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ECOSEL: AN AUCTION MECHANISM FOR FOREST ECOSYSTEM SERVICES

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Abstract. This paper describes the foundations of a market mechanism that was designed to stimulate more efficient provisions of forest ecosystem services to society. The proposed tool is a competitive multi-unit public goods subscription game of incomplete information. A conceptual and mathematical characterization of the game is followed by an illustrative example where Pareto-efficient bundles of timber, carbon and mature forest habitat services of a real forest are used in a simulated bidding game. Attractive features of the mechanism include the use of multi-criteria optimization to ensure only the most cost-efficient bundles of ecosystem services are offered for bidding, and that it does not rely on regulatory control or on complex valuation exercises that are otherwise needed in alternative methods such as the cap-and-trade scheme.

Keywords: Multi-objective optimization, integer programming, public good provisions, auctions

1 Introduction

Many forest benefits are public goods characterized by various degrees of *non-excludability* and *non-rivalry* (e.g., Pagiola et al. 2004, p 10). It is usually impractical to exclude one from enjoying a forest's scenery or a patch of old-growth forest even if the individual did not pay for the privilege (*non-excludability*). Similarly, enjoying the forest's scenery doesn't reduce its supply (*non-rivalry*). As is well-known in public economics, markets typically under-provide public goods. In a forestry context, the consequences can be severe as forest landowners or other decision makers choose the most profitable land management alternative that is available to them. Real estate development or other forms of land conversions that typically compromise or eliminate ecosystem functions are often privately efficient alternatives to the landowner. In the United States alone, hundreds of thousands of hectares of non-federal forestland are lost each year due to urban sprawl (Alig et al. 2003) – a detrimental process that is partly induced by the market's inability to reward landowners who preserve their forests. Intensive timber production can also lead to decreased provisions of ecosystem services, and command-and-control regulatory responses might be counterproductive as they often give an incentive for private landowners to abandon forest management and convert to real estate or to another non-forest end-use in order to avoid regulatory restrictions (Bradley et al. 2009). In rural areas where timber production is the only profitable land use option, forest-dependent communities also suffer from the lack of functioning ecosystem services markets. Volatile timber prices, housing market downturns, and the nation's increasing reliance on imported wood compromise the economic viability of these communities. Native American, forest-dependent tribes in the Pacific Northwest, such as the Colville and Yakama Nations are particularly exposed to this problem (Affiliated Tribes of Northwest Indians Natural Resources Committee 2009). A functional market for ecosystem services would allow communities to diversify their revenue sources and reduce their reliance on timber. It would also allow timber industries to reduce harvest intensity and better serve the values of the public concerned with environmental issues.

Many pricing mechanisms that have been proposed or used in the past for environmental services have been regulatory in nature. They internalize environmental externalities, positive or negative, by setting up an apparatus that would ensure their excludability and rivalry. Price (tax or subsidy), quantity (cap-and-trade), or hybrid mechanisms (e.g., Roberts and Spence 1976) can be used to achieve this purpose. The European Union's mandatory carbon emissions trading scheme (EU ETS) is one example of cap-and-trade that could allow a credit mechanism for sequestering carbon through forest management. However, there is currently active debate regarding the appropriateness of using various forest management techniques and accounting practices within this scheme. The literature on the policy instrument choice is extensive (e.g., Goulder and Parry 2008), and includes numerous forestry applications (e.g., Bowers 2005).

Alternatives to regulatory penalties or tax incentives for increasing the provisions of forest ecosystem services include certification schemes and auctions. Certification providers such as the Forest Stewardship Council (FSC) promote ecosystem services by labeling forest products that are produced in sustainably managed forests. Extensive monitoring mechanisms are in place to ensure that on-the-ground management, as well as the entire supply chain, is in compliance with the certification standards. The mechanism seeks to capture a unique market segment: people who are willing to pay for sustainably produced forest products (e.g., Kollert and Lagan 2006). However, the costs of certification are borne by the landowner without an immediate payoff, and the certification schemes do not aim at cost-efficient production of forest ecosystem services.

Auctions have also been applied to determine the market prices of ecosystem-related products such as carbon emissions credits (Buckley et al. 2006) or the location of sewage treatment plants (Minehart and Neeman 2002). Reverse auctions, where the auctioneer is the buyer and the bidders are the sellers have been used to distribute public funds for the production of ecosystem services (Greenhalgh et al. 2007). In a reverse auction, the government encourages landowners to bid on services they can provide on a competitive basis. Landowners submit proposals as to how they will provide key public goods such as reduced phosphorus pollution, sedimentation, increased wildlife habitat or other benefits that are being targeted by the conservation program. Stoneham at al. (2002) describes the BushTender program's use of reverse auctions as a way to maintain biodiversity in Australia. A similar reverse auction approach has been proposed and tested for United States military bases where adjacent landowners would bid to provide habitat for endangered species (McKee and Berrens 2001). The electronic BushBroker exchange program utilizes combinatorial double auctions to administer the trade of native vegetation offsets in Victoria, Australia (Nemes et al. 2008).

We propose an alternative market mechanism, called ECOSEL, that (1) unlike cap-and-trade or taxation programs, does not rely on regulatory control, (2) unlike reverse auctions, does not require a central purchasing entity but allows any number of buyers to coordinate or compete in a bidding process for specific management plans that lead to desired bundles of ecosystem services, and (3) unlike certification schemes, produces ecosystem services at the lowest possible costs. A conceptual introduction to the ECOSEL framework is followed by a formal, mathematical characterization. We then illustrate the concept using data from a real forest as an example. After discussing the results of the case study, we conclude by highlighting the innovative elements of the approach and analyze some of the potential policy implications.

2 The ECOSEL concept

The rationale behind ECOSEL is the following. A forest landowner can manage their land in a variety of ways within the constraints of applicable laws and regulations. Some management alternatives lead to more, while others lead to less environmental services for the public. For example, a forest landowner might decide to clear-cut their forest and convert it to a non-forest use. This would likely compromise the ability of the land to provide forest habitat for wildlife, sequester carbon or potentially clean water for downstream users. Alternatively, the same landowner could preserve the forest cover and retain many ecosystem functions. This option, however, would result in opportunity costs due to forgone timber or development revenues, or both. While some landowners are willing to forgo opportunities like these, many will opt for the option conferring the highest financial return to their asset (land). ECOSEL aims to provide a decentralized mechanism where bidders interested in the production of ecosystem services pay compensation to the landowner for the costs that are associated with the desired changes in management. ECOSEL achieves this by combining optimization with a unique auction platform.

3 The optimization component

Typically, there are a large number of compromise management alternatives between opposing solutions such as development or harvest versus preservation that are available to the landowner. Some of these compromises are *Pareto-efficient* with respect to the environmental outputs they would lead to, and with respect to the associated implementation cost. In this context, a management alternative is Pareto-efficient if none of the associated environmental outputs or the associated cost can be improved (i.e., increased for environmental outputs, or decreased for costs) without compromising another output. The notion of Pareto-optimality is critical because it identifies management options that lead to different bundles of forest ecosystem services in the most (opportunity) cost-efficient ways possible. ECOSEL identifies these cost-efficient options for a given forestland, time period, and a predefined set of ecosystem outputs using specialized multi-objective optimization techniques (see Tóth et al. 2006 and Tóth and McDill 2009). A rigorous mathematical programming framework is used to explicitly capture the management decisions of the landowner along with the spatiotemporal interactions of these decisions and their impacts on ecosystem services and implementation costs.

The outcome of the optimization process is a production possibilities frontier (e.g., Figure 1) for the relevant ecosystem service outputs from which total or marginal ecosystem service production costs can be derived. This key feature of ECOSEL is far from trivial: a significant obstacle to functioning ecosystem markets is often a lack of understanding of the underlying natural production processes, and a lack of easily identifiable least-cost ecosystem production options. Indeed, the notion of "costs" and "tradeoffs" are relevant only when minimum costs or tradeoffs of producing a particular combination of ecosystem services are identified. The ECOSEL optimization component entails the use of detailed data on the physical characteristics of the forest, as well as simulation and GIS modeling to generate the Pareto-efficient set of tradeoffs between ecosystem services and costs. As a practical matter, ECOSEL seeks to provide potential sellers with a tool that can be used to derive the supply function for a unique combination of ecosystem services to be produced on a unique piece of forestland. If successfully adopted this feature of ECOSEL should prove attractive to forest landowners, many of whom lack the capacity to develop such supply surfaces themselves.

3.1 The market (auction) component Once a set of Pareto-efficient management plans is identified, an auction takes place where bids are solicited for plans that are selected by the landowner. Competing management plans could be selected in a variety of ways but the inclusion of management options that will likely attract bidding for ecosystem services are in the interest of the landowner. The seller also decides how information about the management plans is shared with the bidders. The opportunity costs found through optimization serve as the basis for the reserve prices to be used in the auction. The management plan for which the combined value of bids exceeds the corresponding reserve price by the largest margin at the end of the auction (i.e., the profit-maximizing plan) is implemented by the landowner, leading to a bundle of services that were desired by the bidders. Legal contracts and third-party oversight ensure that the plan is implemented in due course and no unjustifiable deviations occur. Legal and third-party expenses can be are likely incorporated into the reserve prices. Should the bids fall short of the reserve prices, all bids are returned to the participants and the auction concludes without any forest management commitments put in place.

