic geography model developed in Krugman (1991) provides a framework to study the spatial distribution of economic activity and interregional migration. It generates renewed interests in regional studies. Building on Krugman's framework, Helpman analyzes the importance of non-tradable goods (housing stock) in shaping the economic geography. He replaces the agricultural sector in Krugman's model by a non-tradable good to highlight the role of market access and regional characteristics in shaping the spatial distribution of population (Ottaviano and Puga, 1998; Puga, 1999 and 2002; Fujita and Krugman 2004; Hanson, 2005; Redding and Sturm, 2005). In Helpman's model, increasing returns to scale and trade barrier provide a force for agglomeration, while regional immobile non-tradable resource (housing stock) constitutes congestion forces and favors dispersion (Ottaviano and Puga, 1998; Redding and Sturm, 2005). The introduction of the immobile housing stock in Helpman's model echoes the theory that wage difference may be only one reason for globalization to bring convergence in income levels, but not the only reason (Ottaviano and Puga, 1998). The departure from Krugman's assumptions leads to some strikingly different results: in Krugman's model low transport costs lead to agglomeration and high transport costs lead to dispersion, whereas in Helpman's model, low transport costs lead to dispersion and high transport costs lead to agglomeration (Helpman, 1998; Ottaviano and Puga, 1998).

There are distinct benefits to adopt Helpman's framework in both theoretical and empirical studies. Helpman's assumptions are perhaps more consistent with the expenditure structures in the United States. As previous consumer expenditure surveys revealed, housing and related services account for a large share of consumer expenditures. Housing cost differentials are the largest single component of interregional cost living differences (Beeson and Eberts, 1989). The non-tradability of housing stocks between regions forces households to evaluate quality-of-life factors when making location decisions. Helpman's modifications, in his own words, "seem to be closer to standard urban economic models". Empirical studies adopting his theoretical framework (e.g. Hanson, 2005; Redding and Sturm, 2005) explain more spatial variation in economic development (Neary, 2001).

In this paper, we extend Helpman's framework to investigate the effects of locational amenities on interregional migrations. In particular, we want to explain why some regions with relatively high locational amenities remain undeveloped, while other regions with relatively low locational amenities grow rapidly. Our framework incorporates multimarket equilibriums, in which regional economic activities such as consumption, production, and trade are internally connected. Thus, our framework could be used to evaluate households' location choices with consideration of factors influencing the quality of life and employment opportunity.

We found the effects of locational amenities on interregional migrations are significantly affected by regional economic characteristics, household preferences, and trade barriers. When there are few trade barriers between regions, the immobile housing resource (both land and locational amenities) plays a dispersing role in influencing the spatial distribution of households, and amenities are a major determinant of the spatial distribution of population and economic activities. Similar to the effects of immobile developable lands, higher locational amenities induce more households to move out of densely-populated areas to avoid congestion and enjoy a higher quality of life. In the meantime, this dispersed pattern also brings more manufacture to less-congested regions, provides employment opportunities, and expands local market potentials.

When there is a trade barrier between regions, the situation becomes very complicated. In this case, the effects of locational amenities on interregional migration and spatial distribution of economic activities are strongly affected by household preferences. If the preference for residential space is relatively low compared with the preference for varieties and locational amenities, a large city will likely emerge. Agglomeration of economic activities provides more varieties of tradable goods, offer more job opportunities, and increase the overall quality of life. In this situation, locational amenities have little effect on interregional migration. On the other hand, if the preference for residential space is relatively high compared with the preference for varieties and locational amenities, a dispersed distribution pattern of population will emerge. In this case, immobile housing factors, including land and amenities, induce people to move out of congested areas, and amenities have a larger effect on the spatial distribution of activity. These results should inform the debate about the effect of locational amenities on interregional migrations and regional economic development.

