Outline of a market for ecological connectivity

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Abstract

The paper starts with a short literature review on the relationship of biodiversity to ecological connectivity. A recent article in the journal *Nature* identified the world's biodiversity loss as far exceeding humanity's safe level. Other work has identified ecological connectivity – the ability of species to move across land – as critical for biodiversity.

This paper then explores ideas for using a market to improve ecological connectivity. The markets should incentivise relevant parties, such as government agencies and farms, to implement specific changes to roads and other barriers to wildlife, to improve ecological connectivity within a given budget.

A simple market approach could be a government procurement, in which local agencies and large land owners bid to connect ecological islands for a given amount of money. The government then accepts the bids in rank order of the highest ecological value per dollar, until the budget is used up. This is similar to the Victorian Bush Tender programme. This paper explores how this procurement might be operated.

However, the ecological value of connecting two regions can depend on whether those regions are connected to other regions. Consequently, the problem may need to be solved with an integer program. A more sophisticated market, therefore, would use a combinatorial optimization for clearing. This paper explores how such a combinatorial market might be operated.

Finally, the paper briefly examines the rights associated with ecological connectivity. Ideally, users would trade with each other, rather than simply have an expensive government procurement. But this will require an enormous change in mindset, and the nature of the tradable rights is highly complicated.

1 Intro and lit review on ecological connectivity

This paper gives some very early and preliminary thinking about a possible market for ecological connectivity, a critical support for biodiversity. The problem seems important enough. The United Nations has declared 2010 to the International Year of Biodiversity (CBD 2010). In a recent *Nature* article, Rockström *et al* (2009) identified the current rate of biodiversity loss as far exceeding humanity's safe level. "Today, the rate of extinction of species is estimated to be 100 to 1,000 times more than what could be considered natural. As with climate change, human activities are the main cause of the acceleration." They go on to describe how biodiversity loss erodes the resilience of the biosphere, especially in conjunction with climate change, and disruptions to the nitrogen cycle. In a recent *Science* article, Marton-Lefèvre (2010) writes, "…the International Union for Conservation of Nature documents the extinction risk of 47,677 species: 17,291 are threatened, including 12% of birds, 21% of mammals, 30% of amphibians, 27% of reef-building corals, and 35% of conifers and cycads." She points to cost estimates of this loss "between 1.35 and 3.1 trillion U.S. dollars." The Harvard entomologist EO Wilson (2004) estimated that half of all species could be extinct by 2050.

Biodiversity loss has many causes, including climate change, pollution, introduction of exotic species, commercial overharvesting, and conversion of natural habitats for human use (McCallum and Dobson, 2002). This paper focuses on the last of these. Perhaps surprisingly, the greatest ecological diversity is found not in forests or nearby savannahs, but rather in the ecological gradient between them (Smith et al, 2005).

However, humans criss-cross the environment with sharp lines, for aesthetics (such as building to the edge of waterways), for legal boundaries, and especially for transportation. Transportation networks break up regional ecologies into islands, and create barriers between the islands. In the few places where society has attempted to maintain a region with ecological health, the region has generally been identified by a uniform structure, such as a forest, rather than an ecological gradient (Smith et al, 2005). An ecological gradient is called ecotone. By constructing sharp boundaries through the middle of ecotones, in between the uniform islands (Figures 1 and 2), ecological diversity tends to be reduced.

Figure 1. Riccarton Bush, Christchurch, is an example of an ecological island. Source: Google Maps, 4 Nov 2010.

Figure 2. Ecological fragmentation in Indiana Dunes National Park. Source: Wikipedia, 4 Nov 2010.

Researchers have studied how ecologies are improved by connections, and have developed measures for ecological connectivity (Calabrese and Fagan, 2004; Hartig and Drechsler, 2008a; Kindlmann and Burel, 2008; Marulli and Mallarach, 2005; Moilanen and Nieminen, 2002; Nikolakaki, 2004; Schulte et al., 2006). The measures range from simple to elaborate, can depend on land characteristics, and can vary by species. The measures sometimes include the probability that a species survives.

Work has also been done on models to solve the connectivity problem (Duque et al., 2007; Hajkowicz et al., 2007; Haunert, 2007; Tóth et al., 2006). These models, sometimes called "regionalization models", are typically very hard integer programs, and can be difficult simply to formulate, much less to solve. A land parcel may be modelled as a node, and neighbour adjacency may be modelled as arcs. The regionalization problem, then, is to find a forest where each tree satisfies bounds on attributes, such as the probability that a species will survive. This paper recognizes that a connected set of arcs need not be a tree, but could be a donut shape, or even a nearly dense graph (in the two-dimensional plane), but the general problem is almost the same.