The proposed design of the auction component is a two-phase mechanism, similar to the *Anglo-Dutch* format (Klemperer 1999), that consists of an open bids phase followed by a final round of sealed bidding. The open phase allows the potential buyers of ecosystem services to observe the other players' bids that have already been placed, and make bidding decisions based on these observations. This encourages the players to study each other's values, strategize, send signals, coordinate or compete in order to maximize the likelihood that their preferred option succeeds in the auction. The sealed bids phase serves to minimize free riding that might arise in this context if a potential buyer decides not to bid once it becomes obvious, or very likely, that his preferred management plan wins the auction regardless of his potential contribution. By making the final round of bids blind, the potential buyers are less likely to free ride as they cannot be sure about the status of their preferred plans in the auction. Sealed bidding does not preclude the players voluntarily disclosing their identity to other bidders if they feel that this is what they need to do to reap the benefits of "warm-glow" effects or to induce more collaboration. Once the auction comes to a conclusion and it is successful, the contributors will enter into a legal contract with the seller. At that point, their identity is disclosed to the seller. Whether the buyers' identity is disclosed then to the general public is in the discretion of the parties in the contract. There is some evidence in the public economics literature that moral motivation (Brekke et al. 2002), social norms (Levy-Garboua et al. 2009), confidentiality (Andreoni and Petrie 2004) or "warm-glow" effects (Andreoni 1990) can play a role in the success of a competitive, public good subscription game like ECOSEL. Thus, the mechanism will allow maximum flexibility for the players to disclose or hide their identities.

The auction component of ECOSEL can be thought of as a *competitive* multi-unit, multi-dimension public good subscription game with incomplete information. The competitive nature of the game is important because it differentiates ECOSEL from other subscription games and brings it conceptually closer to auctions. Competition arises because the players likely prefer different outcomes and will bid accordingly to avoid a loss of individual utility that might result from an undesired outcome such as intensive timber harvesting. This is in contrast with typical subscription games where bidders have a common goal, such as building a public park, and they can all coordinate to raise the necessary dollars to reach that goal. Economic theory suggests that subscription games, to which ECOSEL is a special extension, can increase the provision of ecosystem services while earning a profit for the landowner (e.g., Bagnoli and Lipman 1989; Menezes et al. 2001; Barbieri and Malueg 2008). The fact that the theoretical results in support of efficient provisions were found specifically for discrete services (e.g., building a bridge or not) makes the ECOSEL concept a promising alternative. This is

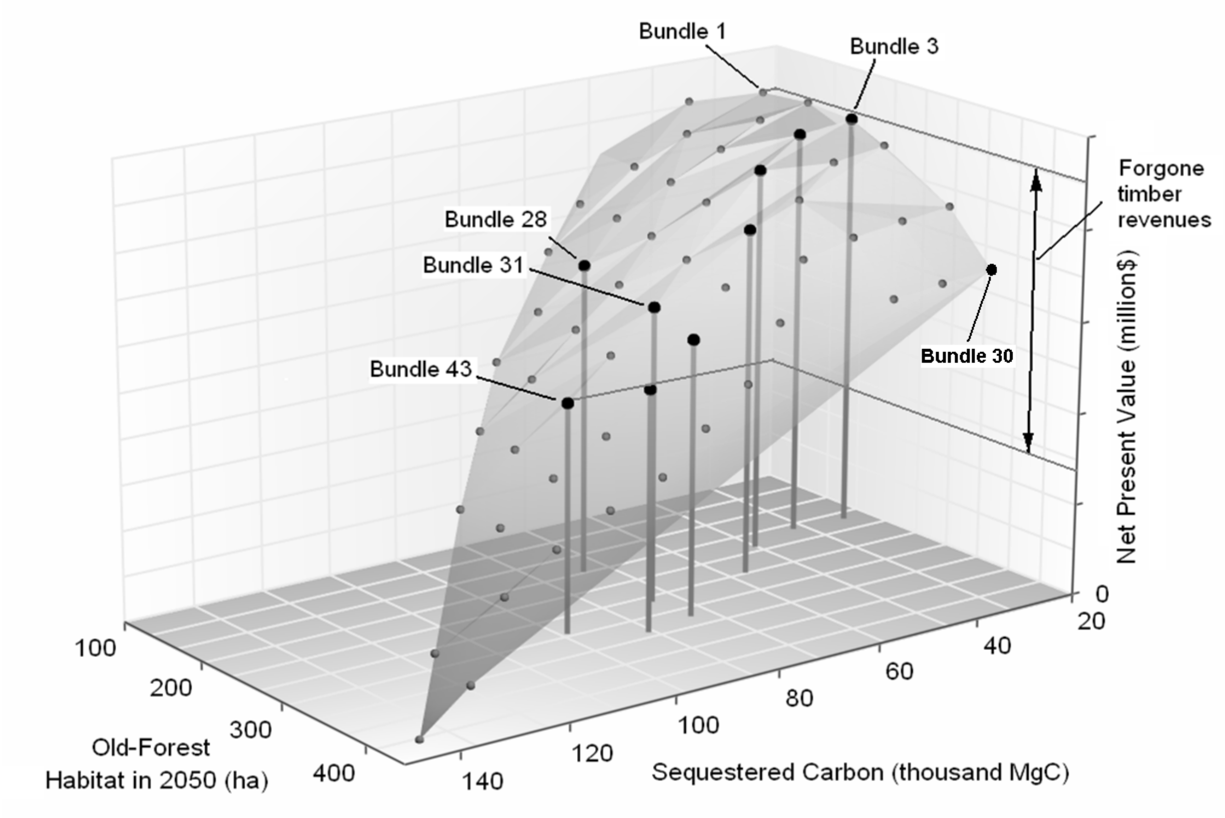

Figure 1: Pareto-optimal forest management plans for Pack Forest, Washington. Each point on the 3-dimensional surface represents a management plan, or equivalently, an ecosystem services bundle. Only six of the bundles are labeled (Source: Tóth et al. 2008).

because the forest management decisions that typically drive the provision of forest ecosystem services are also of the discrete type: should a forest stand be cut or not, should a road link be built to extract wood or not, and so on. The discrete nature of these management decisions is important for the potential success of the proposed mechanism because they make monitoring and third-party supervision simpler and less expensive.

We also like to emphasize that ECOSEL is a voluntary mechanism that provides a platform for both potential sellers and potential buyers of ecosystem services to freely express their *intrinsic motivation*. It gives more freedom to individuals to influence forest management decisions on public or private lands via monetary contributions. More control is also given to the sellers (the forest landowners) because with ECOSEL, they have the option to try to raise dollars for management plans that they cannot afford otherwise. They are in full control because it is up to them to decide which management plans, if any, should be put up for auction. In contrast to regulations that can reward provisions or penalize non-provisions of ecosystem services, it can be argued that ECOSEL is an intervention that *crowds in* intrinsic motivation. The phenomenon of *crowding in* has been shown to contribute to increased provisions of public goods in the context of other games (e.g., Frey and Jegen 2001).

3.2 Mathematical characterization A mathematical characterization of the proposed auction mechanism can be given by letting I denote the set of bundles or combinations of ecosystem services that are available in the auction, and by letting K denote the set of players who are bidding for these services. Subscripts i and j index set I and k indexes set K. Assume that each Player $k \in K$ has a certain value (or utility), v_i^k associated with each Bundle $i \in I$. Finally, let b_i^k denote the final bid that Player k places on Bundle i and let r_i denote the reserve price for Bundle i. The following statements can be made to characterize the ECOSEL game.

(1) *Social Surplus*: If the game – which is open to all potential buyers – is successful and one of the management plans, say Bundle i wins, *social welfare* will increase by social surplus SS_i , which is the sum of the

resulting net benefits to the bidders and the resulting net benefits to the provider (Eq. 1):

$$SS_i = \sum_{k\in K}\left(v_i^k - b_i^k\right) + \sum_{k\in K} b_i^k - r_i = \sum_{k\in K} v_i^k - r_i \quad (1)$$

As it is evidenced by Equation (1), social surplus will only depend on the values that the players assign to the winning scenario and on the associated reserve price. Figure 2 provides a more intuitive exposition of this result: The amount by which the total of bids exceeds the reserve price only affects the bidders' and the provider's respective shares in the benefits. The sum of the two shares, which is the social surplus, remains constant as long as the total value of the bids exceeds the reserve price. If the bids do not exceed the reserve price, then the social surplus is zero.

