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ANALYSIS

Gains from configuration: The transboundary protected area as a conservation tool

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ARTICLE INFO

ABSTRACT

Nearly two hundred transboundary protected areas comprise a portion of the global 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 cannot 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 counterfactual transboundary and isolated protected areas. The model suggests that under certain conditions, transboundary protected areas can achieve greater conservation and production objectives, even in the absence of international cooperative park management. The paper establishes five sufficient conditions for transboundary protected areas to provide greater national welfare, domestic conservation value, or global conservation value than counterfactual isolated protected areas. These conditions are tested for three common conservation objectives. The results suggest that when the objective of conservation is species persistence or interior habitat, conservation groups should encourage transboundary protected areas. However, when the objective of conservation is to extend reserve coverage to the maximum number of species, conservation groups should encourage protected areas where species richness is greatest, whether or not these areas span international borders.

1. Introduction

Transboundary protected areas (TBPAs), or two or more protected areas adjoining across an international border, comprise a large and growing portion of the conservation landscape. Proponents claim that TBPAs outperform isolated protected areas (IPAs) in achieving conservation objectives, while providing ancillary economic, social, and political benefits. Critics contend that these claims are overstated and are not realized in practice. If proponents are correct, then

conservation resources should be preferentially directed toward TBPAs. If critics are correct, then conservation resources should be directed toward protected areas (PAs, or "parks") that best meet other criteria, whether or not they are transboundary in nature. Therefore it is important to establish under which circumstances TBPAs are likely to outperform IPAs in achieving conservation objectives.

Empirical investigations of proponents' claims have been rudimentary to date, and are fundamentally limited by the fact that counterfactual transboundary and isolated protected

areas cannot exist in the same place at the same time. Therefore, this paper develops a theoretical model to directly compare counterfactual isolated and transboundary protected area configurations. This model is presented in Section 3. Whether or not a transboundary configuration outperforms a counterfactual isolated configuration depends on the countries' conservation objective for establishing a park. When this conservation objective satisfies certain sufficient conditions, it can be shown that the transboundary configuration provides greater national welfare, domestic conservation value, or global conservation value. This framework of sufficient conditions is presented in Section 4. As an illustration, this framework of sufficient conditions is tested in Section 5 for three common conservation objectives: species richness, species persistence, and interior habitat. For two of the three objectives, the conditions are met, and the transboundary configuration provides greater conservation value. Implications for conservation are discussed in Section 6.

2. Transboundary parks

For nearly as long as there have been protected areas, there have been transboundary protected areas. 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 parks were combined to form the Waterton-Glacier International Peace Park.

Some of the highest profile protected areas on the planet span international boundaries. Kenya's Masai Mara National Park and the adjoining Serengeti National Park in Tanzania protect 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 Mgahinga Gorilla 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.

As of 2005, Conservation International reports 188 internationally adjoining protected area complexes, in 112 countries, comprised of 818 individual protected areas. These areas span 3.2 million km^2, an area roughly the size of India, or 17% of the global extent of protected areas (Mittermeier et al., 2005). These complexes are distributed across five continents, with 15 in North America, 29 in Central and South America, 33 in Africa, 46 in Asia, and 65 in Europe. In contrast to the IUCN definition of a TBPA (Dudley, 2003), this paper does not require cooperative management for classification 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.

Dozens more TBPAs have been proposed. Nearly twenty future TBPAs have been suggested for southern Africa alone (Hall-Martin and Modise, 2002). The InterAmerican Development Bank is supporting a "Comprehensive Assessment of Transboundary Conservation Opportunities in Latin America," with the goal of identifying at least 10 potential new TBPA sites in Latin America (ProNatura, 2007). The International Union

for the Conservation of Nature (IUCN) envisions a 6000 km European Greenbelt spanning 22 countries along the former Iron Curtain (Terry et al., 2006). The president of South Korea has proposed that the Korean Demilitarized Zone be preserved as a wildlife sanctuary and peace park (Kim, 1997).

This growth in TBPAs is deliberate. The IUCN has a Global TBPA Network and a TBPA Task Force; Conservation International has a Southern Africa Transfrontier Conservation Unit. Two NGOs, the Peace Parks Foundation in Africa and ProNatura in South America, have the explicit goal of establishing more TBPAs.

Even as TBPAs proliferate rapidly, commentary on TBPAs within the conservation literature 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 said 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 et al., 2005). Detractors challenge whether the various stated goals of TBPAs are realized in practice, as well as "whether the methods currently being employed are optimal in relation to the investment and transaction costs of such initiatives" (Sandwith, 2003).

The few empirical studies of TBPAs to date do not support the claim that TBPAs improve conservation and development outcomes. Reyers (2003) compared avian species richness and number of land cover types in five South African parks with and without the inclusion of neighboring countries' adjoining parks. She found that the addition 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 only 40%, despite increasing total protected area size by an average of 110%. Scovronick and Turpie (2006) found that park visitation to South Africa's Kalahari-Gemsbok National Park and Botswana's Gemsbok National Park did not increase following their 2004 integration into the Kgalagadi Transfrontier Park. Two thorough before-and-after studies aim to measure the effect of the newly established, Nevada-sized Kavango-Zambezi Transfrontier Conservation Area on the tourism economy (Suich et al., 2006) and socioeconomic conditions (Scovronick et al., 2007) in Angola, Botswana, Namibia, Zambia, and Zimbabwe.

Empirical testing of greater achievement of conservation objectives by TBPAs is fundamentally limited. A true head-to-head comparison of actual TBPAs with counterfactual IPAs is simply not possible in practice, as both types of parks cannot occupy the place at the same time. There is no way of knowing what would have happened in the studies above 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 a comparison of transboundary and isolated park configurations based solely on the conservation benefits accruing from park size and connectivity would neglect two

key effects relating to countries' economic incentives. First, a large park may provide more conservation benefit than a small park, but it also carries a greater opportunity cost. By contrast, a country can receive spillover of conservation benefit from an adjoining park in a neighboring country, at no cost. Second, strategic interactions occur between countries that can only be captured through a game theory model. An adjoining park in a neighboring country may give a country an incentive to make its own park either larger or smaller than it would have otherwise. This paper advances the study of transboundary parks by providing a game theory model that can be used to compare transboundary parks and counterfactual isolated parks across three criteria – national welfare, domestic conservation benefit, and global conservation benefit.

