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Where to Put Things?
Spatial Land Management with Biological and Economic Objectives

Stephen Polasky, University of Minnesota
Erik Nelson, Unniversity of Minnesota
Jeff Camm, University of Cincinnati
Blair Csuti, Oregon Zoo
Paul Fackler, North Carolina State University
Eric Lonsdorf, University of Minnesota and Lincoln Park Zoo
Denis White, US EPA
Jeff Arthur, Oregon State University
Brian Garber-Yonts, US Forest Service
Robert Haight, US Forest Service
Jimmy Kagan, Oregon State University
Claire Montgomery, Oregon State University
Tony Starfield, University of Minnesota
Claudine Tobalske, Oregon State University and Oregon Natural Heritage Information Center

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Abstract: In this paper we develop a spatially explicit model for analyzing the consequences of alternative land use patterns on species conservation and market-based economic returns. We use the model to search for efficient land use patterns that maximize species conservation objectives for a given level of economic return, and vice-versa. We find that there is minimal conflict between the goals of maintaining minimum viable populations of terrestrial vertebrates, consisting of at least 1000 breeding pairs, and economic returns. Generating the maximum number of species meeting this threshold involves sacrificing less than 1% of economic returns compared to maximum economic returns. When the conservation goal is more ambitious, maintaining 10% or 50% of the maximum potential population for each species, there are large tradeoffs between conservation and economic returns. For the 10% goal, the efficiency frontier is bowed inward indicating high initial marginal costs of conservation.

1. Introduction

Loss of natural habitat is thought to be the primary cause of the loss of terrestrial biodiversity (Wilcove et al. 2000, Wilson 1998). Over the course of recent history, a large fraction of the planet's fertile lands have been converted into agricultural fields, pasture, managed forests, and urban areas. Approximately 38% of the land globally is devoted to agriculture (FAO 2004). Excluding lands without vegetative cover (desert, rock, ice) and boreal lands, agricultural use is approximately 50% (Tilman et al. 2001).

The primary response of conservationists has been to push for a system of biological reserves to maintain natural habitat. Ideally these biological reserves would contain sufficient habitat to provide refuge for all species, a sort of modern Noah's Ark. Currently about 11% of land worldwide has some form of protected status (IUCN categories I-VI; WRI 2005). The distribution of protected land is quite uneven with some types of habitat well protected and other areas not well protected at all. For example, about 30 % of land in Tanzania is protected while most West African countries have less than 5% of land protected (WRI 2005). Within the US, a large fraction of lands in Alaska (and northwestern Wyoming) are protected while a very small portion of in the Midwestern corn belt has protected status.

Despite the importance of biological reserves, there is fairly widespread recognition that conservation must consider what happens beyond the boundaries of protected areas (e.g., Franklin 1993, Miller 1996, Reid 1996, Wear et al. 1996, Daily et al. 2001, Rosenzweig 2003, Polasky et al. 2005). Because biological reserves typically preclude most economic activity, there can be substantial opposition to the expansion of biological reserves. Restrictions on the use of lands can impose costs on existing land users and prevent valuable economic activity in the future. The amount of land set aside for reserves will be limited and will be generally insufficient to sustain all of biodiversity. However, there are some economically valuable land uses that can coexist with at least some conservation objectives. Many species can coexist with some level of human activity and human alteration of the land. Rather than looking solely at where to place biological reserves, the broader land use question is whether conservation objectives can be met on a landscape that includes both human altered lands and protected lands.

In this paper we develop a spatially explicit model for analyzing the consequences of alternative land use patterns on species conservation and market-based economic returns. We use the model to search for efficient land use patterns that maximize species conservation objectives for a given level of economic return, and vice-versa. Finding an efficient land use plan where conservation objectives can be met at minimum opportunity cost on a landscape that includes both human altered lands and protected lands requires an expanded modeling approach and far more data compared to choosing a set of sites to include in a biological reserve network. In the reserve site selection problem, a common approach is to choose sites to represent the maximum number of species at least once in a selected site given a constraint on the number of reserve sites that can be selected (e.g., Church et al. 1996, Camm et al. 1996, Csuti et al. 1997). The only information required to implement this reserve site selection approach is biogeographic information on species ranges so that one knows the species at each site. For the landscape approach used in the paper, we use a biological model that predicts whether a species will meet a conservation target given a land use pattern that generates a habitat mosaic. For each species, we use the land use pattern, species-habitat associations and species range information, to generate a map of suitable habitat patches for that species. We then use area requirements and dispersal ability to predict the number of breeding pairs that can survive on that landscape. The economic model uses information on soil, location, and other site characteristics to predict economic returns for a given site if it were placed in a given land use. We use the combined biological and economic model to search for efficient land use patterns.

We consider several different conservation objectives. In one version, the conservation objective is to maximize the number of species that attain a threshold value of at least 1000 breeding pairs predicted by the biological model to exist on the landscape. One thousand breeding pairs is considered a minimal viable threshold by the Nature Conservancy for its globally most imperiled species rank. We also consider an objective function where the threshold is set not by likelihood of persistence but by the relative population of the species in the landscape versus the landscape's potential for this species. In other words, we compare the predicted population size of the species on a given landscape versus the predicted population for the landscape that is most favorable for the species. In this version of the model we use both 10% and 50% thresholds.

We illustrate our methods for the Willamette Basin, Oregon. Our Willamette Basin model has approximately 10,000 land parcels, seven alternative land uses, and 267 terrestrial vertebrate species. With the exception of Polasky et al. (2005), which uses similar versions of the biological and economic models described in this paper to analyze a 14 x 14 landscape with a three alternative land uses, almost all prior work that combines biological and economic models to evaluate both conservation and economic returns focus on a single species or small set of species and a single economic activity such as forestry (e.g., Montgomery et al. 1994, Haight 1995, Hof and Bevers 1998, Marshall et al. 2000, Calkin et al. 2002, Moilanen and Cabeza 2002, Lichtenstein and Montgomery 2003, Nalle et al. 2004).

In the next section of the paper we describe the biological and economic models. In section 3 we describe the optimization problem of finding land use patterns that achieve a given conservation objective at minimum cost and simple methods for finding solutions to this problem. Section 4 describes the Willamette Basin and relevant data. Section 5 contains results of applying our model to the Willamette Basin landscape. We conclude with a discussion of the methods and results in section 6.

2. The Biological and Economic Models

The land use pattern in the planning region (in our case, the Willamette Basin) is used as input for both the biological and the economic model. The planning region is partitioned into a set of distinct land parcels. A land use pattern specifies the land use for each land parcel in the planning region. The land use pattern and characteristics of each land parcel determine habitat patterns that are used by the biological model to determine how many breeding pairs can exist in the planning region. The land use pattern and characteristics of each land parcel are used in the economic model to determine economic returns in the planning region.

a. The biological model

The biological model is used to predict a land use pattern's ability to support populations of a large suite of species. Each species' appraisal of a land use pattern depends on three species-specific traits: a) habitat compatibility (which includes geographic range, habitat type and special features like whether there is water access), b) the amount of habitat required for a breeding pair, and c) the species' ability to move or disperse between suitable patches of habitat. The last trait, a species' dispersal ability, becomes more important as habitat patches become more fragmented and isolated.

We begin by calculating the number of breeding pairs for each species, $s = 1, 2, \ldots, S$, for each parcel, $j = 1, 2, \ldots, J$. Let X_j^w mean that land use ω occurs in parcel j, $\omega = 1, 2, \ldots, \Omega$. The number of breeding pairs of species s that parcel j can support is given by:

$$Z_{sj} = \frac{A_j H_{sj} C_{sj}(X_j^w)}{AR_s} \tag{1}$$

where A_j is the area of parcel j, H_{sj} is an indicator variable showing whether it is possible for species s to exist in parcel j, $C_{sj}(X_j^w)$ is the habitat compatibility score of parcel j for species s which is a function of land use in parcel j (X_j^w), and AR_s is the amount of area needed by a breeding pair of species s. The indicator variable, H_{sj}, equals 1 if parcel j is within the geographic range of species s and contains suitable physical attributes, and equals zero if parcel j is outside the geographic range of species s or does not contains suitable physical attributes. For example, for a water sensitive species whose range is the foothills of the Cascade Range, $H_{sj} = 0$ for parcels outside foothills of the Cascade Range or those that do not contain water. The habitat compatibility score, $C_{sj}(X_j^w)$, can take on values of 0, 0.5, or 1. A habitat compatibility score of 1.0 means the habitat is very conducive for breeding and feeding activities of a species. A habitat compatibility score of 0.5 means the habitat is marginally suitable for breeding and feeding activities. Marginal habitat is penalized versus prime habitat in that it takes twice as much area to generate the same "effective area" as prime habitat. A habitat compatibility score of 0 means the species does not breed or feed in that habitat. The habitat compatibility score for a parcel depends upon its land use X_j^w. For example, habitat compatibility may be quite different for species *s* if the parcel is in agricultural use, versus forestry use, versus natural habitat conditions. Dividing by AR_s yields the number of breeding pairs that can utilize parcel *j*.

The number of breeding pairs that can be supported on the landscape as a whole is determined not only by how many breeding pairs can be supported on various parcels, but by their proximity to other parcels containing suitable habitat. Isolated fragments of habitat may be unable to sustain a viable population of the species. Close proximity among habitat patches may allow a viable population of the species to survive even though no individual habitat patch is large enough to sustain a population on it own. How species utilize disjoint patches of habitat depends upon the distance between habitat patches and the species dispersal ability. To capture the effect of habitat isolation and fragmentation, we first calculate a range of possible landscape suitability scores for species *s*, from the case with no dispersal limitation among patches (species *s* views all suitable habitat as one single habitat patch), to the case with no dispersal (complete isolation of all non-adjoining habitat). We then place the actual number of breeding pairs supported by the landscape within this range depending upon a measure of connectedness that we describe below.

The maximum number of breeding pairs on the landscape for species *s*, assuming no dispersal limitations, is defined as the sum of all of the number of breeding pairs for species *s* across all parcels:

$$ZMax_s = \sum_{j=1}^{J} Z_{sj} \tag{2}$$

To define the minimum number of breeding pairs on the landscape for species *s*, we need two additional definitions. Let T_s represent the number of breeding pairs necessary to support a viable population for species *s*. Let habitat patch n_s contain all parcels with positive habitat scores for species *s* that adjoin, and let N_s be the set of habitat patches such that N_s contains all parcels with positive habitat scores in one and only one habitat patch. Then, we define the minimum number of breeding pairs on the landscape, assuming that all habitat patches are isolated from all other habitat patches, as the sum of breeding pairs in habitat patches that exceed T_s:

$$ZMin_s = \sum_{n_s=1}^{N_s} Z_{sn_s} \, l_{n_n} \tag{3}$$

where $l_{n_s} = 1$ if $Z_{sn_s} \geq T_s$, and 0 otherwise. For large values of T_s, $Zmin_s$ can be 0. On the other hand, as T_s approaches 0, $Zmin_s$ approaches $Zmax_s$. In the latter case, the landscape suitability score for species *s* will depend only on the total amount of habitat and not its spatial pattern. With large differences between $Zmin_s$ and $Zmax_s$ the spatial pattern of habitat and species dispersal ability can play a large role in determining the number of breeding pairs on the landscape.

