Impacts of transportation costs on biodiversity: an application in forestry

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1 Preamble

In the past century, alteration of the natural land base is thought to have extirpated or caused the extinction of thousands of species worldwide. Since species are global public goods, various efforts have recently evolved that attempt to conserve biodiversity at regional, national, and international scales.

In forestry, such efforts have translated into conservation easements, land exchanges, foreign debt retirements, land withdrawals (in the form of nature reserves), conservation payments, and a host of governmental restrictions (e.g. in the U.S., Northwest Forest Plan) and non-governmental pledges (e.g., forest certification) for more environmentally responsible harvest practices. While these specific actions may be well-intended, it is unclear how each impacts biodiversity.

Furthermore, the role of transportation costs in moving timber from the forest to processing centers has been neglected in modeling impacts of various conservation plans on threatened and sensitive species. In this paper, the impact of common forest harvest regulations and land use restrictions is examined to explore how these can alter the distribution and abundance of the species such provisions are intended to protect. Through optimization, individual landowner decisions are simulated and aggregated according to a regional economic model of timber production. The economic model is maximized over a planning horizon subject to common harvest regulations. Results from the different policy scenarios are then simulated in a sophisticated wildlife simulator to measure likely impacts on species of concern. Preliminary findings suggest that when transportation costs are included in forest landowner harvest decision-making, regional harvest regulations can have a negative effect on biodiversity. This finding is particularly relevant since transportation costs typically are considered when developing conservation plans.

2 Background

Central Place Theory defines a minimum market threshold or geographic market area required to allow a firm to continue operations. This theory assumes monopolistic competition whereby any profits, beyond the opportunity costs of the entrepreneur, are eliminated by new firms entering the market, thus leading to the idea of a minimum threshold or market size necessary for a firm to survive.

A more general augmentation of Central Place Theory is that firms locate where costs are minimized, leading to the maximization of profits. The von Thunen model, based on transportation costs and land rents, states that a firm will locate within a sphere or “von Thunen sphere” where at the center lies the market center. At the market center land rents will be highest but transportation costs to the market center are lowest. As firms locate farther out in the sphere, land rents decline but transportation costs increase, offsetting the drop in rents. Outside the sphere, firms will choose to not participate in that particular market since transportation costs will be too high to be competitive.

In forestry, timber must be transported from the forest to mills for value-added processing. If the mill is defined as the market center and a firm is defined as a forest landowner, then the mill’s sphere of influence includes all landowners who can profitably harvest timber by transporting it to that market center. Despite fixed distances from the market center to individual forest owners, the relationship between mill and landowner is not static. Landowner profitability depends on several factors. These include prevailing market conditions such as demand and prices for timber; advances in silvicultural practices that increase the forest’s growth rate; and the age of the stand since per unit transportation costs decrease with stand age (this follows because larger trees contain more board feet, resulting in less nonmerchantable material at the mill site).

With regard to biodiversity, species viabilities are a function of the habitat quality on the landscape. Landowner harvest decisions affect habitat quality both spatially and temporally. Therefore, species viabilities are dependent on the market center’s sphere on influence. For example, rising commodity prices can offset a landowner’s otherwise prohibitive transportation costs and thereby increase the geographic radius of the mill’s sphere of influence. However, land use regulations—whether governmental or self-imposed—can also impact market dynamics.

Governmental regulations and nongovernmental pledges only affect the timber supply. As the severity of these constraints is increased, the supply of timber is effectively decreased. Assuming that demand for wood fiber-based products does not change, a decrease in supply thus increases prices for timber. The net effect is an increase in the market center's sphere of influence, meaning that forest owners who were once priced out of the market can now participate by harvesting. However, the age of the more distant stands would be expected to be older than stands located closer to the market center, and the harvesting of more distant, older stands could potentially remove important late seral habitat for species of concern.

Governmental and nongovernmental constraints on harvest operations typically do not take into consideration transportation issues, but such constraints endogenously move the market center's sphere of influence. As the radius changes, so do the locations of current and future habitat, leading to ex post changes in species persistence. Therefore, it is anticipated that species persistence can be modeled as a function of transportation costs (among other inputs), and such a model might be capable of delineating critical economic and biophysical thresholds.

