A Game Theory Analysis of the Transboundary Protected Area as a Conservation Tool
(WORKING PAPER—DO NOT CITE)

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Abstract

Nearly two hundred transboundary protected areas comprise a portion of the conservation landscape the size of India, with further expansion anticipated. Proponents claim that transboundary protected areas outperform isolated protected areas in achieving conservation objectives, while regional case studies have led critics to challenge this claim. Empirical investigation into the relative performance of transboundary protected areas is fundamentally limited since these areas can not be directly compared to the isolated protected areas that might otherwise have emerged in the same location. This paper develops a game theory model of park formation to compare transboundary and isolated protected area configurations across three criteria—national welfare, domestic conservation value, and global conservation value. The model suggests that when the primary objective of conservation is to prevent extinction or provide interior habitat, conservation groups should encourage transboundary protected areas. However, when the primary objective of conservation is to extend reserve coverage to the maximum number of species, conservation groups should encourage proteced areas in areas of greatest species richness, whether or not these areas span international borders.

I. Introduction

Transboundary protected areas, or two or more protected areas contiguous across an international border,[1] comprise a large and growing component of the conservation landscape. Proponents claim that transboundary protected areas (TBPAs) offer conservation gains not possible otherwise, as well as ancillary economic, social, and political benefits. Critics contend that these claims are overstated and not realized in practice. If proponents are right, conservation resources should be preferentially directed toward transboundary endeavors. If critics are right, conservation resources should be directed toward projects that best meet other criteria, whether or not they are transboundary in nature. Therefore it is important to develop an understanding for which situations TBPAs are best suited.

[1] In contrast to other typologies on the subject (Dudley, 2003; Braack 2004), this paper does not consider cooperative management to be a requirement to be classified as a TBPA. This more inclusive definition of TBPA is supported by the finding of Zbicz (1999) that in the majority (57%) of internationally adjoining protected areas, actual international cooperation in management is minimal or non-existent.

Empirical investigations of proponents' claims have been rudimentary to date, and are fundamentally limited by the fact that counterfactual transboundary and isolated protected areas (IPAs) can not exist in the same place at the same time. Therefore, Section 3 develops a game theory model to directly compare isolated and transboundary protected area configurations across three criteria—national welfare, domestic conservation value, and global conservation value. Section 4 presents simple conditions which, when satisfied by the benefit function associated with a conservation objective, are sufficient to ensure that transboundary parks are superior to isolated parks in terms of these criteria. Section 5 shows which of these conditions are satisfied by three common conservation objectives: species richness, species persistence, and interior habitat. Section 6 is discussion; Section 7 concludes.

II. Transboundary parks

For nearly as long as there have been protected areas (PAs, or "parks"), there have been transboundary protected areas (TBPAs). Canada's Waterton National Park was gazetted in 1895, with Glacier National Park formed across the border in the USA in 1910. In 1932 the two were combined to form the Waterton-Glacier International Peace Park.

Some of the highest profile conservation areas on the planet span international boundaries. Kenya's Masai Mara National Park and the contiguous Serengeti National Park in Tanzania comprise the archetypical East African savannah ecosystem, famous for its seasonal ungulate migration. Mountain gorillas make their last stand within the adjoining protected areas of Parc National de Virunga in Congo, Parc National des Volcans in Rwanda, and Rwenzori Mountains National Park in Uganda. Iguazu Falls is protected by national parks in both Brazil and Argentina; Victoria Falls is protected by national parks in both Zimbabwe and Zambia.

By 2005, Conservation International reported 188 internationally adjoining protected area complexes, in 112 countries, comprised of 818 individual protected areas. These areas spanned 3.2 million km^2, an area roughly the size of India, or 17% of the global extent of protected areas (Mittermeier 2005). These complexes were distributed across all continents, with 15 in North America, 29 in Central and South America, 33 in Africa, 46 in Asia, and 65 in Europe.

Dozens more TBPAs have been proposed, with nearly twenty future TBPAs suggested for southern Africa alone (Hall-Martin 2002). A 6000 km greenbelt is emerging along Europe's former iron curtain zone, spanning 22 countries (Terry, 2006). The Korean peninsula's demilitarized zone may yet be turned into a wildlife sanctuary and peace park (Kim, 1997). In December 2006, ministers from five southern African nations signed a memorandum of understanding designating 287,000 sq km, an area larger than Nevada, as the Kavango-Zambezi Transfrontier Conservation Area.

This growth in TBPAs is deliberate. The International Union for the Conservation of Nature has a Global TBPA Network and a TBPA Task Force, and Conservation International has a Southern Africa Transfrontier Conservation Unit. There are even two NGOs, the Peace Parks Foundation in Africa and ProNatura in South America, who have as an explicit goal the implementation of more TBPAs.

Even as TBPAs proliferate rapidly, commentary on TBPAs within the conservation community has been mixed. Proponents see transboundary parks as an opportunity for "securing landscape-level conservation at a scale not possible previously" (Hanks, 2001). Furthermore, TBPAs are considered to provide "a wide range of social and political benefits, including reuniting communities divided by arbitrary borders, facilitating the movements of mobile indigenous peoples, helping broker peace and reconciliation between countries with a history of conflict, and generating substantial economic benefits" (Mittermeier, 2005). Detractors challenge whether the various stated goals of TBPAs are realized in practice, and "whether the methods currently being employed are optimal in relation to the investment and transaction costs of such initiatives" (Sandwith, 2003).

It is important to be able to distinguish situations in which transboundary protected areas offer an improvement on traditional one-country isolated protected areas (IPAs) from situations in which they are a distraction. When TBPAs offer something above and beyond what IPAs can offer, conservationists should devote resources preferentially to transboundary endeavors. However, when TBPAs perform less efficiently than IPAs in achieving conservation objectives, then conservationists should direct more resources and political will toward regions of highest conservation priority, whether or not these regions span international boundaries.