The connectivity measure for the landscape uses distances on the minimal spanning tree that links all parcels with positive habitat scores. If there are m_s suitable parcels, there are $m_s - 1$ link distances, $d(i,j)$, that measure the distance between parcels *i* and *j*. The connectivity measure is defined as:

$$D_s = \frac{\sum_{m_s} W\,(b_s, d(i,j))}{m_s - 1} \tag{4}$$

where $0 \le W(b_s, d(i,j)) \le 1$ is a declining function of the distance between parcels *i* and *j* that depends on the dispersal ability category of species *s* (given by b_s). If the Euclidean distance between *i* and *j* is 0 (*i* and *j* are adjacent to each other) then $W(b_s, 0) = 1$ for all b_s. The values of $W(b_s, d(i,j))$ used in this analysis are given in the table below.

$W(b_s, d(i,j))$	**d(*i,j*) (in meters)**							
	0	$\in$(0, 300]	$\in$(300, 900]	$\in$(900, 2700]	$\in$(2700, 8100]	$\in$(8100, 24300]	$\in$(24300, 52000]	>52000
b_s								
1	1.000	0.687	0.325	0.034	0.000	0.000	0.000	0.000
2	1.000	0.911	0.755	0.430	0.080	0.001	0.000	0.000
3	1.000	0.963	0.894	0.714	0.363	0.048	0.002	0.000
4	1.000	0.991	0.972	0.919	0.776	0.468	0.197	0.000

When calculating connectivity in equation (4), we ignore dispersal barriers between patches, such as highways or water. Ideally, *d*(*i,j*) the intra-patch distance measure in equation (4), would be a function not only of distance but of the difficulty of crossing the terrain between the two patches. Constructing such a measure, however, is impractical because there are many possible routes an animal could take between patches and the shortest “effective” path might be indirect.

The number of breeding pairs on the landscape for species *s* combines the measure of connectivity along the maximum and minimum number of breeding pairs on the landscape. We define the number of breeding pairs on the landscape for species *s* as:

$$Z_s = D_s ZMax_s + (1 - D_s) ZMin_s . \qquad (5)$$

In a completely connected landscape, $D_s = 1$, and the number of breeding pairs would just equal $ZMax_s$. On the other hand, if all suitable habitat parcels are completely isolated, $D_s = 0$, there would be no contribution from any other parcel, and only those habitat patches that could sustain a viable population in isolation would contribute to the number of breeding pairs on the landscape.

In the final step of the biological model we translate the number of breeding pairs on the landscape for species *s* into a biological score that we can aggregate across species. We do not aggregate numbers of breeding pairs directly because this would favor relatively abundant species (e.g. mice) over species with relative few breeding pairs (e.g. large predators). We use two different approaches to converting the number of breeding pairs on the landscape into a biological score, one based on the notion of trying to insure that as many species as possible persist on the landscape, and one based on the notion of trying to maintain some fraction of the original or ideal population size of each species. In the persistence version of the objective, a species counts as conserved if and only if the number of breeding pairs on the landscape is equal to or greater than 1000. We use 1000 as the threshold value because this is what the Nature Conservancy uses for its globally most imperiled species rank. It is straightforward to raise or lower this threshold value and rerun the analysis. Using this threshold, define

$LB_S = 1 \text{ if } Z_S \geq 1000$ and 0 otherwise.

In the second version of the objective, a species counts as conserved if the number of breeding pairs on the landscape is equal to or greater than a specified fraction of the number of breeding pairs on the landscape when the landscape is in its most favorable configuration for that species. To find this most favorable configuration for species *s* we make a land use decision on each parcel such that it gives the highest habitat compatibility score possible for that species.

Define the number of breeding pairs given the most favorable landscape as Y_s. In this version we use both 10% and 50% thresholds. Using this version, define $LB_S = 1$ if $Z_S \geq hY_S$ and 0 otherwise, where η = 0.1 or 0.5.

The landscape conservation score is the number of species that meet or exceed the threshold:

$$LB = \sum_{s=1}^{S} LB_S \ . \tag{6}$$

b. The economic model

The economic model is used to predict the present value of commodity production for a given land use pattern. The first step is to predict the present value of commodity production for an individual parcel based on the land use for the parcel and characteristics of the parcel. We then sum these values across all parcels to generate the economic score for the landscape.

It is important to note at the outset that the discussion in this section and the illustrative example discussed below focus on the value of commodity production. In principle, the economic model should include the value of all goods and services generated by the land use pattern, including "ecosystem services," the majority of which are not bought or sold in markets (Daily 1997, Daily et al. 2000). The general approach of the economic model discussed below can include ecosystem goods and services, at least in theory. We do not do so here because of the difficulty, at present, of generating reliable estimates of value. Our analysis, then, illustrates the degree to which there are tradeoffs between the value of commodity production and conservation, rather than attempting to illustrate a complete set of tradeoffs among all potentially valuable goods and services generated by a landscape.

In the application of our model described below, we consider seven land use types. The seven land use types are: 45-year rotation managed forestry (X_j^f), 4 different types of agriculture ($X_j^{a,1}$, $X_j^{a,2}$, $X_j^{a,3}$ and $X_j^{a,4}$), rural residential housing (X_j^h) and biological reserve (X_j^b). The economic model derives the present value of returns associated with each of these seven land uses on each parcel j. Note that the superscript associated with each X_j (e.g., f or a,n) indicates a particular realization of ω (the variable that indexes land use type as introduced in the biology model above). More land uses can be added to the model as long as there are methods to estimate the present value of returns from those uses.

The present value of managed forestry depends upon the productivity of the parcel for growing timber, the price of timber, forestry rotation time and the costs of harvesting timber. Timber yield on parcel j, $y_j^f(t, g_j)$, measured in terms of board feet per unit area, depends upon the age of the timber stand when harvested or rotation time (τ, in years) and the parcel's forestry site index distribution (g_j), which is based on soil, climate conditions and other physical conditions on the site. Timber yield includes production from harvesting and, if $t > 35$, commercial thinning. Timber production per unit area is multiplied by timber stumpage price per board foot, p_f, to determine timber revenue per unit area. Stumpage price per board foot is equal to timber price per board foot, p_t, minus the sum of logging costs per board foot, l_j^f, and hauling costs per board foot, h_j^f : $p_f = (p_t - (l_j^f + h_j^f))$. Logging costs per board foot are a function of a parcel's forest site index distribution and average slope. Hauling costs per board foot are a function of a parcel's average slope and distance to the nearest processing mill. Per unit area maintenance costs of forestry production, $m^f(t)$, is a function of the operation's rotation time choice (τ) but not a function of *j*; the maintenance cost function is the same across parcels. We assume even-aged forestry management with rotations of τ years such that $1/\tau$ fraction of the parcel is harvested each year. Given these assumptions, the present value of economic return from managed forestry with a rotation time of τ is

$$V_j^f = \sum_{t=0}^{\infty} \frac{A_j(p_f y_j^f(t, g_j) - m^f(t))}{t(1+d)^t} \qquad (7)$$

where δ is the annual discount rate. Note that parcel *j* can have multiple managed forestry values; one for each value of τ. In this model we set τ = 45.

The present value of an agriculture operation on parcel *j* depends upon the type of crop grown, the parcel's crop growing productivity, the price of agricultural produce and production costs. Let $y_j^{a,j}$ symbolize agricultural crop yield per unit area for parcel *j* where φ indicates the type of crop grown. $y_j^{a,j}$ is a function of parcel *j*'s soil class distribution and whether parcel *j* is irrigated. The yield is multiplied by the market price for φ, p_a^j, to generate estimated revenue per unit area for growing a crop of type φ on parcel *j*. Per unit area costs of producing φ, c_a^j, are subtracted from revenue to give economic return per unit area. Assuming that agricultural activity occurs every year, the present value of economic return from producing a crop of type φ on parcel *j* is:

$$V_j^{a,j} = \sum_{t=0}^{\infty} \frac{A_j(p_a^j y_j^{a,j} - c_a^j)}{(1+d)^t}. \qquad (8)$$

In this model we consider four types of agriculture, including orchard/vineyard ($X_j^{a,1}$), grass-seed ($X_j^{a,2}$), pasture ($X_j^{a,3}$) and row crops ($X_j^{a,4}$). Each of these four agriculture land use categories have corresponding values, symbolized by $V_j^{a,1}$, $V_j^{a,2}$, $V_j^{a,3}$ and $V_j^{a,4}$.

The present value of rural-residential housing development on parcel *j* is a function of several variables, including the area of the housing lots in parcel *j* (ar_j), the county in which the parcel is located (co_j), the parcel's mean elevation and slope (el_j and sl_j, respectively), rural-residential building density within parcel *j* (bd_j), whether or not all or a portion of parcel *j* is in an Urban Growth Boundary (ugb_j) and a gravity statistic (Kline et al. 2001) that measures *j*'s overall proximity to urban core areas in the Basin (gr_j). In this model it is assumed that, if a parcel is placed into rural-residential use, the whole parcel is developed as rural-residential housing; parcels with rural-residential housing units cannot support other land uses such as hobby farms. Let the present value of rural-residential housing per unit area in parcel *j* be given by the function v_j^h. Therefore, the present value of economic return from rural-residential housing is:

$$V_j^h = A_j v_j^h(ar_j, co_j, el_j, sl_j, bd_j, ugb_j, gr_j)\ . \qquad (9)$$

The total landscape economic score, *LE*, sums the present value of commodity production of each parcel given its land use. Define W_j^w = 1 if parcel *j* is in land use ω and zero otherwise.

For example if $X_j^w = X_j^{a,2}$ then $W_j^{a,2}$ = 1 and W_j^w = 0 for all other ω. Then the landscape economic score for a given land use pattern is

$$LE = \sum_{j=1}^{J} \sum_{w \in W} W_j^w V_j^w \tag{10}$$

where Ω is the set of all seven land use types in the model.

