Reserve selection with land market feedbacks

Van Butsic [a,b,c,*], David J. Lewis [d], Volker C. Radeloff [a]

[a] University of Wisconsin Madison, Department of Forest and Wildlife Ecology, 1630 Linden Drive, Madison, WI 53706, USA
[b] Humboldt-Universität zu Berlin, Unter den Linden 6, 10099 Berlin, Germany
[c] Leibniz Institute of Agricultural Development in Central and Eastern Europe, Theodor-Lieser-Str. 2, D-06120 Halle, Germany
[d] University of Puget Sound, Department of Economics, 1500 N. Warner, Tacoma, WA 98416, USA

ABSTRACT

How to best site reserves is a leading question for conservation biologists. Recently, reserve selection has emphasized efficient conservation: maximizing conservation goals given the reality of limited conservation budgets, and this work indicates that land market can potentially undermine the conservation benefits of reserves by increasing property values and development probabilities near reserves. Here we propose a reserve selection methodology which optimizes conservation given both a budget constraint and land market feedbacks by using a combination of econometric models along with stochastic dynamic programming. We show that amenity based feedbacks can be accounted for in optimal reserve selection by choosing property price and land development models which exogenously estimate the effects of reserve establishment. In our empirical example, we use previously estimated models of land development and property prices to select parcels to maximize coarse woody debris along 16 lakes in Vilas County, WI, USA. Using each lake as an independent experiment, we find that including land market feedbacks in the reserve selection algorithm has only small effects on conservation efficacy. Likewise, we find that in our setting heuristic (minloss and maxgain) algorithms perform nearly as well as the optimal selection strategy. We emphasize that land market feedbacks can be included in optimal reserve selection; the extent to which this improves reserve placement will likely vary across landscapes.

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1. Introduction

Land use change is the leading cause of habitat and biodiversity loss globally (MA, 2005). Currently, over 83% of the terrestrial surface of the earth has been influenced by humans and this number is expected to increase (Sanderson et al., 2002; Foley et al., 2005). Reserves act as refuges for biodiversity by preventing anthropogenic change in areas of particularly high conservation value. Land market feedbacks, however, may undermine the ability of reserves to protect ecosystems by increasing returns to undeveloped lands that neighbor reserves (McConnell and Walls, 2005; Armsworth et al., 2006; Tóth et al., 2011), potentially leading to increased development in previously unprotected but also undisturbed areas. Effective conservation in a dynamic world therefore requires developing conservation planning methods which account for land market feedbacks.

Historically, reserve selection focused primarily on maximizing the ecological benefits of establishing reserves, while minimizing reserve size (Williams et al., 2005; Moilanen et al., 2009). This selection strategy led to spatially efficient reserves, but is of somewhat limited relevance for public policy due to limited information on conservation costs. Lately, there has been increased research on the role land markets play in efficiently establishing reserves with much attention focused on to how to best select reserves while facing a budget constraint (Ando et al., 1998; Costello and Polasky, 2004; Armsworth et al., 2006; Wilson et al., 2006; Underwood et al., 2008; see Arponen et al., 2010 for a critique of this approach). This research has called for reserve selection strategies that address three important components of land markets: land costs, development threat, and feedbacks between reserve establishment and future land costs and development threats.

Land markets potentially undermine conservation goals through equilibrium and partial-equilibrium feedbacks (Berck and Bentley, 1997; Armsworth et al., 2006). Partial equilibrium land market feedbacks take place when any location-specific characteristic that determines the market value of a parcel is influenced by actions on neighboring parcels. For example, purchasing

* Corresponding author. University of Puget Sound, Department of Economics, 1500 N. Warner, Tacoma, WA 98416, USA.
E-mail address: vanbutsic@gmail.com (V. Butsic).

Table 1
Land market feedbacks.