The few empirical studies of TBPAs to date do not support the claim that TBPAs improve conservation and development. Reyers (2002) compared the avian species richness and land cover richness of five South African parks with and without the inclusion of neighboring countries' contiguous parks. She found that the inclusion of neighboring country parks increased the average number of bird species found within the protected area by only 7.1%, and land cover types by 40%, despite increasing total protected area size by an average of 110%. Scovronick (2006) found that park visitation to South Africa's Kalahari-Gemsbok National Park and Botswana's Gemsbok National Park decreased insignificantly following their 2004 integration into the Kgalagadi Transfrontier Park, though he concluded that this decline in tourism could have been attributed to the concurrent name change from the more resonant "Kalahari National Park." Suich, Busch, and Barbancho (2006) have undertaken a more comprehensive examination of the regional tourism economy in Angola, Botswana, Namibia, Zambia, and Zimbabwe before and after the formation of the Kavango-Zambezi TFCA. The analysis of the impacts of the TFCA will not be available until the 'after' study is completed several years from now.

While claims of TBPA superiority can be tested empirically to some extent, a true head-to-head comparison of actual TBPAs with counterfactual IPAs is simply not possible in practice, as both types of parks can not operate in the same physical space and time. There is no way of knowing in the studies above what would have happened to species richness or tourism had an isolated park been created instead of a transboundary park. However, an analytical model can be used advantageously to compare what would happen in the same countries, in the same location, at the same time, with the same biological and economic parameters, if the countries were to form either TBPAs or IPAs.

Attempting to construct a model of transboundary parks based solely on the biological benefits accruing from size or connectivity of parks would neglect two key effects relating to the economic incentives of countries. First, while larger parks may provide more biological benefit, they also come at greater cost. Insatiable biological demand for more living space is tempered in the real world by the increasing opportunity costs of competing land uses. Adjoining parks in a country's neighbor are able to provide a positive externality of conservation benefit, but at no cost to the country. Secondly, strategic interactions that occur between countries can only be captured through a game theory model. One country's park size and location may give the neighboring country an incentive to make their park either larger or smaller than they would have otherwise.

This paper advances the study of transboundary parks by providing a game theory model which can be used to compare transboundary parks and counterfactual isolated parks across three criteria – national welfare, domestic conservation benefit, and global conservation benefit. This paper leaves aside controversies of whether TBPAs create international peace (Westing, 1998) or acrimony (Wolmer, 2003), and whether their result has been community development or disenfranchisement (Turner, 2004). Neither does the model comment on whether the legal framework necessary for establishing TBPAs is consistent with existing international laws (Young, 2003; Tamburelli 2003). The model developed in this paper focuses solely on conservation benefit and opportunity cost. While peace dividends or challenges to cooperative management are clearly important considerations for land use planners in some contexts, these should not obscure the fundamental question of whether and when the conservation benefits of transboundary parks outweigh the opportunity costs of this land use.

III. Game theory model of park formation

In this transboundary problem, an ecoregion extends across two neighboring countries, *i*,*j*. Within each country this ecoregion can be divided between protected land and unprotected land. Areas of protected land function as habitat islands that are not economically exploited. Contiguous protected areas are assumed to create a single habitat island, while isolated parks are assumed to create ecologically unconnected habitat islands. Unprotected land provides value through economic exploitation, but provides no habitat. Land within the ecoregion is homogenous in its potential value as habitat or for exploitation.

Countries value both conservation and exploitation. A protected area benefits a country through the achievement of biological conservation objectives, but also costs a country through foregone opportunities for economic exploitation. To maximize value from its share of the ecoregion, a country faces two sequential decisions—whether to locate a protected area in the interior or along a shared border, and what size this protected area will be. Countries first simultaneously decide park location. If both countries protect land contiguously on the border, the park configuration is "transboundary," *T*. Otherwise, the park configuration is "isolated," *I*. After observing the park configuration, each country simultaneously chooses a protected area size, X_i or $X_j \geq 0$, to maximize its national welfare. National welfare, $w_i(X_i, X_j)$, is a weighted difference of domestic conservation benefit, $b_i(X_i, X_j)$, and opportunity cost, $c_i(X_i)$. The cost function is increasing in the size of the country's protected area, and can vary in functional form between countries. A country's opportunity cost is unaffected by the size or contiguity of the neighboring country's protected area.

Conservation benefit is a biological metric that quanties a protected area's provision of the country's conservation objective. Conservation benefit could measure number of species, population size, or probability of extinction. No initial assumption is made regarding the functional form of the conservation benefit, as this functional form will derive from the ecological literature of the conservation objective in question. For instance, species richness is concave in protected area size, while interior habitat is convex.

Domestic conservation benefit is the conservation benefit a country receives from its own park. It is assumed that a country has no intrinsic existence value for the conservation benefit provided by its neighbor's park—$b_i(0, X_j)=0$. A country always benefits directly from its own protected land. A country benefits from protected land in a neighboring country if and only if the park configuration is transboundary.

Global conservation benefit, $g(X_i, X_j)$, is the conservation benefit to the world at large from the overall configuration of parks in both countries. Under a transboundary parks configuration, global conservation benefit accrues from the single habitat island—$g^T(X_i, X_j) = b_i(X_i+X_j,0)$. Under an isolated parks configuration, the global conservation benefit $g^I(X_i, X_j)$ will vary by conservation objective. While domestic conservationists may be concerned with domestic conservation benefit, and global conservationists may be concerned with global conservation benefit, the agents deciding park size in the problem are countries, which are non-cooperatively maximizing national welfare.

Country i chooses X_i to maximize national welfare:

$$\max_{X_i} \; w_i(X_i, X_j) = \phi_i b(X_i, X_j) - \tau_i c_i(X_i), \tag{1}$$

where X_j is country j's choice variable when configuration is T, and $X_j=0$ when configuration is I. Parameters ϕ_i, $\tau_i > 0$ weight the relative value placed by countries on domestic conservation benefit and opportunity cost. ϕ_i also scales the biological metric to a dollar value. These weights can vary across countries. The cost function, $c_i(X_i)$, can also vary in functional form between countries.