In an important respect, the economic model is simpler than the biological model. The value of commodity production on a parcel is solely a function of the parcel's characteristics. Nearby or adjoining parcels do not influence the economic score for a parcel. Two conditions must hold for economic return on a parcel to depend only on the parcel's characteristics. First, commodity prices must not be significantly influenced by local supply. In other words, the commodities in our model are assumed to be sold on a national or global market in which is local production makes up a small fraction of the total supply and therefore, expanding or contracting local production has an insignificant impact on market price. The place where this assumption is a stretch is the rural residential land market. In reality, expanding the number of homes in an area should impact the price in that area. In principle, it would be possible to incorporate a downward sloping demand for residential development. We did not incorporate that feature into this model so that we could keep the economic model linear, which greatly simplifies our computational approach to finding solutions. Second, there must not be any "externalities" from adjacent land uses. Examples of positive externalities include a premium for housing values for adjacency to biological reserves or open space (e.g., Schulz and King 2001, Thorsnes 2002, Tryvainen and Miettenen 2000) and the effect of pollinators on crop yields (e.g., Nabman and

Buchmann 1997, Allen-Wardell et al. 1998). Examples of negative externalities include pollution runoff from a parcel that lowers productivity of downstream parcels.

3. Optimization Problem and Heuristic Solution Methods

Our goal is to find efficient land use patterns for which it is not possible to increase the biological score without decreasing the economic score, and vice versa. In general, there will be many efficient land use patterns. Finding the complete set of efficient land use patterns traces out an efficiency frontier (also called a production possibility frontier) that illustrates what is feasible to attain and the tradeoffs between increasing the biological return and increasing the economic return.

The combined biological and economic optimization problem can be written quite simply as follows:

$$\begin{aligned} & Max\ LB \\ & s.t.\ LE \geq \bar{L} \end{aligned} \tag{11}$$

where the maximization is taken over the choice of land use in each parcel in the planning region. In words, the problem is to find a land use pattern (i.e., placing every parcel in the planning region into one of the model's land use categories) with the highest possible biological score that guarantees an economic return at least as large as $\bar{L}$. By varying the required economic threshold, $\bar{L}$, a whole family of solutions can be found that trace out the efficiency frontier. The frontier can also be found by maximizing the landscape economic score, LE, subject to a constraint that the landscape biological score meet a certain threshold.

The formulation of the problem given above is deceptively simple. Because the optimization problem is an integer program involving a large number of parcels each with several potential land uses, and because the biological model involves non-linear spatial considerations, finding an optimal solution to this problem can be exceedingly difficult. There is no easy way to find points on the efficiency frontier.

We use several heuristic methods to search for good solutions to this problem. In the first method, we start with all parcels in a biological reserve, which generates an economic score of 0. We use a proxy for the biological score in the heuristic because calculating the biological score is relatively slow (on the other hand, the economic score is quick to calculate because the economic model is linear). The proxy biological score that we use is: $ZMax = \sum_{s=1}^{S} ZMax_s$, which is the sum of breeding pairs on the landscape for each species, when there is no dispersal limitation, summed over all species. We then search over all single parcel land use changes that improve the economic score, finding the one with highest *ZMax* score. We continue in this way until no further improvements are possible. Then, using the landscapes generated by the heuristic as inputs, we calculate the landscape biological score (*LB*) to trace out the estimated efficiency frontier. There are two reasons why this is a heuristic method rather than an optimizing method. First, it is a local (greedy) search rather than a global search and so may fail to find solutions that require several changes in combination to gain an improvement in score. Second, it uses a proxy biological score, one that ignores spatial considerations (as connectivity is the time consuming step in the model). Although the proxy does not take connectedness into account, the results discuss below seem to suggest that *ZMax* and *LB* are highly correlated and generally differ by a fixed amount.

In the second heuristic method we maximize a simplified (linear) biological objective in order to speed the search for points, subject to a constraint that the solution must attain or exceed a specified economic score. By varying the level of the economic constraint we can find a number of potential frontier points. The biological objective we use is to maximize the sum over all species of the habitat area for each species. Formally, this problem can be written as:

$$
\begin{aligned}
& Max \sum_{j=1}^{J} \sum_{w=1}^{\Omega} \sum_{s=1}^{S} A_j H_{sj} C_{sj} (X_j^w) \\
& s.t. \\
& \sum_{j=1}^{J} \sum_{w=1}^{\Omega} V_j^w X_j^w \geq \underline{E} \\
& X_j^w = 0 \text{ or } 1 \\
& \sum_{w=1}^{\Omega} X_j^w = 1
\end{aligned}
\qquad (12)
$$

where $\underline{E}$ is the lowest landscape economic score allowed. While this heuristic allows for a global search, it does so with a simplified biological objective so that points found may not lie on the efficiency frontier.

4. The Willamette Basin, Biological and Economic Data

a. The planning region – Willamette Basin

The planning region used in this paper is the Willamette Basin (Figure 1). The Willamette Basin is defined as the Willamette River watershed, bordered on the east by the crest of the Cascade Range and on the west by the crest of the Coast Range. The parcel map for the Willamette Basin was created starting from a 30x30 meter square grid map of land cover in the

Basin (ORNHIC 2000). Each 30 x 30 square pixel was coded into one of 21 different land cover types based on land cover in the Basin around 1990 (the list of the 21 land cover types is contained in the Appendix). We combined adjacent pixels of the same land cover type to form land parcels. We limited parcel sizes to a maximum of 750 hectares (with the exception of four parcels that are slightly larger). This combination process yielded a total of 51,252 parcels. Of these, 6,003 were water and 34,877 were developed parcels (industrial, low, medium and high density residential development and/or transportation infrastructure). We assumed that currently developed parcels would not be undeveloped so that there was no management choice for either the water parcels or the developed parcels and these were excluded from further consideration. There were a further 2,196 parcels that were not water or developed but had at least some portion of the parcel lie within an urban growth boundary (UGB). Oregon's land use laws require that all cities and town within Oregon specify a UGB in which all concentrated development is supposed to occur. Lands outside the UGB can only be developed to low density rural residential levels. We excluded management consideration of lands within a UGB, though undeveloped parcels within a UGB were used in the biological model as they contribute habitat (in this analysis undeveloped parcels within the UGB include agricultural lands) . After excluding water parcels, developed parcels and parcels within the UGB, we had 8,176 remaining parcels on which management decisions can be made.

There are 14 land cover types that we used in the model after excluding water and developed land cover types and there are seven potential land uses. There is a single land cover type for managed forests, rural residential, row crops, orchard/vineyard, grass seed, and pasture land uses. However, biological reserve parcels and parcels within an urban growth boundary have several possible land cover types. Possible land use covers (habitat types) for biological reserves are prairie, riparian forest, emergent marsh and old growth conifer (120 year old and older). We assumed that land placed in a biological reserve will revert to its dominant potential natural vegetation (PNV). PNV describes the type of vegetation coverage that would emerge on the parcel if human influence in the parcel was reduced to a minimum. Possible habitat types for parcels in urban growth boundaries are orchard/vineyard, grass seed, pasture, row crops, emergent marsh, scrub/shrub, prairie, oak savanna, oak and other hardwood forest, old growth conifer (120 year old and older), mixed conifer/deciduous forest, and riparian forest. We assumed that parcels in an urban growth boundary would retain their current habitat type ("current" refers to maps from 1990).. Figure 2 shows the existing distribution of land cover types for the Willamette Basin.

We assembled a set of other data for each parcel, including:

- land cover/habitat type in 1990 (ORNHIC 2000);
- the density of perennial streams that lie within and on the parcel's border (ORNHIC 2003a);
- whether the parcel contains at least one irrigation point-of-use permit (OWRD 2001);
- agriculture soil class distribution (PNW-ERC 1999a);
- 100-year Douglas fir forestry site index distribution (USDA-NRCS 2001b);
- distance to the nearest processing mill (Latta and Montgomery 2004, personal communication with Claire Montgomery)
- average elevation (PNW-ERC 1999b);
- average slope (PNW-ERC 1999d);
- dominant PNV (ORNHIC 2003b);
- a gravity statistic that measures j's overall proximity to urban core areas in the Basin

- rural-residential building density;
- county location (OGEO 1998a); and
- whether the parcel is in an urban growth boundary (OGEO 1998b).

b. Biology model on the planning region

The set of 267 terrestrial vertebrate species used in this paper is culled primarily from a set of 279 terrestrial vertebrate species identified in a United States Environmental Protection Agency report on species that breed or feed in the Willamette River Basin (Adamus et al. 2000). However, 21 of the 279 species identified in the EPA report were dropped from our species database for one of two reasons: the species is either an exotic species whose natural home range does not include the Basin (e.g., House Mouse, Nutria, Rock Dove), or the species has been extirpated from the Basin (e.g., Yellow-Billed Cuckoo, Gray Wolf, Grizzly Bear). In addition, we added nine species not identified in the EPA report to our database. These species were determined to have natural home ranges that extend into the Basin (Verts and Carraway 1998, Adamus et al. 2001, St. John 2002, and Marshall et al. 2003). A complete list of the 267 species is given in the Appendix.

Based on information in the EPA study, each species in our species database was given a habitat compatibility score for each of the 14 habitat categories. The Appendix lists $C_{sj}(X_j^w)$ for every species s and habitat type ω.

Other species-specific parameters in the biological model are geographic range, water resource needs, the minimum amount of area needed for a breeding pair, and dispersal ability. Geographic range and water resource needs are combined in the indicator variable H_{sj}. H_{sj} equals 1 if parcel j is within the geographic range of species s and parcel j contains the water resources required by species *s* (Adamus et al. 2000 contains the geographic ranges of nearly all species use in our model; see figure 3 and the figure 3 legend for aggregated view of species' geographic ranges in the Basin). If a species *s* is not considered water sensitive then H_{sj} only equals 0 if *j* is out of species *s*' range. If a species *s* is considered water sensitive then H_{sj} only equals 1 if *j* is in species *s*' range and parcel *j* contains a positive perennial stream density (the designation of water sensitive species was based on the professional judgment of co-authors Csuti, White, Kagan, Starfield and Lonsdorf). The minimum amount of area needed for a breeding pair for species *s*, AR_s, is used in the biological model in equation (1). Dispersal ability class of species *s*, b_s, is used in equation (4) of the biological model. We found few resources that gave both an area requirement and dispersal ability class for the species used in our model. A few guidelines for AR_s and b_s values were found in Brown 1985 and Lichtenstein and Montgomery 2003. However, AR_s and b_s values are primarily based on the following assumptions: area requirements scales to the size of the animal (larger animals require more habitat), larger animals disperse further than smaller animals, birds disperse further than mammals and mammals disperse further than amphibians/reptiles. See the Appendix for each species value for AR_s and b_s.

c. Economic model on the planning region

Four agriculture values (orchard/vineyard, grass-seed, pasture and row crops) for each parcel on the Basin map were found by using equation (10), other data and equations found in OSUES 2002, OSUES 2003 and relevant parcel data (i.e., soil class distribution, irrigation permit data, parcel area and elevation). It was assumed that any parcel with at least one irrigation permit grew irrigated crops. (Best practice techniques do not include the irrigation of land designed for pasture. Therefore, any parcel that practiced irrigation farming – any parcel containing at least one irrigation permit – was assumed not to be a pasture operation).