3 Ecological and economic sub-models

Past efforts at projecting wildlife population responses to management regimes have been hampered by computing power, available species data, and shortage of suitable models. Recently, technological enhancements and increased availability of species vital rates, habitat preferences, and dispersal information have accelerated the development of species simulators with increased realism and flexibility. One such wildlife simulator that was developed and is used by the US Environmental Protection Agency is PATCH (a Program to Assist in Tracking of Critical Habitat). PATCH is a spatially explicit, stochastic simulator that uses GIS imagery to link a vertebrate's life history characteristics to the quality and distribution of habitat throughout a landscape. The software was specifically designed to work with complex landscape structures composed of different habitats of various shapes, sizes, distributions, and qualities. The model simulates a population of individuals that are born, disperse, breed, and die. Landscape change is simulated by loading different maps of habitat quality as time progresses, and the subsequent effects on species populations (hence on extinction or extirpation risk) are explicitly followed.

The results presented in this work use PATCH to measure the impact on selected species from different types of harvest constraints. By simulating with PATCH the management regimes found by the optimization model, viability and risk can be directly estimated. In addition, potential contributions to habitat from non-reserved sites or areas with altered management intensity are included, even if they offer no improvements.

Society receives multiple market-based benefits from resource extraction that can be approximated with a standard economic measure of welfare—the sum of consumer and producer surpluses. The measure can be applied at both a landowner and regional scale to more comprehensively relate costs of a conservation strategy. Furthermore, welfare from resource extraction can be measured over multiple, linked time periods. The sum of regional consumer and producer surpluses is used here as a means of simulating competitive market equilibrium outcomes at a landscape scale. For simplicity, it is assumed that ownership behavior is predictable in that an individual ownership will attempt to maximize its financial return over a planning horizon subject to its harvest and transportation costs, market conditions, and governmental or self-imposed restrictions. It is also assumed that an individual owner is a price-taker in the market place. An ownership's extraction decisions then are made taking into account current and perceived future prices for the resource, which are based in part on regional demand and total quantities extracted per time period. To simulate collective ownership behavior at a landscape level, regional demand for the resource is used in this paper to dynamically set a price based on the total quantity extracted per time period. For example, if a conservation strategy decreases the available supply of a resource (e.g., through land withdrawal or restrictions on allowable practices), then this increases the market center's sphere of influence and thus permits the harvest of more distant stands that may be of greater habitat value to critical species.

To model economic and ecological interactions at a larger scale, the summation of consumer and producer surpluses aggregates incremental ownership decisions to simulate impacts on habitat at both the landowner and regional level. This links the economic to the ecological component of the system. Further, the model has flexibility to adjust likely management actions at the individual level based on changes in market price and regional supply and demand. This is more appropriate and realistic than a typical assumption of non-changing prices per period and negligible transportation costs when modeling at larger spatial scales.

4 Optimization model

To formulate the objective function, the following notation is used. Let $j = 1, \ldots, M$ refer to a specific management area or ownership, and $t = 1, \ldots, T$ represent each time period in the planning horizon. Further, index unique harvest prescriptions $w = 1, \ldots, W$ that could be assigned to unit j over the planning horizon. For the purposes of this work, it is assumed that each unit j can either be clear-cut or no action taken in each t; hence, there are 2^T possible prescriptions.

Define binary decision variables:

$$x_{jw} = \begin{cases} 1 \text{ if unit } j \text{ is assigned prescription } w \\ 0 \text{ otherwise} \end{cases}$$

and parameters:

h_{jt}^{w} = quantity of the resource taken from unit j in period t according to prescription w; in forestry, this time-series of amounts corresponds to harvest volumes that come directly from a growth and yield simulator and depend on unit j's age class at the outset of the horizon, as well as the time between harvests

Q_t = total harvest volume in period t such that $Q_t = \sum_{j=1}^{J} h_{jt}^{w}$

$D_t(Q_t)$ = log demand price as a function of total harvest volume in period t

c_{jt}^{w} = harvest and haul cost for unit j in period t as determined by prescription w

r = discount rate.