This game will generally have either one or two Nash equilibria. In the first Nash equilibrium, the "isolated equilibrium," both countries locate parks in their interior, and the park configuration is isolated. Park sizes X_i^I* and X_j^I* represent the subgame perfect equilibrium park sizes in independent national welfare maximization problems under the isolated park configuration. This equilibrium always exists, because when one country locates a park in its interior, the other country is indifferent between an interior park and a border park, as the configuration will be isolated in either case. In a possible second Nash equilibrium, the "transboundary equilibrium," both countries locate parks contiguously along the border, and the park configuration is transboundary. This equilibrium only exists when parks provide greater or equal national welfare in a transboundary configuration than in an isolated configuration. When one country locates a park along the border, the other country's best response is always to locate its park along the border as well. Park sizes X_i^T* and X_j^T* represent the subgame perfect Nash equilibrium park sizes in a simultaneous, non-cooperative national welfare maximization game under the transboundary park configuration.

The Nash equilibrium park sizes determine the national welfare, domestic conservation benefit, and global conservation benefit that accrue under the transboundary or isolated park configuration. $w_i^I(X_i^I*, X_j^I*)$ and $w_i^T(X_i^T*, X_j^T*)$ represent the national welfare accruing to country i in an isolated equilibrium and transboundary equilibrium, respectively. $b_i^I(X_i^I*, X_j^I*)$ and $b_i^T(X_i^T*, X_j^T*)$ represents the domestic conservation benefit accruing to country i in an isolated equilibrium and transboundary equilibrium, respectively. $g^I(X_i^I*, X_j^I*)$ and $g^T(X_i^T*, X_j^T*)$ represent the global conservation benefit accruing to the world at large in an isolated equilibrium and transboundary equilibrium, respectively.

IV. Sufficient conditions for transboundary park superiority

Whether the transboundary equilibrium or isolated equilibrium is superior in providing national welfare, domestic conservation benefit, or global conservation benefit will depend on the functional form of the conservation benefit function $b_i(X_i, X_j)$. This functional form will vary by the conservation objective in question. Rather than test the superiority of the transboundary equilibrium for each conservation objective in turn, I establish a general framework of sufficient conditions for TBPA superiority. If the conservation benefit function associated with a particular conservation objective satisfies these conditions, then the transboundary equilibrium is superior to the isolated equilibrium in providing national welfare, domestic conservation benefit, or global conservation benefit for that conservation objective. Section V will show whether or not several common conservation objectives satisfy these conditions.

Spillover condition: The domestic conservation benefit provided by a country's protected area is increasing in the size of the neighboring country's contiguous protected area.

$$\frac{\partial b_i(X_i, X_j)}{\partial X_j} > 0 \qquad \forall\ X_i, X_j \tag{2}$$

Insatiability condition: The domestic conservation benefit provided by a country's protected area is increasing in the size of the protected area.

$$\frac{\partial b_i(X_i, X_j)}{\partial X_i} > 0 \qquad \forall\ X_i, X_j \tag{3}$$

Strategic complementarity condition: The domestic conservation benefit provided by a marginal increase in size to a country's protected area is increasing in the size of the neighboring country's contiguous protected area. The term strategic complement derives from Bulow (1985).

$$\frac{\partial^2 b_i(X_i, X_j)}{\partial X_i \partial X_j} > 0 \qquad \forall\ X_i, X_j \tag{4}$$

Increasing returns to scale condition: The domestic conservation benefit provided by a marginal increase in size to a country's protected area is increasing in the size of the protected area

$$\frac{\partial^2 b_i(X_i, X_j)}{\partial X_i^{\,2}} > 0 \qquad \forall\ X_i, X_j \tag{5}$$

Subadditivity condition: Global conservation benefit accruing from an isolated configuration of two protected areas does not exceed the sum of the benefit accruing from each individual protected area.

$$g^I(X_i, X_j) \le b_i(X_i,0) + b_j(0, X_j) \tag{6}$$

Proposition 1: If the spillover condition is satisfied, then national welfare is greater under the transboundary equilibrium than under the isolated equilibrium.

Proof that if $\frac{\partial b_i(X_i, X_j)}{\partial X_j} > 0$, then $w_i^T(X_i^T*, X_j^T*) > w_i^I(X_i^I*, 0)$

By definition $X_i^T* = \max\limits_{X_i} w_i^T(X_i, X_j^T*)$, so $w_i^T(X_i^T*, X_j^T*) - w_i^T(X_i^I*, X_j^T*) \ge 0$. National welfare is increasing in the neighboring country's park size, because of the subsidy condition and because opportunity cost is unaffected by the neighboring country's park size. This implies that $w_i^T(X_i^I*, X_j^T*) - w_i^T(X_i^I*, 0) > 0$. Finally, by construction $w_i^T(X_i^I*, 0) = w_i^I(X_i^I*, 0)$. Therefore, $w_i^T(X_i^T*, X_j^T*) - w_i^I(X_i^I*, 0) =$

$[\, w_i^T(X_i^T*, X_j^T*) - w_i^T(X_i^I*, X_j^T*) \,] + [\, w_i^T(X_i^I*, X_j^T*) - w_i^T(X_i^I*, 0) \,] + [\, w_i^T(X_i^I*, 0)$ -
$w_i^I(X_i^I*, 0) \,] > 0.$

National welfare is greater under the transboundary equilibrium greater than under the isolated equilibrium whenever the spillover condition is satisfied. However, this greater welfare does not necessarily entail greater conservation benefit. This difference could be caused by lower opportunity cost resulting from smaller park size. Two more conditions must be satisfied to ensure that domestic conservation benefit is greater under the transboundary equilibrium than under the isolated equilibrium.

Proposition 2: If the spillover condition, insatiability condition, and strategic complementarity condition are satisfied, then domestic conservation benefit is greater under the transboundary equilibrium than under the isolated equilibrium.