A 45-year rotation managed forestry value for each parcel on the Basin map was found by using equation (9), equations found in Curtis 1992, Curtis et al. 1981, Fight et al. 1984, King 1966, Latta and Montgomery 2004, relevant parcel data (i.e., 100-year Douglas fir forestry site index data converted to 50-year site index data, average slope and area), and lumber processing site data (personal communication with Claire Montgomery).

We used OLS to fit a linear version of $V_j^h(ar_j, co_j, el_j, sl_j, bd_j, ugb_j, gr_j)$, the per unit area rural-residential value function from equation (9), to actual Basin rural-residential data. Specifically,

$$
\begin{aligned}
\log\left(v_j^h\right) = & \; b_0 + b_1 ar_j + b_2 Lane_j + b_3 Linn_j + b_4 Marion_j + b_5 Benton_j \\
& + b_6 Clackamas_j + b_7 Multnomah_j + b_8 Washington_j + b_9 Polk_j \\
& + b_{10} Yamhill_j + b_{11} el_j + b_{12} sl_j + b_{13} bd_j + b_{13} \log\left(gr_j\right) + u_j
\end{aligned}
\tag{9a}
$$

where ***Colombia**$_j$* is the base county dummy variable and ***Lane**$_j$*, ***Linn**$_j$*, ***Marion**$_j$*, ***Benton**$_j$*, ***Clackamas**$_j$*, ***Multnomah**$_j$*, ***Washington**$_j$*, ***Polk**$_j$* and ***Yahmill**$_j$* are county dummy variables. Definitions and sources for this data are noted above.

Finally, we assumed that parcels put into biological reserve have no management costs.

This model also assumes that these built-up areas do not affect the economic conditions on all parcels. Economic returns on forestry, agriculture and rural-residential parcels are affected by built-up areas (for example, salt runoff from roads may affect agriculture productivity, the location of roads can affect a forestry operation’s management costs and, as discussed above, the density and location of housing units can affect the price of new housing). However, as discussed above, to make the economic model tractable and fairly simple we choose to ignore externalities, including those generated by built-up areas. Therefore, built-up areas, while on the Basin map, have a minimal effect on the maximization heuristic and on the biological and economic values of the changeable parcels.

5. Results

Using the methods described in section 3 on the Willamette Basin data described in section 4, we searched for the efficiency frontier for three different cases assuming different conservation thresholds: a) 1000 breeding pairs, b) 10% of maximum number of breeding pairs, and c) 50% of maximum number of breeding pairs. These thresholds get increasingly difficult to satisfy as we move from (a) to (c).

a. One-thousand breeding pairs threshold

We begin by showing the results of the analysis assuming the conservation goal is the persistence of the maximum number of species in the Basin, where persistence is modeled by whether the landscape can support 1000 breeding pairs of a species. The results of this analysis are shown in figure 5. The most striking feature of the efficiency frontier shown in figure 5 is its L-shape. Starting from the lower right with the landscape that maximizes the economic score, the frontier moves upward in what appears to be an almost vertical line. The maximum landscape economic score at the point on the far southeast of figure 5 is $27,589 million. This landscape generates a biological score of 243. The landscape at the kink of the L generates the maximum biological score (253 species meeting the threshold of 1000 breeding pairs) and an economic score of $27,340 million, a reduction in the economic score of less than 1%. Given the large magnitude of the present value of economic activities when considering the entire Willamette Basin, even a 1% reduction is a substantial amount, $249 million. This expenditure would allow ten additional species that would not persist on the landscape otherwise to do so. These species are ones that need relatively large amounts of natural habitat and include.

It is worth noting that the vast majority of species (243 out of 267) can persist on the landscape even when it is devoted to maximizing economic returns. This result occurs because many species in the Willamette Basin can co-exist with managed forests and there are large blocks of managed forest in the Cascade Range and to a lesser extent in the Coast Range. Some species also thrive in rural residential or agricultural land. There are 14 species that do not persist in the Basin even when the landscape is chosen to maximize the biological objective. What this analysis highlights is the relatively small number of species for whom special planning is needed if they are to persist on the landscape.

Comparing land use between the landscape that generates the maximum economic score (shown in figure 6), and the landscape at the kink of the L (shown in figure 7), we find a decrease in 45-year rotation forestry from 5,190 to 4,340 parcels, rural residential from 1953 to 1770 parcels, orchard-vineyards from 801 to 664 parcels (and small decreases in row crop agriculture and grass seed). There is a large increase in the number of parcels in biological reserves from 77 to 1277 parcels. The 77 parcels placed on biological reserves in the landscape devoted to maximizing economic returns are parcels that have such poor productivity and location far from any city or town such that no economic activity generates a positive return. The other 1200 parcels placed in biological reserves have some opportunity cost, though an efficient solution finds relatively low economic value parcels that accomplish the biological objective of providing necessary habitat for ten additional species.

The frontier in figure 5 is virtually identical whether we use the biological measure based solely on amount of habitat ignoring connectivity issues (*ZMax*) or the biological measure that includes connectivity (*LB*). If this were true in general, it would greatly simplify the biological modeling and the search process in the combined biological-economic model.

b. Ten percent of maximum number of breeding pairs threshold

It can be argued that the conservation goal should not be mere persistence of species represented by having at least 1000 breeding pairs, but some reasonable fraction of the population of species that the landscape could support. In this section we take as the threshold counting a species as conserved if the landscape generates a population that is at least 10% of the maximum population that the landscape could support if devoted to that managing for that species.

The efficiency frontier using the 10% threshold is shown in figure 8. The general shape of this efficiency frontier is different from that found for the case of the 1000 breeding pair threshold. The efficiency frontier is bowed inward at the right hand side indicating high marginal costs for the first increments to the biological score when starting from a landscape that maximizes economic value. A number of costly changes must be made in order for more species to get above the 10% threshold as compared to the landscape that maximizes economic returns. After this initial investment is made, the frontier climbs steeply to near the maximum biological score, followed by a nearly flat section to get to the absolute maximum biological score. The land use pattern at the corner of the curve, where the biological score is nearly maximized but still scores fairly well on the economic dimension, is shown in figure 9. This landscape generates a biological score of 215 and an economic score of $24,457 million. This represents a loss of economic value of over $3 billion dollars in order to increase the number of species who meet the 10% population threshold by approximately 50 fifty species. In this landscape, almost 4000 parcels are placed in biological reserve, coming largely out of 45-year rotation forestry though all other land uses also decline.

c. Fifty percent of maximum number of breeding pairs threshold

The efficiency frontier using the 50% threshold is shown in figure 10. Though there is still something of a recognizable kink point in the frontier, there are far more tradeoffs between obtaining a high biological score and a high economic score. The kink occurs at a landscape that generates an economic score of over $5 billion less than the maximum economic score. This landscape also generates a biological score approximately 20 species less than the maximum obtainable (though this maximum occurs only when economic returns are reduced by approximately 80% from the maximum). As the stringency of the biological objective is increased, the frontier is shifted downward as fewer species make the threshold, and the tradeoffs with economic cost become more pronounced.

6. Discussion

In this paper we developed a biological model that generated the number of breeding pairs of various species as a function of land use decisions, and an economic model that generated the present value of economic returns as a function of land use decisions. We then searched for land use decisions that were efficient in the sense that it was impossible to increase the one score (biological or economic) without decreasing the other. We applied this analysis using data from the Willamette Basin in Oregon for three different biological objectives: a) a species conservation threshold of at least 1000 breeding pairs, b) a species conservation threshold of having population at least 10% of the maximum population for the species, c) a species conservation threshold of having population at least 50% of the maximum population for the species.

One striking result from the analysis is the minimal conflict between maintaining a viable population consisting of at least 1000 breeding pairs and economic returns. Generating the maximum number of species meeting this threshold (253 out of 267 species) meant sacrificing less than 1% of economic returns compared to the landscape that generated maximum economic returns. Because we modeled the present value of land use generated by the entire Willamette Basin the total value of economic returns was quite high (maximum of $27.6 billion) so that even an amount that is less than 1% of this total adds up to a substantial sum of money ($249 million). However, this figure covers the present value of all lost economic value of land into perpetuity. It does seem unreasonable to think that a combination of a government bond issue along with purchases by conservation organization could finance this amount. Attaining persistence of all species for which persistence is possible, as measured by attaining 1000 breeding pairs, seems like a potentially feasible objective within the Willamette Basin.

On the other hand, trying to meet a conservation objective that gets species to 10% or 50% of their maximum potential population does not appear to be economically viable. Obtaining high levels of each of these objectives requires sacrifice of economic returns in the billions of dollars. In the case of the 10% objective, the efficiency frontier is bowed inward on the right hand side indicating high marginal costs of providing an increase in the biological objective starting from a low biological score. In all other previous efficiency frontier analyses, the frontier has been concave to the origin so that initial marginal costs were low and increased as the level of conservation increased (e.g., Montgomery et al. 1994, Ando et al. 1998, Polasky et al. 2001, Nalle et al. 2004).

It is possible that some of the specific results on the 10% and 50% threshold frontiers are artifacts of our using heuristic approaches to generate the efficiency frontier. Perhaps if we had found the true efficiency frontier some of the specific results would change. We are continuing to work on improving the heuristic approaches to reduce concerns over the shape of the frontier being an artifact of the solutions the heuristic approaches were able to find. For the case of the 1000 breeding pair threshold, use of heuristics is unlikely to matter as there is very little room for improvement over the L-shaped efficiency frontier that we found.

The results in this paper should be viewed as suggestive rather than being used as prescriptive of which particular parcels should be devoted to which particular land use. Details of particular parcels may preclude certain uses even though the analysis here indicates those uses are beneficial. However, the overall pattern of tradeoffs between conservation objectives and economic returns, and the general characteristics of land that should be placed in various land uses to generate points on the efficiency frontier are findings that should be robust and could guide conservation planning in the Basin.