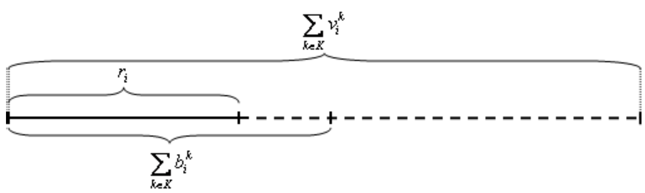

Figure 2: Social surplus generated by the ECOSEL mechanism depends only on the reserve price of the winning management plan and the combined value that the buyers assign to the bundle of ecosystem services that result from the plan.

(2) *Theoretical Welfare Maximum*: The Theoretical Welfare Maximum is reached at Bundle i if, of all the bundles of ecosystem services that are available in the auction, it is Bundle i that is collectively valued the highest by the players relative to the associated reserve price (Eq. 2):

$$\sum_{k\in K} v_i^k - r_i = \left(\underset{j\in I}{Max}\sum_{k\in K} v_j^k - r_j\right) \quad (2)$$

(3) *Winning Conditions*: There are two necessary conditions for Bundle i to win. First, the total value of bids on Bundle i must exceed the reserve price (Inequality 3). Second, the amount of this excess must be greater than the excesses at any of the other bundles (Eq. 4). These two conditions together are sufficient to determine if a particular bundle is winning in the auction or not.

$$\sum_{k\in K} b_i^k - r_i \geq 0 \quad (3)$$

$$\sum_{k\in K} b_i^k - r_i = \underset{j\in I}{Max}\left(\sum_{k\in K} b_j^k - r_j\right) \quad (4)$$

4) *Efficiency*: An outcome of the ECOSEL mechanism is efficient if (2), (3) and (4) all hold, i.e., if the winning management scenario maximizes social surplus. The rate at which ECOSEL can induce efficient outcomes measures the tool's capacity to efficiently provide public goods to society. If only inequality (3) holds, the management plan that leads to Bundle i is economically feasible, but both (3) and (4) must hold for the plan to be economically optimal.

Finally, the constrained utility maximization objective of each individual player (denoted by Player $\overline{k}$, where $\overline{k} \in K$) of the ECOSEL game can be characterized by the following function:

$$u_{\overline{k}}\left(v^{\overline{k}}, b^{\overline{k}}\right) = Max\left\{\begin{array}{r} \sum_{i\in I}\left[\left(v_i^{\overline{k}} - b_i^{\overline{k}}\right)\cdot Pr_b\right]: \\ b_i^{\overline{k}} \leq B_{\overline{k}}, b_i^{\overline{k}} \geq 0 \forall i\in I \end{array}\right\} \quad (5)$$

where:

$$\begin{aligned} Pr_b \quad = \quad & Pr\left\{b_i^{\overline{k}} + \sum_{k\in K\setminus\overline{k}} b_i^k \geq r_i, b_i^{\overline{k}} + \right. \\ & \left. + \sum_{k\in K\setminus\overline{k}} b_i^k - r_i = \underset{j\in I}{Max}\left(\sum_{k\in K} b_j^k - r_j\right)\right\} \end{aligned}$$

and where $v^{\overline{k}}, b^{\overline{k}}$ are the value and bid vectors of Player $\overline{k}$, consisting of $v_i^{\overline{k}}$ s (for $\forall i \in I$) , that denote the final value that Player $\overline{k}$ assigns to Bundle i , and of $b_i^{\overline{k}}$ s (for $\forall i \in I$) , that denote the final dollar bid that Player $\overline{k}$ places on Bundle i at the end of the auction. Lastly, $B_{\overline{k}}$ is the budget of Player $\overline{k}$.

Function (5) maximizes the expected net benefits of Player $\overline{k}$ given a set of values with respect to the bundles and a set of final bids. The expected net benefits of Player $\overline{k}$ are equal to the sum of differences between the values that Player $\overline{k}$ assigns to the bundles and the dollar value that Player $\overline{k}$ eventually bids, times the probability that these bundles actually win the auction. The probability of Bundle i winning is equal to the probability that the combined value of bids on Bundle i exceeds the associated reserve price by a positive margin, times the probability that this margin is greater than the margins associated with any of the other bundles. In other words, a bundle of services, i.e., a management plan, wins the auction only if (1) it gives positive net revenues for the provider, and (2) if this positive net revenue is greater than all the other net revenues that would be provided by the other plans. Finally, budget $B_{\overline{k}}$ puts an upper bound on each of the bids that can be placed on the bundles by Player $\overline{k}$ - assuming that bids placed on bundles that do not win the auction are refunded. If a no-refund policy is followed, then the budget constraint must be changed to $\sum_{i \in I} b_i^{\overline{k}} \leq B_{\overline{k}}$.

It is important to point out that we assume that value vector $v^{\overline{k}}$ might change in the open, initial phase of the auction as the players progressively articulate their preferences in the light of the other players' bids: vector $v^{\overline{k}}$ represents only the final values that Player $\overline{k}$ assigns to the different bundles of services that are available in the auction. Note that while $b^{\overline{k}}$ is a vector of variables representing the final bidding decisions of Player $\overline{k}$, the sum of the other players' bids placed on each bundle, i.e., $\sum_{k \in K \setminus \overline{k}} b_i^k$ for $\forall i \in I$, are unknown to and, to a large extent, uncontrolled by Player $\overline{k}$. If bid withdrawals were not allowed, however, which is a potential design option, the players would be able to establish lower bounds on the $\sum_{k \in K \setminus \overline{k}} b_i^k$ s for $\forall i \in I$ before placing their final bids. This design might be advantageous as it would allow a relatively straightforward mathematical characterization of the probabilities that particular bundles win the auction given the observed bids of the players during the open phase of the auction.

4 A case study

This section illustrates the ECOSEL concept using the University of Washington's 1,740 ha Pack Forest as an example. Pack Forest is a self-sustaining operation with revenue coming predominantly from timber production. The dual mission of the forest is to demonstrate sustainable forest stewardship and to generate revenues to support students and other programs at the School of Forest Resources, University of Washington. Since Pack Forest is located at the suburban-wildland interface of the Tacoma metropolitan area, the real estate value of the land is estimated to be significantly higher than its forest value which creates pressure to develop the property, compromising one of the forest's core missions. To reduce conversion risk, the administration is interested in increasing revenue from ecosystem services rather than by intensifying timber production. The case study simulates the choices and constraints that thousands of private forest landowners face in the region.

Based on preliminary assessment of stakeholder demand, ECOSEL was used to identify forest management plans for Pack Forest over 45 years (2005-2050) that would lead to Pareto-optimal combinations of carbon sequestration, old-forest habitat production and timber revenues. These management plans are spatiotemporally explicit in that they show what would have to be done on the ground and when to produce the bundled ecosystem services (see Figures 3 and 4). For simplicity, carbon sequestration was defined based on the net change of carbon content in estimates of standing bucked timber volumes between 2005 and 2050 given a particular management plan. "Old-forest" habitat was defined as the total area of forest stands that would be older than 115 years at the end of the planning horizon if a given management plan was implemented. We note that in real auctions, where ultimately it is the buyers' demand that determines which ecosystem services should be produced and how, more sophisticated definitions could be used.

The following three-objective mathematical programming model was used to generate the management plans. The novelty of the program is its ability to quantify the tradeoffs between carbon sequestration and old-forest habitat production. The model was solved using specialized, discrete, multi-objective optimization techniques that were introduced and tested by Tóth et al. (2006) and Tóth and McDill (2009).

4.1 The model formulation

$$Max \sum_{m \in M} c_{mt} x_{mt} \tag{6}$$

$$Max \sum_{m \in M} \sum_{t \in T} s_{mt} x_{mt} \tag{7}$$

$$Max \sum_{m \in M} \sum_{t \in J_m} A_m x_{mt} \tag{8}$$

subject to:

$$\sum_{t \in T} x_{mt} \leq 1 \quad \forall m \in M \tag{9}$$

$$\sum_{m \in M} v_{mt} \cdot A_m \cdot x_{mt} - H_t = 0 \quad \forall t \in T \setminus \{0\} \tag{10}$$

$$b_{lt} H_t - H_{t+1} \leq 0 \quad \forall t \in T \setminus \{0, \max_T t\} \tag{11}$$

$$-b_{ht} H_t + H_{t+1} \leq 0 \quad \forall t \in T \setminus \{0, \max_T t\} \tag{12}$$

$$\sum_{m \in C} x_{mt} \leq |C| - 1 \quad \forall C \in \mathrm{X} \quad and \quad \forall t \in T \setminus \{0\} \tag{13}$$

$$\sum_{m \in M} \left[A_m \sum_{t \in T} (Age_{mt}^T - \overline{Age}^T) x_{mt} \right] \geq 0 \tag{14}$$

$$x_{mt} \in \{0, 1\} \quad \forall m \in M, \quad and \quad \forall t \in T \tag{15}$$

where the decision variable is:

x_{mt} = a binary decision variable whose value is 1 if management unit m is to be harvested in period t. In other words, x_{mt} represent a harvesting prescription for management unit m. When $t = 0$, the value of the binary variable is 1 if management unit m is not harvested at all during the planning horizon (i.e., x_{m0} is the "do-nothing" alternative for management unit m).