Type of effect	Market mechanisms	Scale of feedback	Estimating feedback
Equilibrium effect	1. Increased demand for non-developed land by conservation groups shifts demand outward, leading to more undeveloped land being traded in the market (Armsworth et al., 2006) at a higher price. 2. Conversion of land from agriculture or forestry to reserves can decrease the supply of commodities. This has the usual long run effect of increasing prices for commodities, leading to more potential land conversions as new entrants seek the now higher returns to extractive uses (Berck and Bentley, 1997; Jantke and Schneider, 2011).	Feedbacks occur when land purchases are large enough to shift the demand curve or significantly reduce the supply of commodities. Empirically, there is evidence that supply side restrictions in forestry have had large price effects (Berck and Bentley, 1997) when over 20% of timber supply is protected. There is less evidence for agricultural shifts; modeling exercises have explored effects at the scale of 5–30 million ha of protection (Jantke and Schneider, 2011).	Equilibrium land market effects can be calculated directly by estimating the price elasticity of land supply and land rents, or indirectly by estimating the own price elasticities of land based commodities (Armsworth et al., 2006; Jantke and Schneider, 2011; Tóth et al., 2011).
Partial Equilibrium (Amenity) effect	Reserve establishment typically increases the amenity value of land. This generally increases the value of housing relative to agriculture or forestry, increasing future purchase prices and threat levels (Wu and Plantinga, 2003; Lewis et al., 2009).	Amenity effects may increase prices of land adjacent to even small reserves. Amenity effects are likely also present for very large purchases (McConnell and Walls, 2005). This amenity effect is often constrained to parcels very near the amenity.	Hedonic estimates of land prices, and discrete choice models of land development can be used to estimate land market feedbacks, given that the endogenous nature of reserve establishment is accounted for (Lewis et al., 2009).

a reserve may increase the returns to developing neighboring land by generating an amenity value (see McConnell and Walls, 2005 for a review of this literature). Reserve establishment may also have equilibrium effects on the land market through either a reduction in the supply of land-based commodities such as crops or timber, or through an increase in the demand for undeveloped land by conservation organizations, both of which raise prices for undeveloped land. Equilibrium and partial equilibrium feedbacks can increase both the cost of purchasing neighboring lands, along with increasing the threat that neighboring lands develop, which can potentially undermine the conservation gains of reserve establishment (Table 1, Armsworth et al., 2006; Jantke and Schneider, 2011; Tóth et al., 2011).

While there is strong theoretical evidence that land market feedbacks may undermine conservation, there is scant empirical evidence confirming the importance of these dynamics in real world settings. Indeed, most reserve selection strategies that account for both cost and threat (Costello and Polasky, 2004; Wilson et al., 2006; Newburn and Berck, 2006; Moilanen and Cabeza, 2007; Spring et al., 2007) ignore land market feedbacks. This is likely due to the difficulty in estimating land market feedbacks from commonly used threat and cost data. In order to calculate the effect of land market feedbacks, cost and threat estimates must themselves be functions of reserve establishment and land development, and must be dynamically updated throughout the selection algorithm in order to reflect changing states of the landscape. Lacking such estimates, the effect of land market feedbacks on reserve selection has remained primarily of theoretical importance, and conservation practitioners have been given little guidance as to the extent to which these feedbacks may undermine their efforts.

Estimating the partial equilibrium effects of reserve establishment on land prices and development is complicated by the non-random application of reserve status, which can result in selection bias (Andam et al., 2008; Butsic et al., 2011; Carrion-Flores and Irwin, 2010). Such selection bias can occur if there are differences in the distributions of covariates inside and outside of the reserve (selection on observables), or if unobserved correlation exists between reserve establishments, land characteristics, and land markets (selection on unobservables (Cameron and Trivedi, 2005; Ch. 25)). For example, land near reserves often demands a premium price. Statistically, however, it can be difficult to separate the price effects of reserve establishment from the price effects of other amenity values which may impact land prices even in the absence

of a reserve. For example, reserves are often located in scenic landscapes, and property in this landscape can command a premium due to both the reserve and the scenery. Since scenery is difficult to quantify, its lack of measurement confounds the estimation of reserves on prices and development threat. In order to estimate land market feedbacks, one must separately identify the effects of reserves on land prices and development threat from the effects of correlated unobservables such as scenery.

Recent advances in econometrics have increased our ability to estimate the effects of reserve establishment. In certain settings, reserve establishment can be argued to be uncorrelated with unobserved land market attributes and such "quasi-experimental" data can be used to estimate the effect of reserve establishment (Spalatro and Provencher, 2001; Lewis et al., 2009; Horsch and Lewis, 2009). In other locations, where selection bias arises from observable variables, explicitly modeling the reserve sighting process through propensity score matching or regression discontinuity analysis has been an effective strategy to correct for selection bias (Bento et al., 2007; Andam et al., 2008; Butsic et al., 2011). Likewise, when selection bias arises through correlated unobservable land characteristics, methods such as full information maximum likelihood estimation have been used to account for selection bias (Lewis et al., 2009; Butsic et al., 2011). Here we take advantage of these advances in modeling land markets to integrate consistently estimated effects of reserve establishment and development density into the reserve selection problem, allowing us to account for land market feedbacks. Even when land market feedbacks are accounted for, incorporating land cost and development threat into reserve selection remains challenging (Costello and Polasky, 2004). Cost and conservation threat are usually correlated (Wilson et al., 2006), and that means that it is not clear *a priori* whether limited conservation funds should be concentrated on inexpensive land that has a low probability of development, or parcels that are severely threatened but also expensive. Stochastic dynamic programming and mixed integer programming can be used to solve the reserve selection problem if costs and threat levels are known (Costello and Polasky, 2004; Wilson et al., 2006), although empirical examples are rare (but see Haight et al., 2005; Tóth et al., 2011). Likewise although the validity of heuristics in such settings has been discussed theoretically (Wilson et al., 2006; Carwardine et al., 2010), there are relatively few real world test where optimal outcomes can be compared to heuristics over multiple trials.

