Welfare and Biodiversity Tradeoffs in Urban Open Space Protection

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Abstract: In this paper, we analyze the optimal spatial pattern of open space and residential development in an urban model that includes provision of both local and global public goods. In our model, households choose where to live based on land prices, proximity to employment, and amenity values that include access to open space (local public good). Open space also provides habitat for biodiversity (global public good). We applied the model in the Twin Cities Metropolitan Area and include endogenous land prices, land taxes that finance the purchase of open space, heterogeneous land quality, multiple employment locations, and pre-existing spatial features, such as institutional and environmental amenities. Based on this application we develop an efficiency frontier that shows tradeoffs between maximum welfare of households, which includes provision of local public goods, and provision of habitat for biodiversity, which is assumed to not affect household welfare. We show there is the potential for a large increase in biodiversity conservation with only modest reductions in welfare when starting from a spatial pattern of development that maximizes household welfare. Biodiversity conservation can be improved by changing the spatial configuration of open space towards higher quality habitat and aggregating protected areas to increase contiguity.

1. Introduction

More than eighty percent of the U.S. population lives in urban areas (U.S. Census 2009), and in many of those areas the rates of land conversion from open space to developed uses far exceed rates of population growth (Fulton et al. 2001). Between 1982 and 1997, the amount of urbanized land in the U.S. increased by 47 percent, from approximately 51 million acres in 1982 to approximately 76 million acres in 1997. During this same period, the nation's population grew by only 17 percent (Fulton et al. 2001).

Two consequences of land conversion from increased development are the local and global loss of valuable ecosystem services from open space. Open space provides benefits to local residents in the form of aesthetic amenities, recreational opportunities, filtration of pollution that may improve water and air quality, among others. Open space also provides benefits that accrue more broadly (nationally or globally) such as carbon sequestration and habitat for biodiversity. Empirical evidence from hedonic property price models has shown that urban residents value nearby open space (Geoghagen 2002, Hobden et al. 2004, Irwin 2002, Lutzenhiser and Netucil 2001, Mahan et al. 2000, Thorsnes 2002, Tyrvainen and Miettinen 2000, Wu et al. 2004). Hedonic property price studies in the Twin Cities Metropolitan Area in Minnesota have found positive values of open space on nearby property values, with a few exceptions. Sander and Polasky (2009) found that home sale prices increased with closer proximity to parks, trails, lakes, and streams. Home sale prices also increased with the areal extent of views and the amount of water and grassy land covers in views. Both Anderson and West (2006) and Klaiber and Phaneuf (2010) found a positive value of open space on property values on average, though each found considerable heterogeneity of effects depending on type of open space and neighborhood context. Doss and Taff (1996) found strong positive effects on property values from having a view of a lake, as well as being in closer proximity to lakes and some types of wetlands (though not forested wetlands). Finally, Sander et al. (2010) found an increase in property values from an increase in neighborhood tree cover.

Concerns of local citizens about loss of open space and the local amenities they provide has led state and local governments to raise public funds in support of land conservation (Kotchen and Powers 2006, Nelson *et al*. 2007, Ruliffson *et al*. 2002). Since 1996, state and local governments passed an average of 91 ballot measures per year raising an average of $2.2 billion dollars to acquire and protect open space (Trust for Public Land 2014).

Loss of open space can also lead to the loss of ecosystem services with more widespread benefits including loss of carbon sequestration, and the loss of habitat that supports biodiversity. Ewing et al. (2005) found that 60% of the "nation's rarest and most imperiled species are found within designated metropolitan areas" (p. viii) with many endangered species located in rapidly urbanizing areas experiencing the greatest loss of open space. Under the U.S. Endangered Species Act, development can be curtailed if it would cause habitat loss that would harm a listed species. Conflicts between development and endangered species conservation have occurred in the San Francisco Bay Area over the Mission Blue Butterfly (Beatley 1992), in Orange County just south of Los Angeles over the California gnatcatcher (Zink et al. 2000), east of Los Angeles in San Bernadino County over the Coachella Valley fringe-toed lizard (Beatley 1992), near Austin, Texas over the black-capped vireo and other species (Taylor 1994), among others.

Concerns about the loss of ecosystem services with national or global benefits, such as the loss of habitat and harm to endangered species, may or may not align with welfare considerations of local residents. For example, restrictions on development to conserve endangered species, might lead to reductions in aggregate local welfare, both in terms of limits on development and the pattern or open space and the amenities it provides to local residents (Innes et al. 1998, List et al. 2006). Making good decisions about urban land use requires consideration on how land use affects the provision of both local public goods as well as provision of more global public goods. The weight placed on each of these different types of public goods will affect the optimal land use within an urban area, where the weight represents the relative importance of local versus global public goods.

We address the optimal amount and location of open space in an urban area taking account of the provision of local and global public goods and estimate the potential tradeoffs between local public goals that affect household welfare and global public goods related to biodiversity protection. To do this we analyze a discrete space urban model with endogenous choice of the location of open space and development. Households choose a neighborhood of their residence based on its proximity to employment opportunities, proximity to open space, and the size of a housing plot and consumption that they can afford given their income and real estate prices in that neighborhood. Increasing the amount of open space increases environmental amenities but also constricts the amount of land available for housing. We analyze an open city model where population adjusts in a way to keep household utility constant. Though household utility is constant, real estate prices are not. Land rents are determined endogenously in the model and rise and fall with the overall attractiveness of the city. In the model, expenditures on housing are captured in the household's choice problem but we do not capture land rents. Assuming that land rents accrue to some individuals in society then maximizing welfare is equivalent to maximizing land rents in an open city model. We analyze the optimal amount and location of open space given the dual objective of maximizing welfare as well as biodiversity conservation. This maximization is constrained by land availability and property tax revenue, which finances provision of open space. Biodiversity conservation is a function of heterogeneous quality, spatial proximity, and size of natural areas protected as open space. We show how the optimal pattern of open space and development varies with different weights on open space amenity values and biodiversity conservation. Solving the model for different weights illustrates the tradeoffs between household utility and conservation objectives.

The existing literature in urban and environmental economics has not addressed the question of the optimal provision of open space with dual objectives of maximizing household welfare and biodiversity conservation. Several studies have analyzed the equilibrium effects of specific open space configurations using structural economic models of household location choice (see Irwin et al. 2009, Irwin 2010 for reviews). Most of these models extend the urban economics models developed by Alonso (1964), Mills (1967, 1972), and Muth (1969) and include an exogenously determined central business district (CBD), a population of households with identical incomes and preferences, travel costs that depend on the distance between residence and CBD, and household utility that depends in part on proximity to open space amenities. Two-dimensional urban models with pre-determined locations of open space have been analyzed to determine the location of city boundaries and conditions that lead to sprawl (i.e., areas of development that are disjoint from the existing developed areas) (Wu and Plantinga 2003, Wu 2006). These models show that public open space may cause leapfrog development when placed outside the city and travel cost to the CBD is sufficiently low. Further, open space provision can increase or decrease the city's population and area depending on the size and location of the open space. For instance, if a relatively large open space with low amenity value is located near the CBD, it can reduce the city's population by eliminating desirable sites for development (Wu and Plantinga 2003). Finally, if the amenity benefit of an open space parcel is enjoyed by households throughout the city in addition to households close by, then city size, land rent, and household welfare are all greater (Kovacs and Larson 2007).

While analyses of urban models provide insight into the effects of specific open space configurations, most of those studies do not address questions about the optimal provision of open space. Lee and Fujita (1997) analyze the effects of greenbelts that form a ring of open space around the central business district and determine the optimal placement of a greenbelt. Yang and Fujita (1983) solve for the optimal pattern of open space in a one-dimensional formulation and show that the optimal density of open space is a uniform proportion of area independent of distance from the CBD when environmental amenities are purely local (i.e., no amenity spillover effects). They briefly consider the case with amenity spillover in a one-dimensional discrete-space model with five neighborhoods. Tajibaeva et al. (2008) use a discrete-space urban model based on Yang and Fujita (1983) to determine the optimal pattern of open space, housing, and land value given realistic features such as multiple business centers, existing open space amenities, and amenity values of agricultural land. In contrast to continuous-space urban models, the discrete-space model assumes distinct neighborhoods in which developable land is homogeneous within a neighborhood but heterogeneous across neighborhoods. Open space provides environmental amenities within the neighborhood it is located and may provide amenities in other neighborhoods (amenity spillover). The presence of amenity spillover has a strong effect on the results. When open space is a local public good that affects only the immediate neighborhood, it is optimal to provide the same amount of open space in all neighborhoods. With amenity spillover effects, optimal open space provision differs across neighborhoods, depending on the transportation cost. With high transportation cost, it is optimal to provide open space in a greenbelt at the edge of the city with housing concentrated near the city center.