The auxiliary/accounting variables are:

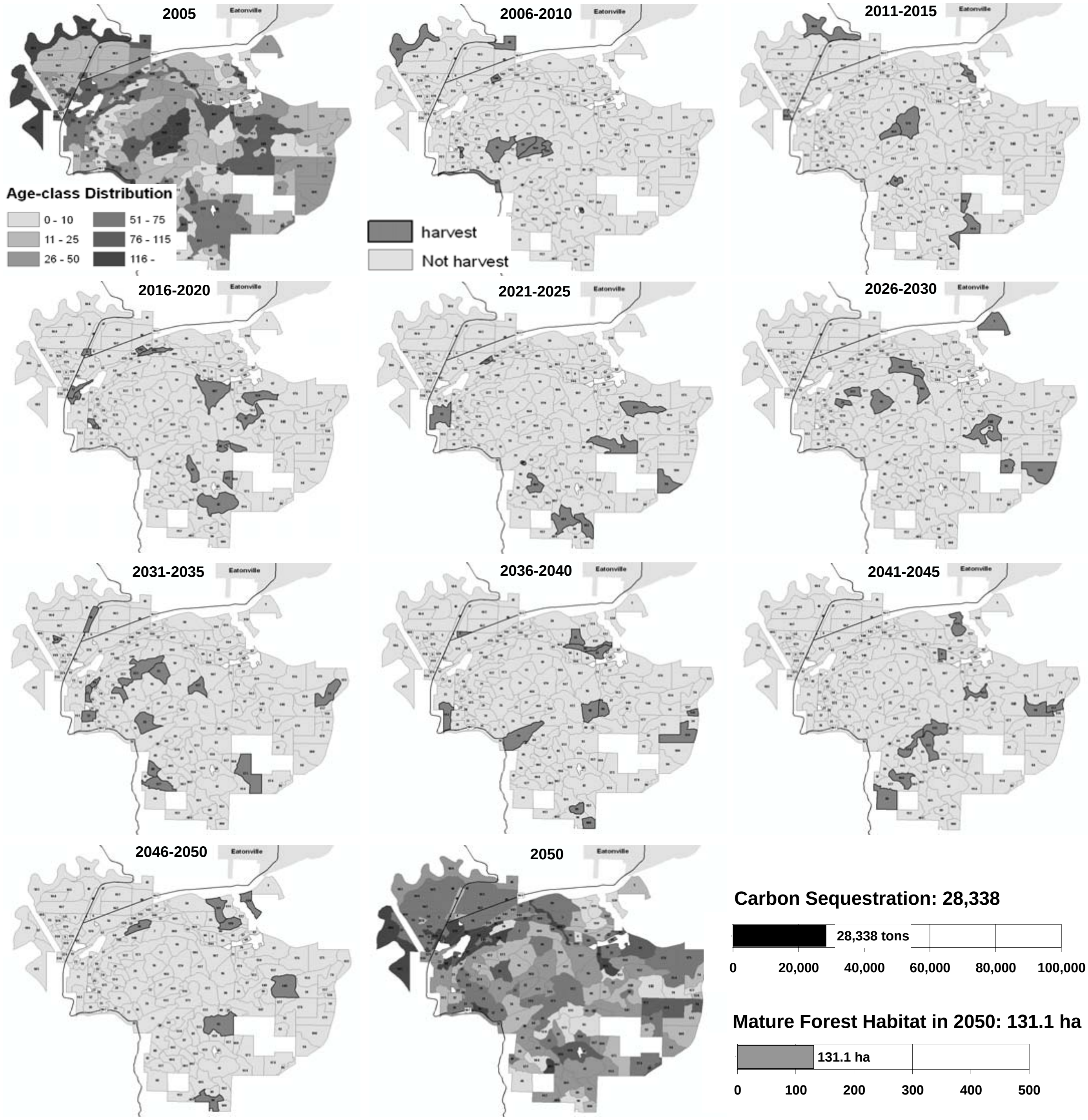

Figure 3: Spatial forest plan for Pack Forest (2005-2050) leading to Bundle 1. The map on the top left shows the current, the one in the bottom middle shows the future (2050) age-class distribution of the forest if the plan is implemented. Darker colors indicate older stands. The dark polygons on the nine maps in between show the stands that are to be cut in the respective 5-yr planning periods if the plan is to be implemented.

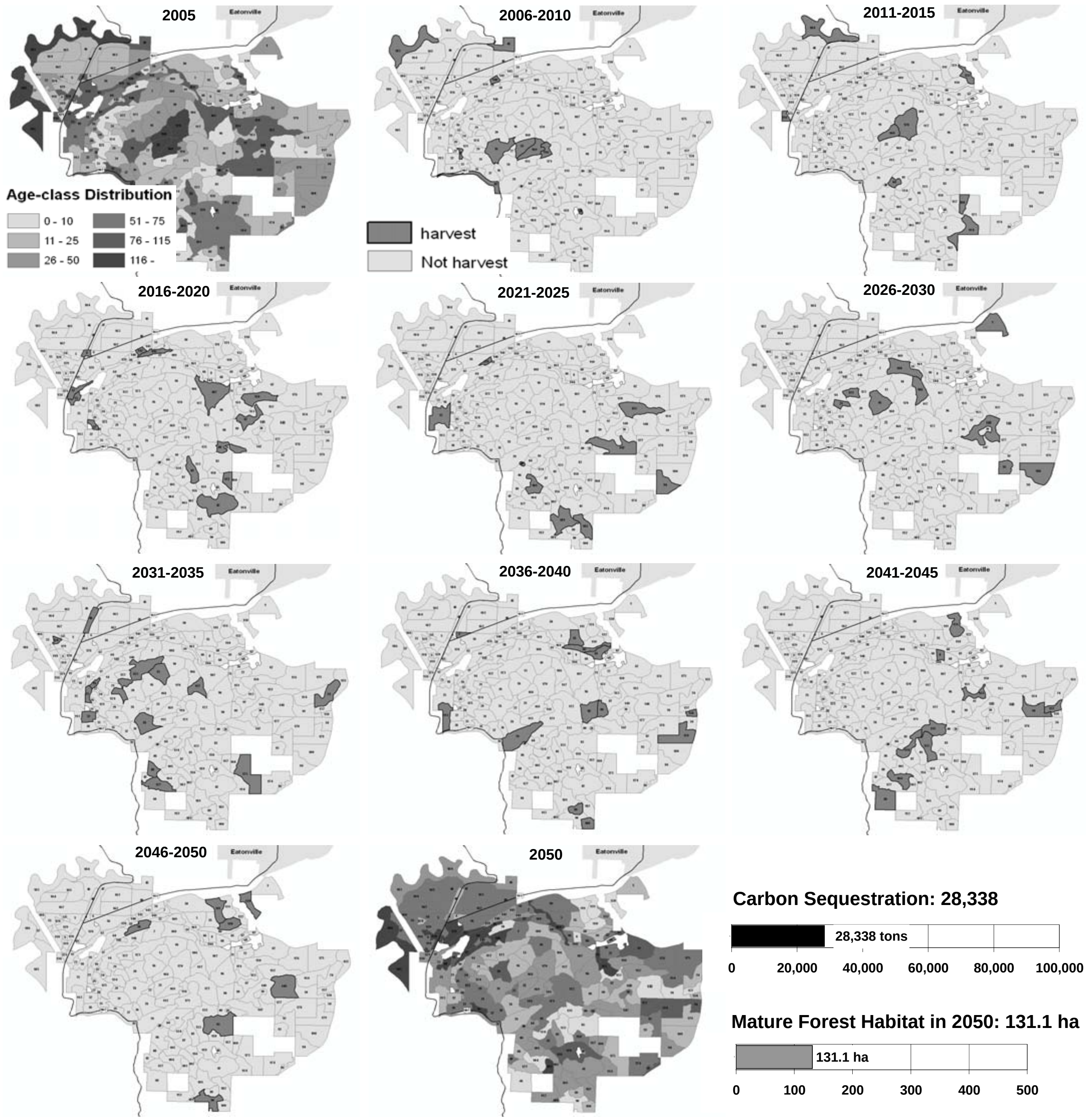

Figure 4: Spatial forest plan for Pack Forest (2005-2050) leading to Bundle 43. The map on the top left shows the current, the one in the bottom middle shows the future (2050) age-class distribution of the forest if the plan is implemented. Darker colors indicate older stands. The dark polygons on the nine maps in between show the stands that are to be cut in the respective 5-yr planning periods if the plan is to be implemented.