The results reported in this version of the paper are preliminary. There will be further fact checking of the biological and economic data. In addition, we plan to add several additional land uses. Rather than having a single type of biological reserve that reverts back to potential natural vegetation, we will allow restoration to other potential habitat types (at some cost). We will also consider transition costs. For example, if the current land use is agriculture and we would like to transition to forestry, it takes time for the trees to grow so that there is a delay between the land use change and the onset of forestry activities. And finally, we plan to further investigate how much spatial pattern of habitat and connectivity matter. If as found in our analysis, there is not much difference between choosing land use based solely on the amount of habitat with minimal concern for spatial pattern of habitat in most cases, this would be an important practical result. Ignoring spatial considerations would considerably simplify the biological model and allow for much faster search for efficient solutions.

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Figure Legends

Figure 1: Willamette Basin Map.

Figure 2: Land cover in the Willamette Basin circa 1990. The Cascade and Coast Ranges are dominated by conifer forests while the valley floor is dominated by low-structure agriculture. The land cover categories that exist in the Basin but are not represented on the map are "High Structure Agriculture," "Native Grass," "Native Grass (wet)," "Willamette Prairie," and "Riparian Open." These categories are not shown because they were rare (6 parcels or less on the whole landscape).

Figure 3: Habitat potential in the Willamette Basin. This map shows the habitat potential of each parcel in terms of number of species when land use is chosen to maximize habitat potential. Generally, the Cascade Range has higher value habitat in terms of species numbers than the valley floor. There are many species with geographic ranges that do not include the valley floor. Whether this is because they have not been observed on the valley floor in recent times because it has been heavily modified by human activity or because this really is outside of their range is less clear.

Figure 4: Economic potential in the Willamette Basin. This map shows the economic potential of each parcel in dollars per hectare when land use is chosen to maximize economic returns. Land near Portland at the top of the Basin and extending down the valley through Salem and Corvallis areas tends to be the highest value land. Land becomes progressively less valuable as elevation increases in the Cascade Range.

Figure 5: Efficiency frontier for the 1000 breeding pair threshold. The present value of economic activity generated by the land use pattern is shown on the horizontal axis. The number of species that meet the threshold of having at least 1000 breeding pairs given the land use pattern is shown on the vertical axis. The blue diamonds represent the economic-biological landscape score combination found by using *ZMax*, which ignores spatial connectivity issues, to evaluate the biological score. The red squares represent the economic-biological landscape score combination found by using *LB*, which incorporates connectivity, to evaluate the biological score. Note that these evaluations generate virtually the same efficiency frontier.

Figure 6: Land use pattern that maximizes economic returns (most southeast red square on the efficiency frontier in figure 5, *P1*). The landscape economic score given this land use pattern is $27,589 million and the landscape biological score given this land use pattern is 243. The land use type counts on this land use pattern are as follows: Orchard/vineyard agriculture ($w = a,1$) = 801; Grass seed agriculture ($w = a,2$) = 120; Pasture agriculture ($w = a,3$) = 0; Row crop agriculture ($w = a,4$) = 35; 45-year rotation forestry ($w = f$) = 5190; Rural-residential development ($w = h$) = 1953; and Conservation ($w = b$) = 77.

Figure 7: Land use pattern that lies at the kink of the efficiency frontier for the 1000 breeding pair threshold (the most northeastern red square on the frontier in figure 5, *P2*). The landscape economic score given this land use pattern is $27,340 million and the landscape biological score given this land use pattern is 253. This represents a loss of $249 and a gain of

10 species compared to the land use pattern associated with the most southeastern red square on the frontier in figure 5. The land use type counts on this land use pattern are as follows: Orchard/vineyard agriculture ($w = a,1$) = 664; Grass seed agriculture ($w = a,2$) = 94; Pasture agriculture ($w = a,3$) = 0; Row crop agriculture ($w = a,4$) = 31; 45-year rotation forestry ($w = f$) = 4340; Rural-residential development ($w = h$) = 1770; and Conservation ($w = b$) = 1277.

Figure 8: Efficiency frontier for the 10% population threshold. The present value of economic activity generated by the land use pattern is shown on the horizontal axis. The number of species that meet the threshold of having 10% of the maximum possible population for the species is shown on the vertical axis. The biological score is evaluated using *LB*, which incorporates connectivity. The efficiency frontier is bowed inward at the right hand side indicating high marginal costs for the first increments to the biological score when starting from a landscape that maximizes economic value.

Figure 9: Land use pattern associated with the kink of the efficiency frontier for the 10% population threshold. The landscape economic score given this land use pattern is $24,457 million and the landscape biological score given this land use pattern is 215. The land use type counts on this land use pattern are as follows: Orchard/vineyard agriculture ($w = a,1$) = 479; Grass seed agriculture ($w = a,2$) = 47; Pasture agriculture ($w = a,3$) = 0; Row crop agriculture ($w = a,4$) = 28; 45-year rotation forestry ($w = f$) = 2612; Rural-residential development ($w = h$) = 1029; and Conservation ($w = b$) = 3981.

Figure 10: Efficiency frontier for the 50% population threshold. The present value of economic activity generated by the land use pattern is shown on the horizontal axis. The number of species that meet the threshold of having 50% of the maximum possible population for the species is shown on the vertical axis. The biological score is evaluated using *LB*, which incorporates connectivity. The tradeoff between increasing the number of species that meet the 50% threshold and economic returns is much greater than for either the 1000 breeding pairs or the 10% threshold.

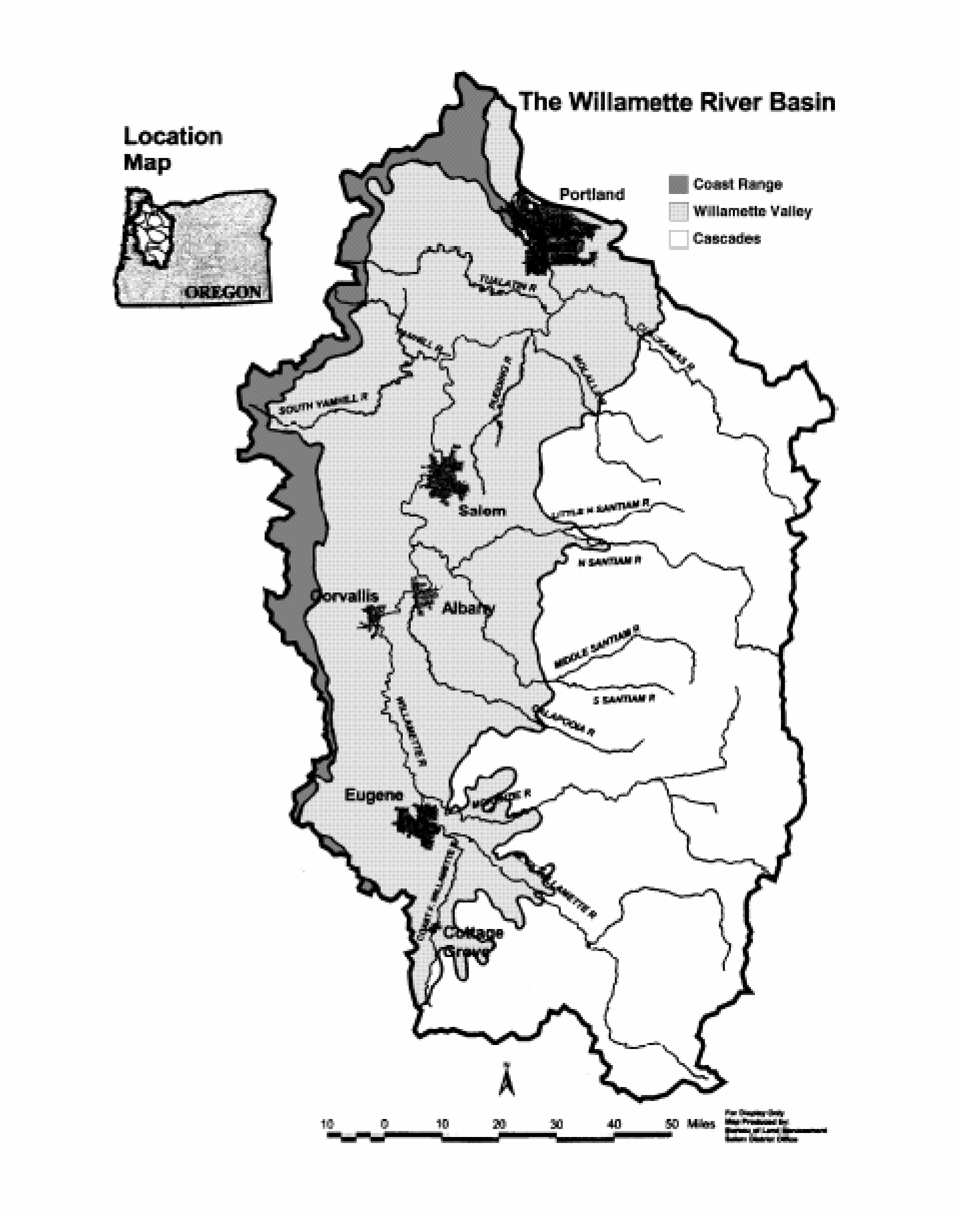

Figure 1 (Source: Willamette Restoration Initiative 1999)