4.5 Reference

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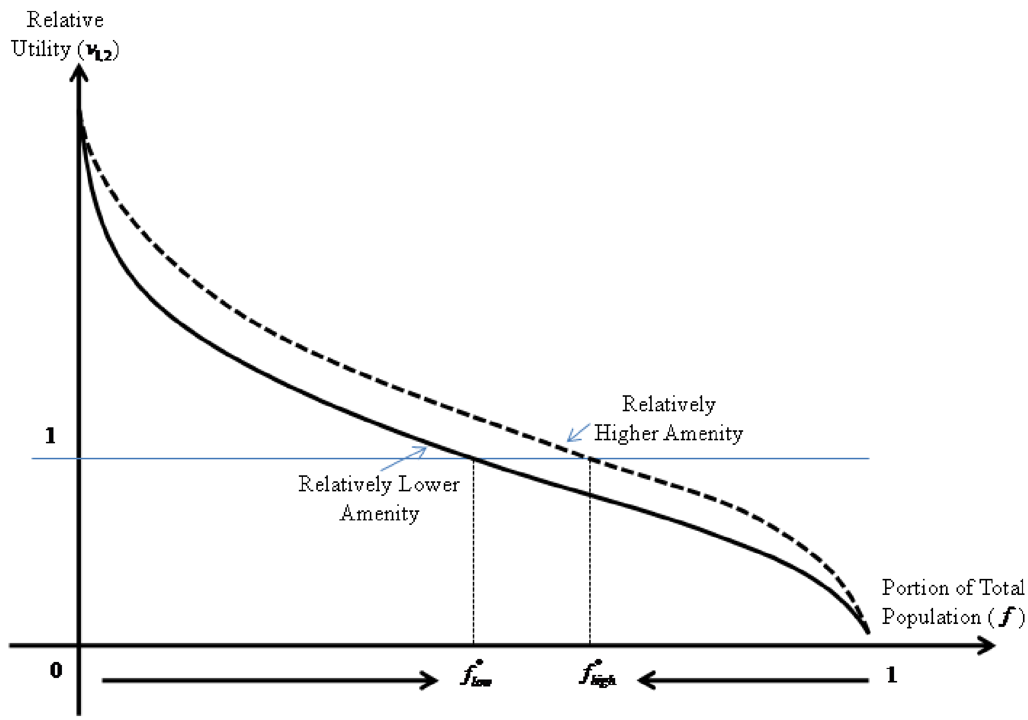
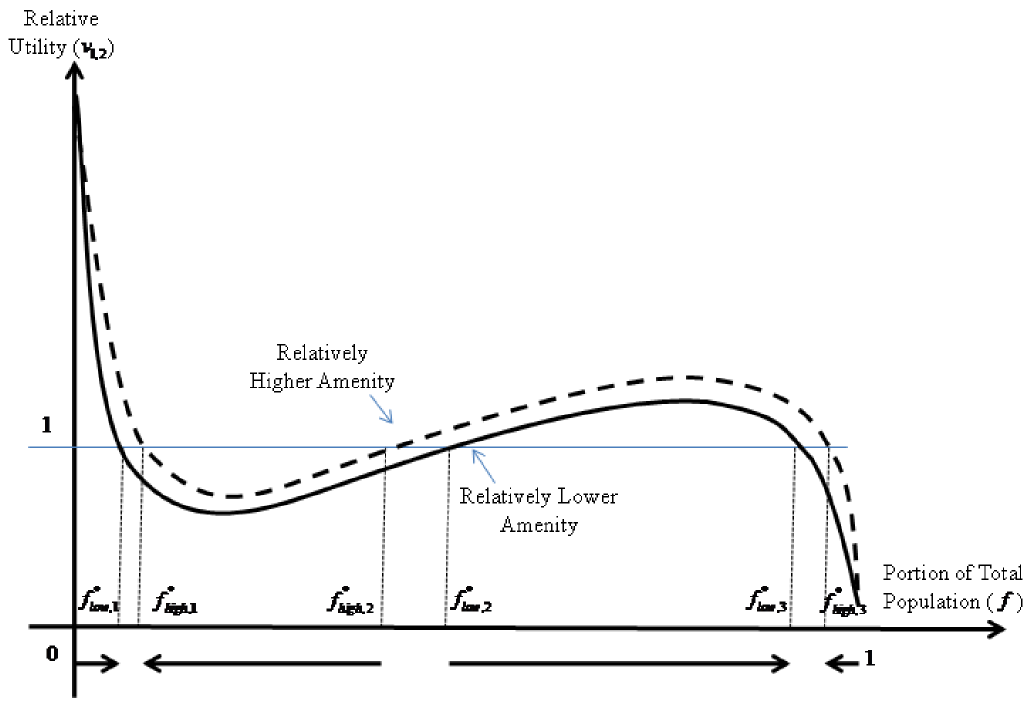