Land use patterns also determine habitat provision for biodiversity. The field of conservation planning has developed spatial metrics of biodiversity conservation and computational tools to determine reserve designs that maximize those metrics (see Moilanen *et al*. 2009 and Billionnet 2013 for reviews). For example, site selection models have been developed to maximize species representation within reserves (Camm et al. 1996, Church et al. 1996), account for probabilistic species occurrence (Haight *et al*. 2000, Camm *et al*. 2002), and account for species' habitat preferences, area requirements, and dispersal abilities (Polasky *et al*. 2008), subject to economic constraints related to site purchase and management. Although site selection models are beginning to include endogenous effects of land protection on development, land prices, and subsequent protection costs (Armsworth *et al*. 2006, Toth et al. 2011, Dissanayake and Onal 2011, Butsic et al. 2013), none account for the effects of open space on household location choice and welfare.

We apply our model to analyze the effects of various patterns of open space on both welfare and biodiversity using data from the Twin Cities Metropolitan Area. When the goal is to maximize welfare (i.e., maximize the value of land rents in the city), the optimal provision of open space is heavily skewed towards the urban boundary nearly forming a ring around the city. When the goal slightly shifts to maximizing biodiversity, the optimal location of open space becomes more clustered and shifts away from the urban boundary and towards areas with higher habitat quality or closer to existing parks. Our results suggest that protecting open space to attain biodiversity conservation has relatively little impact on household welfare. However, even minor shifting of optimization priorities from maximizing land rents to maximizing the effective habitat continuity results in very different optimal landscape patterns.

The paper is organized as follows. In Section 2, we develop a discrete-space urban model of optimal provision of open space. Section 3 describes the economic and land-use data from the Twin Cities Metropolitan Area (Minneapolis–St. Paul, MN, USA) and parameterizes the model. Section 4 solves the model numerically to analyze how different priorities between the economic and biodiversity objectives affect the optimal size and location of open space, household welfare, biodiversity conservation, and spatial pattern of residential development and land values. We include concluding comments in Section 5.

2. The model

We consider a discrete space city that consists of J neighborhoods. Neighborhoods contain land that can be allocated to residential development or open space. In addition, neighborhoods also contain pre-existing commercial and industrial development as well as natural and institutional amenities. Let l_j be the total area available for residential and open space land use in neighborhood j.

Each household chooses a neighborhood j in which to reside. Three main factors determine choice over neighborhoods. The first factor is the amount of consumption good, c_j, and the amount of residential land, h_j, that a household can afford while residing in neighborhood j. The affordability is affected by housing price in neighborhood j, which is denoted by p_j, property tax τ levied by the government on residential land, and household's income v. The price of the consumption good is normalized to one.

The second factor is the commuting cost between the neighborhood of residence and the nearest employment location b. Neighborhoods with commercial land use provide employment opportunities. Because different neighborhoods throughout the city use land for commercial purposes, there exist multiple employment locations $b = 1, 2, \ldots, B$. Let $d_j^c = \min\{d_{jb}\}_{b=1}^{B}$ be the commuting distance from neighborhood j to the nearest employment location b. Then the cost of commuting to and from work is a function of distance $f\left(d_j^c\right)$.

The third factor is the environmental and institutional[1] amenities in the neighborhood of residence as well as in the nearby neighborhoods. Let A_j denote all amenities accruing to households in neighborhood j. A_j is a function of open space $\{a_k\}_{k=1}^{J}$, preexisting amenities $\{z_k\}_{k=1}^{J}$, and distance $\{d_{jk}\}_{k=1}^{J}$ from the neighborhood of residence j to the neighborhood of amenities k, such that $d_{jk} > 0$ for all $j \neq k$ and $d_{jk} = 0$ for $j = k$.

The households have identical income v and preferences $u\left(c_j, h_j; A_j\right)$ over consumption, residential land, and amenities. In the numerical application below we assume the utility function to be Cobb-Douglas:

$$(2.1) \quad u\left(c_j, h_j; A_j\right) = c_j^{\alpha} h_j^{\beta} A_j^{\gamma},$$

where $\alpha, \beta, \gamma \in (0,1)$, $\alpha + \beta + \gamma = 1$, and

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[1] Preexisting institutional amenities include, but are not limited to, existing religious, educational, social, cultural, governmental, or major health care facilities.

(2.2) $A_j(a_1,\ldots,a_J)=\sum_{k=1}^{J}(\delta_a a_k+\delta_z z_k)\exp(-\delta_d d_{jk})$

Equation (2.2) revised for proportion of area instead of total area

(2.2 proportion) $A_j(a_1,\ldots,a_J)=\sum_{k=1}^{J}\left(\delta_a\frac{a_k}{l_k}+\delta_z\frac{z_k}{l_k}\right)\exp(-\delta_d d_{jk})$

is the function of open space and preexisting amenities decreasing in distance where δ's are parameters associated with amenities and distances. For each neighborhood j, a household maximizes its preferences (2.1) subject to its budget constraint:

(2.3) $c_j+p_j^{\tau}h_j+f(d_{cj})\leq v,$

where $p_j^{\tau}=(1+\tau)p_j$ is the market price and property tax τ levied on the residential land use.

We consider the case of an open city, where no arbitrage across locations holds for all neighborhoods implying that $u(c_j,h_j,A_j)=\overline{u}$ for all neighborhoods j. In order for a household to maintain utility level $\overline{u}$, a household establishes the maximum price that it is willing to pay to reside in each neighborhood j. This maximum price is the bid-rent function, given as:

(2.4) $F(h_j,A_j(a_1,\ldots,a_J),\overline{u})=\frac{v-c_j(h_j,A_j(a_1,\ldots,a_J),\overline{u})-f(d_j^c)}{h_j},$

where $c_j(h_j,A_j,\overline{u})$ is the inverse function of $u(c_j,h_j,A_j)=\overline{u}$. For simplicity, we designate absentee landowners who collect all land rents.

The city government provides open space by participating in the land market. To finance its provision of open space the government levies tax τ on residential land use. The government has a balanced budget and equates its open space expenditure to tax revenue from residential development

(2.5) $\sum_{j=1}^{J}\tau p_j(l_j-a_j)=\sum_{j=1}^{J}p_j a_j$.

The city government solves for the optimal provision of open space, a_j, residential land use, h_j, and number of households, n_j, in each neighborhood j for all $j=1,2,\ldots,J$. In doing so, it considers both the economic components, such as endogenous prices and households' welfare, and the biodiversity implications. In the following we develop a biodiversity score and then specify the problem of optimal provision of open space.

2.1. Biodiversity score

Our biodiversity score is a function of the size and aggregation of natural areas protected as open space. Let φ_j be an aggregation score based on the amount of protected open space and its proximity to other open space in the region. Letting d_{jk} be the distance between neighborhoods j and k, the proximity score for each neighborhood j is:

$$(2.6) \quad \varphi_j\left(a_1,\ldots,a_J\right)=\sum_{k=1}^{J} a_k \exp\left(-\sigma d_{kj}\right),$$

where σ is a non-negative weight attached to the distance between neighborhoods. The aggregation score for each neighborhood j discounts open space that is farther away. In this case, neighborhoods with more open space protected close by have higher aggregation scores. The effective habitat contiguity score is the sum of protected areas weighted by aggregation scores:

$$(2.7) \quad B\left(a_1,\ldots,a_J\right)=\sum_{j=1}^{J} \varphi_j a_j \; .$$

2.2. Optimal provision of open space

The optimal provision of open space, a_j, residential land, h_j, and population density, n_j, for all neighborhoods $j = 1,\ldots,J$ maximizes the weighted dual objective of the bid-rent function net of opportunity cost of an alternative land use pattern and the effective habitat continuity score:

$$(2.8) \quad \begin{aligned} &\max_{\{h_j,n_j,a_j\}_{j=1}^{J}} \mu \sum_{j=1}^{J}\left(\left(F\left(h_j, A_j\left(a_1,\ldots,a_J\right),\bar{u}\right)-p_j^g\right)n_j h_j - a_j p_j^g\right)+\left(1-\mu\right)B\left(a_1,\ldots,a_J\right) \\ &\text{subject to} \; n_j h_j + a_j \le l_j \; \text{for all} \; j=1,\ldots,J, \end{aligned}$$

where p_j^g is agricultural land price and functions $F\left(h_j, A_j, \bar{u}\right)$ and $B(a)$ are as defined in equations (2.4) and (2.7) respectively. Recognizing that city planners attach different priorities to the goals of maximizing household net benefit and maximizing biodiversity conservation, we consider different weights from primarily economic considerations, of $\mu = 1$, to primarily biological considerations, of $\mu = 0$, and construct the entire spectrum of solutions for $\mu \in [0,1]$. We then analyze the resulting tradeoff in the optimal provision of open space.