Game theory models have been used in natural resource economics to distill problems of strategic interaction among resource users to their essential elements. Models of Cournot competition in particular have been used to demonstrate gains from cooperation. Gordon (1954) shows that the result of a common pool, open access fishery is rent dissipation among firms. Levhari and Mirman (1980) show that cooperative management between duopolistic fishing nations results in greater fish population as well as greater economic returns. Salant (1976) finds greater oil stocks and economic returns for Cournot-competing oil producers in a cartel than in a competitive market. This paper contributes to the game theory and natural resource economics literature by showing the possibility of welfare and conservation gains from spatial configuration of resource use, even in the absence of cooperation.

This paper leaves aside questions of whether TBPAs create international peace (Westing, 1998) or acrimony (Wolmer, 2003), and of whether they have resulted in community development or disenfranchisement (Turner, 2004). Neither does the model comment on whether the legal framework necessary for transboundary conservation is consistent with existing international laws (Young, 2003; Tamburelli and Guillet, 2003). While peace dividends or challenges to cooperative management are clearly important considerations for land use planners in some contexts, the model developed in this paper focuses solely on conservation benefit and opportunity cost.

3.   A game theory model of park formation

In the transboundary parks problem, an ecoregion extends across two neighboring countries, i, j. Within each country this ecoregion can be divided between protected land and unprotected land. Unprotected land is put into production for ranching, agriculture, or forestry, but provides no habitat. Protected land provides habitat, but no production. Isolated protected areas are assumed to create ecologically discrete habitat islands, while adjoining protected areas are assumed to create a single habitat island. Land within the ecoregion is assumed to be homogenous in its potential value as habitat or for production.

Countries value both conservation and production. A protected area benefits a country through the achievement of conservation objectives, but also costs a country through foregone production. 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 adjoining along 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, $X_j \geq 0$, 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, $c_i(X_i)$. A country's opportunity cost is increasing in the size of its protected area. A country's opportunity cost is unaffected by the size or adjacency of the neighboring country's protected area. The opportunity cost function is allowed to vary in functional form between countries; it is possible for opportunity cost to rise more steeply in one country than in another.

Conservation benefit is a biological metric that quantifies a protected area's provision of a country's conservation objective. Conservation benefit could measure, for example, the number of species contained in a park, probability of species persistence within a park, or amount of interior habitat provided by a park. 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 amount of interior habitat is convex.

Domestic conservation benefit is the conservation benefit one country receives from the park sizes and configuration. In the isolated park configuration, a country's domestic conservation benefit is determined only by the size of its own park – $b_i^I(X_i)$. Under the transboundary park configuration, a country can also receive indirect benefit from an adjoining protected area in the neighboring country – $b_i^T(X_i, X_j)$. Domestic conservation benefit is an ecological production function which does not vary across countries – $b_i^I(X) = b_j^I(X) \forall X; b_i^T(X,X') = b_j^T(X,X') \forall X,X'$. A transboundary park with no adjoining protected area is considered identical to an isolated park by construction – $b_i^T(X_i,0) = b_i^I(X_i)$.

Global conservation benefit, $g(X_i, X_j)$, is the conservation benefit to the world at large from the overall size and configuration of parks in both countries. Under the transboundary park configuration, global conservation benefit accrues from the single habitat island using the same ecological production function as domestic conservation benefit – $g^T(X_i,X_j) = b_i^I(X_i + X_j)$. Under an isolated park configuration, the global conservation benefit $g^T(X_i,X_j)$ will vary by conservation objective.

In the isolated park configuration, country i chooses X_i to maximize national welfare in a single-agent welfare maximization problem:

$$\max_{X_i} w_i^I(X_i) = \phi_i b_i^I(X_i) - c_i(X_i). \tag{1}$$

In the transboundary park configuration, country i chooses X_i to maximize national welfare in a non-cooperative game:

$$\max_{X_i} w_i^T(X_i, X_j) = \phi_i b_i^T(X_i, X_j) - c_i(X_i). \tag{2}$$

The parameter $\phi_i > 0$ weights the value country i places on domestic conservation benefit relative to opportunity cost,

and scales the biological metric to a dollar value. The weight of this parameter is allowed to vary across countries; it is possible for preference for conservation benefit relative to opportunity cost to be higher in one country than another.

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 single-agent national welfare maximization problems. The isolated 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 adjoining along the border, and the park configuration is transboundary. The transboundary equilibrium exists only 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 equilibrium park sizes in a Cournot–Nash national welfare maximization problem.

In each configuration, the equilibrium park sizes will determine the national welfare, domestic conservation benefit, and global conservation benefit that accrue. The national welfare accruing to country i is represented by $w_i^I(X_i^{I*}, X_j^{I*})$ under the isolated equilibrium and $w_i^T(X_i^{T*}, X_j^{T*})$ under the transboundary equilibrium. The domestic conservation benefit accruing to country i is represented by $b_i^I(X_i^{I*}, X_j^{I*})$ under the isolated equilibrium and $b_i^T(X_i^{T*}, X_j^{T*})$ under the transboundary equilibrium. The global conservation benefit accruing to the world at large is represented by $g^I(X_i^{I*}, X_j^{I*})$ under the isolated equilibrium and $g^T(X_i^{T*}, X_j^{T*})$ under the transboundary equilibrium.

Though national welfare may be larger under the transboundary equilibrium, this model makes no predictions about which of the two Nash Equilibrium configurations will actually occur. A transboundary configuration could occur if the two countries understand the benefits to be gained from a transboundary configuration and solve a coordination game. Or, the transboundary configuration could occur merely due to random chance or exogenous cost considerations. An outside agency such as an international conservation group could nudge the outcome toward the transboundary configuration by subsidizing government-to-government negotiations, increasing the probability that countries solve the coordination game.