H_t = the total volume of sawtimber in m ^{3} harvested in period t ; and

The parameters are:

M = the set of management units in the forest (where the cardinality of M , $|M|$, is 186 for Pack Forest);

T = the set of planning periods in the planning horizon ($|T| = 9$ for Pack, based on 5-year long planning periods and a 45-year long planning horizon);

A_m = the area of management unit m in hectares;

c_{mt} = the discounted net revenue per hectare if management unit m is harvested in period t , plus the discounted residual forest value based on the projected state of the stand at the end of the planning horizon;

s_{mt} = the amount of carbon sequestered in management unit m over the entire planning horizon if unit m is cut in period t ;

v_{mt} = the volume of sawtimber in m ^{3} /hectare harvested from management unit m in period t ;

b_{lt} = a lower bound on decreases in the harvest level between periods t and $t+1$;

b_{ht} = an upper bound on increases in the harvest level between periods t and $t+1$;

C = one *cover*, or groups of contiguous management units, whose combined area is just above the maximum harvest opening size;

X = the set of all covers;

J_m = the set of all prescriptions under which management unit m meets the minimum age requirement (115 years) for mature forest habitat at the end of the planning horizon in 2050;

Age_{mt}^T = the age of unit m at the end of the planning horizon if it is cut in period t ; and

$\overline{Age}^T$ = the target, area-weighed average age of the forest at the end of the planning horizon.

Function (6) represents the traditional, commodity production function. It maximizes the discounted net revenues from the forest over the 45-year long planning horizon. The following assumptions were made. The real prices of the four major wood products that can be produced at Pack Forest; Douglas-fir (*Pseudotsuga menziesii*), red alder (*Alnus rubra*), western redcedar (*Thuja plicata*) and pulp; were assumed to be \$ 1,239/m ^{3} , \$1,416/m ^{3} , \$2,832/m ^{3} and \$495/m ^{3} , respectively (2.36 m ^{3} /1000 MBF- Briggs 1994). While we assumed that the real wood prices would not change during the planning horizon, a higher-than-market discount rate of 7% was used to hedge against abrupt changes in timber prices or against other unforeseeable events such as natural disasters. The fixed timber sale costs were set to \$98.9/ha, while the variable timber sale costs were set to \$330.4/m ^{3} for all four products. The regeneration costs were assumed to be \$516.5/ha and the timber sale costs to be \$2,300 per sale—all costs were drawn from actual costs of recent management at Pack Forest (Duane Emmons, personal communication).

Function (7) maximizes the net carbon sequestered in the forest over the 45 year long planning horizon. Coefficient set s_{mt} was calculated based on the net expected change in carbon content of standing merchantable timber in each stand between 2005 and 2050 given different harvest scenarios. Merchantable timber volume projections were provided by Pack Forest's in-house calibrated version of the Landscape Management System (McCarter 2001), and were converted to Mg carbon equivalents using Harmon et al.'s (1996) conversion function: $m_C = dVc$, where m_C is Mg carbon equivalent, d is wood density, V is timber volume in m ^{3} , and c is a volume conversion factor for carbon. A Westside Washington Cascades wood density of 0.43 Mg/m ^{3} and a volume conversion factor of 0.52 g C/g wood were used in the case study. For simplicity, soil, detritus and other important carbon pools were not accounted for in the estimates of carbon coefficients. Once the characteristics of market demand for particular carbon accounting practices becomes clear, more (or less) precise carbon estimates could populate the proposed optimization model. Finally, Function (8) maximizes the combined area of stands that are older than 115 yrs at the end of the planning horizon.

Constraint set (9) ensures that each management unit in the forest can only be harvested at most once during the planning horizon. Since none of the stands in Pack Forest are managed on a rotation shorter than 45 years, this restriction is reasonable. Constraint sets (10)-(12) ensure that the total harvest volume flow will not fluctuate beyond a certain limit from one period to the next. Bounds b_{lt} and b_{ht} determine the percentage by which the harvest volume can go below or above the level in the previous period. In this study, we set b_{lt} and b_{ht} to be equal to 0.1 and 0.2, respectively.

Inequality set (13) represents the green-up constraints, as formulated by McDill et al.'s (2002) Path Approach. These constraints ensure that the size of contiguous clearcuts never exceeds a certain limit. Washington State's Forest Practices Rules provide specific green-up criteria for landowners exceeding 48.6 ha harvests units; we used a 40.5 ha limit and some simplifying assumptions that fit Pack Forest and its small average ($<$ 10ha) and maximum (24 ha) stand size. The length of the green-up period was set to be equal to the length of one planning period, which is 5 years. Constraint (14) ensures that the area-weighted average age of the forest at the end of the planning horizon will be at least $\overline{Age}^T$. Along with the harvest flow and the green-up constraints, these restrictions protect the forest from being overharvested. The average ending age parameter was set to 50 years in this experiment, which is slightly higher than the current, 2005 average of 45 years. Constraints set (15) identifies x_{mt} as binary.

4.2 Optimization results The Pareto-efficient solutions found for the three-objective model are shown in Figure 1. Each point represents a management plan in terms of projected carbon sequestration, old-forest habitat production and timber revenues that would be attained if the plans were implemented. The 3-dimensional production possibilities frontier (a.k.a., *efficient* or *tradeoff frontier*) in Figure 1 illustrates the tradeoffs that are associated with the production of the three outputs. An interesting result of this case study is that tradeoffs exist between old-forest habitat production and carbon sequestration given the definitions we used. If the two ecosystem outputs were perfectly compatible, the efficient frontier would not be a 3-dimensional surface but a 2-dimensional poly-line. In practical terms, if the forest owner was willing to forgo some, but not all timber revenues, then he or she would have to choose from a set of management plans that lead to more carbon sequestration or more old-forest habitat production but not necessarily to a maximum of both. There are some tradeoffs, and some of these tradeoffs can be illustrated by comparing Bundle 28 with 30 (Figure 1). While both plans would lead to roughly the same discounted net timber revenues (US$8.2M for Bundle 28 and US$7.9M for Bundle 30), Bundle 28 leads to only 497.6 hectares of mature forest habitat in 2050 relative to the 872.3 hectares that would be produced by Bundle 30. On the other hand, Bundle 28 would result in almost 4 times more carbon sequestration (76,789 MgC) than Bundle 30 (21,034 MgC). It is clear that one has to weigh the relative importance of carbon sequestration vs. old-forest habitat production to make a management decision. Finally, it is important to emphasize that the tradeoffs between these two non-timber outputs might look very different if different carbon accounting was used, or if an alternative definition of "old-forest habitat" was chosen.

4.3 Bundle selection and mock auctions for Pack Forest Of the bundles found (only six are shown on Fig. 1), the Director of Pack Forest selected five (Bundle 1, 3, 28, 31, 43) for hypothetical bidding. While Bundle 1 represents the management alternative that would maximize net timber revenues for the landowner, the other four plans would lead to more of one or both of the non-timber outputs at gradually increasing opportunity costs (vertical axis). For illustration, Figures 3 and 4 map out the management plans that would lead to Bundles 1 and 43, respectively. The top left maps show the initial, while the bottom middle maps show the final age-class distribution of the forest given the two harvest schedules. Note the darker tone of the ending age-class distribution in Bundle 43. This indicates that this plan would allow more mature forest habitat to develop by the end of the planning horizon: 302.3 ha will be older than 115 years in 2050 if Bundle 43 is chosen compared to the 131.1 ha for Bundle 1. The maps on Figures 3 and 4 between the initial and the final age-class distributions show the sequence and the spatial allocation of harvest activities that would have to take place if the associated plans were to be implemented.

The reserve prices of the bundles were calculated based on forgone timber revenues. To simulate what a real auction might look like, and to see if people were interested in bidding for forest ecosystem services at Pack Forest, three mock auctions were organized. Seventy-five people including forest landowners, timber industry, academia, state officials and representatives of environmental and conservation organizations participated in the first auction. Each participant was given $10 that they could either keep or use in the auction. The five of the bundles shown on Figure 1 plus a Transfer of Development Rights (TDR) option were used for the experiment. TDR allows the buyer to develop more compactly in designated urban areas while paying compensation to the rural landowner (Pack Forest in this example) for not developing. The management plans that would lead to the five bundles were also given to the players in the form of maps such as those shown on Figures 3 and 4. The players were told that the auction pools their dollars if they are placed on the same bundle. The reserve prices were adjusted to the total dollar amount given to the participants so that each bundle could be purchased by the group. The TDR option was assigned the lowest reserve price as it would allow maximum managerial flexibility for the landowner as long as no development occurs (Figure 5). The other options would not only preclude development but they would also require that the landowner follows a particular management plan. As a reward for successful bidding, the auctioneers pledged to double the winning bids and donate the dollars to a forest conservation, carbon offsets or academic organization. The donations to these three entities were proportional to the amount of ecosystem services that would result from the winning scenario. The bidding took place in several rounds where the current totals of the bids were displayed on a large screen in a chart similar to Figure 5. To mimic sealed bids, the display was disabled during the final round of bidding.