Since the household's preferences are strictly increasing in housing, the total land constraint holds with equality and we can substitute $l_j - a_j$ from the land constraint into the objective function for $n_j h_j$. After the substitution we can obtain the optimal housing allocation as a function of amenities, distance, and utility level by maximizing the bid-rent function in equation (2.4) over housing. With these two substitutions and using the utility function from equation (2.1), the optimization problem (2.8) can be restated as follows:

$$(2.9) \quad \max_{\{a_j\}_{j=1}^{J}} \mu \sum_{j=1}^{J}\left\{\frac{\alpha^{\alpha/\beta}\beta A_j^{\gamma/\beta}\left(v-\theta d_j^c\right)^{(\alpha+\beta)/\beta}}{\left(\alpha+\beta\right)^{(\alpha+\beta)/\beta}\bar{u}^{-1/\beta}}\left(l_j - a_j\right)-p_j^g l_j\right\}+\left(1-\mu\right)\sum_{j=1}^{J}\varphi_j a_j \; ,$$

where θd_j^c is a linear function for the cost of commuting to work function (i.e., $f\left(d_{cj}\right)$ in equation 2.3) and A_j is a function of $a_1,\ldots,a_J$ as defined in equation (2.2).

2.3. Tax constrained optimal provision of open space

So far we have been considering the optimal provision of open space constrained by physical availability of space. Once the optimal open space pattern $\{a_j^*\}_{j=1}^J$ that solves problem (2.8) is established, we can find corresponding competitive equilibrium price for each neighborhood *j* (see Appendix A for derivation of a competitive equilibrium allocation and prices):

$$(2.10)\quad p_j = \frac{\alpha^{\alpha/\beta}\beta A(a_1,\ldots,a_J)^{\gamma/\beta}}{(1+\tau)\bar{u}^{1/\beta}}\left(\frac{v - f(d_j^c)}{\alpha+\beta}\right)^{(\alpha+\beta)/\beta}.$$

Using this price (2.10) and the government's budget equation (2.5), we can find the tax rate that supports this optimal provision of open space in a competitive equilibrium.

In practice, a municipal government is constrained not only by the physical availability of space but also by the publicly acceptable land tax. When there is an upper bound on the acceptable tax rate, a tax constrained or second best allocation of open space $\{\hat{a}_j\}_{j=1}^J$ solves the following problem:

$$(2.11)\quad \begin{aligned} &\max_{\{h_j,n_j,a_j\}_{j=1}^J} \mu\sum\nolimits_{j=1}^J \left(\left(F\left(h_j, A_j(a_1,\ldots,a_J),\bar{u}\right) - p_j^g\right)n_j h_j - a_j p_j^g\right) + (1-\mu)B(a_1,\ldots,a_J) \\ &\text{subject to}: n_j h_j + a_j \le l_j \text{ for all } j = 1,\ldots,J, \\ &\qquad \sum\nolimits_{j=1}^J \tau p_j(a_1,\ldots,a_J)(l_j - a_j) = \sum\nolimits_{j=1}^J p_j(a_1,\ldots,a_J)a_j, \\ &\qquad \tau \in [0,1] \text{ given}, \end{aligned}$$

where p_j is the competitive equilibrium price as a function of $a_1,\ldots,a_J$ in equation (2.10). Substituting equation (2.10) for prices into the government's budget equation (2.5) as well as using the same substitutions as when deriving equation (2.9) we can restate constrained optimization problem (2.11) as follows:

$$(2.12)\quad \begin{aligned} &\max_{\{a_j\}_{j=1}^J} \mu\sum_{j=1}^J \left\{\frac{\alpha^{\alpha/\beta}\beta A_j^{\gamma/\beta}\left(v - \theta d_j^c\right)^{(\alpha+\beta)/\beta}}{(\alpha+\beta)^{(\alpha+\beta)/\beta}\bar{u}^{1/\beta}}(l_j - a_j) - p_j^g l_j\right\} + (1-\mu)\sum_{j=1}^J \varphi_j a_j \\ &\text{subject to}: \sum\nolimits_{j=1}^J \tau A_j^{\gamma/\beta}\left(v - f(d_j^c)\right)^{\frac{(\alpha+\beta)}{\beta}}(l_j - a_j) = \sum\nolimits_{j=1}^J A_j^{\gamma/\beta}\left(v - f(d_j^c)\right)^{\frac{(\alpha+\beta)}{\beta}} a_j. \end{aligned}$$

In the following sections we solve the model by applying it to the case of the Twin Cities. We first parameterize the model and then analyze the optimal configurations of open space and residential development and the associated optimal landscape patterns and welfare implications

3. Data and parameter values

We apply our model of optimal provision of open space to the seven-county metropolitan area surrounding Minneapolis and St. Paul, Minnesota, USA, (Figure 1). The study area is divided into 689 neighborhoods, where each neighborhood is defined as an existing U.S. census block varying in size from 0.21 km^2 to 222 km^2, covering a total of 7704 km^2. The location and boundaries of each neighborhood are determined by their latitude and longitude coordinates. For each neighborhood, we assemble the area in existing commercial development, parks, institutional amenities, water, and residential and undeveloped land (Table 1) using the 2000 Generalized Land Use data set for the region (Metropolitan Council 2007). Areas of existing commercial development (462 km^2) are fixed at their current values. Areas of existing parks (660 km^2), institutional amenities (132 km^2), and water (500 km^2) are treated as amenities and are also fixed at their current values. Preexisting amenities for each neighborhood *j* consist of parks, z_j^a, institutional amenities, z_j^i, and open water bodies, z_j^w, such that $z_j^a + z_j^i + z_j^w = z_j$. In the numerical application we add preexisting parks to new open space to determine the open space aggregation score, restating equation (2.6) as

$$\varphi_j(a_1,\ldots,a_J) = \sum_{k=1}^{J} \left(a_k + z_k^a\right)\exp\left(-\sigma d_{kj}\right).$$

Areas of existing residential development (1412 km^2) and undeveloped land (4538 km^2) are combined into one undeveloped land base (5950 km^2) that represents land available for residential development or protection as open space. We identify two neighborhoods representing downtown Minneapolis and St. Paul as employment centers (Figure 1) and compute the vector of the distances between each neighborhood and the nearest downtown. We also compute the matrix of distances between each neighborhood and all other neighborhoods in the city.

The biodiversity score is based on the amount, heterogeneous quality, and aggregation of protected open space. The Metropolitan Council has identified regionally significant natural resource areas in the seven-county Twin Cities metropolitan region (Metropolitan Council 2007). The natural areas cover 892 km^2 (12% of 7704 km^2) and include forest, grassland, and wetland habitat. Each natural area is rated as moderate, high, or outstanding quality based on its size, shape, cover-type diversity and adjacent land use. Throughout the study area, there are 11, 211, and 670 km^2 of moderate, high, outstanding quality natural areas. We overlay the maps of natural areas and census blocks and compute the total natural area coverage by quality class in each neighborhood. Natural areas occur in 215 neighborhoods (31% of 689 blocks) and cover 0.01-77 km^2 of those neighborhoods (Figure 1). Within each neighborhood, we assume that natural areas occur only within the undeveloped land class.

To embody this heterogeneity of existing and newly protected open space into the biodiversity score (Eqs. 2.6 and 2.7), let $q = 1,\ldots,4$ represent the quality of open space, where $q = 1$ represents open space that is not designated as a natural area and $q = 2, 3, 4$ represent natural areas with moderate, high, and outstanding qualities, respectively. Then, a_j^q, for all *j* and *q* is a decision variable for the area of neighborhood *j* that is protected open space of type *q*, where $a_j^q \le \bar{a}_j^q$, the upper bound on the area of neighborhood *j* that can be protected as open space type *q*. Let ω^q measure the effectiveness of creating habitat for biodiversity on land of quality type $q = 1,\ldots,4$. Then, effective habitat area in neighborhood *k* is a function of the area of existing parks z_k^a and area of newly protected open space of different habitat qualities: $\omega^1(z_k^a + a_k^1) + \sum_{q=2}^{4} \omega^q a_k^q$, where the area of existing park, z_k^p, is open space that is not designated as natural area (i.e., habitat of quality type 1). We assume that the effectiveness parameter ω^q increases with the quality of natural areas: $\omega^1 = 0.1$, $\omega^2 = 0.6$, $\omega^3 = 0.8$, and $\omega^4 = 1.0$.

The parameter values of the optimization models are summarized in Table 2. Annual household income is $45,700 for Minneapolis–St. Paul in 2009 (Bureau of Economic Analysis, 2010). We calibrate the reservation utility level to 0.12 to match the Twin Cities current (2009) size of 1.14 million households. We base the price of agricultural land on the average value of $6428 per ha ($2602 per acre). We assume the consumption, housing, and amenity shares in the utility function (2.1) to be equal to 0.56, 0.36, and 0.08, respectively. Annual transportation cost for commuting to work is $413 per km. To compute annual transportation cost, we assume a travel speed of 40 km/h, a wage of $23.78 per h (hourly wage in Minneapolis–St. Paul in 2009; Minnesota Department of Employment and Economic Development, 2009), fuel and vehicle maintenance costs of $0.20 per km, and 520 one-way commutes per year (5 round trips per week for 52 weeks). We assume that the distance parameter in the amenity function is equal to 0.10 so that open space in one neighborhood contributes to the utility of people in surrounding neighborhoods at a level that decays slowly with distance. We perform sensitivity analysis to determine the effects of increasing this distance decay parameter from 0.10 to 1.0. The distance parameter in the aggregation score of the biodiversity function is 0.10. We assume that existing amenities enter the amenity function in the same fashion as open space.