Here we fully embed land market dynamics (feedbacks, costs, and threats) into an optimal reserve selection strategy. Our paper has four main objectives. First, we demonstrate a method of reserve selection which accounts for partial equilibrium land market feedbacks in addition to costs and threats. Second, we test the importance of including land market feedbacks in an empirical reserve selection setting. Third, we test the performance of heuristic algorithms vs. the optimal reserve selection strategy when costs and threat levels are known over multiple empirical trials. Finally, we test the effectiveness of a conservation program to preserve an important indicator of ecosystem function − coarse woody debris (CWD) − in a rapidly developing land market.

2. Methods

2.1. Study area

Our study area was Vilas County in northern Wisconsin, an area typical of quickly developing amenity rich rural landscapes. The county has a population of just over 20,000 and covers over 850 square miles (U.S. Census, 2012). The county has long been a bastion for second home development due to its 1300 lakes. Since 1960, over half of all new homes have been built on parcels adjacent to a lake (Schnaiberg et al., 2002). The dense development along some lakes has led to a host of ecosystem changes including: decreased growth rates for bluegills (Schindler et al., 2000) and largemouth bass (Gaeta et al., 2011), decreased amounts of coarse woody debris in the littoral zone (Christensen et al., 1996), amphibian extirpation (Woodford and Meyer, 2003), and exotic invasion (Carpenter et al., 2007).

Vilas County has predominantly relied on zoning to control housing growth, and its effects on property prices and development density have been modest (Spalatro and Provencher, 2001; Horsch and Lewis, 2009; Lewis et al., 2009). Recently, local and national land trusts, along with the state government have begun to purchase private land for conservation. Between 2004 and 2007, the Nature Conservancy, with joint funding from the State of Wisconsin's Knowles−Nelson Stewardship Fund, purchased over 3000 acres in Vilas County at a cost of over $4,000,000 (State of Wisconsin, 2007). In addition, a local land trust − Northwoods Land Trust − has been actively acquiring properties in the County (Northwoods Land Trust, 2010).

We conducted our study on 16 lakes. These lakes were chosen because they had been analyzed previously in the land development (Lewis et al., 2009) and hedonic (Horsch and Lewis, 2009) property value models and contained a feasible number of developable parcels to apply SDP (2−7 parcels). The lakes represented a gradient of size and existing development densities (Table 2). On average, a parcel in our dataset could subdivide into 8 new parcels given local zoning laws.

2.2. Program description and reserve selection algorithms

We simulated a conservation program which established reserves over a 16 year time period − represented by four, 4-year time steps − by purchasing private land. The objective of the

reserve selection was to maximize the amount of coarse woody debris present at the end of the program given a budget constraint of $500,000 per period. Changes in the budget did not change the results qualitatively. It was not possible to borrow beyond the budget, but any money left over at the end of each period earned interest (5%) and could be used in subsequent time periods. Money left over at the end of the program did not factor into the objective function.

Parcels were in one of three states at the beginning of our simulations: (1) developed parcels that were already built to the maximum allowable density (i.e., zoning prohibits further subdivision); (2) undeveloped parcels that could that subdivide further (i.e., zoning allowed for more parcels to be created from the parent parcel); and (3) protected parcels that were already owned by the state or non-profit groups. Only undeveloped parcels could change state, and they could either develop, be protected, or remain undeveloped. When an undeveloped parcel was protected, only the portion of the parcel absent of development was purchased. For example, if a parcel has one residence but was large enough to subdivide into a total of seven parcels, then it was possible to purchase and protect the six additional parcels, but the existing residence and a parcel equal to the minimum size allowed by zoning remained in private ownership. In this way the conservation program purchased private land but not existing structures.