The second mock auction was identical to the first, except that the subjects were students. The third experiment involved 14 bidders who represented a variety of environmental organizations interested in forest ecosystem services. This time, the purchasing power of the players was adjusted to their stated annual conservation

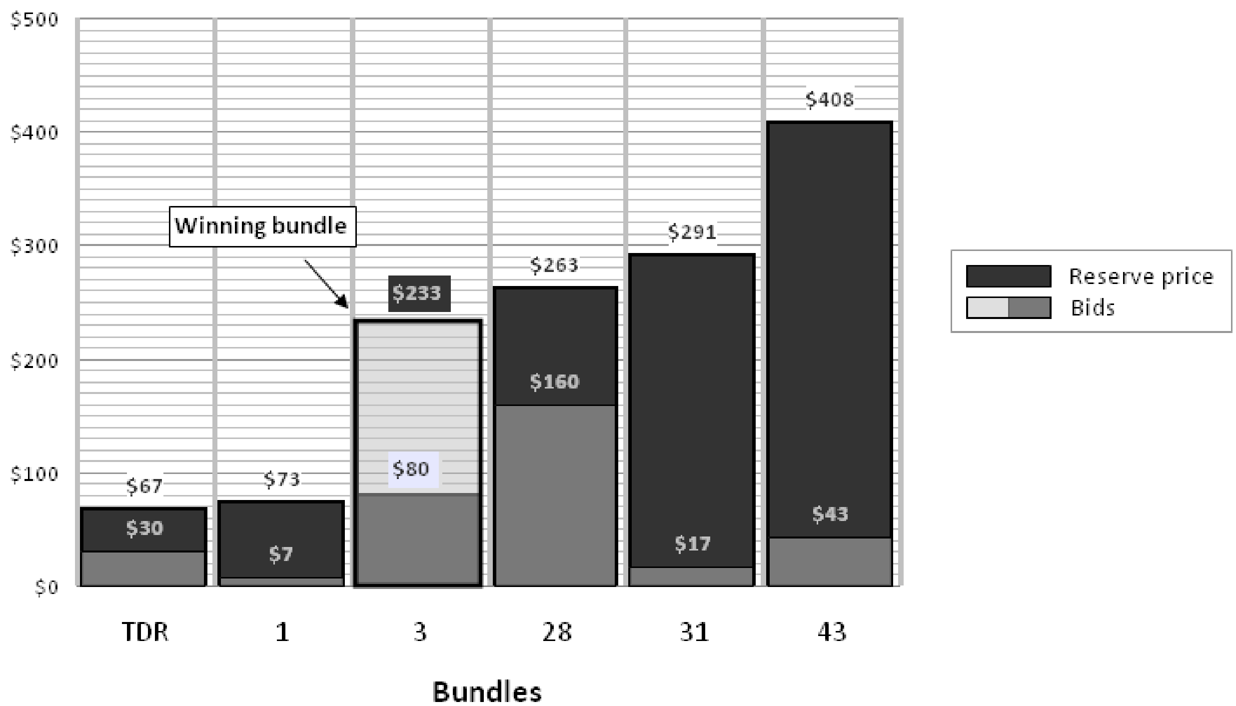

Figure 5: The final snapshot of the bidding chart used to symbolically sell old-forest habitat and carbon sequestration services from Pack Forest, Washington. The black bars are the reserve prices and the light/dark gray bars represent the aggregate value of the bids that were placed on the bundles (dark gray=those below the reserve price; light gray=those above the reserve price) (Source: Tóth et al. 2008).

budgets, which ranged from US$0 to US$1M. This information was acquired from the bidders anonymously prior to the mock auction. The dollar amounts to be allocated to the players for use in the experiment were proportional to their stated budgets and ranged from a minimum of US$2 to a maximum of US$59. Those players who represented organizations with large conservation budgets were given much larger funds than those who reported smaller budgets. A random monetary endowment was provided to those who did not volunteer a conservation budget or volunteered a small amount. As in the first two auctions, the reserve prices were adjusted to the total bidding power of the attendees. Two sessions, each comprising several rounds of bidding, were arranged: communication was not allowed among the bidders in the first but it was allowed in the second session. The players were not informed in advance about the existence of the "communication" session. Finally, prior to the mock auction, the participants were asked to identify their most preferred bundle of ecosystem services, so that we would have a grasp of their stated preferences.

Our goal was to find out (1) if bidding can occur despite the fact that the subjects had the option of keeping their monetary endowments, (2) if the outcome of the auction could be different with communication being allowed among the bidders, and (3) if the preferred bundle of services revealed by the outcome of the auctions could be different from the bundle that was preferred by the players prior to the bidding process.

5 Results and discussion

In sum, we found that (1) bidding can occur in the ECOSEL game and free riding was limited under experimental settings, (2) communication can have an impact on the outcome of the auction, and (3) the stated preferences of potential buyers of ecosystem services can be different from the preferences that they reveal through monetary sacrifices.

The final result of the first mock auction is shown in Figure 5. Bundle 3 was the winning scenario generating US$153 for the hypothetical provider. The fact that 65% of the dollars that were given to the participants were used in the auction indicates that free riding was limited and that people were interested in funding forest ecosystem services. The second mock auction, which was similar to the first, was played with University of

Washington undergraduates and resulted in Bundle 43 winning. The significance of this latter result is that free riding was again minimal despite the lower expected income levels of the subjects relative to the US$10 endowments.

The progression of the bidding in the third auction is shown in Figure 6 and 7. Figure 6 illustrates the non-communication, while Figure 7 illustrates the communication session. The communication session was terminated after the fourth round of bidding as the players expressed satisfaction with the outcome at that stage.

The non-communication session resulted in the TDR, the communication session resulted in Bundle 3 winning. This suggests that communication could lead to different, possibly more expensive outcomes – perhaps as a result of better coordination among the players. It is notable that neither of the two outcomes matched the stated preferences of the players. Four of the 14 players expressed preference for Bundle 43 prior to the auction, three expressed preference for Bundle 31. Bundle 28 and 3 were both preferred by 2 players each and the TDR Bundle and Bundle 1 were preferred by one player each. Finally, one player did not specify any preference.

The non-communication session generated US$9, the communication session generated US$17 for the hypothetical provider. Forty-two percent of the money that was put into play was used in the non-communication auction, and 52% was used in the communication auction indicating that the effects of free riding were limited and willingness to promote ecosystem services existed among the attendees. Finally, the results in Figure 6 and 7 suggest that the relative standing of the competing management plans in the auction can change dramatically as a result of revised bidding strategies, or perhaps, as a result of the changing values of the players.

While the mock auctions in this study served only to illustrate the ECOSEL concept and were not meant to provide formal data in support of certain features of the auction design (e.g., communication policy) or the potential efficacy of the method, our observations of the players' behaviors suggest that bidding can occur in the proposed game and the outcomes can vary depending on the design. Since the design variables of the ECOSEL game are not limited to whether or not communication should be allowed among the bidders, extensive experimental testing must take place in order to streamline the mechanism before a real auction is administered on the ground. The list of key variables that need testing includes (1) the reserve price disclosure policy, (2) bid withdrawal and reallocation policy, (3) communication policy, and (4) the number of bundles to offer for bidding.

Reserve price disclosure refers to the decision whether or not reserve prices should be revealed to the bidders during the auction, or should be kept hidden and the players would be notified only if a particular reserve price has been met. Rules for bid withdrawals or reallocations could also make a difference in the outcome of the auction, and so could the communication policy. On the one hand, subject communication may act to erode seller profits as bidders coordinate to just exceed reserve prices, thereby undermining the incentives for the seller to participate in ecosystem markets, while on the other hand, subject communication might help to focus the buyers and increase the provisions of ecosystem services. The number of bundles of services presented for the auction might also affect auction performance. A small number of bundles might provide insufficient flexibility and the subjects might be unsatisfied with the choices offered. At the same time, a large number of bundles may prove to be too difficult for the subjects to analyze and this might result in scattered bids preventing convergence towards a potentially successful outcome (as in Bagnoli et al. 1992). Finally, the optimal choice of design might also depend on the objectives of the auctioneers. An auction mechanism might be sought that maximizes the net benefits to the provider. Another could maximize social surplus and achieve efficient public provisions of ecosystem goods. The empirical and theoretical testing of the key design features, as well as the method's capability to increase the public provision of ecosystem services are the subject of ongoing research. The preliminary results are summarized in Tóth et al. (2009).

5.1 Novelty and limitations The ECOSEL concept has two major innovative elements. The first is using the notion of Pareto-optimality (Pareto 1909) in designing *Pareto-efficient* bundles of public goods that are produced by mutually-exclusive forest management plans. The second is a two-phase auction mechanism that attempts to sell these plans by inducing collaborative bidding through an initial open bids phase, and by sealing the final round of bids in order to minimize free riding and increase seller revenue.