4. Results

This section discusses the main findings of this paper and analyzes optimal spatial configuration of open space and residential development. We find that even minor shifting of optimization priorities from maximizing land rents to maximizing the biodiversity measure results in very different optimal landscape patterns and welfare implications.

4.1. Benchmark case or land use currently on the landscape

We start with a benchmark case where open space is limited to the existing parks and no new land acquisition designated as open space. Given this existing open space configuration we solve for the market equilibrium prices, residential development, and population density with no property tax. This benchmark case is illustrated in Figure 2a. Higher housing densities and land prices are concentrated near downtown Minneapolis and St. Paul and adjacent to parks along the Mississippi River and the lakes located centrally as well as in counties West of Minneapolis and North of St Paul. This residential development solution throughout the city fits closely with the actual residential development currently on the landscape (Figure 1). This match of our model generated solution to actual spatial pattern also reflects the amenity values that households place on urban open space. The benchmark biodiversity score is normalized to 100 and is based solely on existing parks and water bodies (Table 3, column 1). Net benefit per household, which we define as the maximum willingness to pay net of opportunity cost, is equal to $18,568 (equal to total net benefit of $21.23 billion divided by 1.14 million households).

4.2. Maximizing land rents

Given the benchmark case described above, we now introduce property tax levied on residential land use. Tax revenue finances acquisition of new open space. The pattern of new open space and residential development as well as optimal taxation depend on the municipal objectives that range from primarily maximizing land rents to primarily maximizing biodiversity and anywhere on the objectives spectrum between these two extremes. First, consider the case when the primary goal is to maximize land rents. In this case, we find that the optimal configuration of open space is heavily skewed towards the urban boundary nearly forming a ring around the city (Figure 3, row 1). This result is consistent with earlier findings by Yang and Fujita (1983) and Tajibaeva *et al* (2008). Large areas of land in the peripheral neighborhoods with the lowest property values and located furthest from the employment centers are designated as new open space while high density housing is concentrated near downtown Minneapolis and St. Paul. Compared to the benchmark case, the amount of open space nearly doubles, adding 513 km^2 of newly protected open space to the already existing 660 km^2 in parks. Of these total new acquisitions 41% of new open space is located on Regionally Significant Natural Areas with higher land quality. As a result, the biodiversity score doubles to 209 compared to the benchmark case of 100 (Table 3, column 2). In this case the optimal property tax is 6%. Because of the increase in amenities associated with new open space, the city becomes more attractive and the number of households increases slightly from 1.14 to 1.15 million. While new open space pulls more people into the city, it also restricts the amount of land available for residential development. As a result, the increased population density along with higher prices serve as a push effect. Despite the introduction of a 6% tax the net benefit per household increases by 1% compared to the benchmark case with no property tax and no new open space. It appears that the optimal expansion of open space in the urban area more than compensates the introduction of optimal taxes, higher population density, and higher prices.

4.3. What if biodiversity matters: shifting priorities toward biodiversity maximization while keeping taxes fixed

So far we discussed the case when the primary objective was to maximize land rents. In this section we expand our analysis by putting more emphasis on biodiversity maximization. Shifting optimization priority away from land rent and towards the biodiversity objective changes the size, location, and quality of new open space (Figure 3). The location of new open space shifts away from the periphery to neighborhoods that have higher habitat quality and are closer to existing parks and the city centers. Compared to the case of maximizing land rents, the total area of new open space decreases but is more clustered. For example, shifting the priority towards biodiversity preservation from $\mu = 0.99$ to $\mu = 0.90$ decreases protection of low quality areas by 301% from 301 km^2 to 0 km^2 and increases protection of the outstanding natural areas by 70% from 152 km^2 to 258 km^2 (Table 3). As a result, the biodiversity score more than doubles compared to the maximizing land rents case increasing from 209 to 471 and quadruples compared to the benchmark case with no taxes. Because higher quality natural areas are located in neighborhoods with higher property values, the improvement in biodiversity comes at the expense of a 1.07% net loss of the land rent income (from \$21.55 to \$21.32 billion) and a 43% reduction of the total protected area (from 513 km^2 to 291 km^2). The land use pattern emerging from prioritizing biodiversity emphasizes protection of high quality natural areas that are more clustered together in neighborhoods located closer to the urban center as opposed to a more spread out peripheral open space protected in the maximum land rent approach. As a result of protecting less open space the city attracts fewer households (a reduction from 1.15 to 1.13 million households). However, while the overall population slightly decreases, population density in neighborhoods surrounding the city centers and open space clusters increases. When open space is more clustered and centrally located, population density is higher in central neighborhoods and lower in peripheral neighborhoods than in the case when open space is spread around the periphery. Similar pattern applies to property values that are lower on average but are higher in central areas.

Relative to the benchmark case, prioritizing biodiversity objectives with a fixed tax results in higher bid rent, lower population density, and more open space, but higher property values. We find that introducing of biodiversity objectives with moderate tax leads to overall improvement compared to the benchmark.

These results suggest that the biodiversity measure can improve by changing the spatial configuration of open space towards lands with higher quality natural areas with slight reductions in household net benefit and population density but with larger plot areas. We analyze the full spectrum of the tradeoff between total land rent and biodiversity objectives given a 6% tax rate (Figure 4a) (We explore the solution with optimal taxes in the next section.). The biodiversity score can be increased by a factor of 2.3 (from 209 to 481 %) with a reduction of total land rent by only 2% (from \$21.55 to \$21.22 billion).

4.4. Prioritizing biodiversity with optimal taxes

Up to this point, we solved for the optimal tax for land rent maximization and kept tax fixed at this optimal rate while changing the priorities away from land rent maximization and towards the biodiversity conservation objective. We now relax this assumption and allow taxes to change solving for the optimal tax for different priorities for the two objectives. As we continuously prioritize the biodiversity conservation objective (i.e., μ gets smaller), the total area of new open space, optimal tax rate, and biodiversity score increase (Table 4). With more open space protected to improve the biodiversity score, there is less land available for residential development resulting in higher land prices, lower population, and lower total land rent. Consider the tradeoff between land rents and biodiversity with optimal taxes, even at 19% property tax the metro area achieves most of the biodiversity benefits that correspond to an increase in biodiversity measure to 825 from 100 in the benchmark case with no taxes (Figure 4b). This eight-fold increase in biodiversity comes at the expense of 0.9% reduction in land rents compared to the bench mark case. At 19 to 20 percent tax rate the tradeoff cure achieves a “golden point.” Up to a 20% tax there are high returns to biodiversity at a low cost (very steep tradeoff curve). However, above 20%, tax becomes a burden on the metro area resulting in large reductions in land rents and only marginal improvements in biodiversity (flat tradeoff curve).

Consistently prioritizing the biodiversity objective also changes the pattern of open space protection. In comparison with the maximum land rent solution (μ = 0.99), instead of only putting new open space in the periphery, the optimal solution with μ = 0.90 positions new open space throughout the city, along the Mississippi river, and a concentration in the northern suburbs where large natural areas are located (Figure 5). New open space is also located in neighborhoods with natural areas that are closer to the central business districts. Households are concentrated near the central business districts, and housing density is lower near the periphery. Land prices are higher near the central business districts, and higher than those for the maximum land rent solution.

4.5. Spillover effect

So far in our analysis we assumed that households may benefit from open space amenities throughout the city as a whole with only moderate reduction of benefits in distance from the neighborhood of residence. We now conduct sensitivity analysis and examine the effects of reducing amenity spillover effect so that the benefits of environmental amenities start to rapidly decrease with distance and households benefit primarily from open space amenities in their own and nearby neighborhoods. We find that as spillover effect decreases the city becomes less attractive and fewer people want to reside in the metro area. As a result land rents become lower. We also find that low spillover effect has a negative impact on biodiversity.

When the primary goal is to maximize land rents, we find that new open space is mostly located in neighborhoods near the urban boundary where there are few existing parks (Figure 6, row 1); however, the map of new and existing open space shows a relatively uniform distribution across the city. Because open space amenities outside a neighborhood no longer contribute to household utility, the amenity variable in the household utility function is lower and households need more residential space and more open space within their neighborhood to reach the fixed utility level. As a result, while most neighborhoods have open space, there are fewer households and lower land values. Compared with the maximum land-rent solution with high amenity spillover (Table 3), the solution with low amenity spillover (Table 5) has slightly less new open space (501 km^2) but more Regionally Significant Natural Areas (267 km^2) resulting in a higher biodiversity score (275). Further, the solution with low amenity spillover has fewer households (0.72 million) and lower net benefit per household ($17,908). The tax rate necessary to support the optimal provision of new open space is 8%.