($A_1 = 1.2/1.5$, $A_2 = 1$, $H_1 = H_2 = 1$, $\theta = 0.3$, $\varepsilon = 2$, $\gamma = 0.4$, $\tau = 1.0$, and $(1-\theta)\gamma > 0$)

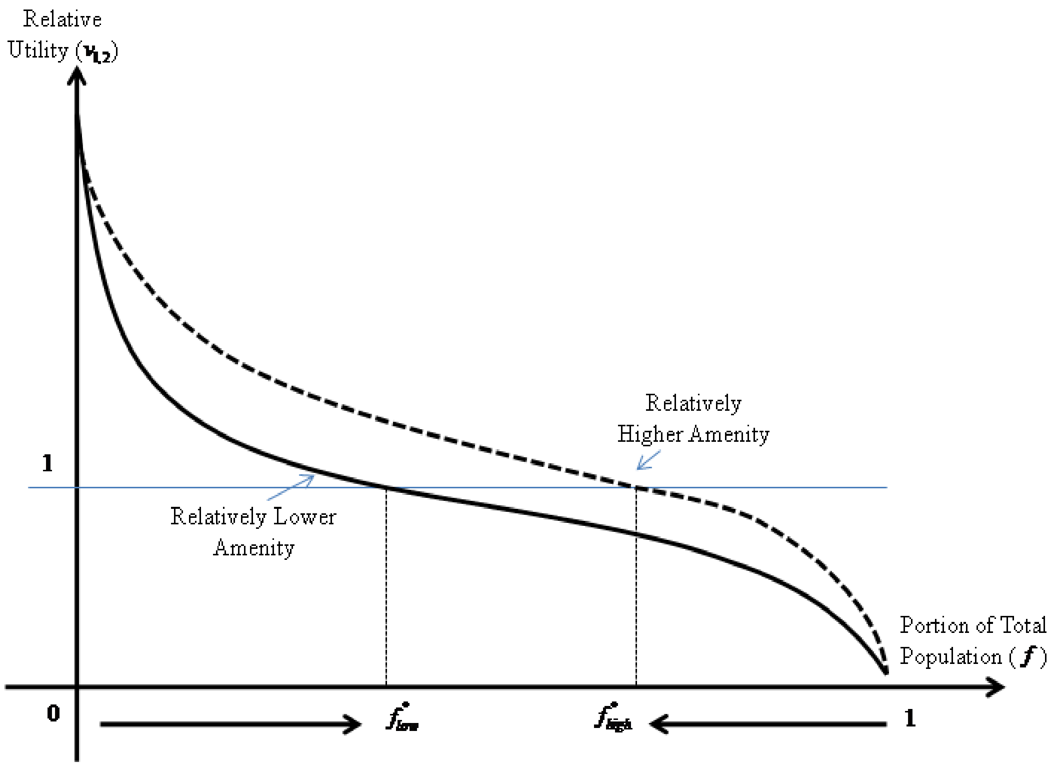
Figure 4.1 Locational Amenities and the Spatial Distribution of Population between the Two Regions



($A_1 = 1.2/1.5$, $A_2 = 1$, $H_1 = H_2 = 1$, $\theta = 0.3$, $\varepsilon = 2$, $\gamma = 0.4$, $\tau = 6.0$, and