The concept of Pareto-efficiency has apparently never been used to determine which bundles of public goods should be put up for an auction and at what reserve prices. ECOSEL's optimization module uses the concept of Pareto-efficiency to identify forest management plans that lead to various bundles of ecosystem services at minimal opportunity costs. These opportunity costs then serve as bases for the reserve prices in the auction. The benefits of finding management plans (i.e., bundles of ecosystem services) with minimal reserve prices are twofold. First, lower prices are more likely to attract bidders, which in turn could increase the auctioneer's revenues. Second, the auctioneer's credibility is greatly

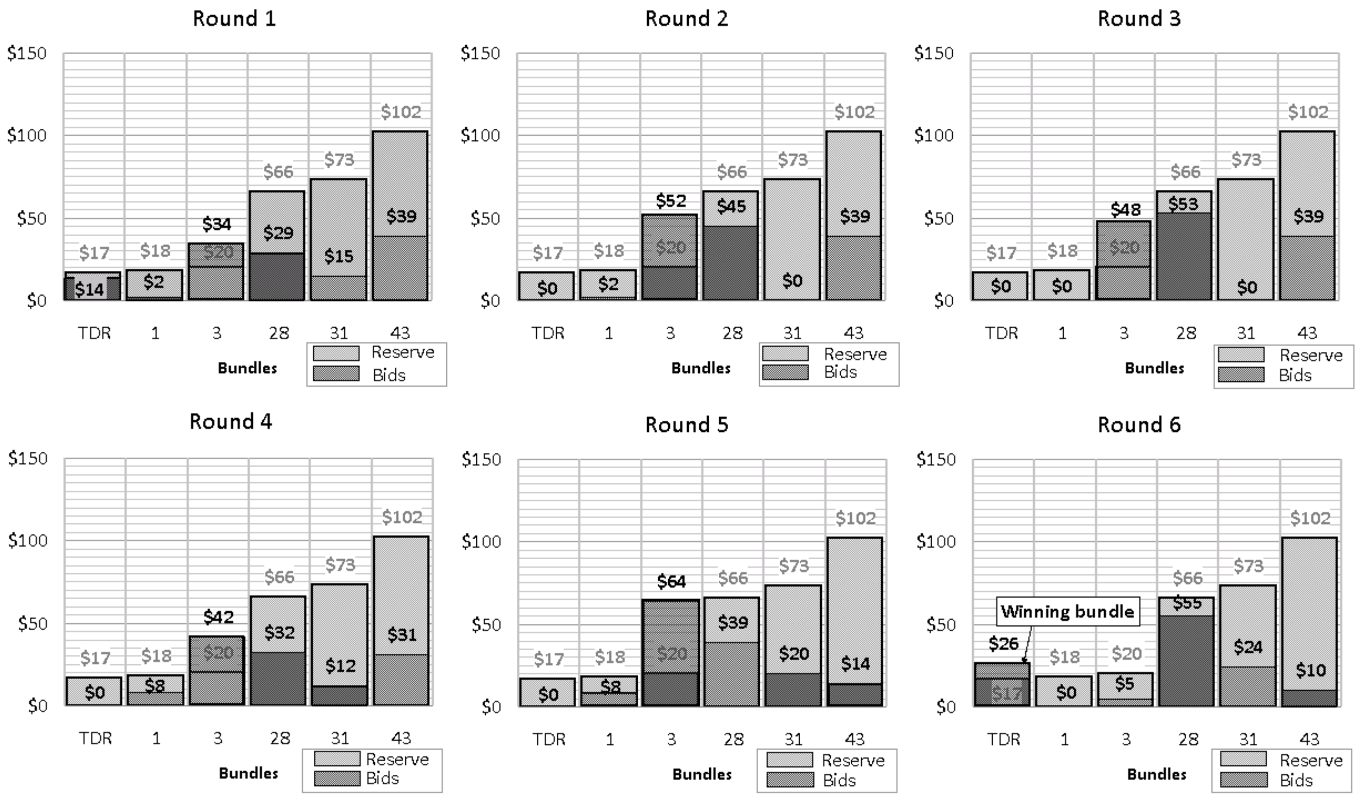

Figure 6: The progression of bidding in the non-communication auction. Light gray bars represent the reserve prices and the darker bars represent the accumulated bids in each of the six bidding rounds.

enhanced if, after presenting the available options to the potential buyers, he can show that no other management plans exist that would lead to similar bundles of ecosystem services at a lower cost, or would lead to better bundles at the same opportunity cost (i.e. the bundles are Pareto-optimal).

From an auction theoretical perspective, our proposed two-phase mechanism resembles the *Anglo-Dutch* auctions (Klemperer 1999) in that it attempts to maximize the sellers' revenues by combining an open bids process with sealed bidding to encourage entry and to stimulate players to bid close to their true values. ECOSEL can be viewed as a *competitive* public goods contribution game with multiple thresholds and a refund, where, instead of a single item, multiple, mutually-exclusive bundles of public services are offered in the form of management plans. Contributions are solicited for these plans simultaneously, and the plan where the combined value of contributions most exceeds the reserve price (a.k.a., the *provision point*) will be implemented, and the contributions are fully refunded should the bids fall short of any bundle threshold. To our knowledge, this is the first study and application of a multiple-unit, multiple-dimension public good subscription game of incomplete information. *Incomplete information* refers to the fact that the players of the ECOSEL game don't have complete information about the other participants; their values, in particular, with respect to the services being sold. In addition, the mutually-exclusive nature of the items for sale also differentiates ECOSEL from combinatorial auctions (Rassenti et al. 1982), where combinations of several items can be sold to different bidders and the question is which combination should be allocated to which bidder to maximize the auctioneer's revenue. We note that the forest landowner could theoretically divide his land into several pieces and conduct separate auctions for each piece sequentially or simultaneously. This extension of the technique is subject to future research.

One important feature of ECOSEL is that it allows potential buyers of forest ecosystem services to view the other buyers' anonymous bids before they make a contribution. Even after a bid is placed, the bidder can re-

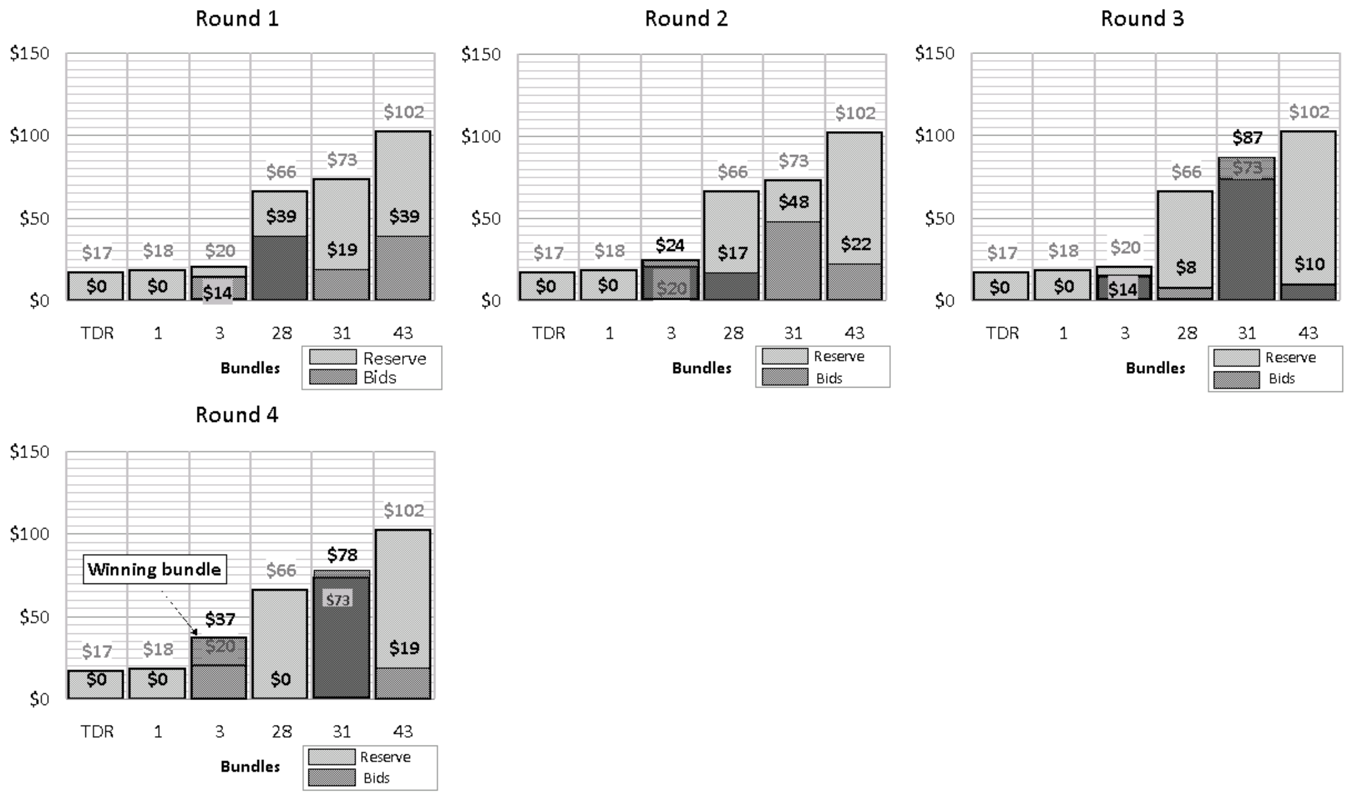

Figure 7: The progression of bidding in the communication auction. Light gray bars represent the reserve prices and the darker bars represent the accumulated bids in each of the six bidding rounds.

allocate, or possibly withdraw the bid in the light of new information about the other players' behavior. ECOSEL is therefore also a learning tool that stakeholders can use to better understand their own preferences with respect to forest ecosystem services. While in private goods auctions, most bidders have a good estimate of how much a particular item is worth to them, in the case of public goods, this is not likely to be the case. The monetary value of forest ecosystem services is poorly understood. The open format of ECOSEL encourages bidders to send signals, cooperate and strategize anonymously as they learn which options are preferred by others. The idea is that buyers with relatively small purchasing power can join forces with others to raise dollars in order to make a management alternative succeed in the auction even if the reserve price of that alternative is high. Moreover, since compatible services such as carbon sequestration and old-forest habitat production can be bundled in this framework, bidders seeking carbon credits can join those who care more about old-growth forest habitat, and share the costs of a particular management plan that provides both of these benefits at the same time.