Proof that if $\frac{\partial b_i(X_i, X_j)}{\partial X_j} > 0$, $\frac{\partial b_i(X_i, X_j)}{\partial X_i} > 0$, and $\frac{\partial^2 b_i(X_i, X_j)}{\partial X_i \partial X_j} > 0$, then
$b_i^T(X_i^T*, X_j^T*) \;\geq\; b_i^I(X_i^I*, 0)$:

The second order condition is satisfied by assumption. Assuming an interior solution, solutions will be where first order conditions are satisfied—$\frac{\partial w_i^T(X_i^T*, X_j^T*)}{\partial X_i}$ =0 and $\frac{\partial w_i^I(X_i^I*, 0)}{\partial X_i} = 0$. So,

$$\frac{\partial w_i^T(X_i^T*, X_j^T*)}{\partial X_i} - \frac{\partial w_i^I(X_i^I*, 0)}{\partial X_i} = 0 \qquad (7)$$

We can prove by contradiction that $X_i^T* \;\geq\; X_i^I*$. We know that $\frac{\partial^2 w_i(X_i, X_j)}{\partial X_i \partial X_j}$ > 0, because of the strategic complementarity condition and because opportunity cost is unaffected by the neighboring country's park size. This implies that $\frac{\partial w_i^T(X_i^T*, X_j^T*)}{\partial X_i}$ - $\frac{\partial w_i^T(X_i^T*, 0)}{\partial X_i}$ > 0. Again, by construction $w_i^T(X_i^I*, 0) = w_i^I(X_i^I*, 0)$. Now suppose that $X_i^T* < X_i^I*$. Then by the assumption of concavity of the objective function, $\frac{\partial w_i^T(X_i^T*, 0)}{\partial X_i}$ - $\frac{\partial w_i^T(X_i^I*, 0)}{\partial X_i}$ > 0. So, $\frac{\partial w_i^T(X_i^T*, X_j^T*)}{\partial X_i}$ - $\frac{\partial w_i^I(X_i^I*, 0)}{\partial X_i}$ =

$$[\frac{\partial w_i^T(X_i^T*, X_j^T*)}{\partial X_i} - \frac{\partial w_i^T(X_i^T*,0)}{\partial X_i}] + [\frac{\partial w_i^T(X_i^T*,0)}{\partial X_i} - \frac{\partial w_i^T(X_i^I*,0)}{\partial X_i}] + [\frac{\partial w_i^T(X_i^I*,0)}{\partial X_i} - \frac{\partial w_i^I(X_i^I*,0)}{\partial X_i}] > 0.$$

But this contradicts (7). Therefore,

$$X_i^T* \geq X_i^I*. \tag{8}$$

Park size will be larger under a transboundary equilibrium than under an isolated equilibrium. This implies that $b_i^T(X_i^T*,0) - b_i^T(X_i^I*,0) \geq 0$ by the insatiability condition. Further, $b_i^T(X_i^T*, X_j^T*) - b_i^T(X_i^T*,0) \geq 0$ by the spillover condition. By construction $b_i^T(X_i^I*,0) = b_i^I(X_i^I*,0)$. Therefore, $b_i^T(X_i^T*, X_j^T*) - b_i^I(X_i^I*,0) = [b_i^T(X_i^T*, X_j^T*) - b_i^T(X_i^T*,0)] + [b_i^T(X_i^T*,0) - b_i^T(X_i^I*,0)] + [b_i^T(X_i^I*,0) - b_i^I(X_i^I*,0)] \geq 0$.

Domestic conservation benefit will be greater under a transboundary equilibrium than under an isolated equilibrium when the conditions above are met. However, this superiority in domestic conservation benefit does not assure that global conservation benefit, $g(X_i, X_j)$, will be greater under a transboundary equilibrium than under an isolated equilibrium. Greater conservation benefit from increased park size could potentially be offset by lower conservation benefit from increased overlap in benefit due to park contiguity. Two more conditions must be satisfied to ensure that global conservation benefit will be greater under a transboundary equilibrium than under an isolated equilibrium.

Proposition 3: If the spillover condition, insatiability condition, strategic complementarity condition, increasing returns to scale condition, and the subadditivity condition are satisfied, then global conservation benefit is greater under the transboundary equilibrium than under the isolated equilibrium.

Proof that if $\frac{\partial b_i(X_i, X_j)}{\partial X_j} > 0$, $\frac{\partial b_i(X_i, X_j)}{\partial X_i} > 0$, $\frac{\partial^2 b_i(X_i, X_j)}{\partial X_i \partial X_j} > 0$, $\frac{\partial^2 b_i(X_i, X_j)}{\partial X_i^2} > 0$, and $g^I(X_i, X_j) \leq b_i(X_i,0) + b_j(0, X_j)$, then $g^T(X_i^T*, X_j^T*) \geq g^I(X_i^I*, X_j^I*)$:

As we have shown above, park size will be larger under a transboundary equilibrium than under an isolated equilibrium when the spillover, insatiability, and strategic complementarity conditions are met. So by the insatiability condition, $b_i(X_i^T* + X_j^T*,0) \geq b_i(X_i^I* + X_j^I*,0)$. By the increasing returns to scale condition, $b_i(X_i^I* + X_j^I*,0) \geq b_i(X_i^I*,0) + b_i(X_j^I*,0)$. By construction, $b_i(X_j^I*,0) = b_j(0, X_j^I*)$. And by the subadditivity condition, $b_i(X_i^I*,0) + b_j(0, X_j^I*) - g^I(X_i^I*, X_j^I*) \geq 0$. So,

$$g^T(X_i^T*,X_j^T*) - g^I(X_i^I*,X_j^I*) = [g^T(X_i^T*,X_j^T*) - b_i(X_i^T*+X_j^T*,0)] +$$
$$[b_i(X_i^T*+X_j^T*,0) - b_i(X_i^I*+X_j^I*,0)] + [b_i(X_i^I*+X_j^I*,0) - b_i(X_i^I*,0) + b_i(X_j^I*,0)] +$$
$$[b_i(X_j^I*,0) - b_j(0,X_j^I*)] + [b_i(X_i^I*,0) + b_j(0,X_j^I*) - g^I(X_i^I*,X_j^I*)] \geq 0.$$

Global conservation benefit will be greater under the transboundary equilibrium than under the isolated equilibrium if the conditions above are satisfied.

V. Conservation objectives and sufficient conditions

Remember, to ensure that national welfare is greater under the transboundary parks equilibrium than under the isolated parks equilibrium, a conservation objective must satisfy the spillover condition. To ensure that domestic conservation benefit will be greater under the transboundary equilibrium than under the isolated equilibrium, a conservation objective must additionally satisfy the insatiability condition and the strategic complementarity condition. Finally, to ensure that global conservation benefit will be greater under the transboundary equilibrium than under the isolated equilibrium, a conservation objective must additionally satisfy the returns to scale condition and the subadditivity condition. If we know under what circumstances common conservation objectives satisfy these conditions, then we know when the transboundary configuration is superior to the isolated configuration in meeting those objectives. Three common conservation objectives are shown here as illustrative examples, though the framework allows us to determine whether the transboundary configuration is superior for any conservation objective for which benefits can be expressed mathematically as a function of protected area size.