$$\frac{(1-\gamma\varepsilon)}{(\varepsilon-1)} + \theta\gamma > 0 \text{)}$$

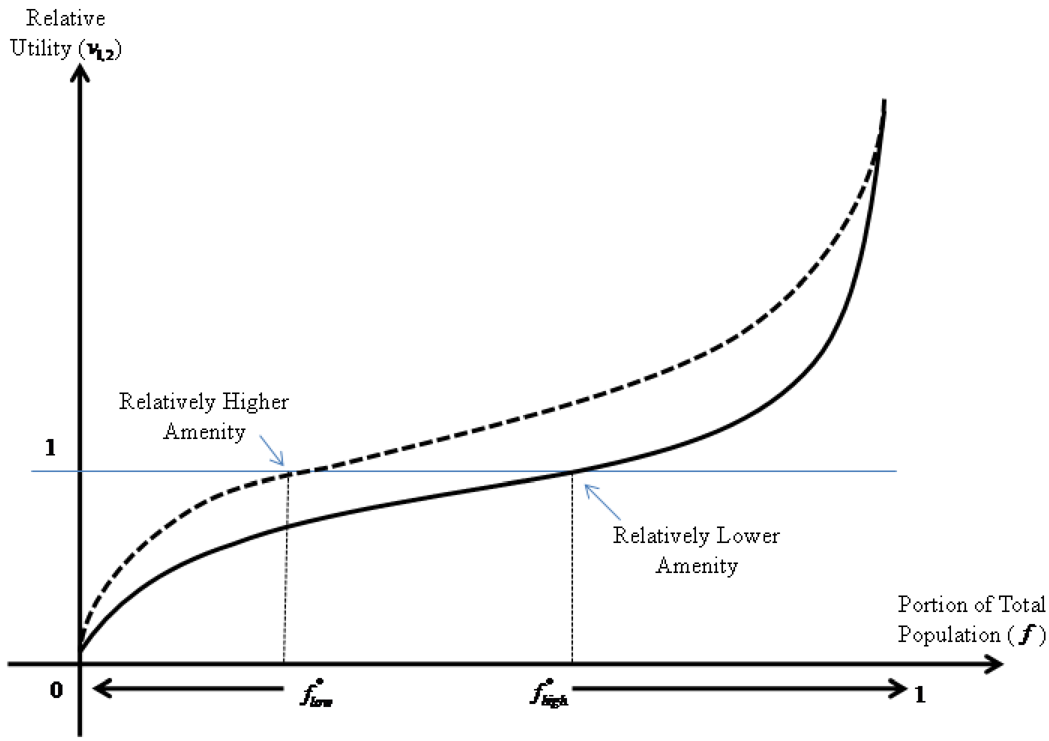
Figure 4.2.a Locational amenities and the spatial distribution of population between the two regions



($A_1 = 1.2/1.5$, $A_2 = 1$, $H_1 = H_2 = 1$, $\theta = 0.3$, $\varepsilon = 2$, $\gamma = 0.7$, $\tau = 6.0$, and

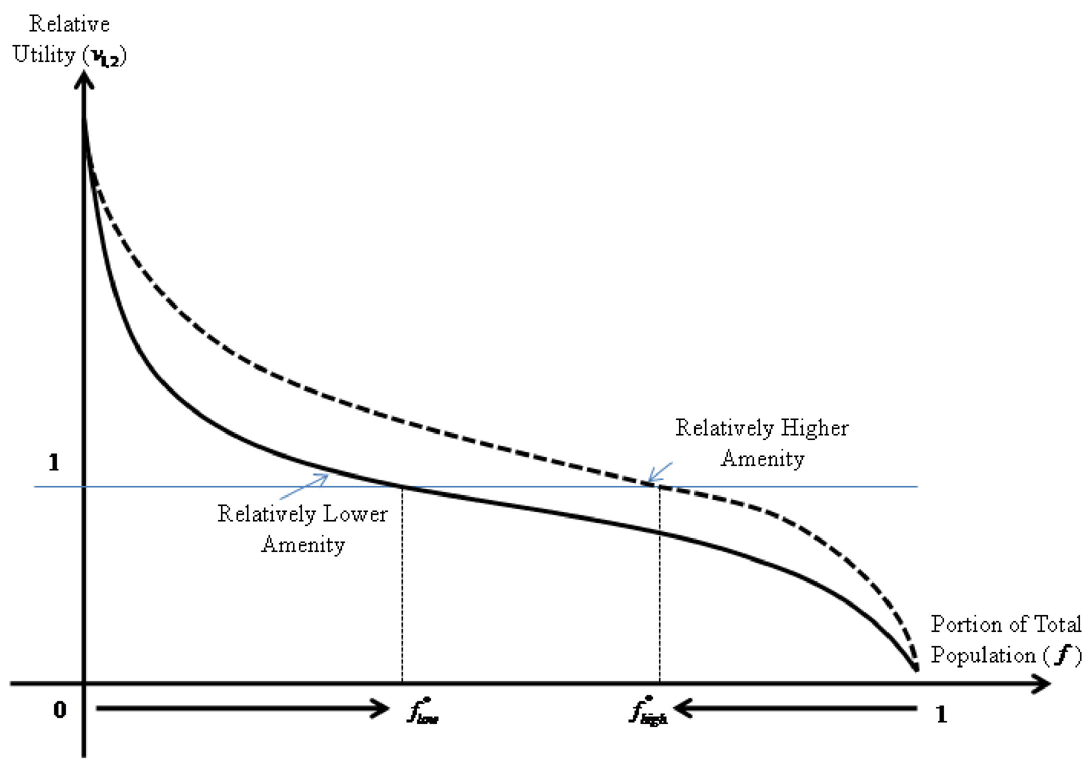
$$\frac{(1-\gamma\varepsilon)}{(\varepsilon-1)} + \theta\gamma < 0 \text{)}$$