We formulated the reserve site selection problem as a series of decisions regarding which parcel(s) to protect over four time periods. In each time period, conservation costs, expected development threat, and the ecological benefit of each parcel were known. We used stochastic dynamic programming (SDP) to solve for the optimal sequential selection of reserves (Costello and Polasky, 2004). The optimal policy gives the best action (which parcel(s) to protect) in each period as a function of the current state of the lake. Using SDP we were able to select the parcel (or either no or multiple parcels) in each period which resulted in the highest expected CWD at the end of the 16 year planning horizon. SDP can be challenging to implement due to the curse of dimensionality (Wilson et al., 2006) and high data requirements. For example, solving the SDP problem for a lake with seven developable lots took over 20 h, while the heuristic algorithm took only minutes. Therefore, we also implemented two common heuristic selection algorithms − maxgain which in this case maximizes the amount of shoreline purchased in each time period and is based on cost estimates but not threat estimates, and minloss − which minimize the amount of shoreline developed in each period by focusing selection on the most threatened parcels (see Supporting information for a mathematical treatment of SDP, maxgain and minloss).

2.3. Input model no. 1 − hedonic model of land costs

Conservation costs were estimated using a hedonic model of property values. Hedonic models use data on observed property transactions in local land markets to measure the impact of characteristics on property prices. The method is frequently used in environmental and urban economics to analyze property markets and to estimate households' marginal willingness-to-pay for changes in neighborhood attributes, such as air quality or protection from crime (see Kuminoff et al. (2010) for a review of issues in this literature).

Conservation costs for our analysis were calculated from Horsch and Lewis (2009). The model specified the contributions of various parcel specific (assessed structure value, lot size, number of feet of shoreline frontage, feet of frontage squared), lake specific (lake size, distance to towns, lake clarity, depth, zoning regulations, development density, fishing quality, and whether or not the lake has

Table 2
Selected summary statistics for lakes used in study.

	Average	Min	Max	St. dev
# of parcels	44.43	7	131	31.759
Depth (ft)	32.98	13	80	17.41
Size (acres)	138.90	15	555	121.29
% Protected land	8	0	80	21
Development density (parcels/per acre)	0.49	0.11	2.2	0.51

experienced exotic invasion from Eurasian water milfoil) and time specific (captured through yearly time dummies) characteristics on property prices using publically available data from county, state, and federal sources (see Horsch and Lewis (2009) for more details). The coefficients from this model were used to calculate the expected cost of purchasing undeveloped parcels, given a set of parcel and lake characteristics. In this model *protected land* positively affects the price of parcels through reducing *development density*. Given that the impact of *protected land* in our setting is to limit future development and therefore development density, we expect this result to be somewhat weaker than elsewhere.

2.4. Input model no. 2 − land-use change model of the threat of development

The threat (or probability) of development for each parcel along with the expected number of new lots created in the event of a subdivision was calculated using an econometric land-use change model originally developed by Lewis et al. (2009). The model was estimated with spatial data on historical parcel subdivisions from 1974 through 1998, whereby the development status of every parcel across the landscape is tracked in four year intervals. Similar parcel-level spatial data has been used in environmental and urban economic analyses of urban sprawl (Irwin and Bockstael, 2002; Carrion-Flores and Irwin, 2004), water quality effects of development (Bockstael, 1996), and the effects of land-use planning on development patterns (Newburn and Berck, 2006). Most models in this literature generate estimated probabilities of parcel-level land-use change as a function of the net economic returns to land, and various parcel, local, or regional attributes.

Two land-use decisions were modeled in Lewis et al. (2009): (1) a binary outcome of whether a parcel subdivided during each four-year interval, and (2) the number of new parcels created upon subdivision. These two decisions were jointly estimated with a maximum simulated likelihood procedure. The resulting estimates characterized the contribution of parcel specific (frontage, frontage squared, soil type), lake specific (development density, % protected land, water clarity, lake size, lake depth, distance to town and zoning regulation), and time specific (dummy variables for each panel) characteristics, along with a host of interactions, on the probability a parcel would subdivide as well as how many new lots were created when a parcel subdivides. The main findings of the model are that protected land increases threat level for some small parcels but decreases threat level for many larger parcels. The effect on large parcels is evidence that neighboring conserved land and parcel size are land value complements − whereby owners are willing to pay more for a marginal unit of parcel size when that parcel is located near reserved land. For a full description and interpretation of the data and model see Lewis et al. (2009).