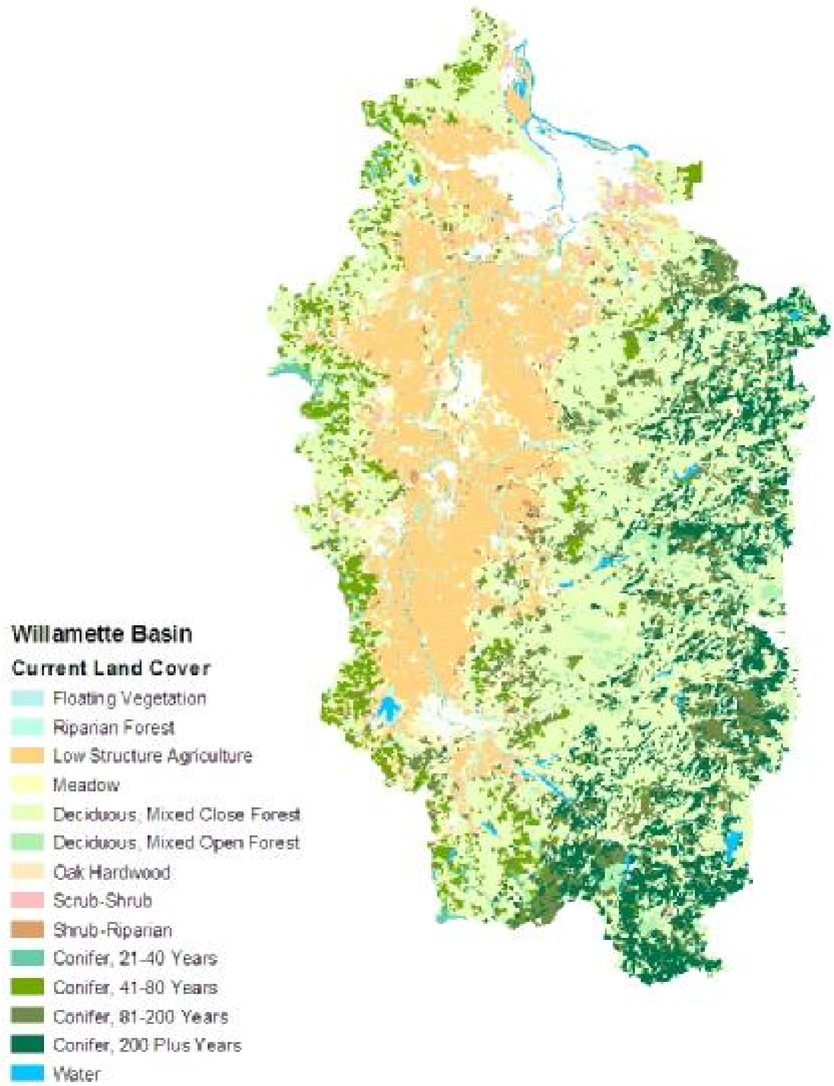
Willamette Basin
Current Land Cover
Floating Vegetation
Riparian Forest
Low Structure Agriculture
Meadow
Deciduous, Mixed Close Forest
Deciduous, Mixed Open Forest
Oak Hardwood
Scrub-Shrub
Shrub-Riparian
Conifer, 21-40 Years
Conifer, 41-80 Years
Conifer, 81-200 Years
Conifer, 200 Plus Years
Water

Figure 2

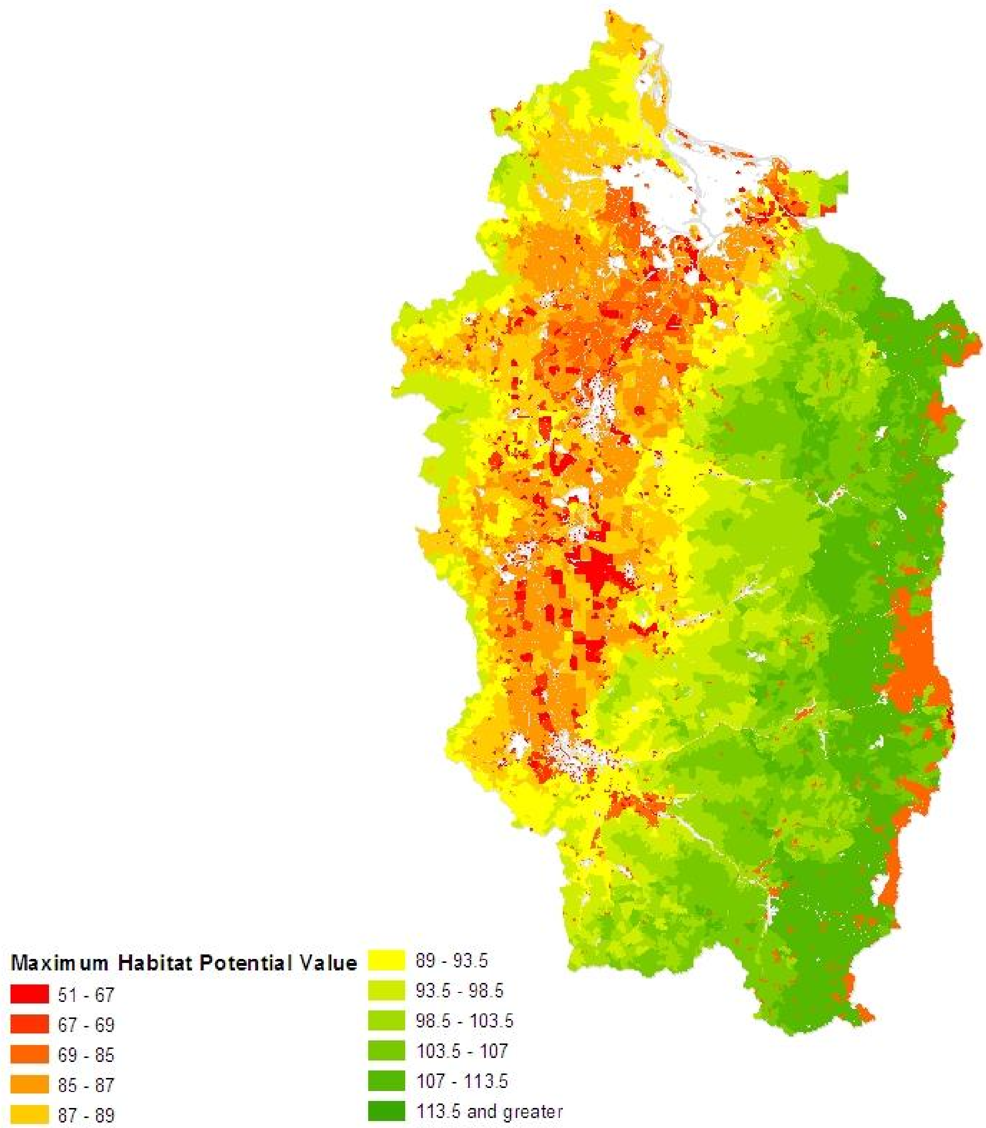
Maximum Habitat Potential Value
51 - 67
67 - 69
69 - 85
85 - 87
87 - 89
89 - 93.5
93.5 - 98.5
98.5 - 103.5
103.5 - 107
107 - 113.5
113.5 and greater

Figure 3

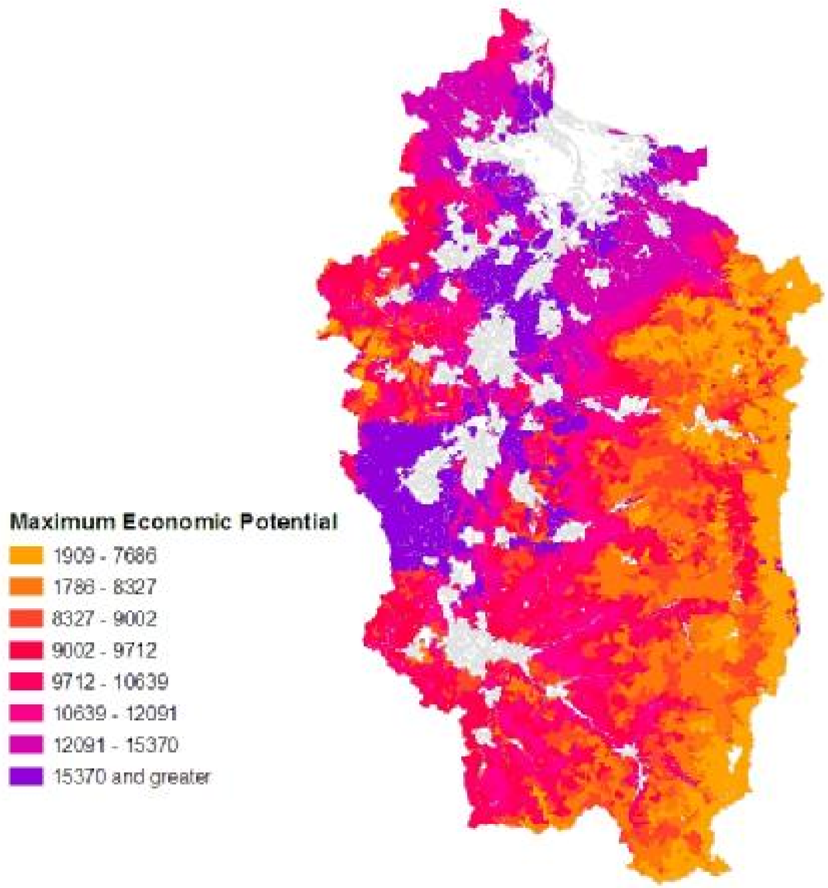
Maximum Economic Potential
1909 - 7686
1786 - 8327
8327 - 9002
9002 - 9712
9712 - 10639
10639 - 12091
12091 - 15370
15370 and greater

Figure 4

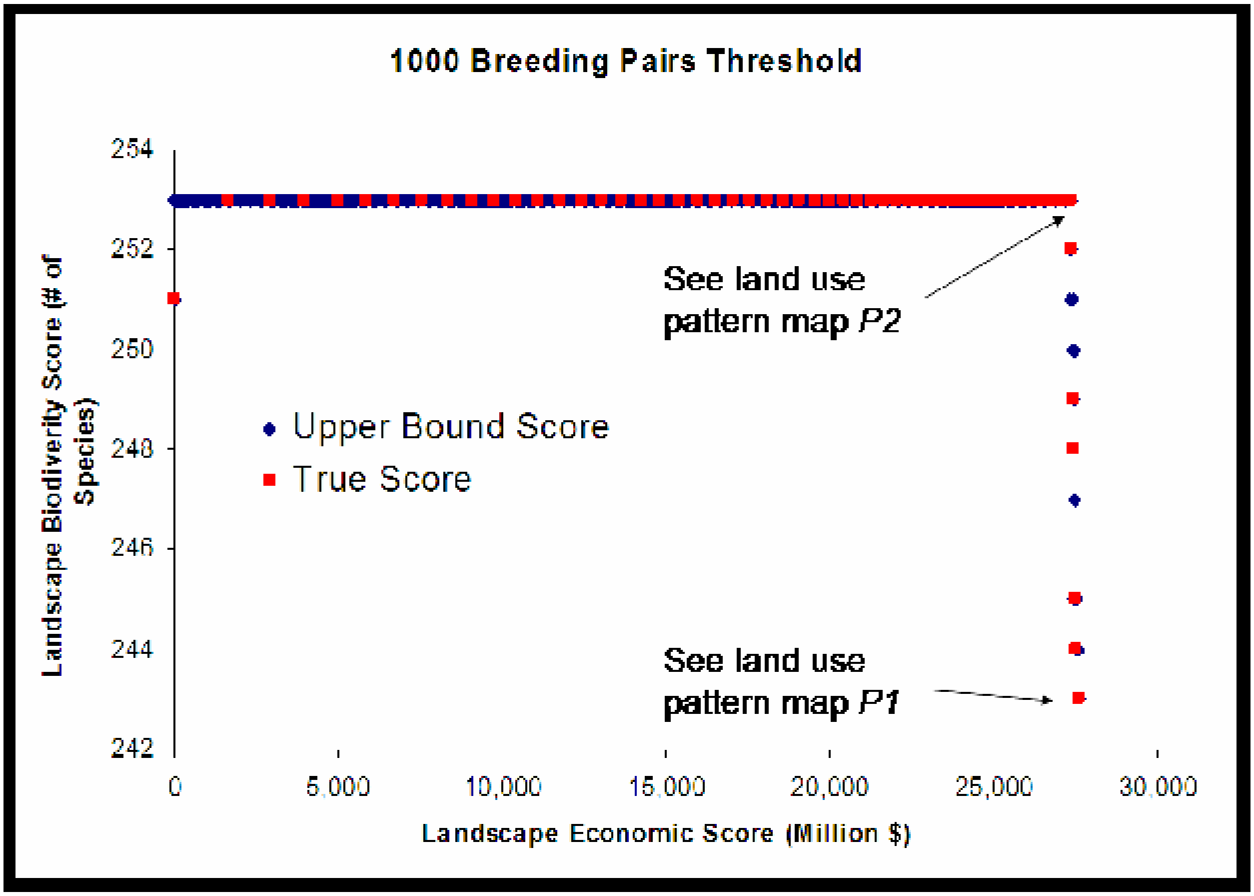
1000 Breeding Pairs Threshold
254
252
250
248
246
244
242
Landscape Biodiverity Score (# of Species)
0
5,000
10,000
15,000
20,000
25,000
30,000
Landscape Economic Score (Million $)
See land use pattern map P2
See land use pattern map P1
Upper Bound Score
True Score