This paper examines only the case when the objective function is concave $-\frac{\partial w_i^{T2}(X_i, X_j)}{\partial X_i^2} < 0$, $\frac{\partial w_i^{I2}(X_i)}{\partial X_i^2} < 0$. When the objective function is nonconcave, it is trivially simple to determine whether the transboundary equilibrium provides greater national welfare, domestic conservation benefit, or global conservation benefit. When the objective function is nonconcave, park size will be a corner solution. A country will protect no land or all land within an ecoregion, depending on which provides greater welfare. As long as positive spillover between parks occurs, countries will have greater welfare under the transboundary equilibrium than under an isolated equilibrium. Countries will be more likely to protect all land

under the transboundary configuration, so domestic conservation benefit and global conservation benefit will be greater under the transboundary equilibrium as well.

4. A framework of sufficient conditions for TBPA 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 form of the conservation benefit function $b_i(X_i, X_j)$. This functional form will vary by conservation objective. Rather than test the superiority of the transboundary equilibrium for each conservation objective in turn, this paper establishes a general framework of sufficient conditions for TBPA superiority. If the conservation benefit function associated with a particular conservation objective satisfies certain conditions, presented below, then the transboundary equilibrium provides greater national welfare, domestic conservation benefit, or global conservation benefit than the isolated equilibrium for that conservation objective. In Section 5, this framework is applied to three common conservation objectives, to see which can be better achieved with a TBPA.

4.1. Spillover condition

The domestic conservation benefit provided by one country's protected area is increasing in the size of the neighboring country's adjoining protected area:

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

4.2. Insatiability condition

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

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

4.3. Strategic complementarity condition

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

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

4.4. 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:

$$\frac{\partial^2 b_i(X_i, X_j)}{\partial X_i^2} > 0 \qquad \forall\ X_i, X_j. \tag{6}$$

4.5. Subadditivity condition

Global conservation benefit accruing from two isolated protected areas does not exceed the sum of the global conservation benefit accruing from each individual protected area:

$$g^I(X_i,X_j) \leq b_i(X_i) + b_j(X_j) \ \forall \ X_i,X_j. \tag{7}$$

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 $w_i^T(X_i^{T*},X_j^{T*})>w_i^I(X_i^{I*})$:

By definition $X_i^{T*} = \max_{X_i} w_i^T(X_i,X_j^{T*})$, so $w_i^T(X_i^{T*},X_j^{T*})-w_i^T(X_i^{I*},X_j^{T*})\geq 0$. National welfare is increasing in the neighboring country's park size, because the spillover condition is satisfied and because opportunity cost is unaffected by the neighboring country's park size. This implies that $w_i^T(X_i^{I*},X_j^{T*})-w_i^T(X_i^{I*},0)>0$. By construction $w_i^T(X_i^{I*},0)=w_i^I(X_i^{I*})$. Therefore, $w_i^T(X_i^{I*},X_j^{T*})-w_i^I(X_i^{I*})=[w_f(X_i^{T*},X_j^{T*})-w_i^T(X_i^{I*},X_j^{T*})]+[w_i^T(X_i^{I*},X_j^{T*})-w_i^T(X_i^{I*},0)]+[w_i^T(X_i^{I*},0)-w_i^I(X_i^{I*})]>0$. When the spillover condition is satisfied, the presence of a neighboring country's adjoining park increases a park's conservation benefit without increasing the park's cost. The country's production possibility frontier for conservation and production from an ecoregion is expanded by a transboundary configuration, increasing national welfare.

Corollary 1. *If the spillover condition is not satisfied, then national welfare is not greater under the transboundary equilibrium than under the isolated equilibrium.*

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

By definition $X_i^{I*} = \max_{X_i} w_i^I(X_i)$, so $w_i^I(X_i^{T*})-w_i^I(X_i^{I*})\leq 0$. National welfare is nonincreasing in neighboring country's adjoining park size, because the spillover condition is not satisfied and because opportunity cost is unaffected by the neighboring country's park size. This implies that $w_i^T(X_i^{T*},X_j^{T*})-w_i^T(X_i^{T*},0)\leq 0$. By construction $w_i^T(X_i^{T*},0)=w_i^I(X_i^{T*})$. Therefore, $w_i^T(X_i^{T*},X_j^{T*})-w_i^I(X_i^{I*})=[w_i^T(X_i^{T*},X_j^{T*})-w_i^T(X_i^{T*},0)]+[w_i^T(X_i^{T*},0)-w_i^I(X_i^{T*})]+[w_i^I(X_i^{T*})-w_i^I(x_i^{I*})]\leq 0$. When the spillover condition is not satisfied, the presence of a neighboring country's adjoining park decreases a park's conservation benefit without decreasing the park's cost. The country's production possibility frontier for conservation and production from an ecoregion is contracted by a transboundary configuration, decreasing national welfare.

National welfare is greater under the transboundary equilibrium than under the isolated equilibrium if and only if the spillover condition is satisfied. However, greater national welfare does not ensure greater conservation benefit. Greater national welfare might be due solely to 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 $b_i^T(X_i^{T*},X_j^{T*})\geq b_i^I(X_i^{I*})$:

The second order condition is satisfied because the objective function $W_i^T(X_i,X_j)$ has been assumed to be concave. In 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 $\frac{\partial w_i^I(X_i^{I*})}{\partial X_i}=0$. So,

$$\frac{\partial w_i^T(X_i^{T*},X_j^{T*})}{\partial X_i}-\frac{\partial w_i^I(X_i^{I*})}{\partial X_i}=0. \tag{8}$$