2.5. Input model no. 3 − an ecological model of coarse woody debris (CWD) in lakes

We coupled the land market models with an ecological model which related CWD to housing density. CWD is an important link between lakes and forest ecosystems in Northern Wisconsin, promoting production of benthic invertebrates, and offering refuge to prey fishes, which in turn are consumed by piscivorous fishes (Roth et al., 2007). Christensen et al. (1996) modeled the amount of CWD located along a given shoreline as a function of residential density for 16 lakes located in Vilas County and the adjoining county to the north, Gogebic County, Michigan. When analyzing the mean CWD for each lake, the amount of CWD was significantly negatively correlated with residential density (Christensen et al.,

1996). We applied the coefficients from this model to calculate CWD on each lake under alternative development scenarios.

2.6. Land market feedbacks

In our setting, land market feedbacks were propagated through two variables: (1) *development density*, defined as the total number of parcels/lake size (i.e., developed + undeveloped parcels/lake size), which is influenced by reserve establishment and land development over time; and (2) *protected land*, defined as the % of shoreline owned by the government or non-profit organizations, which is a direct measure of reserve establishment. Both variables are calculated at the lake level.
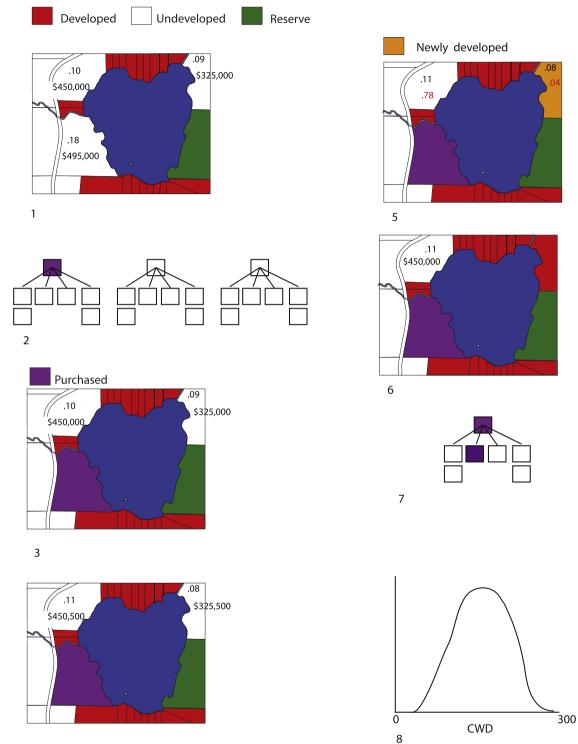
Development density may be endogenous as it is a function of past subdivision decisions which may be correlated with unobservable qualities of the lake or parcel. In the land use transition model, Lewis et al. (2009) estimated the effects of *development density* by including the state of each lake in 1974 as a proxy for a lakes inherent desirability, along with the time-varying development density on each lake during each four-year interval. This econometric correction is similar to the Mundlak−Chamberlin device (Mundlak, 1978) widely used in panel data models. In our application, unobserved lake level heterogeneity is specified as a function of past development level. We also included this variable in a variant of the model used by Horsch and Lewis (2009) and found no differences in the estimated results.

Protected area likewise may suffer from observable or unobservable selection bias since many protected areas are placed in areas with unobserved characteristics that influence the development potential of land. For example, conservation agencies in the U.S. often conserve scenic landscapes which are also desirable for development. In our study area, we exploit a unique historical feature whereby public land is primarily abandoned farmland which proved unprofitable after the area was harvested of its timber. Most of this land was defaulted to the state from 1930 to 1950 (Flader, 1983) and thus its spatial distribution is unlikely to be influenced by unobserved variables that likely affect current property prices or transition probabilities.

2.7. Land use simulations and policy effects

To quantify the policy impacts of reserve establishment, along with the uncertainty of these impacts, we integrated the results of the SDP and heuristic algorithms into a land use simulation (Fig. 1). The land use simulation was run 1000 times to create a distribution of realized landscapes. At the end of the simulations, the SDP, heuristic, and baseline simulations were compared to calculate the effect of the conservation program on the amount of CWD. We calculated changes in mean and median CWD. Likewise we used a two sided Kolmogorov−Smirnov test to test for differences in the shape and location of the distributions of the outcomes. The null hypothesis is that both the shape and location of the distributions are the same, rejecting the null hypothesis indicates that one or both, the shape, or location differ.