Figure 5

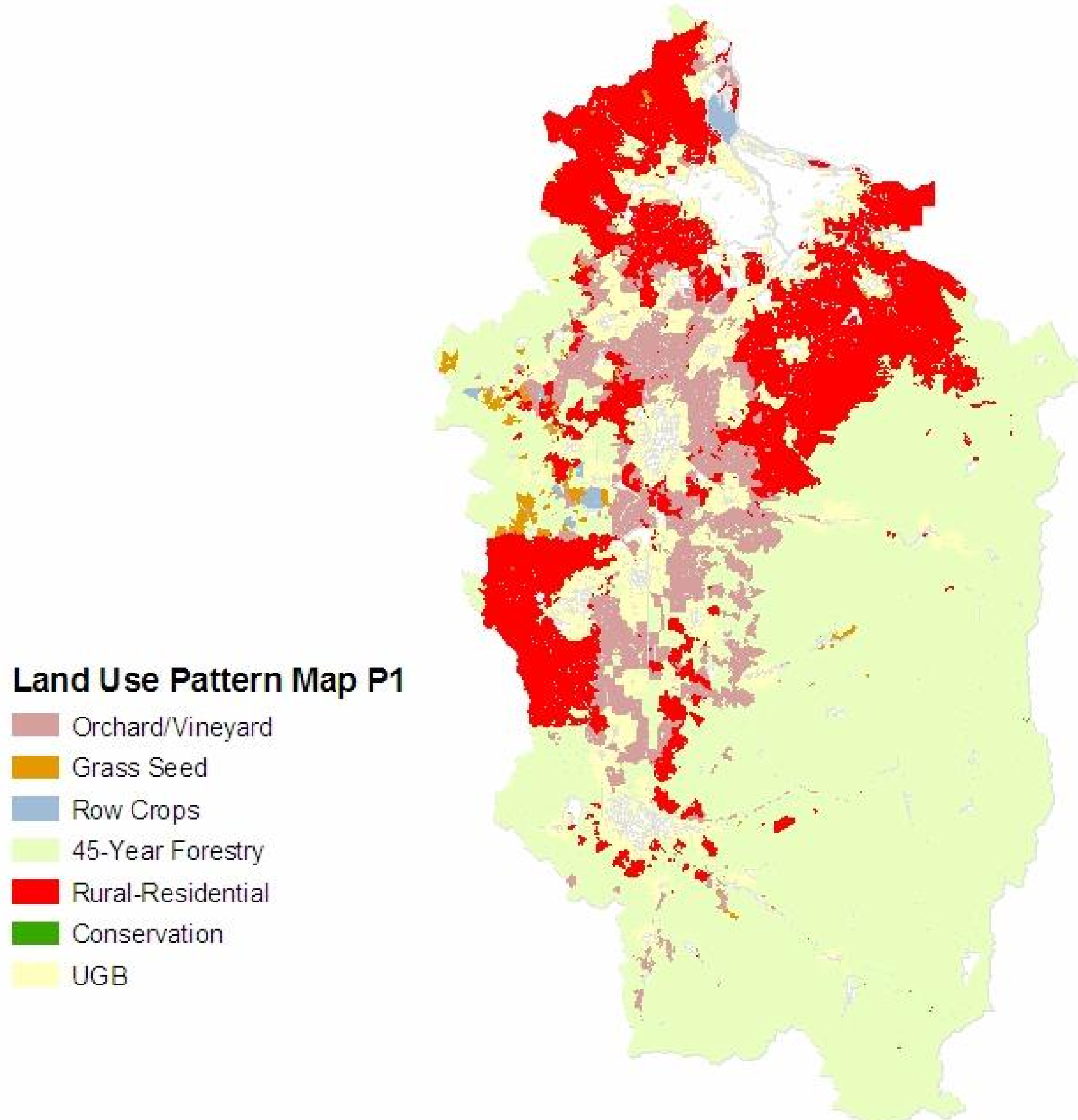
Land Use Pattern Map P1
Orchard/Vineyard
Grass Seed
Row Crops
45-Year Forestry
Rural-Residential
Conservation
UGB

Figure 6

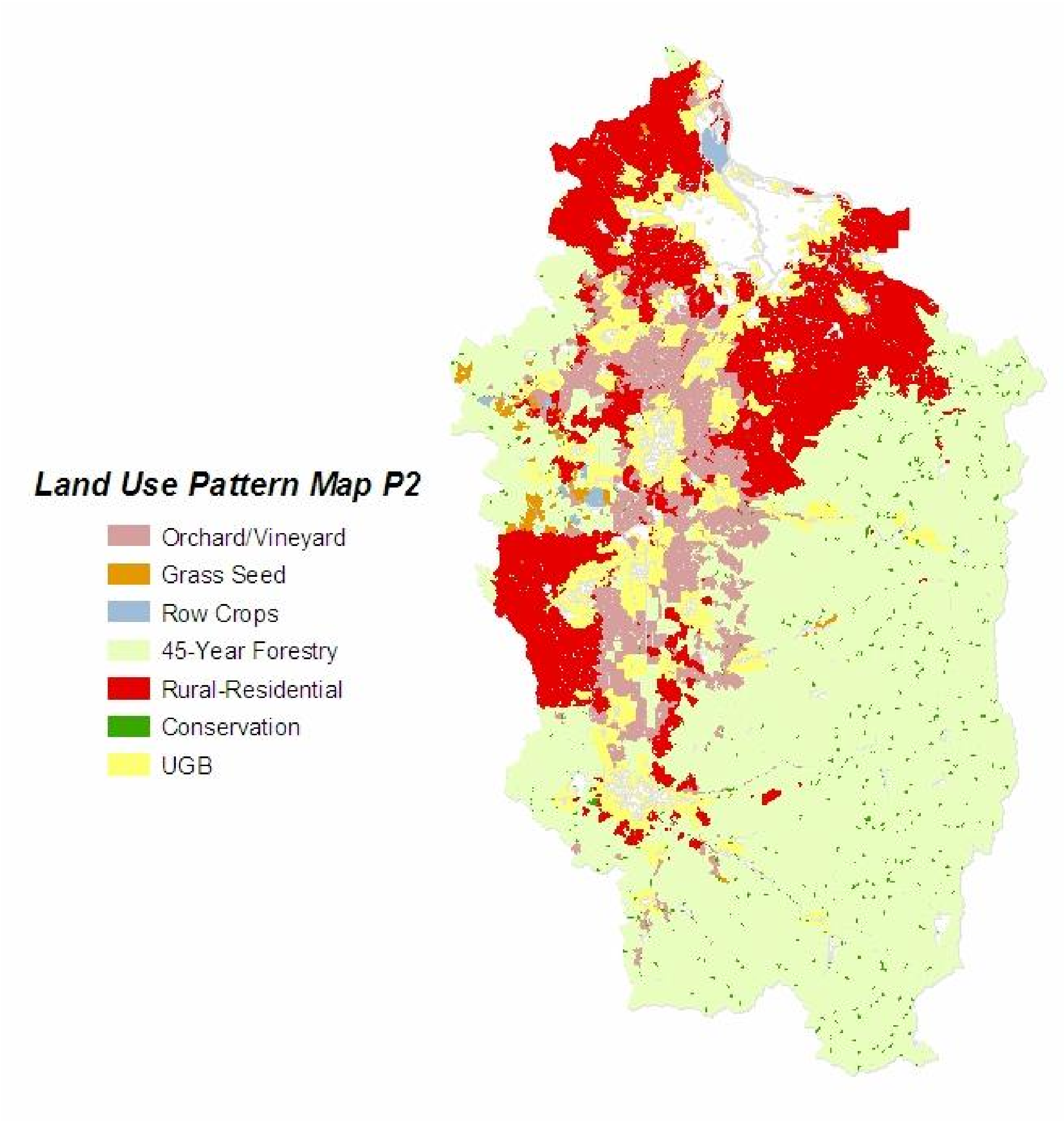
Land Use Pattern Map P2
Orchard/Vineyard
Grass Seed
Row Crops
45-Year Forestry
Rural-Residential
Conservation
UGB