Faith et al (2003) expressed pessimism about the regionalization models, pointing out that the solutions have never been implemented. They propose "policy algorithms," and propose a simplistic auction involving provisional offers to owners. The auction would be funded by a central source, so it is a procurement. The authors develop an elaborate framework for quantifying biodiversity.

Market approaches have also been previously studied. Hartig and Drechsler (2009) made a case for using spatial incentives. Jack et al (2008) gives an overview of payment systems, focusing mainly on government procurements and the developing world. They point out that traditional conservation payments can result in weak results with uncertain outcomes, and perverse behaviours where users stay in business simply to collect payments.

A particularly interesting market approach is Nemes et al (2008), who apparently have actually implemented a market to incentivize cultivation of native vegetation in Australia. They defined a "habitat score" based on the quality of the area. Trades must satisfy spatial and quality restrictions. The market trades contracts, which commit landowners to manage native vegetation for a specified period of time, after which the site is protected permanently. Contracts are held in custody by government; government's role is limited to facilitating the market, and designing and monitoring contracts. Buyers pay for monitoring and compliance. This market design addresses the temptation of landowners to avoid contractual obligations, the temporary reduction in quality as exotic vegetation is cleared, and the probabilistic success of native vegetation.

While the market of Nemes et al (2008) incentivises cultivation of native plants, it omits connectivity. Trade is multilateral rather than a procurement. Reeson et al (2008) considered connectivity, but as a procurement, not as multilateral trade. Those authors observed a significant coordination problem, in which connectivity requires neighbours to work together. They also observed the potential for gaming, where a land owner in the middle of a potential corridor could raise their price. In a lab setting, the authors found that an iterated (multi-round) auction allowed participants to work around others' gaming behaviours.

2 An outline of a market for eco-connectivity

This paper attempts to develop a "policy algorithm" as Faith et al (2003) seek, while addressing the lack of spatial connectivity in Nemes et al (2008). The goal is a multilateral market, not a procurement (or not only a procurement), that will incentivize the spatial solutions. In this market, government desires to maintain or increase the total ecological connectivity within a given region.

Buyers may be landowners with insufficient eco-connectivity rights to their own property (possibly lost through some process such as eminent domain), or they may be landowners who wish to reduce the eco-connectivity of their property. The government may also be a buyer, seeking to raise the eco-connectivity of a given region. Sellers would be land owners who offer to improve the eco-connectivity of their land above its current status, or above their current rights level.

To help buyers avoid sellers who may have hold-out power (such as in the middle of a developing corridor), all bids would be visible to all participants, as in Nemes et al (2008). The market could suffer moral hazard, where a contract appears attractive but is actually difficult to implement. To remedy this, the market manager must approve sell bids. Sellers have their bids vetted by an ecologist and a contract manager. As in Nemes et al (2008), sellers pay for this process (e.g., for site visits).

Given the set of bids, the market manager would enumerate sets of connected edges, $t = 1, \ldots, T$, each with ecological value $V_{s,t}$ for species s. Each edge set is associated with a set of bids which satisfy constraint sets 2 and 3 below.

Indices

b, contract.

$i, j = 1,\ldots,I$, land owner, assumed to be in one-to-one correspondence with land parcels.

$(i, j) \in \mathit{Edges}$, indicating the adjacency of parcels *i* and *j*.

$s = 1,\ldots, S$, species

$t = 1,\ldots,T$, enumerated sets of connected edges.

Parameters

$A_{i,j,t} = 1$ if edge (i,j) is part of set *t*, else 0.

Budget = maximum amount that the market manager is willing to pay.

$C_{s,i,j,b}$ = increase in directed eco-connectivity $i \rightarrow j$ obtained for species *s*, if the market manager accepts contract *b* from user *i*. $C_{s,i,j,b} > 0$ for sell bids and $C_{s,i,j,b} < 0$ for buy bids.

$K_{s,i,j}$ = previously recognized eco-connectivity for parcel *i*, to connect to parcel *j*, for species *s*.

$\mathit{BuyPrice}_{i,j,b}$ = price on the buy bid from user *i*, to disconnect to parcel *j*, contract *b*.

$\mathit{SellPrice}_{i,j,b}$ = price on the sell bid from user *i*, to connect to parcel *j*, contract *b*.

Buyset_i = user *i*'s constraints on their bids (e.g., if $\mathit{buybid}_{i,j,b} = 1$, then $\mathit{buybid}_{i,k,b} = 1$).

$\mathit{Sellset}_i$ = user *i*'s constraints on their bids (e.g., if $\mathit{sellbid}_{i,j,b} = 1$, then $\mathit{sellbid}_{i,k,b} = 1$).

T_s = overall ecological connectivity target for species *s*.

$V_{s,t}$ = ecological value of set *t* for species *s*.

Variables

$\mathit{sellbid}_{i,j,b} = 1$ if the market manager accepts sell bid from user *i*, to connect parcel *i* to parcel *j*, contract *b*, else 0.