To test for the effect of land market feedbacks, we ran the simulation with *development density* and *protected land* at their estimated values and compare these outcomes to simulations where the effect of *development density* and *protected land* are not updated throughout the simulation. We tested for differences in means, medians, and the shape of the distribution between the full model and the simulations that ignored land market feedbacks. We also calculated the increased costs of land acquisition at the end of the program due to reserve establishment by comparing the cost of remaining parcels in the baseline simulation to the cost of the parcels where reserves are established. Again we tested for

Fig. 1. A three parcel example of the landscape simulation methodology. 1. Each parcel is assigned to its state in 2006. Parcels that are undeveloped are assigned prices and transition probabilities (threat levels) based on empirical models (Horsch and Lewis, 2009; Lewis et al., 2009). 2. Stochastic dynamic programming is used to choose which parcel offers the highest expect benefit (CWD) at the end of the planning horizon given the state of the lake. 3. If the SDP determines that purchasing a parcel maximizes the expected benefit a parcel is selected as a reserve. It is possible that the optimal decision is to select either zero, or more than one parcels in a given time period. 4. Neighboring prices and threat levels are adjusted according to how the selection decision affects the state of the lake. 5. Random numbers from the unit interval are drawn for each developable parcel. If the number is smaller than the threat level of the parcel, that parcel subdivides and a number of new lots develop. Otherwise the parcel stays undeveloped. 6. Price and threat levels are updated based upon the new state of the lake. 7. Steps 3—6 are repeated until the end of the 16 year program. 8. Steps 3—7 are repeated 1000 times resulting in a distribution of coarse woody debris (CWD). Steps 1—8 are repeated for 16 lakes across Vilas County, for two heuristic algorithms, and with threat and cost feedbacks equal to zero.

differences between selection algorithms by comparing means, medians, and the shape of the distribution of 1000 simulations.

3. Results

3.1. Baseline land development throughout the 16 year simulation

Under the baseline land use simulation, changes in residential density are heterogeneous over the 16 lake sample. Residential density increased by an average of 10.5% over the 16 year simulation. The maximum density change was 46% and the minimum change was 1.4%. These changes resulted in similarly heterogeneous decreases in CWD. On average, CWD decreased by 36% over the 16 year simulation. Thus, under the baseline simulation both the built and natural environment show marked changes.

3.2. CWD and development changes under the reserve program

The reserve program had heterogeneous effects on residential density and CWD, regardless of selection strategy. Averaging over all 16 lakes, the optimal selection strategy reduced residential density by about 7% at the end of the program when compared to the baseline. Mean CWD at the end of the 16 year simulation was 218.83 CWD/km when the program was in effect (under the SDP

selection algorithm) compared to 210.71 CWD/km for the baseline simulations, an increase of nearly 4%. The largest CWD increase due to the reserve program was 38.05 CWD/km, and the largest percentage increase in CWD due to the program was a 28% increase (Fig. 2).

3.3. The effect of threat feedbacks

We found that ignoring threat feedbacks (i.e., *development density* and *protected land* are not updated) leads to only small changes in landscape development, and hence CWD. Under the baseline simulations the distribution of CWD does not differ significantly when threat feedbacks are ignored. Ignoring threat feedbacks lead to slightly higher (but statistically insignificant) changes in CWD throughout the simulation for all 16 lakes. Protecting land increased threat levels to some small parcels, thus increasing the probability of development and decreasing CWD. For some larger parcels, however, threat level actually decreased as reserves increased, reducing the overall impact of the threat level. Thus, the overall results of the threat feedbacks were perhaps muted by these off setting effects. We find similar results for all three selection algorithms, indicating that establishing new reserves has negligible effects on threat levels in our setting (Table 3).
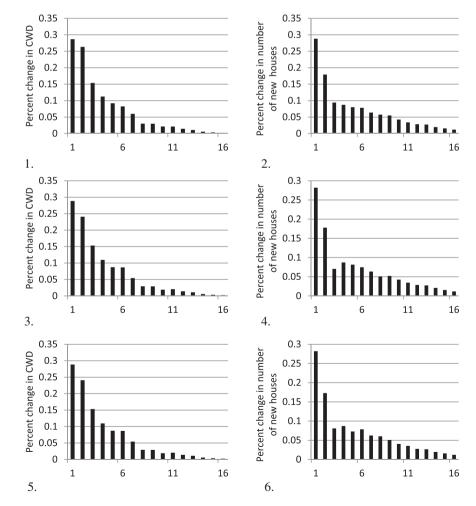

Fig. 2. Changes in CWD and number of houses compared to baseline simulations. Graphs in the left column represent the percent change in CWD for all sixteen lakes ranked from highest change to lowest change using the three selection methods compared to baseline simulations for 1) the SDP, 3) the maxgain algorithm, and 5) the minloss algorithm. Graphs in the right column represent the percent change in new houses built over the 16 year simulation ranked from highest to lowest for the selection methods compared to the baseline simulation for 2) the results using SDP, 4) the maxgain algorithm, and 6) the minloss algorithm.