Species Richness

Species richness measures the number of species found in an area. Richness can be tallied across all species, or can be specific to a certain taxonomic grouping such as mammals, birds, cichlid fish, or vascular plants. Species richness is a primary motivator for conservation groups. Both Conservation International's mission of protecting biodiversity "hotspots" (Myers, 2000) and the Nature Conservancy's "conservation by design" (Groves, 2003) direct conservation activities toward regions that have high species richness, among other criteria such as threat or cost.

A solid foundation of conservation planning literature (Church, 1996; Ando, 1998) and software (Possingham, 2000) has been established to maximize the species richness contained in a reserve network. Reserve site selection theory generally treats species richness on any parcel of land as an exogenously assigned score, which is fully achieved if the parcel is included within a reserve network, and is zero if the parcel is excluded. The framework developed in this paper differs in that species richness is endogenous to the total size of the protected area, following the theory of island biogeography (MacArthur, 1967), and parks are assumed to function as habitat islands (Newmark, 1987).

The well-established archipelagic and intraprovincial species area relationships of island biogeography have modeled species richness on a plot of land on an island as increasing at a decreasing rate in both the size of the plot and the size of the island. Extending this relationship to habitat islands, species richness in a country's park is increasing at a decreasing rate in both the size of the park and the size of the overall TBPA. When considering the conservation benefit of species richness, $b_x(X_i,X_j)$ takes on the following form:

$$b_i(X_i, X_j) = aX_i^{m}(X_i + Xj)^{n}\text{, where m, n, m+n} \in (0,1). \tag{9}$$

Here, m represents the rate at which species richness increases in plot size, while *n* represents the rate at which species richness increases in total habitat island size. The parameters, *m*, intraprovincial species richness, and *n*, archipelagic species richness, have been the subject of extensive empirical investigation. The common range of these perimeters is $m \in$ (0.10-0.20), and $n \in$ (0.25-0.45) (Rosenzweig, 1995).

Proposition 4.1: If the objective of creating protected areas is species richness, then national welfare is greater under the transboundary equilibrium than under the isolated equilibrium.

Proof: $\frac{\partial b_i(X_i, X_j)}{\partial X_j} = anX_i^{m}(X_i + X_j)^{n-1} > 0 \;\forall$ m, n, X_j, so the spillover condition is satisfied $\forall$ m, n, X_j. Since the spillover condition is satisfied, Proposition 4.1 is true by Proposition 1.

Proposition 4.2: If the objective of creating protected areas is species richness, then domestic conservation benefit parks is not demonstrably greater under the transboundary equilibrium than under the isolated equilibrium.

Proof: $\frac{\partial b_i(X_i, X_j)}{\partial X_i} = aX_i^{m-1}(X_i + X_j)^{n-1}[m(X_i + X_j) + nX_i] > 0 \;\forall$ m, n, X_j, so the insatiability condition is satisfied $\forall$ m, n, X_j. Furthermore, $\frac{\partial^2 b_i(X_i, X_j)}{\partial X_i \partial X_j} =$

$anX_i^{m-1}(X_i + X_j)^{n-2}[(m+n-1)X_i + mX_j] > 0$ when $\frac{X_i}{X_j} < \frac{m}{1-(m+n)}$, so the strategic complementarity condition is satisfied when $\frac{X_i}{X_j} < \frac{m}{1-(m+n)}$. However, the observed range of these parameters is m$\in$ (0.10-0.20), and n$\in$ (0.25-0.45). So $\frac{m}{1-(m+n)} \in$ (0.15-0.58). It is therefore not possible for the strategic complementarity condition to be satisfied for both countries. Since the strategic complementarity condition is not satisfied, Proposition 4.2 is true by Proposition 2.

Proposition 4.3: If the objective of creating protected areas is species richness, then global conservation benefit is not demonstrably greater under the transboundary equilibrium than under the isolated equilibrium.

Proof: $\frac{\partial^2 b_i(X_i, X_j)}{\partial X_i^{\,2}} =$

$aX_i^{\,m-2}(X_i + X_j)^{n-2}[X_i^{\,2}(m+n)(m+n-1) + 2mX_iX_j(m+n-1) + X_j^{\,2}m(m-1)] < 0$ ∀ m, n, X_j., so the increasing returns to scale condition is unsatisfied ∀ m, n, X_j.

Although the functional form that describes global species richness as a function of two countries' domestic species richness is unspecified, the subadditivity condition is satisfied. The number of species across two parks can not be greater than the sum of species in each individual park, and can be less than the sum if there is any overlap between species.

Since the increasing returns to scale condition is unsatisfied, Proposition 4.3 is true by Proposition 3.

Species Persistence

Species persistence represents the probability that a species will survive rather than become extinct within a given area. Protected areas are frequently established with the objective of preventing the extinction or improving the probability of persistence of a particular species. Parks have been established to protect globally recognized endangered species such as pandas, gorillas, okapis, and komodo dragons, as well as more humble endangered birds or butterflies.

Persistence can be measured in multiple ways. Population viability is the probability that a species will persist in an area over a given time period. Expected time until extinction is the mean length of time for a species to go extinct in a given area. This species "life expectancy" is used as the objective function in this model.