Similar to the cases with high amenity spillover, shifting optimization priority away from land rent and towards the biodiversity objective changes the locations of new open space to neighborhoods that have higher habitat quality and are closer to existing parks and the city centers (Figure 6). Shifting the priority towards biodiversity preservation from $\mu = 0.99$ to $\mu = 0.60$ decreases non-natural areas in the protected areas from 235 km^2 to 0 km^2 and increases the outstanding natural areas from 199 km^2 to 282 km^2 (Table 5). As a result, the biodiversity score increases from 275 to 559. Because higher quality natural areas are located in neighborhoods with higher property values, the improvement in biodiversity comes at the expense of a 3% net loss of the land rent income (from $12.93 to $12.50 billion) and a 30% reduction of the total protected area (from 501 km^2 to 352 km^2). As a result of protecting less open space and shifting protected land to neighborhoods with higher quality natural areas, the city attracts fewer households (a reduction from 0.72 to 0.68 million households) and lower average land value (a reduction from $16,823/ha to $15,978/ha).

4.6. Are the location and size of existing parks optimal?

We ask the question of whether the location and size of the existing parks in the Twin Cities metro area are optimal. To answer this question, we examine the optimal configuration of open space and residential development when there is no existing open space. We find that the optimal allocation that prioritizes biodiversity goals and levies moderate land value tax resembles the closest the current Twin Cities landscape ($\mu = 0.6$ and $\tau = 15\%$). It is interesting to note that this finding is consistent with various national rankings placing the Twin Cities metro area among the top US cities (Ranked 1st among “America’s Top 20 Healthiest Cities” Forbes; ranked 4th among “Top 10 Healthiest, Happiest Cities in America” ABC news). This spatial configuration indicates revealed preferences in the Twin Cities metro area for the urban planning objectives that prioritize biodiversity (i.e. $\mu = 0.6$ instead of $\mu = 1$). Compared to the spatial configuration with existing parks (660 km^2), the optimal spatial configuration that maximizes land rent has 500 km^2 of new open space located mostly on the periphery of the city (Figure 2b). The total land rent and land prices are lower because there is no endowment of existing parks providing open space amenities (Table 6). With the biodiversity objective, 889 km^2 of new open space are located primarily in neighborhoods with natural areas, which are concentrated along the Mississippi river and on the northern fringe of the city (Figure 2b). As a result, the biodiversity score is much higher than the solution with existing open space while the number of households and land values are about the same (Table 6). The solution that maximizes biodiversity (Figure 2b) is closest to the existing open space configuration (Figure 2a) to the extent that existing parks are located in neighborhoods with natural areas. However, there are many existing parks in neighborhoods close to the city center, which are not present in either of the optimal solutions, suggesting that an optimal solution with a low spillover effect, which tends to spread out open space across the city, might be closer to the existing configuration.

5. Conclusion

Urban economic models that analyze the spatial pattern of housing development as a function of the size and location of open space can be extended for use in conservation planning. Discrete space models, such as the one we present for the Twin Cities, can be used to determine optimal spatial patterns of open space and housing subject to physical constraints on land availability and practical constraints on tax rate given a planner's objectives of maximizing household welfare and biodiversity. Analysis of the impacts of the planner's preferences for the objectives allows determination of the tradeoffs among alternative open space acquisition strategies. Results from the Twin Cities application suggest that planners can protect additional open space for conservation without much loss in household welfare, and these gains can be obtained with a reasonably low property tax rate.

Conservation planning, i.e., applying systematic approaches to biodiversity conservation, is a relatively new field (Margules and Pressey 2000, Moilanen et al. 2009). For example, Armsworth et al. (2006) combined economic analysis of land markets with conservation planning to show how buying land for conservation may increase land prices, change the pattern of development, and reduce conservation metrics. Toth et al. (2011) used this framework in an integer programming model to select reserve sites over time to maximize biodiversity protection while accounting for land-price feedbacks that arise from open-space amenity premiums and shifts in market equilibriums.

This paper expands the existing framework by embedding a model of residential location choice, which depends on land value, commuting cost, and open space amenities, within a city planner's problem of determining the optimal provision of open space and residential land use. Doing so allows analysis of the effects of increasing biodiversity conservation on endogenous land prices, housing density, and household welfare. Further, our model accounts for important spatial linkages among land units, either for ecological or for economic reasons. For example, the conservation value of setting aside a land parcel may depend on the amount of conserved land nearby. The value of land for development may be enhanced by being adjacent to conservation land because households prefer the amenities of nearby open space.

There are additional questions that remain for future research. We emphasize that our application is stylized in the sense that we determine optimal housing pattern for a developable land base that includes existing housing. Work is needed to construct a more realistic model in which existing housing is accounted for in open space and development decisions. Perhaps of greater importance is the explicit incorporation of timing. Conservation land purchases, as well as development, do not happen instantaneously but unfold with time. One approach to a dynamic analysis of open space provision is to develop an economic agent-based model of land use, which allows for the tracking of the transitional dynamics of development, both over space and time as the urban area grows (e.g., Magliocca et al. 2012). A dynamic model will allow consideration of many additional issues beyond those captured in static analysis.

Appendix A. Open-city equilibrium

Given an open space allocation $\{a_j\}_{j=1}^J$, preexisting amenities $\{z_j\}_{j=1}^J$, property tax τ, agricultural rental prices $\{p_j^g\}_{j=1}^J$, location of business centers $\{b_s\}_{s=1}^B$, and a uniform utility level $\bar{u}$ in an open city, define a competitive equilibrium allocation $\{c_j, h_j, n_j\}_{j=1}^J$ and price $\{p_j\}_{j=1}^J$ such that:

1. Households maximize their preferences (equation 2.1) subject to their budget constraint (2.3). The solution to this household's constrained utility maximization problem are demand functions for consumption, $c_j = \frac{\alpha\left(v - f\left(d_j^c\right)\right)}{\alpha + \beta}$, and housing, $h_j = \frac{\beta\left(v - f\left(d_j^c\right)\right)}{(\alpha + \beta)(1 + \tau)p_j}$.
2. Utility level is equal to $\bar{u}$ for all neighborhoods $j=1,\ldots,J$.
3. A neighborhood is included into the city boundary when $p_j \geq p_j^g$ for all neighborhoods $j=1,\ldots,J$.
4. The government balances its budget equation (2.5).
5. The land market $n_j h_j + a_j \leq l_j$ clears for all neighborhoods $j=1,\ldots,J$.
6. The total city population is the sum of households in each neighborhood j, $\sum_{j=1}^J n_j = N$.

The following are a competitive equilibrium allocation and price that satisfy conditions 1 through 6.

$$c_j = \frac{\alpha\left(v - f\left(d_j^c\right)\right)}{\alpha + \beta},$$

$$h_j = \left(\frac{\alpha + \beta}{\alpha}\right)^{\alpha/\beta} \left(\frac{\bar{u}}{\left(v - f\left(d_j^c\right)\right)^{\alpha} A^{\gamma}}\right)^{1/\beta},$$

$$n_j = \left(l_j - a_j\right)\left(\frac{\alpha}{\alpha + \beta}\right)^{\alpha/\beta} \left(\frac{\left(v - f\left(d_j^c\right)\right)^{\alpha} A^{\gamma}}{\bar{u}}\right)^{1/\beta},$$

$$p_j = \frac{\alpha^{\alpha/\beta} \beta A_j^{\gamma/\beta}}{(1 + \tau)\bar{u}^{1/\beta}} \left(\frac{v - f\left(d_j^c\right)}{\alpha + \beta}\right)^{(\alpha + \beta)/\beta}.$$

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Table 1. Land area

Land type	Area (km^2)
Land total	7,704
Commercial development	462
Parks	660
Institutional amenities	132
Water	500
Undeveloped land	5,950
Natural area total	892
Moderate	11
High	211
Outstanding	670

Table 2. Parameter values.

Parameter	Notation	Value
Consumption good share	α	0.56
Housing share	β	0.36
Amenity share	γ	0.08
Income ($1000 per year)	v	45.70
Utility level in an open city	$\bar{u}$	0.12
Amenity value for a unit of open space	δ_a	1.00
Amenity value for a unit of pre-existing feature	δ_z	1.00
Distance weight for amenity function	δ_d	0.10
Distance weight for fragmentation score	σ	0.10
Price of agricultural land ($1000 per ha)	p^g	6.43
Transportation cost ($1000 per km per year)	θ	0.41

Table 3. Optimal solutions with no tax, with the optimal tax (6%) when priority is given to maximizing land rent ($\mu = 0.99$), and with tax fixed at 6% and decreasing priority, μ, for the maximum land rent objective. These cases assume a large spillover effect, $\delta_d = 0.1$, for open space amenities.