The partial optimization model is then:

Max
$$\sum_{t=1}^{T}\left(\int_{q=0}^{Q_t} D_t(Q_t)\partial q - \sum_{j=1}^{M} c_{jt}^{w}\right)\frac{1}{(1+r)^{t-1}} \qquad (1)$$

subject to:
$$\sum_{w=1}^{W} x_{jw} = 1 \qquad \text{for } j = 1, \ldots, M \qquad (2)$$

$$x_{jw} = 0 \text{ or } 1 \qquad \forall\ (j, w) \qquad (3)$$

Equation (1) represents the discounted sum of consumer and producer surpluses. For each period t, the regional price for the quantity of the resource extracted in that period is determined from the price-quantity relationship given by the continuous demand curve for timber. What this means at the ownership level is that if the harvest and transportation costs exceeds revenue during any t, then extraction will be postponed. This feature is particularly useful if a resource grows in value over time. The optimal solution of (1) consists of the combination of extraction decisions over a region and planning horizon that maximizes an individual owner's return on average, and thus maximization simulates aggregate landowner behavior. Pertaining to forestry, each planning unit j can be harvested multiple times over the horizon to reflect the range of options afforded by different starting conditions (e.g., beginning forest age classes) and price fluctuations between periods. Individual ownership extraction decisions are aggregated to a regional level by defining the total quantity in t, Q_t, as the sum of all quantities extracted by individual ownerships in t. Constraint (2) ensures that only one set of harvest activities is assigned to unit j. Lastly, constraint (3) restricts all management decisions to binary values in each time period to reflect an ownership's option to either "do something" or "do nothing" in each t.

Land withdrawals aimed at promoting species protection are depicted by permanently eliminating timber harvests on reserved lands without production constraints on non-reserved lands. Let $p = 1,\ldots, P$ index a generic reserve proposal, and let R_p define the set of management units j that are to be reserved under proposal p. Regional economic impacts of each of these three reserve proposals can be assessed by maximizing (1) subject to (2), (3), and the restriction that all units j in reserve proposal R_p cannot be harvested over the planning horizon.

Another approach for species conservation in forestry is represented by common forest certification regulations. Adjacency and green up restrictions are typical aspects of such conservation plans. Adjacency restrictions disallow harvests during the same time period on forested parcels within a neighborhood of the harvested stand. Green up restrictions are temporal extensions of adjacency constraints that disallow harvests within a neighborhood for a pre-specified number of time periods.

Adjacency and green-up restrictions were allowed to vary for this study since these were expected to have greater impacts on the two species of concern. To develop the optimization model for forest certification-type regulations, the following notation is introduced. Let A_j^1 refer to the set of units that share a common edge or node with unit j, and let A_j^2 refer to the set of management units in A_j^1 *and* the additional units that share a common edge or node with any units in A_j^1 (but excluding unit *j* itself, so that $j \notin A_j^1$ and $A_j^1 \subset A_j^2$). Let *G* represent the number of time periods that must pass before harvesting can occur in any of the units in A_j^1 or A_j^2 if unit *j* is harvested. Also, let *d* = the required adjacency neighborhood, so that *d* = 1 or 2. Regional economic impacts of each set of certification restrictions may be assessed by maximizing (1) subject to (2), (3), and the specific set of adjacency and green up restrictions to be explored.

5 Application and expected results

The economic, ecological, and optimization models are applied to a 2 million ha forested landscape in Oregon, U.S.A. The area was remotely sensed and classified by dominant land use type with pixel resolution of 30 m. Coniferous forest types were further delineated into 10-year age classes. The existing road network and location of processing centers was overlaid to obtain estimates of transportation costs from each unit j to each processing center.

Different land withdrawal proposals and forest certification regimes will be imposed through specific constraints, and the augmented optimization model will be solved over a 100-year planning horizon with decadal time increments. For each management unit *j*, there are therefore 2^{10} possible courses of action. Since the application contains approximately 19,600 autonomous ownerships, the total number of decision variables (approximately 20 million) prohibits exact solution, and so a variant of Simulated Annealing will be employed.

Each solution will then be assessed in the wildlife simulator, PATCH, to measure how well each management strategy promotes biodiversity. This will be done for two species—the Pacific fisher (a cousin of the mink) and the Pileated woodpecker—that are considered to be threatened by the Oregon Department of wildlife. Both species differ in their habitat requirements, movement abilities, and vital rates.

Further, for each management strategy, the timing and location of harvest decisions can be explicitly tracked, and per unit transportation costs will be recorded to assess how the sphere of influence of the processing centers changes relative to each type of conservation plan. Cost curves that plot how aggregate transportation costs impact the different species will be developed. From preliminary work, it is found that certain conservation policies strongly influence the radius of the market center's sphere of influence, resulting in reduced population sizes of critical species. This suggests unintended policy externalities on population sizes—and thus biodiversity—can be modeled as a function of transportation costs.