The size of a species geographic range has been found to be the most powerful single determinant of species extinction risk or persistence (Purvis, 2000). I model mean time to extinction as a function of protected area size using the Lande (1993) ceiling population growth model as annotated in Morris (2002). A species of population size n on a patch experiences a stochastic growth rate, , expressed through parameters for a mean, , and variance, σ^2, of natural logarithm of growth rate. The parameter c= $\frac{\mu}{\sigma^2}$. The patch has a carrying capacity, K, which acts as a ceiling to population size. Here, n_{t+1}= n_t if $n_t \leq K$, and n_{t+1}=K if if $n_t \geq K$. Initial population size is equal to K. If population size falls below the quasi-extinction threshold of n=1, the species becomes extinct. A greater carrying capacity means a smaller chance that a species will be driven to extinction by a few bad years in succession. Importantly, mean time to extinction, $\overline{T}$, is increasing at an increasing rate in carrying capacity. In this model carrying capacity is assumed to be linearly related to the size of the habitat island formed by the protected area, $K=a(X_i+X_j)$. $\overline{T}$ can be modeled as follows:

$$b_i(X_i, X_j) = \overline{T} = \frac{1}{2\mu c}([a(X_i + X_j)]^{2c} - 1 - 2c\ln([a(X_i + X_j)]) \qquad (10)$$

Proposition 5.1: If the objective of creating protected areas is species persistence, then national welfare is greater under the transboundary equilibrium than under the isolated equilibrium.

Proof: $\frac{\partial b_i(X_i, X_j)}{\partial X_j} = \frac{1}{2\mu c}(2ac[a(X_i + X_j)]^{2c-1} - \frac{2c}{X_i + X_j}) > 0 \;\forall$ c, $, a(X_i+X_j)>1$

so the spillover condition is satisfied $\forall$ c, $, a(X_i, X_j)>1$

As long as the total habitat island has a carrying capacity greater than one individual, mean time to extinction within a park will be increasing in the size of the neighboring country's park, and the spillover condition will be satisfied. Since the spillover condition is satisfied, Proposition 5.1 is true by Proposition 1.

Proposition 5.2: If the objective of creating protected areas is species persistence, then parks will provide greater domestic species persistence under the transboundary equilibrium than under the isolated equilibrium, for species with low demographic stochasticity.

Proof: $\frac{\partial b_i(X_i, X_j)}{\partial X_i} = \frac{1}{2\mu c}(2ac[a(X_i + X_j)]^{2c-1} - \frac{2c}{X_i + X_j}) > 0 \;\forall$ c, $, a(X_i+X_j)>1$, so the insatiability condition is satisfied $\forall$ c, $, a(X_i+X_j)>1$.

As long as the total habitat island has a carrying capacity greater than one individual, mean time to extinction within a park will be increasing in the size of the park, and the insatiability condition will be satisfied. Furthermore,

$\frac{\partial^2 b_i(X_i, X_j)}{\partial X_i \partial X_j} = \frac{1}{2\mu c}(2a^2c(2c-1)[a(X_i + X_j)]^{2c-2} + \frac{2c}{(X_i + X_j)^2}) > 0$ when $c>0.5$ or when $c<0.5$ and $a(X_i+X_j)<(1-2c)^{-1/2c}$, so the strategic complementarity condition is always satisfied when $c>0.5$ or when $c<0.5$ and $a(X_i+X_j)<(1-2c)^{-1/2c}$.

As long as $c>0.5$, mean time to extinction is increasing at an increasing rate in the neighboring country's contribution to park size, so the strategic complementarity condition is satisfied. When $c<0.5$, carrying capacity must be very, very small for the same to be true (e.g. $K<13$ when $c=0.45$, $K<3$ when $c=0.1$). So, for populations with relatively low demographic stochasticity, the strategic complementarity condition is satisfied. Since the insatiability and strategic complementarity conditions are satisfied, Proposition 5.2 is true by Proposition 2.

Relatively low demographic stochasticity, c>0.5, is most likely to be the case for species with long lives, long generations, low birthrates, and low annual fluctuations in fecundity and mortality. These are precisely the large charismatic species parks are generally designed to protect.

Proposition 5.3: If the objective of creating protected areas is species persistence, then parks will provide greater global species persistence under the transboundary equilibrium than under the isolated equilibrium, for species with low demographic stochasticity.

Proof: $\frac{\partial^2 b_i(X_i, X_j)}{\partial X_i^2} = \frac{1}{2\mu c}(2a^2 c(2c-1)[a(X_i + X_j)]^{2c-2} + \frac{2c}{(X_i + X_j)^2})$ > 0 when c>0.5 or when c<0.5 and $a(X_i+X_j) < (1-2c)^{-1/2c}$, so the increasing returns to scale condition is satisfied when c>0.5 or when c<0.5 and $a(X_i+X_j) < (1-2c)^{-1/2c}$.

As long as c>0.5, mean time to extinction is increasing at an increasing rate in a country's own contribution to park size, and the increasing returns to scale condition is satisfied. When c<0.5, carrying capacity must be very, very small for the same to be true. So, for populations with relatively low demographic stochasticity, the increasing returns to scale condition are satisfied.

For a proof that the subadditivity condition is satisfied for species persistence, see Appendix A. Since the increasing returns to scale and subadditivity conditions are satisfied, Proposition 5.3 is true by Proposition 3.

The mean time to extinction objective does not include time preference, implicitly assuming a zero discount rate. However, imposing a positive discount rate means that transboundary parks will have the greatest benefit for those species for which additional area has a significant effect on extinction risk in the short term. These are species with low populations, low population densities, and large area requirements.

Interior Habitat

A class of common conservation objectives have benefits related to park area and costs related to the length of the park perimeter. Interior habitat is a representative conservation objective of this class; core area is beneficial, while edge effects mean that area along the perimeter is neutral or detrimental. This class includes wilderness value, where wilderness is defined as land greater than a minimum distance from human dominated landscape outside the park (e.g. Skonhoft, 2001). This class also includes minimizing the cost of enforcing the park perimeter through fencing or law enforcement.

Minimizing human-wildlife conflict is also a conservation objective of this class. The assumption that the magnitude of human-wildlife conflict is proportional to the length of park perimeter is supported by findings that distance from a park is a significant explanatory variable for individual occurrences of crop-raiding by foraging forest mammals in Uganda, India, and Sumatra (Naughton-Treves, 1998, Sekhar, 1998, Linkie 2007). However, several studies indicate that the spatial pattern of human-elephant conflict is more likely to be driven by distance to settlements and roads than distance to parks (Hoare 1999, Smith, 2000, Sitati 2003), perhaps because elephants travel fearlessly far beyond the confines of protected areas.