$\mathit{buybid}_{i,j,b} = 1$ if the market manager accepts buy bid from user *i*, to disconnect parcel *i* to parcel *j*, contract *b*, else 0.

$z_{s,i,j}$ = undirected connectedness of edge (i, j) for species *s*. This could be a percentage, where $0 \leq z_{s,i,j} \leq 1$, but is assumed more general here.

$y_{s,t} = 1$ if set *t* for species *s* is selected, else 0.

Model EcoConnect1

1. Maximize $\sum_{(i,j)}\sum_b (\mathit{BuyPrice}_{i,j,b}\, \mathit{buybid}_{i,j,b} - \mathit{SellPrice}_{i,j,b}\, \mathit{sellbid}_{i,j,b})$.
2. $\mathit{sellbid}_{i,j,b} \in \mathit{Sellset}_i$, for all $(i,j) \in \mathit{Edges}$, and all contracts *b*,
3. $\mathit{buybid}_{i,j,b} \in \mathit{Buyset}_i$, for all $(i,j) \in \mathit{Edges}$, and all contracts *b*.
4. $z_{s,i,j} \leq \sum_b (C_{s,i,j,b}\, \mathit{buybid}_{i,j,b} + C_{s,i,j,b}\, \mathit{sellbid}_{i,j,b}) + K_{s,i,j}$ for all $(i,j) \in \mathit{Edges}$, and all species *s*,
5. $z_{s,i,j} \leq \sum_b (C_{s,j,i,b}\, \mathit{buybid}_{j,i,b} + C_{s,j,i,b}\, \mathit{sellbid}_{j,i,b}) + K_{s,j,i}$ for all $(i,j) \in \mathit{Edges}$, and all species *s*.
6. $y_{s,t} \leq A_{i,j,t}\, z_{s,i,j}$ for all relevant *s, i, j, t*.
7. $\sum_t A_{i,j,t}\, y_{s,t} \leq 1$ for all $(i,j) \in \mathit{Edges}$.
8. $\sum_t V_{s,t}\, y_{s,t} \geq T_s$ for each species *s*.
9. $-\sum_{(i,j)}\sum_b (\mathit{BuyPrice}_{i,j,b}\, \mathit{buybid}_{i,j,b} - \mathit{SellPrice}_{i,j,b}\, \mathit{sellbid}_{i,j,b}) \leq \mathit{Budget}$.
10. $\mathit{buybid}_{i,j,b}, \mathit{sellbid}_{i,j,b}, y_{s,t} \in \{0,1\}$, $z_{s,i,j} \geq 0$.

Explanation

The objective (1) maximizes the buyer and seller surplus.

Constraint sets 2 and 3 allow traders to specify restrictions on their bids. For example, a trader may wish that any two of three bids must be taken together, to ensure some economy of scale in connecting to more than one neighbour.

Constraint sets 4 and 5 imply that connectivity requires that coordination must be two ways.

Constraint set 6 allows set t only if all bids for set t are selected.

Constraint set 7 requires that at most one tree with edge (i, j) can be selected. Otherwise, the connectivity of a given edge could be counted more than once.

Constraint set 8 requires that target connectivity be met for each species.

Constraint set 9 is a budget constraint that may be imposed by the market manager.

3 Discussion

3.1 Initial rights

To obtain an initial right $K_{s,j,i}$, owner i should be able to bring a project to government for approval, done presumable at the owner's expense. This would not require a bid in the market. To make this easier for land owners, government could publish a list of best management practices which government would accept as increasing eco-connectivity. Following this, government should recognize existing best management practices as providing some initial right $K_{s,j,i}$.

3.2 Poor definition of rights

Ideally, the market would allow a land owner in one area of the region to buy "connectivity" in another area, thereby allowing the increase in the seller's connectivity to offset a loss of connectivity on the buyer's property. To make this work, the buyer must understand exactly how his or her land will change in regard to connectivity, and also exactly the nature of the connectivity purchased. Further, the market manager would have to recognize that the buyer would now hold a right to connectivity, though the buyer's own property now lacked it.

The nature of the right is ill-defined here because the measure of connectivity is ill-defined. (That it is multi-dimensional due to many species makes the rights more complicated, but in principle still manageable.) Given the poor agreement on connectivity measures in the ecological literature, society's ability to find agreement seems even less likely. One solution is to raise funds through taxes, and run the market as a procurement with no buy bids. The problem with a tax-and-procure approach is that it provides no obvious way to *require* a given land owner to improve their land's connectivity. Any land owner could hold out for an arbitrarily large amount of money, with sufficiently high targets T_s.