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 the strategic complementarity condition is satisfied 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, we know that $\frac{\partial w_i^T(X_i^{T*},0)}{\partial X_i}-\frac{\partial w_i^T(X_i^{I*},0)}{\partial X_i}>0$. This implies that $\frac{\partial w_i^T(X_i^{T*},X_j^{T*})}{\partial X_i}-\frac{\partial w_i^I(X_i^{I*})}{\partial X_i}=\left[\frac{\partial w_i^T(X_i^{T*},X_j^{T*})}{\partial X_i}-\frac{\partial w_i^T(X_i^{T*},0)}{\partial X_i}\right]+\left[\frac{\partial w_i^T(X_i^{T*},0)}{\partial X_i}-\frac{\partial w_i^T(X_i^{I*},0)}{\partial X_i}\right]+\left[\frac{\partial w_i^T(X_i^{I*},0)}{\partial X_i}-\frac{\partial w_i^I(X_i^{I*})}{\partial X_i}\right]>0$. But this contradicts Eq. (8). Therefore,

$$X_i^{T*}\geq X_i^{I*}. \tag{9}$$

Park size will be greater under the transboundary equilibrium than under the isolated equilibrium. This implies that $b_i^T(X_i^{T*},0)-b_i^T(X_i^{I*},0)\geq 0$ because the insatiability condition is satisfied. Further, $b_i^T(X_i^{T*},X_j^{T*})-b_i^T(X_i^{T*},0)\geq 0$ because the spillover condition is satisfied. By construction $b_i^T(X_i^{I*},0)=b_i^I(X_i^{I*})$. Therefore, $b_i^T(X_i^{T*},X_j^{T*})-b_i^I(X_i^{I*})=[b_i^T(X_i^{T*},X_j^{T*})-b_i^T(X_i^{T*},0)]+[b_i^T(X_i^{T*},0)-b_i^T(X_i^{I*},0)]+[b_i^T(X_i^{I*},0)-b_i^I(X_i^{I*})]\geq 0$. When the strategic complementarity condition is satisfied, the marginal benefit provided by each additional unit of park size is increased by the presence of a neighboring country's adjoining park. Countries have incentive to make their parks larger under the transboundary configuration to than they would have under the isolated configuration, resulting in greater domestic conservation benefit.

Domestic conservation benefit will be greater under the transboundary equilibrium than under the isolated equilibrium if the three conditions above are satisfied. If all three conditions are not satisfied, domestic conservation benefit could be greater in either equilibrium. Greater domestic conservation benefit does not ensure greater global conservation benefit. Greater conservation benefit from increased park size might be offset by lower global conservation benefit from increased overlap in benefit provided, due to park adjacency. Two more conditions must be satisfied to ensure that global conservation benefit will be greater under the transboundary equilibrium than under the 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 $g^I(X_i,X_j)\leq b_i(X_i)+b_j(X_j)$, then $g^T(X_i^{T*},X_j^{T*})\geq g^I(X_i^{I*},X_j^{I*})$:

Remember that global conservation benefit is defined such that $g^T(X_i,X_j)=b_i^I(X_i+X_j)$. So, $g^T(X_i^{T*},X_j^{T*})=b_i^I(X_i^{T*}+X_j^{T*})$. As shown in Eq. (8), park size will be greater under a transboundary equilibrium than under an isolated equilibrium, $X_i^{T*}\geq X_i^{I*}$, $X_j^{T*}\geq X_j^{I*}$,

because the spillover, insatiability, and strategic complementarity conditions are satisfied. So, $b_i^I(X_i^{T*}+X_j^T) \geq b_i^I(X_i^{I*}+X_j^{I*})$ because the insatiability condition is satisfied. Because the increasing returns to scale condition is satisfied, $b_i^I(X_i^{T*}+X_j^{I*}) \geq b_i^I(X_i^{I*}) + b_i^I(X_j^{I*})$. By construction, $b_i^I(X_j^{I*}) = b_j^I(X_j^{I*})$. And because the subadditivity condition is satisfied, $b_i^I(X_i^{I*}) + b_j^I(X_j^{I*}) - g^I(X_i^{I*}, X_j^{I*}) \geq 0$. So, $g^T(X_i^{T*}, X_j^{T*}) - g^I(X_i^{I*}, X_j^{I*}) = [g^T(X_i^{T*}, X_j^{T*}) - b_i^I(X_i^{T*}+X_j^{T*})] + [b_i^I(X_i^{T*}+X_j^{T*}) - b_i^I(X_i^{I*}+X_j^{I*})] + [b_i^I(X_i^{I*}+X_j^I) - b_i^I(X_i^{I*}) - b_j^I(X_j^{I*})] + [b_i^I(X_j^{I*}) - b_j^I(X_j^{I*})] + [b_i^I(X_i^{I*}) + b_j^I(X_j^{I*}) - g^I(X_i^{I*}, X_j^{I*})] \geq 0$. When the subadditivity and increasing returns to scale conditions are satisfied, the larger adjoining parks created by countries under the transboundary configuration provide greater global conservation benefit than the smaller isolated parks created under the isolated configuration. Global conservation benefit will be greater under the transboundary equilibrium than under the isolated equilibrium if the five conditions above are satisfied. If all five conditions are not satisfied, global conservation benefit could be greater in either equilibrium.

Transaction costs are not included in this model, since these costs are likely to be associated with cooperative management rather than with adjoining designation. Also, these costs are unlikely to vary much in the size of the protected area, and so do not affect countries' strategic park size decision as opportunity cost does. If transaction costs are indeed an important modeling consideration, then these costs can be included in $b_i^T(X_i, X_j)$. In this case, $c_i(X_i)$ and $b_i^T(X_i, X_j)$ can be thought of as the separable and joint components of national welfare, rather than opportunity cost and conservation benefit specifically.