Table 3
Average difference between CWD in models with full feedbacks vs. models which exclude feedbacks, with percentage change in italics.[a] The number of lakes in which the distribution differs between the simulation with and without feedbacks is in parenthesis.

	No threat feedback	No cost feedback
Least cost	0.13, *0.0006%* (0)	0.21, *0.0010%* (0)
Expected benefits	−0.01, *0.0005%* (0)	0.7, *0.0032%* (0)
SDP	−0.13, *0.0006%* (1)	−0.07, *0.0003%* (0)
Baseline	0.09, *0.0004%* (0)	0.04, *0.0002%* (0)

[a] Average difference is calculated as average CWD for each lake with missing feedbacks minus the average CWD for each lake using the full feedbacks.

3.4. The effect of cost feedbacks

The effects of ignoring cost feedbacks were small. We tested for significance between the distribution of each algorithm and baseline simulations under the competing feedback assumptions. We found that in all cases the distribution of simulated results did not differ significantly between simulations with and without cost feedbacks (Table 2). Given that this is the case for the baseline simulation and the simulations where reserves were established, we concluded that land development and reserve establishment had negligible effects on future land prices in this setting. The cost feedbacks did increase the costs of purchasing land in the future. In general, however, this change was modest (Table 4). On average reserve establishment increased future cost of purchasing reserves by about $600 per parcel. The maximum increase was slightly over $2000 per parcel. This increase was the result for one small lake where the conservation purchase assured a low residential density into the future.

3.5. Heuristic vs. optimal selection strategies

Averaged over the 16 lakes, the heuristic algorithms performed nearly as well as the SDP algorithm. The SDP algorithm had the highest average CWD and smallest average standard deviation followed by the minloss and maxgain algorithms. The medians of CWD were the same for all three selection algorithms, and lower for the baseline simulation (Table 5). Likewise, at the individual lake level there were few differences between the distributions of the CWD between SDP and the heuristic algorithms (Table 5). The distribution of CWD for the baseline simulations differed on 11 lakes from the distribution of CWD for SDP and both heuristics.

Finally, we examined the maximum difference in CWD between SDP, heuristics, and baseline simulations at the individual lake level. The results show that even in the most extreme cases, the maximum differences between SDP and the heuristics is quite small (1.6 CWD/km for maxgain and 0.74 CWD/km for minloss), indicating that not only did the heuristics work well on average, they did well on each lake individually. In contrast, the largest difference between the baseline and SDP was 38.05 CWD/km (Table 5, Fig. 2).

Table 4
Increase in future conservation costs ($) due to reserve establishment.

	SDP vs. Baseline	Maxgain vs. Baseline	Minloss vs. Baseline
Average increase in price due to cost feedback	600.60	592.09	595.84
Standard Deviation of price due to costs feedback	595.28	596.74	577.48
Maximum increase in price due to cost feedback	2258.69	2272.22	2163.94

Table 5
Number of lakes (out of 16) with significantly different distributions and maximum average difference in CWD between algorithms using the Kolmogorov–Smirnov test. Upper off diagonal numbers are the number of lakes with significantly different distributions of CWD ($p < 0.05$). Lower off diagonal is the maximum difference in CWD.

	Maxgain	Minloss	SDP	Baseline
Maxgain	0	3	4	11
Minloss	1.4	0	4	11
SDP	0.91	1.47	0	11
Baseline	38.05	38.27	38.05	0

4. Discussion

There is strong theoretical evidence that land market feedbacks may undermine conservation, but much less applied knowledge of how important these feedbacks are. Here we attempted to integrate land market feedbacks explicitly into an empirical reserve selection setting by using a novel integration of cost and threat models to account for partial equilibrium land market feedbacks. To estimate feedbacks we use previously published threat and cost models that plausibly estimate the causal impact of reserve establishment. Using such models provides a framework to integrate land market feedbacks into the dynamic market for land.

Our empirical example indicated that land market feedbacks had negligible effects on ecological outcomes. The outcomes from simulations which included the feedbacks did not differ significantly from those that ignored feedbacks. This was true for both costs and threat feedbacks. Likewise, in our setting reserve establishment had negligible impacts on the cost of future conservation.