Figure 7

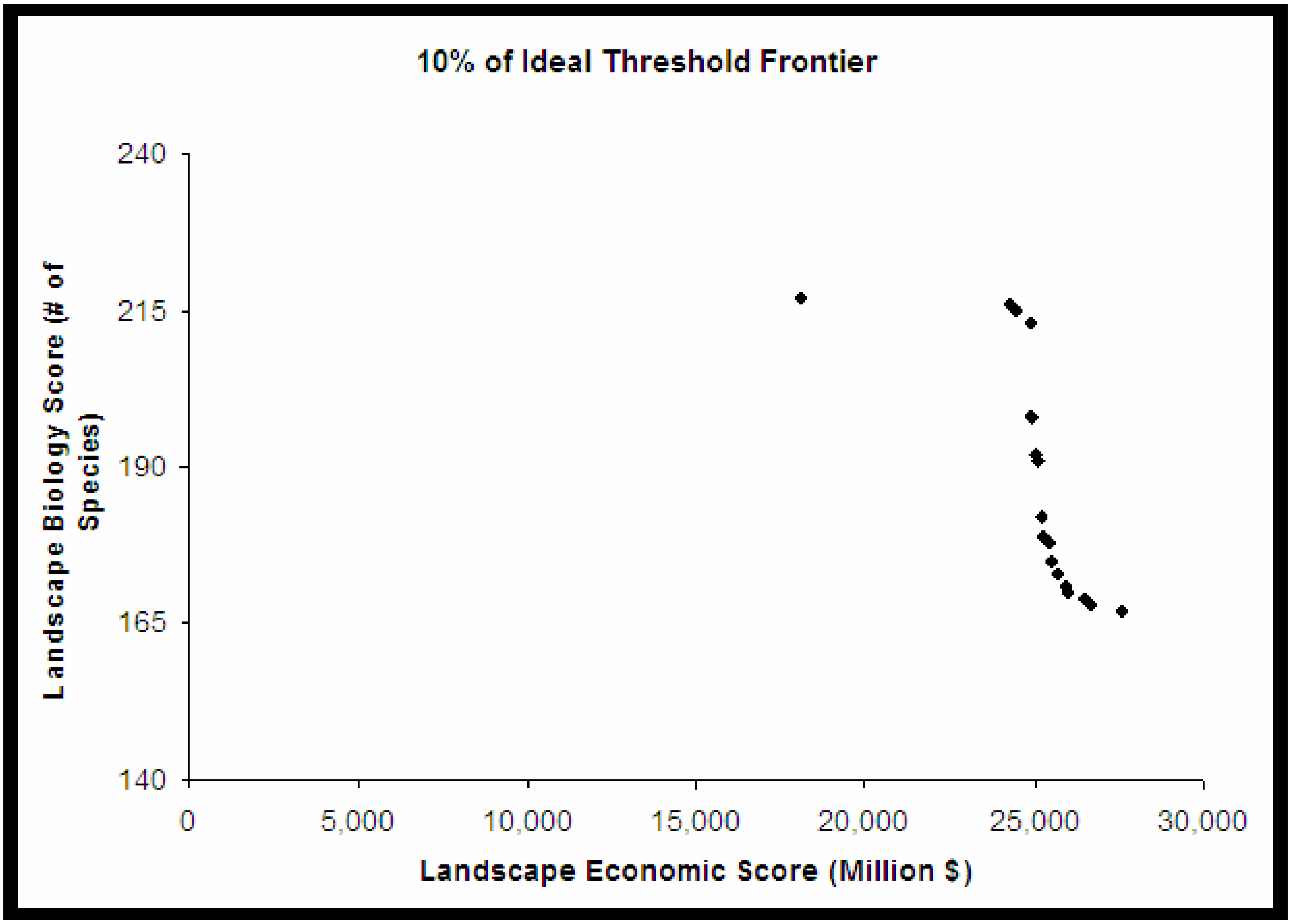
10% of Ideal Threshold Frontier
240
215
190
165
140
Landscape Biology Score (# of Species)
0
5,000
10,000
15,000
20,000
25,000
30,000
Landscape Economic Score (Million $)

Figure 8

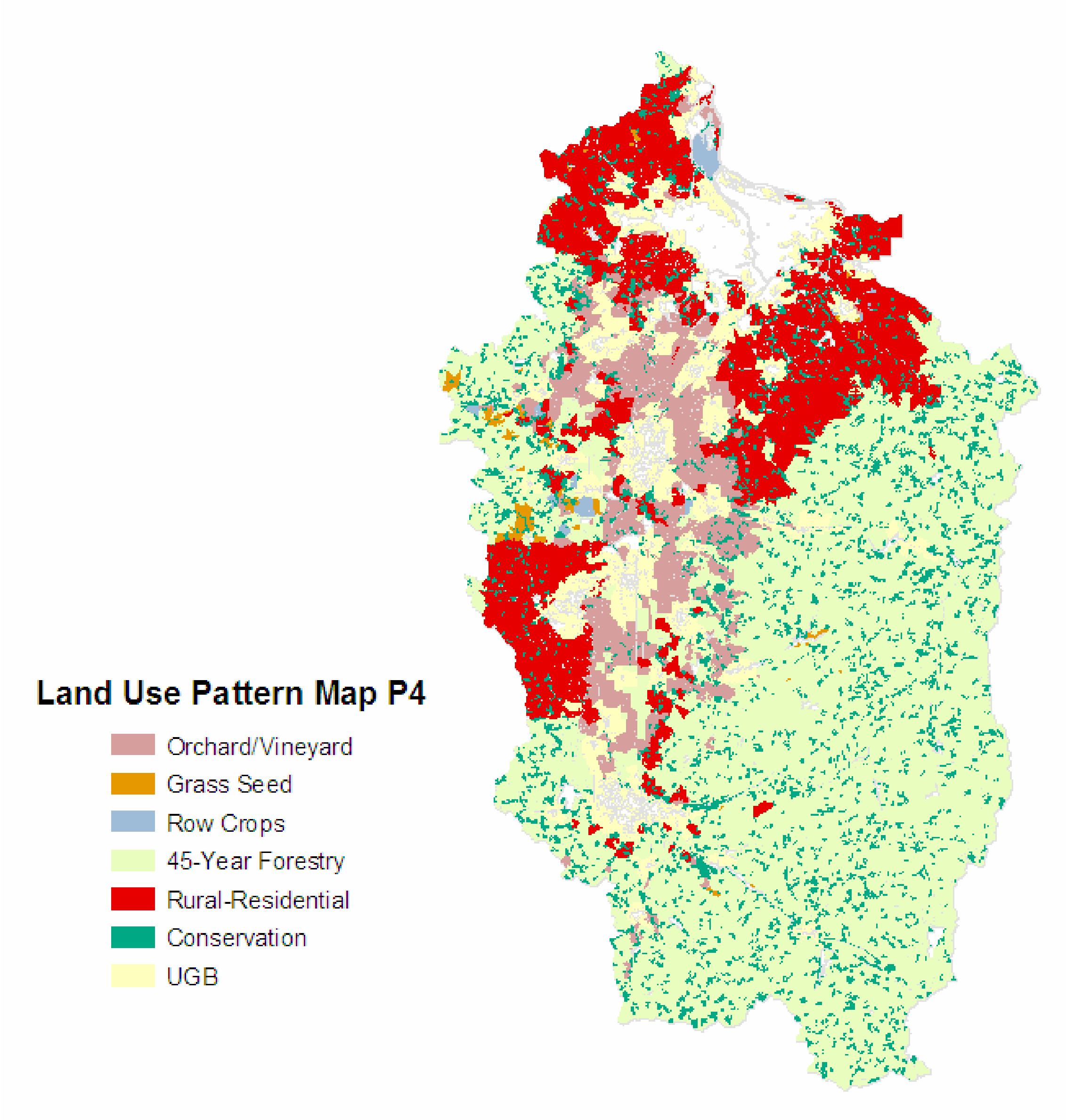
Land Use Pattern Map P4
Orchard/Vineyard
Grass Seed
Row Crops
45-Year Forestry
Rural-Residential
Conservation
UGB

Figure 9

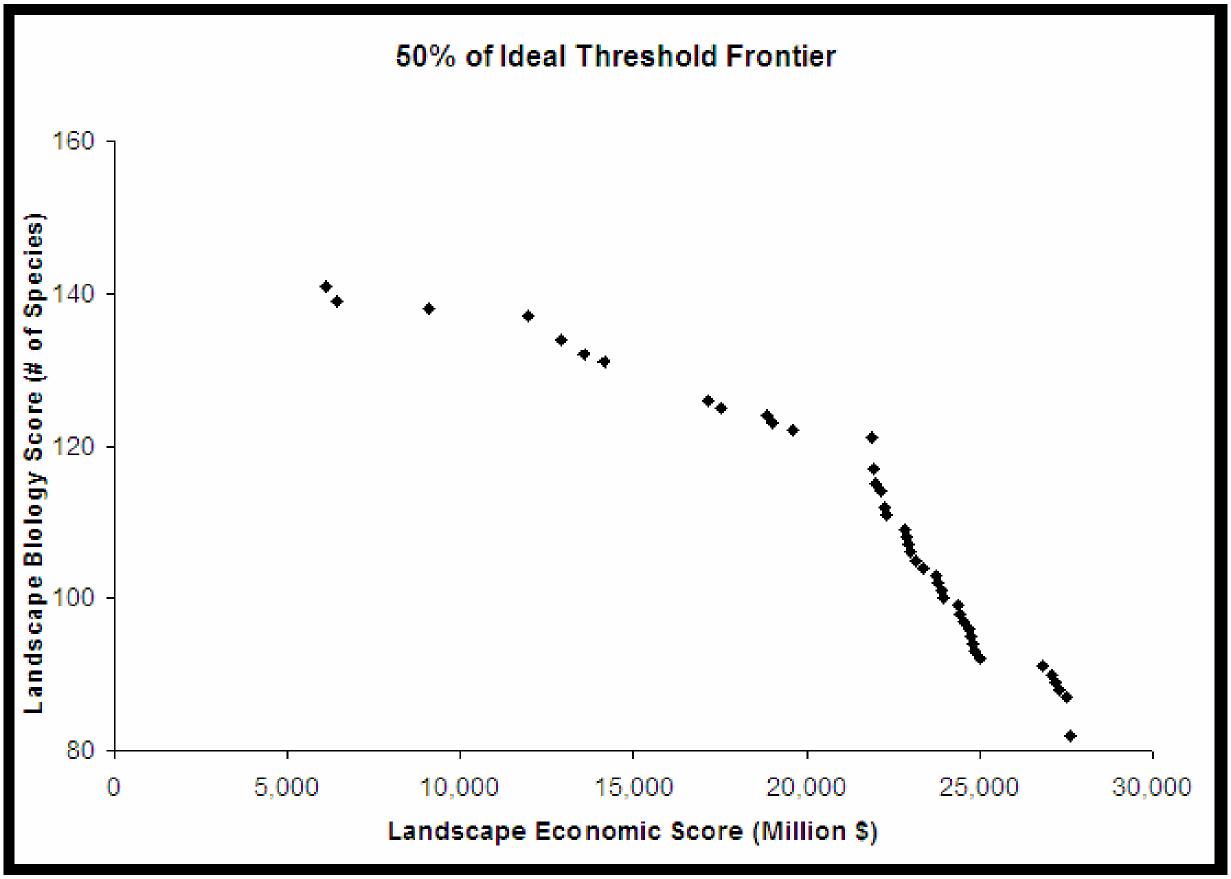
50% of Ideal Threshold Frontier
160
140
120
100
80
Landscape Biology Score (# of Species)
0
5,000
10,000
15,000
20,000
25,000
30,000
Landscape Economic Score (Million $)

Figure 10