The opportunity cost of protecting land has been assumed to be homogenous throughout the ecoregion. If opportunity cost were instead allowed to vary between the interior and the border, two more conditions would have to be satisfied for the three propositions above to hold. To ensure that greater national welfare is provided under the transboundary equilibrium, opportunity cost would have to be equal or lower along the border than in the interior – $c_i(X_i, I) \geq c_i(X_i, B) \forall X_i$, where I and B represent interior and border location respectively. To ensure that greater national conservation benefit and global conservation benefit is provided under the transboundary equilibrium, it can be shown that marginal opportunity cost would have to be equal or lower along the border as well – $\frac{\partial c_i(X_i, I)}{\partial X_i} \geq \frac{\partial c_i(X_i, B)}{\partial X_i}$. These two conditions ensure that welfare and conservation gains from transboundary adjacency along the border are not offset by welfare or conservation losses from protecting land in a region with higher opportunity cost. To the extent that land costs vary systematically between regions, it is reasonable to think that these conditions would be satisfied. Opportunity cost could be higher and steeper in the border region if land rents are reduced by distance to markets and infrastructure, or tenure insecurity. However, differential land cost between regions has not been included in this model, as the main insight to be derived is gains from transboundary park configuration rather than gains from locating a park where land is cheapest.

Any existence value that a country has for its neighbor's park has been assumed not to enter its park size and location decisions – $\frac{\partial b_i^I(X_i)}{\partial X_j} = 0$, $\frac{\partial b_i^T(X_i, X_j)}{\partial X_j} = 0$. If existence values were allowed to enter park size and location decisions, then both the isolated and transboundary equilibrium park sizes would be the solution to strategic non-cooperative games. Determining which of these equilibria provides greater national welfare,

domestic conservation benefit, or global conservation benefit would require a more complex framework of conditions than that which is presented in this paper.

In summary, if and only if a conservation objective satisfies the spillover condition, then national welfare is greater under the transboundary parks equilibrium than under the isolated parks equilibrium. If a conservation objective additionally satisfies the insatiability condition and the strategic complementarity condition, then domestic conservation benefit will be greater under the transboundary equilibrium than under the isolated equilibrium. Finally, if a conservation objective additionally satisfies the returns to scale condition and the subadditivity condition, then global conservation benefit will be greater under the transboundary equilibrium than under the isolated equilibrium. This framework of conditions is displayed in Table 1.

5.   Application of framework to three common conservation objectives

The framework developed in Section 4 and displayed in Table 1 enables us to determine whether the transboundary equilibrium provides greater national welfare, domestic conservation benefit, or global conservation benefit for any conservation objective for which benefits can be expressed mathematically as a function of protected area size. As illustrative examples, the framework is applied to three common conservation objectives: species richness, species persistence, and interior habitat. For each objective, we will test whether the conservation benefit function satisfies the five conditions. This will tell us whether a transboundary equilibrium provides greater national welfare, domestic conservation benefit, or global conservation benefit for that conservation objective.

5.1.   Species richness

Species richness is a count of the number of species found in an area. Richness can be counted across all species, or can be specific to a taxonomic group such as mammals, birds, or vascular plants. A solid foundation of conservation planning literature (Church et al., 1996; Ando et al., 1998) and software (Possingham et al., 2000) has been established to maximize the species richness contained in a reserve network. In the reserve site selection model, a species is contained by the reserve network if that species is contained by a sufficient number of parcels in the network. The model developed in this paper instead treats protected areas as habitat islands (Newmark, 1987). The species richness of a protected area is a function of protected area size, following the theory of island biogeography (MacArthur and Wilson, 1967).

Archipelagic and intraprovincial species area relationships are well-established in island biogeography. In these relationships, species richness on a plot of land on an island is increasing at a decreasing rate in both the size of the plot and the size of the island. Extending this relationship to habitat islands, the species richness in a country's PA is increasing at a decreasing rate in both the size of the PA and the size of the overall TBPA. The conservation benefit of species richness takes on the following form:

$$b_i^T(X_i, X_j) = aX_i^m(X_i + Xj)^n, \text{ where } m, n, m+n \in (0,1). \quad (10)$$

Here, the parameter m represents the rate at which species richness increases in PA size. The parameter n represents the rate at which species richness increases in total TBPA size. The parameters, m and n have been the subject of extensive empirical investigation. The typical range of these parameters is $m \in (0.13–0.18)$, and $n \in (0.25–0.45)$ (Rosenzweig, 2000).

Proposition 4.1. *Species richness satisfies the spillover condition.*

Proof: $\frac{\partial b_i(X_i, X_j)}{\partial X_j} = an X_i^m (X_i + X_j)^{n-1} > 0 \ \forall \ m, n, X_j$. As the size of the total TBPA increases, the number of species found in one PA increases. So, the spillover condition is satisfied $\forall \ m, n, X_j$. □

Proposition 4.2. *Species richness satisfies the insatiability condition.*

Proof: $\frac{\partial b_i(X_i, X_j)}{\partial X_i} = a X_i^{m-1} (X_i + X_j)^{n-1} [m(X_i + X_j) + n X_i] > 0 \ \forall \ m, n, X_j$. A larger PA contains more species, so the insatiability condition is satisfied $\forall \ m, n, X_j$. □

Proposition 4.3. *Species richness does not satisfy the strategic complementarity condition.*

Proof: $\frac{\partial^2 b_i(X_i, X_j)}{\partial X_i \partial X_j} = an X_i^{m-1} (X_i + X_j)^{n-2} [(m+n-1)X_i + m X_j] > 0$ only if $\frac{X_i}{X_j} < \frac{m}{1-(m+n)}$. However, the typical observed range of these parameters is $m \in (0.13–0.18)$, and $n \in (0.25–0.45)$. So $\frac{m}{1-(m+n)} \in (0.20–0.32)$. It is therefore not possible for both $\frac{X_i}{X_j} < 1$ and $\frac{X_j}{X_i} < 1$. As the size of the TBPA increases, the number of additional species gained from increasing the size of one PA is decreasing. So, the strategic complementarity condition is not satisfied. □

Proposition 4.4. *Species richness does not satisfy the increasing returns to scale condition.*

Proof: $\frac{\partial^2 b_i(X_i, X_j)}{\partial X_i^2} = a X_i^{m-2} (X_i + X_j)^{n-2} [X_i^2(m+n)(m+n-1) + 2m X_i X_j (m+n-1) + X_j^2 m(m-1)] < 0 \ \forall \ m, n, X_j$. As the size of a PA increases, the number of additional species gained from increasing the size of the PA is decreasing. So, the increasing returns to scale condition is not satisfied. □

Proposition 4.5. *Species richness satisfies the subadditivity condition.*

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

When species richness is the objective of conservation, national welfare is greater under the transboundary equilibrium than under the isolated equilibrium because the spillover condition is satisfied. Because the strategic complementarity condition is unsatisfied, domestic conservation benefit is not necessarily greater under the transboundary equilibrium than under the isolated equilibrium. Because the increasing returns to scale condition is unsatisfied, global conservation benefit is

not necessarily greater under the transboundary equilibrium than under the isolated equilibrium. See Table 2.