Variables	No Tax	Optimal tax (6%)	Tax fixed at 6% and decreasing priority, μ	
	Benchmark	$\mu = 0.99$	$\mu = 0.90$	$\mu = 0.60$
Total net bid rent ($billion)	21.23	21.55	21.32	21.22
Biodiversity score	100	209	471	481
Average price ($/ha)	25,294	27,022	26,500	26,330
Number of households	1,143,332	1,151,314	1,134,141	1,126,896
Average household area (ha)	0.52	0.47	0.50	0.51
Population density (hhs/km^2)	148	150	147	146
Total new open space (km^2)	0	512.8	291.3	242.5
Non-natural area (km^2)	0	301.4	0.0	0.0
Natural area: Moderate (km^2)	0	3.4	2.1	1.5
Natural area: High (km^2)	0	55.7	31.5	32.2
Natural area: Outstanding (km^2)	0	152.3	257.7	208.8

Table 4. Optimal solutions with the optimal tax rates for decreasing priorities, μ, given to the maximum land rent objective. These cases assume a large spillover effect, $\delta_d = 0.1$, for open space amenities.

Variable	Optimal taxes and decreasing priority, μ		
	$\mu = 0.99$	$\mu = 0.90$	$\mu = 0.60$
Total net bid rent ($billion)	21.55	21.03	17.18
Biodiversity score	209	849	1,132
Optimal tax	0.06	0.20	1.00
Average price ($/ha)	27,022	28,706	31,705
Number of households	1,151,314	1,077,222	773,276
Average household area (ha)	0.47	0.45	0.48
Population density (hhs/km^2)	150	140	100
Total new open space (km^2)	512.8	1117.3	2246.8
Non-natural area (km^2)	301.4	224.8	1354.3
Natural area: Moderate (km^2)	3.4	11.0	11.0
Natural area: High (km^2)	55.7	210.9	210.9
Natural area: Outstanding (km^2)	152.3	670.6	670.6

Table 5. Optimal solutions with small amenity spillover ($\delta_d = 0.5$): no tax, the optimal tax (8%) when priority is given to maximizing land rent ($\mu = 0.99$), and tax fixed at 8% and decreasing priority, μ, for the maximum land rent objective.

Variable	No Tax Benchmark	Optimal tax (8%)	Tax fixed at 8% and decreasing priority μ	
		$\mu = 0.99$	$\mu = 0.90$	$\mu = 0.60$
Total net bid rent ($billion)	12.42	12.93	12.66	12.50
Biodiversity score	100	275	541	559
Average price ($/ha)	14,946	16,823	16,279	15,978
Number of households	685,811	722,784	698,304	683,586
Average household area (ha)	0.87	0.75	0.79	0.82
Population density (hhs/km^2)	89	94	91	89
Total new open space (km^2)	0.00	501.3	403.5	351.8
Non-natural area (km^2)	0.00	234.7	22.9	0.1
Natural area: Moderate (km^2)	0.00	3.5	5.0	3.1
Natural area: High (km^2)	0.00	64.1	76.8	66.2
Natural area: Outstanding (km^2)	0.00	199.0	298.8	282.4

Table 6. Optimal re-parking solutions with 6% and 15% tax rates, different priorities, μ, and large spillover effect, $\delta_d = 0.1$.

Variable	With Existing Open Space	No Existing Open Space				
	No Tax	No Tax	6% Tax		15% Tax	
			$\mu = 0.99$	$\mu = 0.60$	$\mu = 0.99$	$\mu = 0.60$
Total net bid rent ($billion)	21.23	18.07	19.18	18.85	19.47	19.17
Biodiversity score	100	0	182	421	404	740
Average price ($/ha)	25,294	21,537	24,277	23,563	26,326	25,755
Number of households	1,143,332	1,103,563	1,172,458	1,142,886	1,170,586	1,146,582
Average household area (ha)	0.52	0.54	0.47	0.49	0.42	0.44
Population density (hhs/km^2)	148	143	152	148	152	149
Existing parks (km^2)	660	0	0	0	0	0
Total area new parks (km^2)	0	0	500.5	293.5	1006.6	888.7
Non-natural area (km^2)	0	0	214.2	0.1	506.3	1.1
Natural area: moderate (km^2)	0	0	3.4	2.7	4.6	11.1
Natural area: high (km^2)	0	0	46.0	36.0	96.1	205.8
Natural area: outstanding (km^2)	0	0	236.9	254.7	399.6	670.7

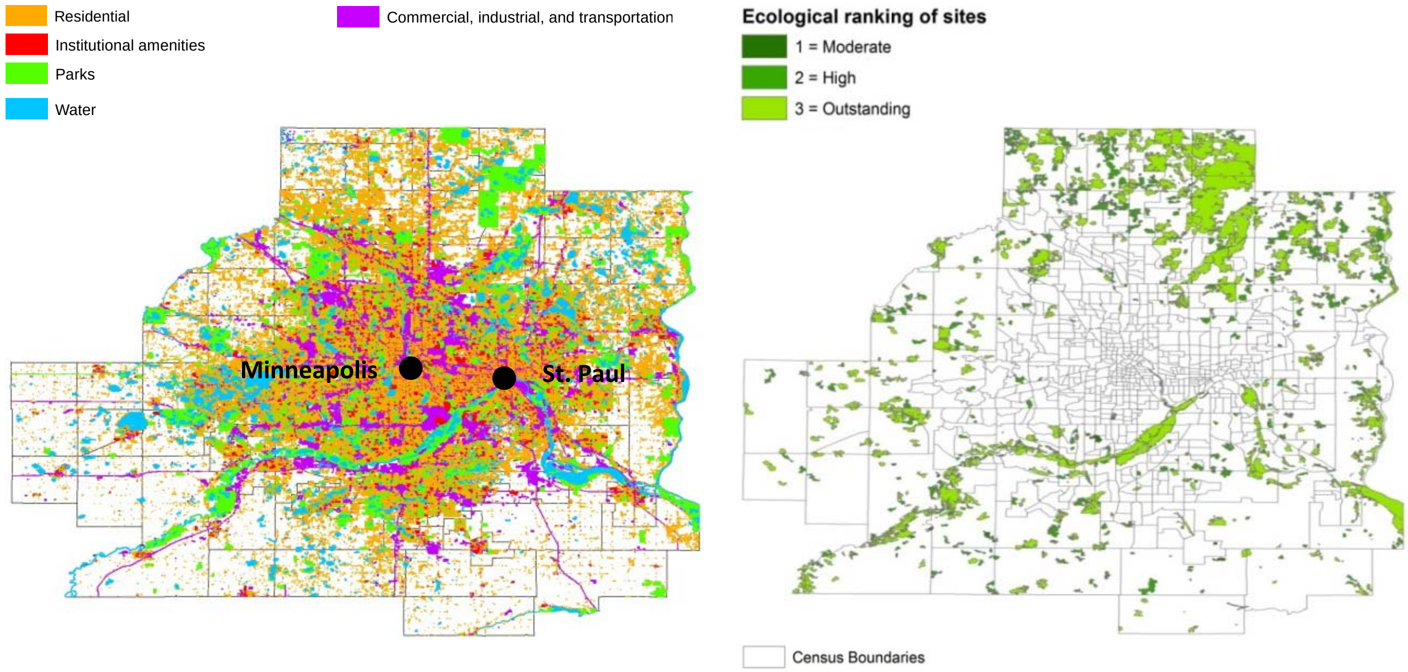


Figure 1. Existing land use and ecological ranking of sites in the seven-county metropolitan area surrounding Minneapolis and St. Paul, Minnesota, USA.