Figure 4.2.b Locational Amenities and the Spatial Distribution of Population between the Two Regions



$$(A_1 = 1.2/1.5,\ A_2 = 1,\ H_1 = H_2 = 1,\ \theta = 0.3,\ \varepsilon = 2,\ \gamma = 0.4,\ \tau \to +\infty, \text{ and } \frac{(1-\gamma\varepsilon)}{(\varepsilon - 1)} + \theta\gamma > 0)$$

Figure 4.3.a Locational Amenities and the Spatial Distribution of Population between the Two Regions



($A_1 = 1.2/1.5$, $A_2 = 1$, $H_1 = H_2 = 1$, $\theta = 0.3$, $\varepsilon = 2$, $\gamma = 0.7$, $\tau \to \infty$, and $\frac{(1-\gamma\varepsilon)}{(\varepsilon - 1)} + \theta\gamma < 0$)

Figure 4.3.b Locational Amenities and the Spatial Distribution of Population between the Two Regions

Endnotes

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[1] The relevant literatures could be found in Graves (1979) ,Haurine (1980), Blomquist et al. (1988), Graves and Waldman (1991), Linneman and Graves (1983), Rosen (1979), Roback (1980 and 1982), Treyz et al. (1993), Banzhaf and Walsh (2008), and others.

[2] According to its definition, a cost of transporting a good that uses up only some fraction of the good itself, rather than using any other resources. The definition in this way does not impact other market.

[3] A higher value of α or ε indicates a lower preference for varieties.

[4] For household i, the expenditure will be allocated as

$$p_l l_{i,k} = (1-\theta)\gamma \frac{E_{i,k}}{(1-\theta\gamma)}; \ \sum_{1}^{n_k} p_{j,k} x_{i,j,k} + \sum_{1}^{n_{-k}} \left(\tau p_{j,-k}\right) x_{i,j,-k} = (1-\gamma)\frac{E_{i,k}}{(1-\theta\gamma)}$$

Summing the above results over all individual households in region k gives:

$$p_l l_k = (1-\theta)\gamma \frac{E_k}{(1-\theta\gamma)}; \ \sum_{1}^{n_k} p_{j,k} x_{j,k} + \sum_{1}^{n_{-k}} \left(\tau p_{j,-k}\right) x_{j,-k} = (1-\gamma)\frac{E_k}{(1-\theta\gamma)}$$

where $x_{j,k} = N_k x_{i,j,k}$, $x_{j,k} = N_k x_{i,j,-k}$, and $E_k = N_k E_{i,k}$.

[5] First, notice that except ε, all parameters in equation (9) are bounded at $+\infty$. Take the limit of equation (9) on both sides as ε approaches $+\infty$.

$$\Rightarrow 1-\theta\gamma = \lim_{\tau\to\infty} \frac{fq^{-\varepsilon}}{fq^{1-\varepsilon}+(1-f)\tau^{1-\varepsilon}}\{(1-\gamma)q+\gamma(1-\theta)[qf+(1-f)]\}$$
$$+\lim_{\tau\to\infty} \frac{(1-f)\tau^{1-\varepsilon}q^{-\varepsilon}}{f\tau^{1-\varepsilon}q^{1-\varepsilon}+(1-f)}\{(1-\gamma)+\gamma(1-\theta)[qf+(1-f)]\}$$

Notice $1-\varepsilon<0$, so $\lim_{\tau\to\infty}\tau^{1-\varepsilon}=0$.

$$\Rightarrow 1-\theta\gamma = \frac{fq^{-\varepsilon}}{fq^{1-\varepsilon}}\{(1-\gamma)q+\gamma(1-\theta)[qf+(1-f)]\}$$

(Notice that this step eliminates $f=0$. In addition, $1-f\neq 0$. Otherwise,

$\lim_{\tau\to\infty} \frac{(1-f)\tau^{1-\varepsilon}q^{-\varepsilon}}{f\tau^{1-\varepsilon}q^{1-\varepsilon}+(1-f)}\{(1-\gamma)+\gamma(1-\theta)[qf+(1-f)]\}$ may not equal zero.)