For every objective of this class, conservation benefit can be modeled as:

$$b_i(X_i, X_j) = ax - b\sqrt{X_i} + c\sqrt{\min\{X_i, X_j\}} + d \qquad \text{where } b>c. \tag{11}$$

This functional form applies to a broad range of stylized PA shapes, including squares and semicircles. For a stylized example, assume that all PAs are squares, with one base of the square along the international border. Here, when PA size=x, the benefit of the PA is $X_i - 4\sqrt{X_i} + \sqrt{\min\{X_i, X_j\}}$. Or, assume that all PAs are semicircles, with the flat base of the semicircle along the international border. Now when PA size=X_i, the benefit of the PA is $X_i - (\sqrt{2\pi} + \frac{2\sqrt{2}}{\sqrt{\pi}})\sqrt{X_i} + (\frac{2\sqrt{2}}{\sqrt{\pi}})\sqrt{\min\{X_i, X_j\}}$.

The first term in (11) represents the benefit from a country's park area. The second term represents the cost from a country's park perimeter. The third term represents the extent to which the cost of a country's park perimeter is reduced by the presence of a neighboring country's protected area.

Proposition 6.1: If the objective of creating protected areas is provision of interior habitat, then national welfare is greater under the transboundary equilibrium than under the isolated equilibrium.

Proof: $\frac{\partial b_i(X_i, X_j)}{\partial X_j} = 0$ when $X_i \leq X_j$; $\frac{\partial b_i(X_i, X_j)}{\partial X_j} = \frac{c}{2\sqrt{X_j}} > 0$ when $X_i > X_j$.

A country's park's costly perimeter is decreased as the country's neighbor increases its park size. The spillover condition is satisfied $\forall$ a, b, c, X_j. Since the spillover condition is satisfied, Proposition 5.1 is true by Proposition 1.

Proposition 6.2: If the objective of creating protected areas is provision of interior habitat, then national interior habitat is greater under the transboundary equilibrium than under the isolated equilibrium.

Proof: $\frac{\partial^2 b_i(X_i, X_j)}{\partial X_i \partial X_j}$ = 0 when $X_i < X_j$; $\frac{\partial^2 b_i(X_i, X_j)}{\partial X_i \partial X_j} = \frac{b-c}{4X_i\sqrt{X_i}}$ >0 when $X_i = X_j$, $\frac{\partial^2 b_i(X_i, X_j)}{\partial X_i \partial X_j}$ = 0 when $X_i > X_j$. When parks are nearly identical in size, an addition to a country's neighbor's park means that an addition to the country's own park size creates less additional perimeter per unit area than it would have otherwise. So, the strategic complementarity condition is satisfied $\forall$ a, b, c, X_j. For proof of the insatiability condition, see Appendix B. Since the insatiability condition and strategic complementarity condition are satisfied, then Proposition 6.2 is true by Proposition 2.

Proposition 6.3: If the objective of creating protected areas is provision of interior habitat, then global interior habitat is greater under the transboundary equilibrium than under the isolated equilibrium.

Proof: $\frac{\partial^2 b_i(X_i, X_j)}{\partial X_i^2} = \frac{b-c}{4X_i\sqrt{X_i}}$ >0 when $X_i \le X_j$; $\frac{\partial^2 b_i(X_i, X_j)}{\partial X_i^2} = \frac{b}{4X_i\sqrt{X_i}}$ >0 when $X_i > X_j$. As park size increases, each addition to park size provides less perimeter per unit area. So, the increasing returns to scale condition is satisfied $\forall$ a, b, c, X_j.

Global interior habitat is the sum of isolated domestic interior habitats, so the subadditivity condition is satisfied. Since the increasing returns to scale condition and subadditivity condition are satisfied, then Proposition 6.3 is true by Proposition 3.

Other conservation objectives

The objectives illustrated above are just three of the most common conservation objectives. However, the framework developed in section III allows us to determine whether the transboundary parks configuration is superior for any conservation objective for which benefits can be expressed mathematically as a function of park size. For instance, preserving an international migratory corridor is a clear opportunity for transboundary parks—the spillover condition and strategic complementarity conditions are met, as one country's park only has a chance to succeed in its objective if the other country has a park in place. Two of southern Africa's most prominent transboundary protected areas, the Kavango-Zambezi and the Great Limpopo, were designed to restore elephant migratory corridors.

Conversely, preventing disease in wild stock is not well served by transboundary parks, because the spillover condition is not met—the capacity for one country's park to maintain a healthy population decreases rather than increases in additions to the neighboring country's park size. For ecosystem services such as carbon sequestration, which are likely to be linear in park size, transboundary protection offers no additional gains.

Tourism

One of the most salient economic benefits provided by protected areas is nature tourism. There is some reason to think that tourism benefit will increase with transboundary parks. First, nature tourism value over the long term may be proportional to the persistence of the biological attraction. When this attraction is a flagship species with a wide home range, transboundary parks provide greater persistence, and therefore more viewing opportunities over a longer period of time. Second, tourism value can be assumed to be proportional to the recreational experience, or the ability to "get away from it all." Transboundary parks provide greater interior habitat and wilderness value, and greater scope for penetrating a minimum distance from a human dominated landscape. On the other hand, when tourism value is related to the underlying biological value of species richness, as in the case of birdwatching or flower spotting, the strategic complementarity condition shows that domestic tourism benefit is not necessarily higher with transboundary parks. In either case, the success of nature tourism at a park is as likely to depend on marketing or trends in tourism demand as on the status of the underlying biological attraction. One country's marketing of a park could provide either a positive or negative spillover to the attractiveness of a neighboring country's park as a destination, depending on whether tourists view the parks as complements or substitutes.

VI. Discussion

The model above shows that transboundary parks are superior to counterfactual isolated parks in the provision of national welfare or conservation benefit when the requisite conditions are satisfied. However, it is not the case that transboundary parks are always inferior when the conditions are not met. Rather, transboundary parks may or may not be inferior. The further a conservation objective diverges from satisfying the conditions, the less likely it is that a transboundary equilibrium is superior in meeting the objective.

As long as the spillover condition is satisfied, there will exist both an isolated and a transboundary Nash equilibria. Although the transboundary equilibrium provides greater welfare to both countries, there is no guarantee that countries will arrive at this equilibrium designating parks independently. An outside agent such as an international conservation group can nudge the outcome toward the transboundary equilibrium by providing incentives for government to government negotiation.