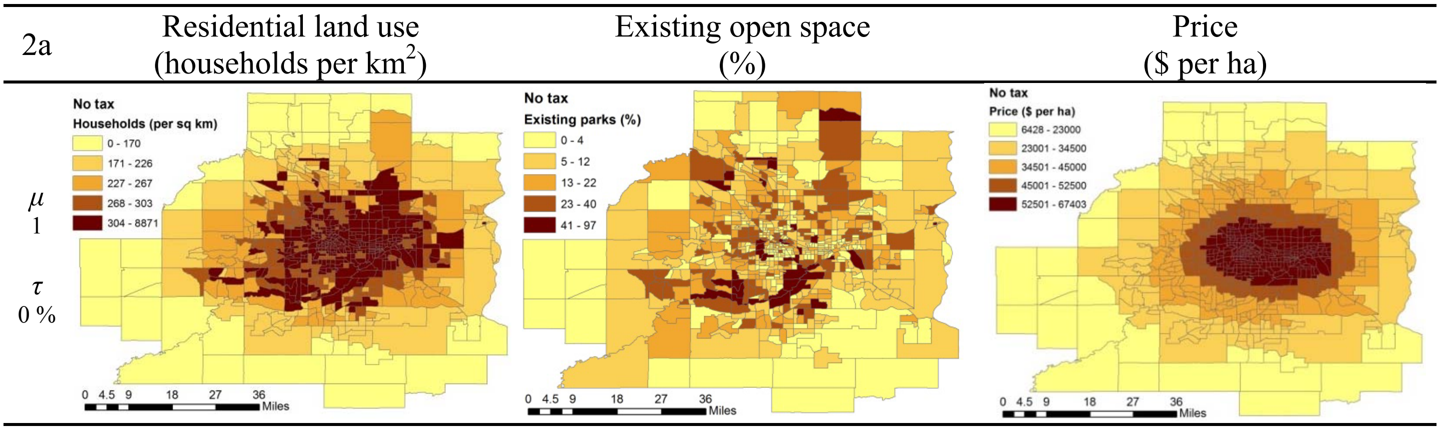


Figure 2a: Market prices and residential land use given existing parks and no new open space

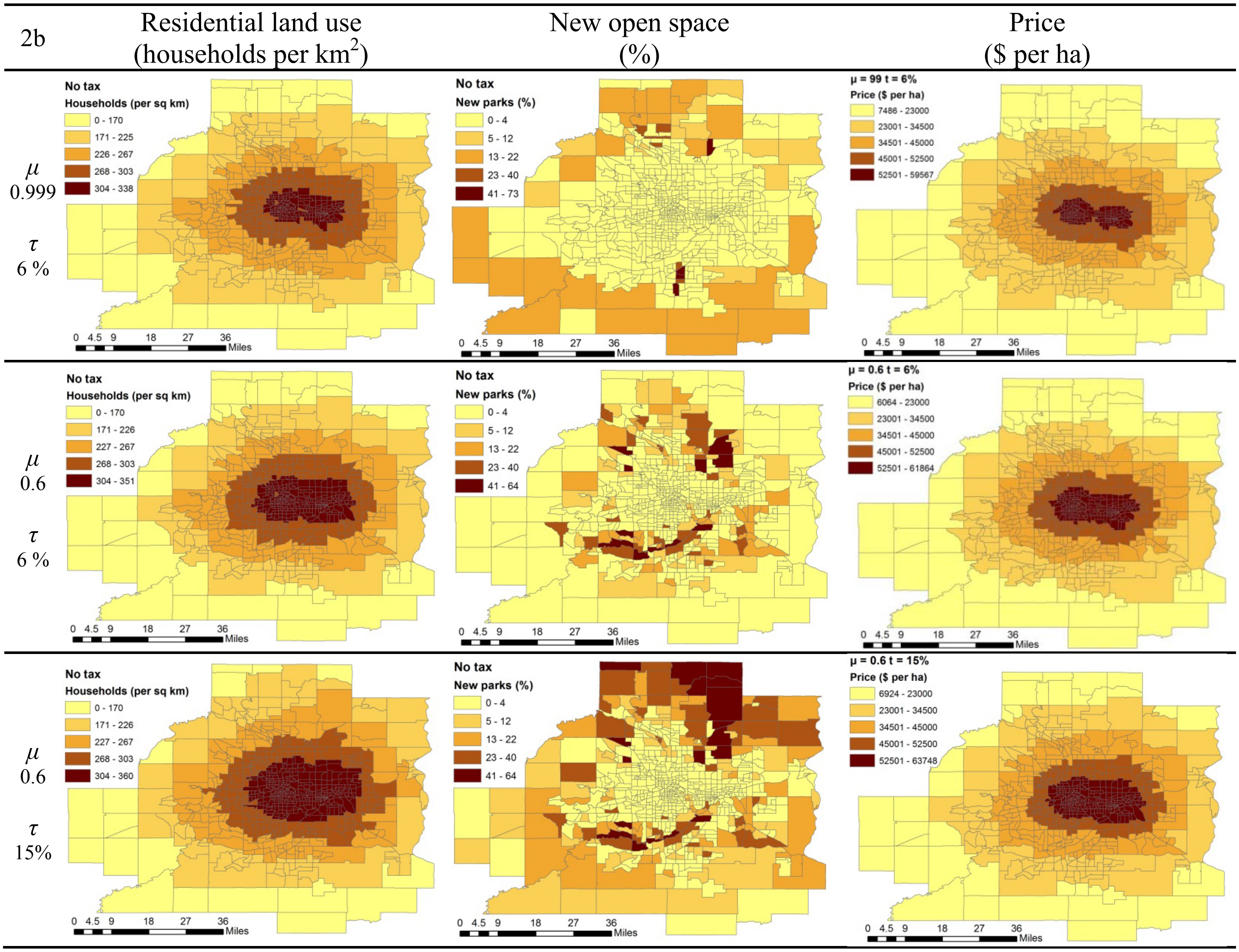


Figure 2b. Optimal residential and open space land use and market prices assuming there is no existing open space.

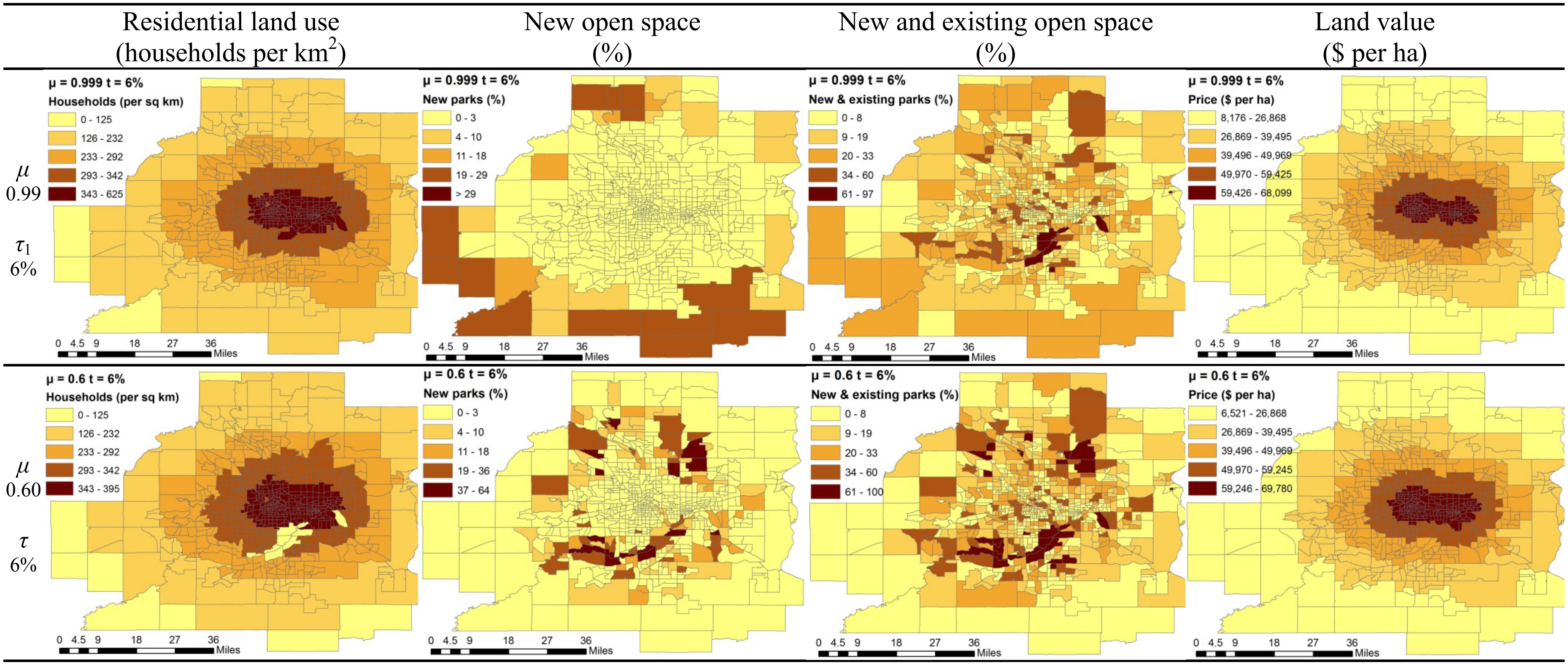
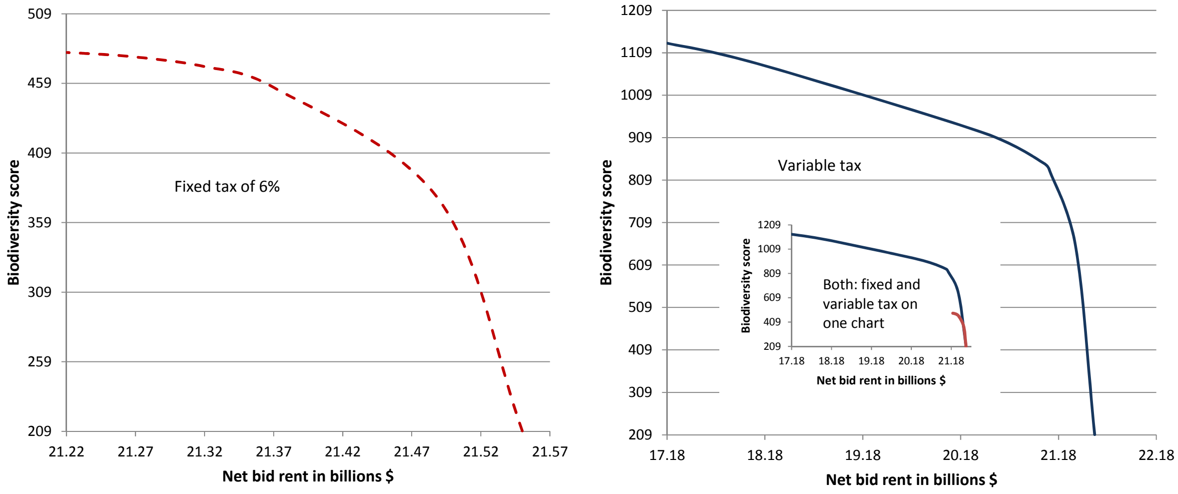