ECOSEL makes use of an auction technique, sealed bidding, in an attempt to discourage free riding. When the auction is sealed, the bidders are not allowed to see each other's bids. Sealed bidding and a refund guarantee is likely to be beneficial to the seller's revenues because it prompts players to place bids that better mirror the final values that they assign to the services being sold.

Another key issue in forest ecosystem markets, besides free riding, is defining baseline management plans, or equivalently, baseline ecosystem service provisions. One of the primary functions of a market mechanism like ECOSEL is a capacity to induce change in on-the-ground management in response to market demand that leads to more ecosystem services than would otherwise be provided. To verify that a positive change is indeed occurring (additionality), a baseline must be established. Typically, establishing a baseline not only requires extensive measurements of the current attributes of the ecosystem but it also requires a great deal of guesswork with respect to what would happen to these attributes if no action was taken. Making matters worse, the provider of an ecosystem service has no incentive to share his true baseline if it is little or no different from the management scenarios that would allow him to sell the services at a profit. Setting a baseline in a cap-and-trade program translates to defining the cap on carbon emissions or on other negative externalities for an industry or a region. The collapse of carbon prices in the European Union Emissions Trading Scheme (from 30 in April 2006 to 0.1 in September 2007), in response to news that some member countries might have issued overly generous caps, shows just how hard it is to define a baseline that drives a functioning market (European Union Emissions Trading Scheme, 2009).

Perhaps the biggest advantage of ECOSEL over conventional regulatory mechanisms is that it can allow the baseline to be set dynamically by the market (i.e., by those bidders who support management options that lead to reduced provisions of eco-services) making the issue of additionality irrelevant to the process. While some management options in an ECOSEL auction might lead to increased ecosystem services, other options can be included that increase timber production or real estate development. When developers bid against timber or conservation interests, there is no need to define reserve prices as the baseline management plans are defined dynamically by the bids placed on the competing services. If the volume of bids occurring on real estate development or intensive timber production options is minimal, then the reserve prices associated with ecosystem services provisions will be low and conservation groups might need to take little or no action to achieve their goals. If, on the other hand, the real estate or timber value of the land in question is high, evidenced by the bids placed on these options, then conservationists would need to raise more dollars to outbid the timber and development interests. Ultimately, the final, sealed bids phase of ECOSEL would stimulate each of these competing groups to place bids that best represent their true preferences. Since the purchasing power of the timber and real estate industries reflects the preferences of the broader population, one can argue that bidding induced between conservationists and industry is a powerful way of measuring the dollar values that people are willing to assign to forest ecosystem services.

A seller would also be endowed with a flexibility to reveal their "stewardship ethic" by either constraining the set of bundles or by not offering a development and/or intensive timber production bundles for sale. As an example, a seller could explicitly offer to shoulder some of the opportunity costs, providing bidders with a "seed capital" (see, e.g., List and Lucking-Reilly 2002) which might increase the efficiency and effectiveness of the mechanism. In contrast, the landowner could choose only expensive, high ecosystem service management plans to contrast against relatively cheap maximum timber revenue options and almost assure an outcome of maximum or near maximum timber harvest–if they can attract bidders at all.

The limitations of the ECOSEL approach must also be highlighted. ECOSEL is an optimization approach, and as such, it has computational boundaries. Solving multicriteria mathematical programs, which is necessary to generate the Pareto-efficient management alternatives for the auction, can be computationally challenging if the modeling variables are discrete, as is the case in spatial forest planning. Moreover, the fact that forest management activities must be scheduled over time adds a temporal dimension to the complexity of the spatial optimization problem. In addition, depending on market demand for particular ecosystem services and accounting practices, further modeling needs might arise. For example, conservationists might want to buy old-forest habitat services only if these occur in large contiguous patches providing interior habitat for wildlife. Modeling old-forest habitat in large patches is possible (see Rebain and McDill 2003, a, b or Tóth and McDill 2009) but it makes the optimization problem harder to solve. In sum, computational boundaries limit the spatial and temporal scale at which ECOSEL can be applied today. One way to mitigate this problem is to divide the land into smaller, computationally viable pieces, and run multiple auctions, or to cut the time horizons and sell ecosystem services over shorter contract periods. A second mitigating factor is that technology is constantly improving, pushing the computational boundaries further back every day.

Lastly, the ECOSEL approach requires an up-front investment by the seller, who needs to gather the necessary inventory and growth and yield data to feed the optimization module, which in turn will inform the management plans for the auction. While these up-front costs could be priced in the reserve prices, there is a chance that the auction fails to generate enough dollars to allow a departure from the default, business-as-usual management plan. This would lead to a net loss to the seller. While a good understanding of the local real estate market and therefore the value of developing or preserving the land would allow the seller to make an informed decision whether to initiate an ECOSEL project or not, there is risk of loss as is the case with most investments. Similar tradeoffs and risks apply to the up-front disclosure of private information on the part of the seller to the potential bidders about their resources.

The success of ECOSEL auctions is likely tied to a number of factors including: 1) proper valuation of timber products and their costs of production, 2) selection of desirable ecosystem services, 3) creating bundles that offer opportunity for broad public agreement, 4) offering a sufficient range of options to attract diverse bidders, 5) properly analyzing and displaying data, and 6) educating bidders on the opportunity and trade-offs provided by various bundles. The most important element in facilitating a successful auction is for bidders to trust every step of the process from data collection and analyses, to the selection of bundles, through the commitment of the landowner to follow through on any selected management option. Landowners who initiate the process focused primarily on the financial bottom line may insufficiently build trust and therefore find few bidders willing to support their efforts.

6 Conclusions

In this article, we introduced a new approach for creating forest ecosystem service markets. The new approach combines multi-objective optimization with auction theory in an attempt to match willing sellers of ecosystem services with willing buyers. We provided a conceptual and a mathematical characterization of the proposed mechanism and illustrated the concept by using real data from an existing piece of working forestland and by simulating the bidding process via mock auctions in stakeholder meetings.

The results from the mock auctions suggest that the ECOSEL mechanism can induce bidding, at least under experimental settings, and that free riding is not necessarily the prevailing strategy of the players. We also found that design options such as allowing communication among the players can have an impact on the outcome of the auction and that the outcomes themselves might reflect very different preferences than those stated by the players prior to the bidding process.

ECOSEL was designed to improve economic efficiency of forest ecosystem service provision by capitalizing on monetary sacrifices that people (both potential buyers and sellers) are willing to make to ensure these goods. ECOSEL can induce change in on-the-ground management towards programs that are attentive to the health and integrity of the resource, only if sufficient willingness to pay for these services exists. If this willingness exists and ECOSEL is broadly applied, the impact on forest management, and on the livelihoods of forest-dependent communities, can be substantial. Depending on how "willing" and able people are to preserve forests and ecosystem functions, a lesser percentage of private forestlands would be converted to real estate or subjected to exploitative management practices. Rural communities and Native American tribes, who are impoverished by waning demand for locally-produced timber and/or increased competition with imported timber, could potentially revitalize their economies and cultures by selling forest ecosystem services. The public would also benefit from ECOSEL by gaining access to a platform that allows them to directly influence land management decisions, through competitive bidding, on private properties that provide public goods.

If the willingness to make monetary sacrifices for forest ecosystem services is negligible, ECOSEL will not be able to influence land management. Still, tangible, transaction-based data, even if it suggests little or no willingness to pay for ecosystem services, can be helpful to policymakers in identifying how much regulatory intervention is needed to promote these services to assure long-term social welfare.

As a decision tool, ECOSEL may also be applied to public forests. Different people want the public forests to be managed in different, often conflicting ways. Since only one management plan can be applied to a piece of land over a specific period of time, compromises must be made. ECOSEL can help in finding compromise management plans that best reflect public preferences as evidenced by the monetary contributions that people are willing to make to fund these plans.

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