An important question pertains to the generality of these results. Prior economic research suggests a positive property price impact of open space, but the strength of these impacts varies greatly (0.91%–35% of a home's value (McConnell and Walls, 2005)). In our case, the average effect of reserve establishment on land prices was less than 1%. Therefore, cost feedbacks may have been weaker in our case than elsewhere. Likewise, the effect of reserve establishment on land conversion is theoretically ambiguous in settings where land develops from sparse housing to more dense housing (Lewis et al., 2009) such as in our case. But when land develops from undeveloped to developed uses, reserve establishment theoretically increases development threat near reserves by increasing the returns to developed land relative to the returns to land in agricultural or forest uses (Wu and Plantinga, 2003). Again, our example may thus represent lesser feedbacks compared to other common settings. Research into the importance of feedback strength to reserve selection in other settings may be a valuable extension of this research (Tóth et al., 2011).

We extend past uses of stochastic dynamic programming (SDP) to solve the reserve selection problem by simulating the program over 16 lakes; in essence creating 16 experiments, which we used to compare the outcome of SDP to the heuristic selection algorithms. Overall, the heuristic algorithms performed nearly as well as SDP. On the majority of the lakes, the distribution of CWD did not differ significantly regardless of what selection algorithm was used, and on each lake the median CWD was equal regardless of selection algorithm. The fact that the heuristic worked well over a large number of real world landscapes gives us confidence in using these selection strategies in cases where all the information needed for the SDP is not available and potentially when the problem to be solved is too large for SDP. Thus our paper joins the growing literature that has found cost only (i.e., return on investment) methods of reserve selection often do a good job of selecting reserves (Wilson et al., 2006; Underwood et al., 2008). Likewise, it is also important to acknowledge that SDP limits us to the use of a small choice set and

that alternative methods such as mixed integer programming (Tóth et al., 2011) may be useful for solving larger problems.

In our example, there is relatively low heterogeneity in threat levels among parcels on the same lake. This was the case because much of what drives transition probabilities are lake level attributes, which are shared by all parcels on the lake. Our empirical results thus support past research that has indicated that heterogeneity in cost and threat estimates increases their importance in reserve selection (Wilson et al., 2006; Perhans et al., 2008; Carwardine et al., 2010).

From a conservation perspective, the simulated program had heterogeneous effects on the total amount of CWD. While the gains at some lakes were marginal, other changes were substantial (up to a 68% increase). Thus, the framework we used provides a second possible selection mechanism: SPD or heuristics can be used to select individual reserve sites within a certain area (either defined by political or ecological borders), and by comparing the simulated results across alternative areas, one can select both what broader areas should receive funding and which individual pieces within its border should be protected. This may be a useful framework when conservation funding decision is nested, for example when federal dollars have to be divided among states.

Although in our case land market feedbacks did not play an important role in reserve selection, we emphasize that state-of-the-science econometric models can be used to integrate land market feedbacks into the reserve selection algorithm, and we show how such models can be used for conservation planning. In many countries, the data for the type of hedonic and land use change models we used here are generally freely available to the public from county, state and federal sources. Where such parcel level data is unavailable, much of the data required to model biological benefits (soil, vegetation, slope, elevation etc.) can also be used to model the land market (Naidoo and Adamowicz, 2006), as net returns to land are affected by such land quality attributes. This may be especially true in the developing world where land conversions are highly correlated with natural resource abundance and hence biodiversity. We encourage further research that integrates land markets into reserve selection, and to use models of land cost and threat levels of similar quality as for the biological aspects of conservation planning.

Here, we address the non-equilibrium impacts of reserve establishment on the land market, that is, our feedbacks are contained within each lake. In this way, the development of a parcel on one lake is unrelated to development on other lakes. Empirically, reserve establishment is likely to have partial equilibrium effects when the size of the reserve is relatively small (such as the reserves simulated here). While there is evidence that many newly established reserves are actually quite small (Armsworth and Sanchirico, 2008), conservationists tend to lobby for the establishment of large reserves, and these may be more likely to have equilibrium land market impacts. Recent work (Jantke and Schneider, 2011; Tóth et al., 2011) indicates that under certain conditions these effects may be important for reserve selection. At the same time, land purchases that have equilibrium effects are still likely to influence neighboring properties through the cost and threat mechanisms developed here. Therefore, integrating land market feedbacks across scales from local amenity effects to equilibrium effects remains a challenge for future work.

Appendix A. Supporting information

Supporting information related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2012.10.018.

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