Figure 3. Optimal residential and open space land use and market prices when the objective is to maximize: (a) land rents ($\mu = 0.99$) and (b) biodiversity conservation ($\mu = 0.60$). Tax rate $\tau = 6\%$. Large amenities spillover effect $\delta_d = 0.1$.



(a) (b)

Figure 4. Tradeoff between biodiversity and land rents with fixed tax (a) and optimal tax (b).

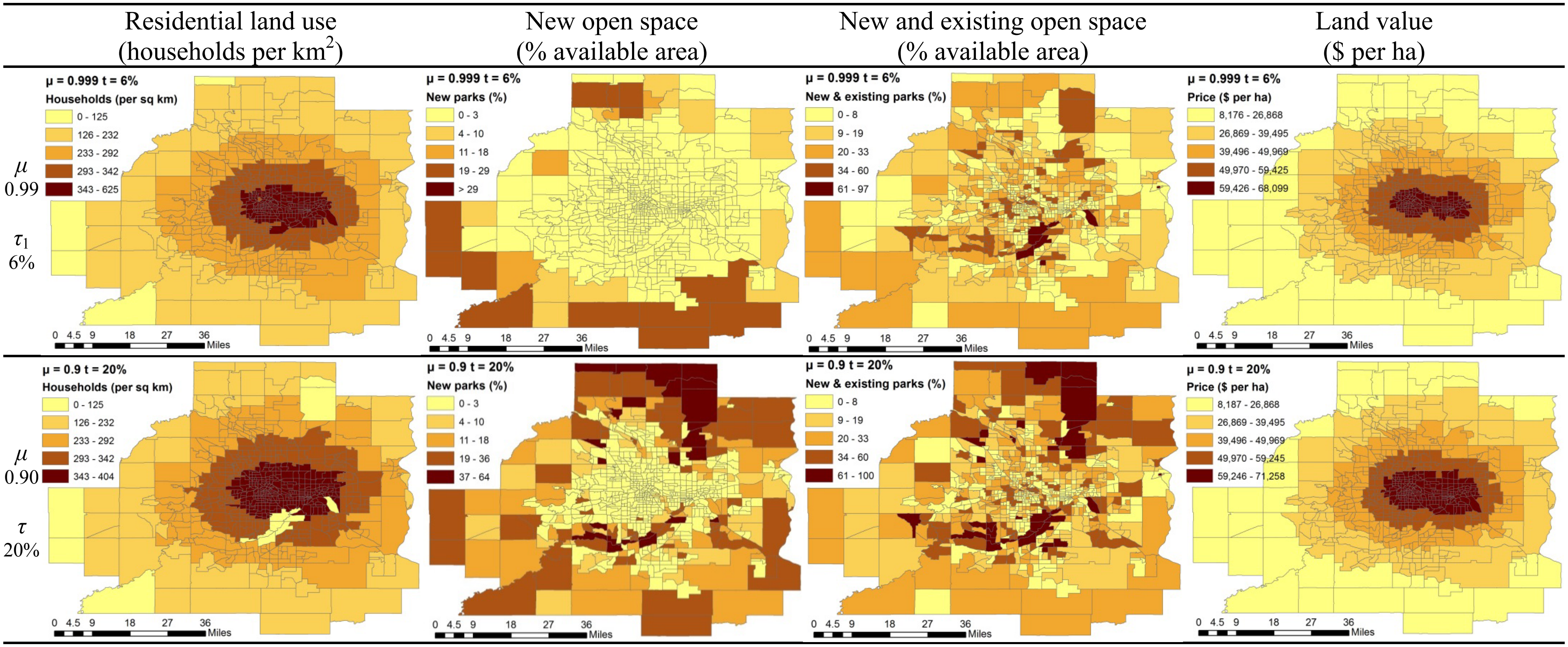


Figure 5. Optimal distribution of households, open space, and land value for solutions with priority given to the land rent objective ($\mu = 0.99$) and priority given to the biodiversity conservation objective ($\mu = 0.90$) and the minimum tax rate, τ, that supports it. These cases assume a large spillover effect, $\delta_d = 0.1$, for open space amenities.

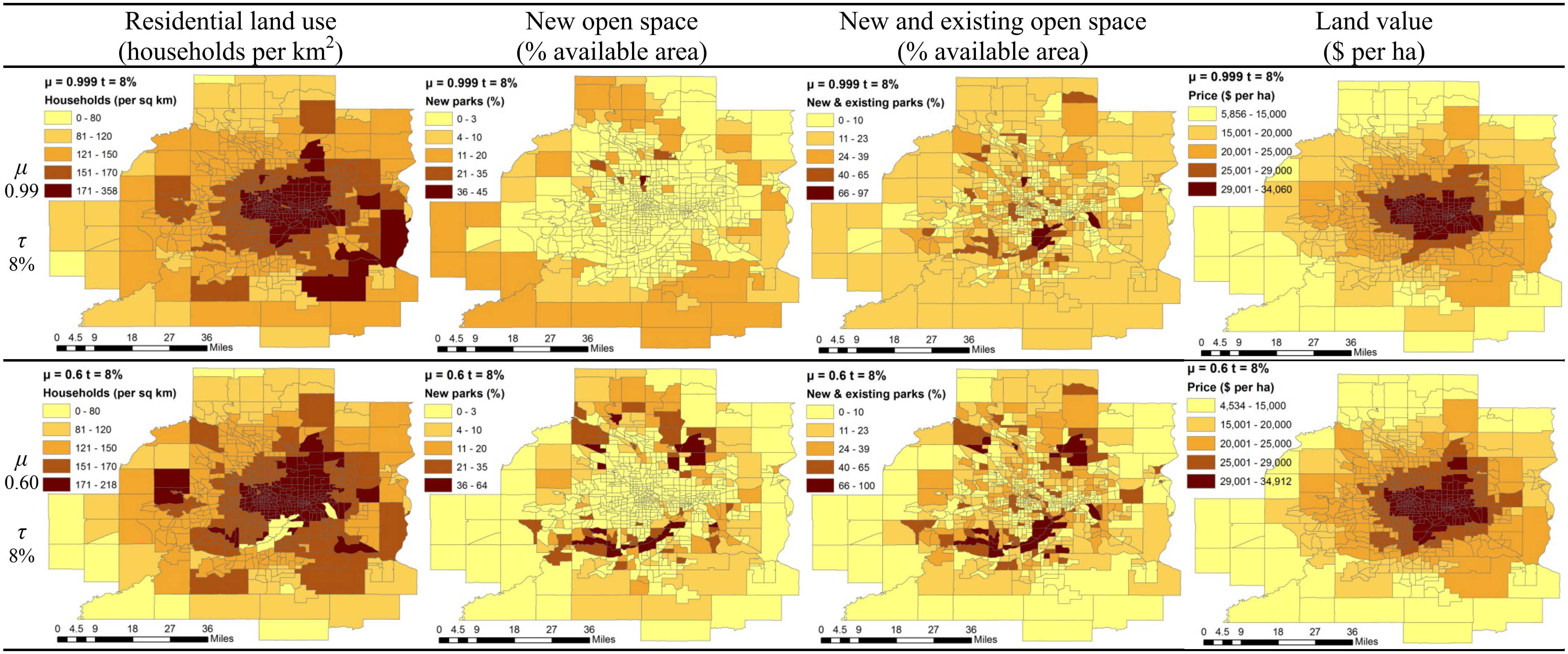


Figure 6. Optimal solutions with small amenity spillover ($\delta_d = 0.5$): Optimal distribution of households, open space, and land value for solutions with priority given to the land rent objective ($\mu = 0.99$) and priority given to the biodiversity conservation objective ($\mu = 0.90$) and tax rate, $\tau = 8\%$.