$$\Rightarrow (1-\theta\gamma)q = q-q\gamma+\gamma(1-\theta)qf+\gamma(1-\theta)(1-f)$$

$$\Rightarrow -\theta\gamma q = -\gamma q+(1-\theta)\gamma qf+\gamma(1-\theta)(1-f)$$

$$\Rightarrow (1-\theta)\gamma q(1-f) = \gamma(1-\theta)(1-f)$$

$$\Rightarrow (1-\theta)\gamma(1-q)(1-f)=0$$

As $\gamma\in(0,1)$, $\theta\in(0,1)$, and $f\in(0,1)$, we have $q=1$.

CHAPTER 5

5. CONCLUSION

This dissertation focuses on the interactions between environmental features and human land-use activities to seek a better understanding of the human-environment relationship. We first investigate the impacts of human activities and environmental features on wildfire occurrence at the WUI in a changing climate, focusing on the impacts of land use changes as measured by their density, connectivity, and mix. Then, we analyze the impacts of wildfire risk on urban development by introducing wildfire risk to a classic urban economics model with locational amenities and a public decision sector to characterize the behaviors of risk-averse local households and government. Finally, we model the role of amenities in influencing interregional migration and the spatial distribution of economic activities, and present a multi-market equilibrium framework that includes consumption, production, and trade.

The findings of the first essay confirm those of previous studies which state that a changing climate in Southern California, projected as a drier and warmer climate, will exert more pressures on the wildfire activities in WUI areas. Our estimates also imply that human activities in and accessibility to the fire-prone areas, evaluated by various land-use patterns and changes, have very complicated relationships with both ecosystems and wildfire activities and exhibit great spatial heterogeneity. Hypotheses tests suggest that the fire mitigation and suppression approaches (e.g., building code and fuel cleaning) adopted on some land uses have been effective in reducing wildfire impacts. Human connectivity to the remote wilderness areas, in general, reduces wildfire burnt areas. By contrast, the areas with low development density are vulnerable to and human activities in these areas might exacerbate wildfires. Seasonal human activities may increase wildfire risk and cancel out the effectiveness of fire mitigation and suppression approaches. Human activities reduce wildfire occurrence in general, but contribute to human-caused wildfire.

In the second essay, our results consistently demonstrate that fire-zone designation policy could greatly impact the urban land-use patterns and community characteristics. A change in fire-related risk has an ambiguous effect on the level of public services and property values. The impacts of fire risks are dependent on households' preferences and community characteristics. The impacts take on various aspects, including land price, development density, number of households, public services, and tax burdens. The influences can be widespread: residents and public decision sectors both inside and outside the fire-prone area could be affected. Wildfire risk can influence multiple income groups in different ways, which help to explain or predict the change in the composition of residents from different income-groups. Our results, conversely, also imply that the greater the difference in recognizing wildfire risk, the bigger the distortion in urban development patterns. With limited knowledge in wildfire risk and high preferences to natural amenities, local residents and public decision sector may challenge the fire-zoning designation and underestimate wildfire risk. If this is the case, over-development in the fire-hazardous area will be an issue that may be quite challenging for wildfire suppression and rescue in the future.

In the last essay, our results suggest that the effects of locational amenities on interregional migrations are significantly affected by household preferences, trade barriers, and other regional economic characteristics. When there are few trade barriers between regions, amenities are a major determinant of the spatial distribution of population and economic activities. When trade barriers do exist, the effects of amenities will be strongly affected by household preferences and other regional economic characteristics. If the preference for residential space is relatively low compared with the preference for varieties and amenities, a large city will likely emerge and amenities will have little effect on interregional migration. Agglomeration is the main factor shaping the urban landscape and distribution of economic activities, while locational amenities only play a limited role. Otherwise, a dispersed distribution pattern of population will emerge and amenities have larger impacts on the spatial distribution of economic activities. In this situation, locational amenities will play important role in influencing the distribution of population and economic activities.

Taken together, this dissertation demonstrates the complexity of human-environment interactions exist in a very broad scale, which can greatly impact both environmental features and human land-use patterns and distribution economic activities. Our results in this dissertation call for more systematic and comprehensive land-use policies and regulations that should take into account of both environmental and social-economic issues at the same time.

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