5.2. Species persistence

Species persistence measures the probability that a species will survive rather than become extinct within a given area. Protected areas are frequently established with the objective of improving the probability of persistence for a particular species. Protected areas have been established to protect endangered species such as pandas, tigers, gorillas, okapis, and komodo dragons, among others.

Persistence can be measured in different ways. Population viability is the probability that a species will persist within an area over a given time period. Mean time until extinction is the expected length of time a species will live until it becomes extinct within a given area. This species "life expectancy" is used as the objective for species persistence in this paper.

The size of a species' geographic range has been found to be the most powerful single determinant of species extinction risk (Purvis et al., 2000). In this paper, mean time to extinction is modeled as a function of protected area size using the ceiling model of density dependent population growth model as annotated by Morris and Doak (2002). In the ceiling model, a species of population size n within a protected area of size X_i experiences a stochastic growth rate, λ. Parameters μ and σ^2 represent the mean and variance of the natural logarithm of growth rate. The parameter $c = \frac{\mu}{\sigma^2}$. The area has a carrying capacity, K, which acts as a ceiling to population size. K is linear in protected area size, $K = a(X_i + X_j)$, where a represents ceiling population density. Here, $n_{t+1} = \lambda n_t$ if $\lambda n_t \leq K$, and $n_{t+1} = K$ if $\lambda n_t \geq K$. Initial population size is equal to K. If population size falls below the quasi-extinction threshold of $n = 1$, the species becomes extinct. In the ceiling model, mean time to extinction takes the following form (Lande, 1993):

$$b_i(X_i, X_j) = \bar{T} = \frac{1}{2\mu c} \left([a(X_i + X_j)]^{2c} - 1 - 2c \ln([a(X_i + X_j)]) \right) \quad (11)$$

A greater carrying capacity means a smaller chance that a species will be driven to extinction by a few bad years in succession. The mean time to extinction objective does not include time preference, implicitly assuming a zero discount rate. However, if a positive discount rate were imposed, then park configuration will have the greatest impact on species facing a significant extinction risk in the short run.

Proposition 5.1. *Species persistence satisfies the spillover condition.*

Proof: $\frac{\partial b_i(X_i, X_j)}{\partial X_j} = \frac{1}{2\mu c} \left(2ac[a(X_i + X_j)]^{2c-1} - \frac{2c}{X_i + X_j} \right) > 0 \ \forall \ c, \mu; a(X_i + X_j > 1) \forall$. As long as the TBPA has a carrying capacity greater than one individual, mean time to extinction within one PA will be increasing in the size of the neighboring country's PA. So, the spillover condition is satisfied. □

Proposition 5.2. *Species persistence satisfies the insatiability condition.*

Proof: $\frac{\partial b_i(X_i, X_j)}{\partial X_i} = \frac{1}{2\mu c} \left(2ac[a(X_i + X_j)]^{2c-1} - \frac{2c}{X_i + X_j} \right) > 0, \ \forall \ c, \mu, a(X_i + X_j) > 1$. As long as the TBPA has a carrying capacity

greater than one individual, mean time to extinction within a PA will be increasing in the size of the PA. So, the insatiability condition is satisfied. □

Proposition 5.3. *Species persistence satisfies the strategic complementarity condition.*

Proof: $\frac{\partial^2 b_i(X_i,X_j)}{\partial X_i \partial X_j} = \frac{1}{2\mu c}\left(2a^2c(2c-1)\left[a(X_i+X_j)\right]^{2c-2} + \frac{2c}{(X_i+X_j)^2}\right) > 0$ when $c>0.5$ or when $c<0.5$ and $a(X_i+X_j)<(1-2c)^{-1/2c}$. As long as $c>0.5$, the gain in mean time to extinction from an addition to one PA is increasing the neighboring country's PA size. 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. Low demographic stochasticity occurs in species with long lives, long generations, low birthrates, and low annual fluctuations in fecundity and mortality. These are the large charismatic species parks are generally designed to protect. □

Proposition 5.4. *Species persistence satisfies the increasing returns to scale condition.*

Proof: $\frac{\partial^2 b_i(X_i,X_j)}{\partial X_i^2} = \frac{1}{2\mu c}\left(2a^2c(2c-1)\left[a(X_i+X_j)\right]^{2c-2} + \frac{2c}{(X_i+X_j)^2}\right) > 0$ 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 PA size. 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 is satisfied. □