This paper does not treat transaction costs associated with the establishment of transboundary parks for two reasons. First, these costs are likely associated with cooperative management rather than contiguous designation. Second, these costs are unlikely to vary much in the size of the protected area, and hence would not affect countries' strategic park size decision in the way that opportunity cost would. To the extent that management costs vary with area, then minimization of management costs can be included in the model as part of the conservation benefit function.

Countries' objective functions were assumed to be concave to support the proof of proposition 2. Relaxing this assumption strengthens the case for transboundary parks as a conservation tool. If the objective function is convex, park size will be a corner solution. Within an ecoregion countries will protect no land whatsoever, or will protect all land available, depending on which provides greater welfare. The spillover condition means that when countries face the choice of protecting all available habitat or none, countries are more likely to protect all available habitat under a transboundary configuration than under an isolated configuration.

Introducing the possibility of transfer payments would extend the model in two ways. First, if international transfer payments are possible, a country will have positive willingness to pay for an increase in its neighbor's park size whenever the spillover condition is met. At least in theory, one country could "purchase" additional conservation from its neighbor. Second, if transfer payments are possible between conservation and economic exploitation interests, transboundary protected areas offer the possibility of a Pareto improving allocation of land and money between these interests whenever the spillover condition is met.

VII. Conclusion

The central motivating claim advanced for the creation of transboundary protected areas is that they achieve conservation objectives more effectively than traditional isolated protected areas. Empirical investigation can only go so far in testing this claim, as TBPAs and IPAs can not exist in the same place at the same time. Theoretical modeling is necessary to compare a transboundary park with the counterfactual transboundary and isolated protected area configurations.

The model advanced in this paper suggests that transboundary protected areas can outperform isolated protected areas in achieving conservation objectives when conditions such as spillover and return to scale are met. Conservation objectives that satisfy these conditions include preventing the extinction of endangered flagship species, providing interior habitat, enforcing park boundaries, and minimizing human-wildlife conflict. When these are the objectives of park formation, countries should locate their parks along international borders, and encourage their neighbors to do the same. Conservation groups should encourage the formation of TBPAs, for instance by subsidizing government-to-government talks. Other conservation objectives such as maximizing species richness within a reserve network do not meet these conditions. For these objectives, conservation groups should target high priority areas for conservation, whether or not these areas span international boundaries.

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Appendix A: Proof of subadditivity condition for species persistence

It can be proven that the subadditivity condition is satisfied for species persistence. That is, when there are two populations, N_i and N_j, on independent patches, each with mean time to extinction represented by $\overline{T_i}$, $\overline{T_j}$, it can be shown that the mean time to extinction for the global population, $N_{i,j}$, is less than the sum of mean time to extinction for each patch, $\overline{T_i} + \overline{T_j}$. To prove this, it is sufficient to show that the probability of survival, P, for the global population at time $\overline{T_i} + \overline{T_j}$ is less than one half. Here $P_t(N_i)$ represents probability of survival of the population i at time t.

Proof that $P_{\overline{T_i}+\overline{T_j}}(N_{i,j}) - \frac{1}{2} < 0$: $P_{\overline{T_i}+\overline{T_j}}(N_{i,j}) - \frac{1}{2} = P_{\overline{T_i}+\overline{T_j}}(N_i) + P_{\overline{T_i}+\overline{T_j}}(N_j) - P_{\overline{T_i}+\overline{T_j}}(N_i)\, P_{\overline{T_i}+\overline{T_j}}(N_j) - \frac{1}{2} = (\frac{1}{2})^{\frac{\overline{T_i}+\overline{T_j}}{\overline{T_i}}} + (\frac{1}{2})^{\frac{\overline{T_i}+\overline{T_j}}{\overline{T_j}}} - (\frac{1}{2})^{\frac{(\overline{T_i}+\overline{T_j})^2}{\overline{T_i}\,\overline{T_j}}} - \frac{1}{2} = \frac{1}{2}[\ (\frac{1}{2})^{\frac{\overline{T_j}}{\overline{T_i}}} + (\frac{1}{2})^{\frac{\overline{T_i}}{\overline{T_j}}} - 1 - (\frac{1}{2})^{\frac{\overline{T_i}}{\overline{T_j}}+\frac{\overline{T_j}}{\overline{T_i}}+1}\ ] < 0\ \forall\ \overline{T_i}, \overline{T_j}$ Since $(\frac{1}{2})^{\frac{\overline{T_j}}{\overline{T_i}}} + (\frac{1}{2})^{\frac{\overline{T_i}}{\overline{T_j}}} - 1 < 0\ \forall\ \overline{T_i}, \overline{T_j}$.

Appendix B: Proof of insatiability condition for interior habitat

$\frac{\partial b_i(X_i, X_j)}{\partial X_i} = a - \frac{b-c}{2\sqrt{X_i}} > 0$ when $X_i \le X_j$ and $X_i > \left(\frac{b-c}{2a}\right)^2$, since $b_i(X_i, X_j)>0$ only when $X_i > (\frac{b-c}{a})^2$, $\frac{\partial b_i(X_i, X_j)}{\partial X_i}>0\ \forall\ X_i \mid b_x(X_i, X_j)>0$. $\frac{\partial b_i(X_i, X_j)}{\partial X_i} = a - \frac{b}{2\sqrt{X_i}} + \frac{c}{2\sqrt{X_j}}>0$ when $X_i > X_j$ and when $X_i > \left(\frac{b\sqrt{X_j}}{2a\sqrt{X_j}+c}\right)^2$. It can be shown that $y>\left(\frac{b\sqrt{X_j}}{2a\sqrt{X_j}+c}\right)^2\ \forall$ a, b>c, X_j. So, $\frac{\partial b_i(X_i, X_j)}{\partial X_i}>0\ \forall$ a, b, c, X_j when $X_i > X_j$.

This shows that if park size is sufficiently large to ensure that the net benefit of the park is positive, then the net benefit of the park always increases from additional size. The perimeter-area ratio decreases in park size. So the insatiability condition is satisfied $\forall$ a, b, c, X_j.