3.3 Individual property requirements

Suppose that some measure can be agreed upon, or that government is willing to impose whatever measure it has chosen. Instead of tax-and-procure, government could require that every land parcel i were part of some local set satisfying a given target T_s. That is, the government tells land owner i, "Your land must be part of some subset with total connectivity T_s", without specifying exactly which subset. This corresponds to dropping the summation on t in constraint set 8: $V_{s,t}\, y_t \geq T_s$ for each species s. This requirement is analogous to zoning, such as when government allows a given land use in a commercial district, but not in a residential district. If the area were rezoned, all land use in the area would have to satisfy the new requirements.

In this case, a user i can purchase connectivity rights from another land owner j, but owners i and j must be part of the same connected set t; the rights are accrued equally to all land owners in the set. Suppose further, that some time after this market, one owner i wanted to reduce the connectivity on his or her land. To remain part of a satisfactory set, owner i would have to pay some other owners (other than j) to increase the connectivity across their land. The reduction of connectivity across owner i's land could still affect the previous owner j, especially if owner j had previously paid for some other owner k to improve the connectivity of j's edge set. In that case, the market manager initializes the parameter $K_{s,j,i}$, indicating that owner j has previously obtained sufficient connectivity. When owner i attempts to buy, feasibility requires that owner j is still in a feasible set, even though owner j did not participate in the market; the responsibility is on owner *i* to offer a sufficient amount to offset the loss of connectivity on parcel *i*, even as it affects other parcels.

3.4 Neighbour coordination

Through constraint sets 4 and 5, the proposed market partially addresses the coordination problem observed by Reeson et al (2008), by explicitly managing two-way connectivity. But this is only a partial attack on the problem, as neighbours must still offer more or less matching bids in the same auction.

Because the market manager must approve contracts, the manager can point out to each bidder *i* which neighbour *j* would be of particular interest for coordination. This process could be assisted by the process of edge set enumeration, as the market manager would be able to determine which edges are likely to allow bidder *i* to join a satisfactory set.

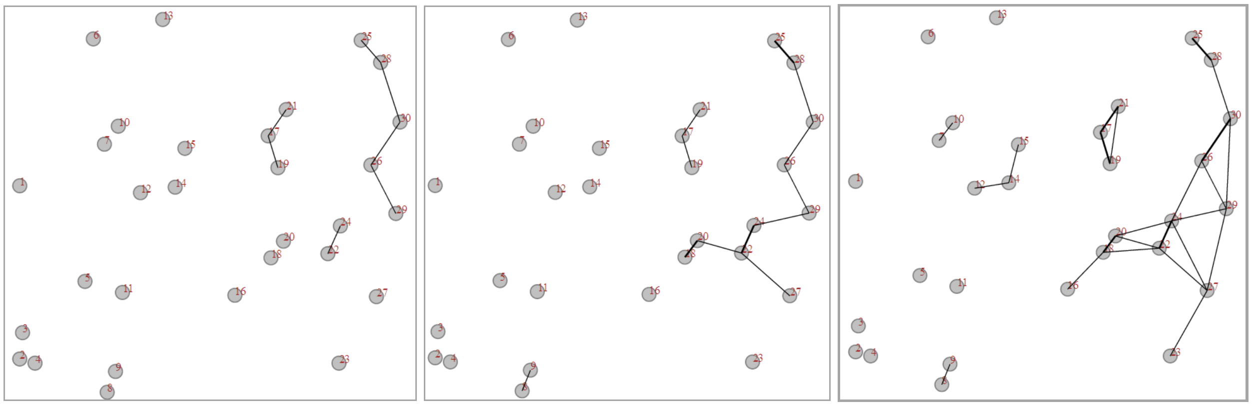
3.5 Revenue adequacy

Net revenue to the market manager is unlikely to be exactly zero because bids are discrete. Nemes et al (2008) solve this problem by allowing any buyer or seller to search for feasible bid sets, and then clear those bids as a market maker; any positive revenue then accrues to the market maker who found the feasible bid set. This gives an incentive for bidders to bid reasonably themselves as well. This could be simulated here, where every set would be required to be revenue adequate, with the excess revenue returned to land owners following some formula.

Alternatively, the government could choose to maintain a running budget. This running budget could have occasional or periodic injections from government. Or the market manager could be required to maintain market revenue between some negative lower limit and some positive upper limit, nearly balancing over time. The extent to which government pays land owners to improve ecological connectivity will likely be subject to political power.

4 Trivial example

This trivial hypothetical example assumes one species. Thirty land owners offer to sell to government, which pays for all work. The value of eco-connectivity is lowest with the lowest numbered land owners (more urban), and increase with node number (toward more rural).



Target $T = 15$. Cost 34.73. $T = 30$. Cost \$73.58 $T = 60$, cost \$167.23.

Figure 3. With an increasing budget, connectivity may increase within existing connected areas.

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