Proposition 5.5. *Species persistence satisfies the subadditivity condition.*

We seek to prove that for two populations, N_i and N_j, in isolated protected areas, with mean time to extinction $\overline{T_i}, \overline{T_j}$, 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 $P_{\overline{T_i}+\overline{T_j}}(N_{i,j}) - \frac{1}{2} < 0 : P_{\overline{T_i}+\overline{T_j}}(N_{i,j}) - \frac{1}{2} = P_{\overline{T_i}+\overline{T_j}}(N_i) + P_{\overline{T_i}+\overline{T_j}}(N_j) - P_{\overline{T_i}+\overline{T_j}}(N_i)P_{\overline{T_i}+\overline{T_j}}(N_j) - \frac{1}{2} = \left(\frac{1}{2}\right)^{\frac{\overline{T_i}+\overline{T_j}}{\overline{T_i}}} + \left(\frac{1}{2}\right)^{\frac{\overline{T_i}+\overline{T_j}}{\overline{T_j}}} - \left(\frac{1}{2}\right)^{\frac{(\overline{T_i}+\overline{T_j})^2}{\overline{T_i}\overline{T_j}}} - \frac{1}{2} = \frac{1}{2}\left[\left(\frac{1}{2}\right)^{\frac{\overline{T_j}}{\overline{T_i}}} + \left(\frac{1}{2}\right)^{\frac{\overline{T_i}}{\overline{T_j}}} - 1 - \left(\frac{1}{2}\right)^{\frac{\overline{T_i}}{\overline{T_j}}+\frac{\overline{T_j}}{\overline{T_i}}+1}\right] < 0 \,\forall\, \overline{T_i}, \overline{T_j}$, because $\left(\frac{1}{2}\right)^{\frac{\overline{T_j}}{\overline{T_i}}} + \left(\frac{1}{2}\right)^{\frac{\overline{T_i}}{\overline{T_j}}} - 1 < 0 \,\forall\, \overline{T_j}, \overline{T_j}$. The mean time to extinction for independent populations on two isolated PAs is less than the sum of mean time to extinction on each PA. If the two populations are not independent, the total mean time to extinction is even lower. So, the subadditivity condition is satisfied. □

When species persistence is the objective of conservation, national welfare is greater under the transboundary equilibrium than under the isolated equilibrium because the spillover condition is satisfied. Because the insatiability condition and strategic complementarity condition are satisfied, domestic conservation benefit is greater under the transboundary equilibrium than under the isolated equilibrium for species

with low demographic stochasticity. Because the increasing returns to scale condition and the subadditivity condition are satisfied, global conservation benefit is greater under the transboundary equilibrium than under the isolated equilibrium for species with low demographic stochasticity. See Table 2.

5.3. 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 (Saunders et al., 1991). This class of objective includes wilderness value, where wilderness is defined as land greater than a minimum distance from the human dominated landscape outside the park (Skonhoft and Solem, 2001). This class also includes minimizing the fencing or law enforcement cost of park perimeter. 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 (Naughton-Treves, 1998), India (Sekhar, 1998), and Sumatra (Linkie et al., 2007). However, this does not appear to be the case for human–wildlife conflict involving elephants. 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 and Kasiki, 2000; Sitati et al., 2003).

For every objective of this class, park area is beneficial while park perimeter is costly. The presence of a neighboring country's adjoining park reduces the length of the costly perimeter. This paper models interior value as follows:

$$b_i(X_i, X_j) = aX_i - b\sqrt{X_i} + c\sqrt{\min\{X_i, X_j\}} \qquad \text{where } a,\ b,\ c>0,\ b>c.$$
(12)

The first term in Eq. (12) represents the benefit from the size of a country's park area. The second term represents the cost from the length of 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. This functional form applies to a broad range of stylized PA shapes, including squares and semicircles. In a stylized example, let all PAs be squares, with one base of the square along the international border. When PA size = X_i, the benefit of the PA is $\gamma X_i - 4\eta\sqrt{X_i} + \eta\sqrt{\min\{X_i, X_j\}}$. Or, let all PAs be semicircles, with the flat base along the international border. When PA size = X_i, the benefit of the PA is $\gamma X_i - \eta(\sqrt{2\pi} + \frac{2\sqrt{2}}{\sqrt{\pi}})\sqrt{X_i} + \eta(\frac{2\sqrt{2}}{\sqrt{\pi}})\sqrt{\min\{X_i, X_j\}}$.

Proposition 6.1. *Interior habitat satisfies the spillover condition.*

Proof: $\frac{\partial b_i(X_i,X_j)}{\partial X_j} = 0$ when $X_i \leq X_j$; $\frac{\partial b_i(X_i,X_j)}{\partial X_j} = \frac{c}{2\sqrt{X_j}} > 0 \,\forall\, c,\ X_j$ when $X_i > X_j$. The length of a PA's costly perimeter decreases as the

neighboring country's adjoining PA increases in size. So, the spillover condition is satisfied. □

Proposition 6.2. *Interior habitat satisfies the strategic complementarity condition.*

Proof: $\frac{\partial^2 b_i(X_i, X_j)}{\partial X_i \partial X_j} = 0$ when $X_i < X_j$; $\frac{\partial^2 b_i(X_i, X_j)}{\partial X_i \partial X_j} = \frac{b-c}{4X_i\sqrt{X_j}} > 0 \,\forall\, b,\, c$ 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 PAs are nearly identical in size, an addition to a neighboring country's adjoining PA means that an addition to the country's own PA size creates less additional perimeter per unit area than it would have otherwise. So, the strategic complementarity condition is satisfied. □

Proposition 6.3. *Interior habitat satisfies the insatiability condition.*

Proof: If $X_i \leq X_j$, then $X_i > \left(\frac{b-c}{a}\right)^2$ because $b_i(X_i, X_j) > 0$ only when $X_i > \left(\frac{b-c}{a}\right)^2$. So, $\frac{\partial b_i(X_i, X_j)}{\partial X_i} = a - \frac{b-c}{2\sqrt{X_i}} > 0 \,\forall\, b,\, c$. If $X_i > X_j$, then $X_i > \left(\frac{b\sqrt{X_j}}{2a\sqrt{X_j}+c}\right)^2$, because $b_i(X_i, X_j) > 0$ only when $X_i > \left(\frac{b\sqrt{X_j}}{2a\sqrt{X_j}+c}\right)^2$. So, $\frac{\partial b_i(X_i, X_j)}{\partial X_i} = a - \frac{b}{2\sqrt{X_i}} + \frac{c}{2\sqrt{X_j}} > 0 \,\forall\, b,\, c$. If a PA is large enough to provide positive net benefit, then a larger park size always provides more area per unit of perimeter. So the insatiability condition is satisfied. □

Proposition 6.4. *Interior habitat satisfies the increasing returns to scale condition.*

Proof: $\frac{\partial^2 b_i(X_i, X_j)}{\partial X_i^2} = \frac{b-c}{4X_i\sqrt{X_i}} > 0$ when $X_i \leq X_j$; $\frac{\partial^2 b_i(X_i, X_j)}{\partial X_i^2} = \frac{b}{4X_i\sqrt{X_i}} > 0$ when $X_i > X_j$. As PA size increases, each unit of area added to PA size adds less perimeter than the previous unit. So, the increasing returns to scale condition is satisfied $\forall\, a,\, b,\, c,\, X_j$. □

Proposition 6.5. *Interior habitat satisfies the subadditivity condition.*

Global interior habitat is the sum of isolated domestic interior habitats, so the subadditivity condition is satisfied.

When providing interior habitat is the objective of conservation, national welfare is greater under the transboundary equilibrium than under the isolated equilibrium because the spillover condition is satisfied. Because the insatiability condition and strategic complementarity condition are satisfied, domestic conservation benefit is greater under the transboundary equilibrium than under the isolated equilibrium. Because the increasing returns to scale condition and the subadditivity condition are satisfied, global conservation benefit is greater under the transboundary equilibrium than under the isolated equilibrium. See Table 2.

5.4.   Other conservation objectives

The conservation objectives illustrated above are just three of the most common. However, the framework developed in Section 3 allows us to determine whether the transboundary park equilibrium provides greater national welfare, domestic conservation benefit, or global conservation benefit for any conservation objective for which benefits can be expressed mathematically as a function of park size. For instance, preserving an international ungulate migration route is a clear opportunity for a TBPA – the spillover condition and

strategic complementarity conditions are satisfied, as one country's park has a chance to succeed in its objective only if the other country has a park in place. Conversely, the goal protecting wildlife stock from disease or poaching is better served by IPAs because the spillover condition is not satisfied; the capacity for one country's park to maintain a healthy population decreases rather than increases in the size of a neighboring country's adjoining PA. For ecosystem services such as carbon sequestration, which are likely to be linear in park size, transboundary protection offers no additional gains.

6.   Discussion and conclusion

The central motivating claim advanced for the creation of transboundary protected areas is that these areas achieve conservation objectives more effectively than traditional isolated protected areas. Empirical investigation is limited in testing this claim, as TBPAs and IPAs cannot exist in the same place at the same time. The theoretical model in this paper suggests that TBPAs can indeed provide greater conservation benefit under certain circumstances.

In the model developed in this paper, park configuration is determined by two countries' independent park location decisions. In the isolated configuration, a country chooses its park size based solely on opportunity cost and the conservation benefit provided by the park. In the transboundary configuration, a country chooses its park size based on its neighbor's park size as well, setting up a strategic interaction. The presence of a neighboring park means that a country may make its own park smaller or larger than it would have otherwise. The equilibrium park size in each configuration determines the amount of domestic and global conservation benefit provided, as well as the amount of production displaced. A framework of conditions on the shape of the conservation benefit function can be used to determine whether the transboundary equilibrium is superior to the isolated equilibrium in providing national welfare, domestic conservation benefit, or global conservation benefit.

As long as parks produce positive spillover of conservation benefit, the transboundary equilibrium will result in greater national welfare. This has two implications for land use policy. First, a country will have a positive willingness to pay for land protection in a neighboring country, raising the possibility of transborder conservation financing. Second, a country's production possibility frontier for conservation and production in an ecoregion is expanded by the presence of a neighboring country's adjoining park. This creates the opportunity for a win–win distribution of land use between conservation and production. Moving from an isolated to a transboundary configuration, a country can achieve more conservation while removing less land from production.

In addition to parks producing positive spillover, if larger parks provide greater conservation benefit, and if a neighboring park increases the benefit from an addition to park size, then the transboundary equilibrium provides greater domestic conservation benefit. In addition, if conservation benefit exhibits increasing returns to scale, and if the whole of an isolated parks

configuration does not provide more global conservation benefit than the sum its parts, then the transboundary equilibrium provides greater global conservation benefit as well.

The transboundary equilibrium can provide greater welfare or conservation benefit even in the absence of cooperative management. Yet, it is not guaranteed that the transboundary configuration will emerge without coordination between countries. International conservation groups can encourage this coordination, for instance by subsidizing government-to-government negotiations.

While the decision to create any specific TBPA depends on biological, economic, social, political, and other considerations, the framework developed in this paper shows the general circumstances when TBPAs are most useful. For instance, the five sufficient conditions are not satisfied for species richness. This suggests that when species richness is the objective of park formation, conservation groups should encourage protected areas where species richness is greatest, whether or not these areas span international boundaries. All five conditions are satisfied, however, for the persistence of long-lived species and for provision of interior habitat. This suggests that conservation groups should encourage TBPAs to promote the survival of endangered species with long life spans, large area requirements, or potential for conflict with humans. For species such as mountain gorillas, African wild dogs, and tigers, TBPAs could mean the difference between survival and extinction.

Acknowledgments

Appendix A

Table 1 – Framework of sufficient conditions for TBPA superiority

If these conditions are satisfied…	…then the transboundary equilibrium provides greater…		
	…national welfare	…domestic conservation benefit	…global conservation benefit
Spillover	sufficient and necessary	Sufficient	Sufficient
Insatiability			
Strategic complementarity	–		
Increasing returns to scale	–	–	
Subadditivity	–	–	

Table 2 – Conservation objectives and TBPA superiority

	Species richness	Species persistence	Interior habitat
Condition satisfied?			
Spillover	Yes	Yes	Yes
Insatiability	Yes	Yes	Yes
Strategic complementarity	No	Yes[a]	Yes
Increasing returns to scale	No	Yes[a]	Yes
Subadditivity	Yes	Yes	Yes
Transboundary equilibrium provides greater…			
National welfare	Yes	Yes	Yes
Domestic conservation benefit	?	Yes[a]	Yes
Global conservation benefit	?	Yes[a]	Yes

[a] For species with low demographic stochasticity ($c > 0.5$).

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