Mechanisms for increasing the biodiversity benefit of reducing emissions from deforestation

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Abstract

An international mechanism to reduce emission from deforestation (REDD+) is likely to deliver substantial benefits for biodiversity. Biodiversity benefits of REDD+ can be increased further through the development of supplemental mechanisms. These mechanisms will be easier to implement if they advance rather than hinder the delivery of climate benefits. In this paper we use a simple numerical illustration and a simulated global REDD+ mechanism to examine the climate and biodiversity benefits of three such supplemental mechanisms: reallocation of fixed funding; additional carbon payments; and supplemental biodiversity payments. In contrast to previous literature, we find that reallocating fixed funding from carbon payments to biodiversity payments can increase climate benefits under certain conditions. Our findings support the consideration of reallocation of fixed funding for REDD+ programs at the national level. Additionally, we find that supplemental biodiversity payments would always directly increase biodiversity benefits, increase climate benefits, and benefit both sellers and buyers of reduced deforestation emissions. Our findings support the promotion of supplemental biodiversity payments for REDD+ at the both international and national level. We discuss the feasibility of implementing "biodiversity matching payments" for REDD+.

Keywords: Biodiversity conservation, climate change, mechanism design, reduced emissions from deforestation and forest degradation (REDD+)

I. Introduction

An international mechanism for the reduction of emissions from deforestation and forest degradation, plus the conservation, carbon stock enhancement and sustainable management of forests ("REDD+"; UNFCCC 2009a) can be expected to have significant co-benefits for biodiversity (Busch et al, revise and resubmit). There is substantial interest in increasing biodiversity benefits of REDD+ still further (Kapos et al. 2008; ATBC/GTO 2009; Campbell 2009; Harvey et al. 2009; Venter et al. 2009; Strassburg et al. 2010). An opportunity exists to increase the biodiversity benefits of REDD+ through supplemental incentive mechanisms for biodiversity.

Whether supplemental biodiversity mechanisms would help or hinder climate goals affects the likelihood of their implementation. If biodiversity mechanisms are perceived to operate at the expense of climate change mitigation efforts, then biodiversity concerns could be shut out from climate negotiations which are already complicated and fractious. On the other hand, if biodiversity mechanisms can be shown to increase the effectiveness and efficiency of climate efforts, then Parties to the United Nations Framework Convention on Climate Change (UNFCCC) are more likely to welcome such efforts as complementary.

In this paper we compare the impact on climate and biodiversity of three alternative supplementary policy mechanisms for increasing the biodiversity benefits arising from REDD+. These policy mechanisms are reallocation of fixed funding, additional purchases of REDD+ credits, and supplemental payments for biodiversity. We present results from both a simple numerical model that distills the problem to its essential elements, and from a richer 85-country partial equilibrium model that simulates an international REDD+ mechanism with leakage and country incentives to participate based on national reference levels. We devote particular attention to analysis and discussion of a particular policy mechanism—reallocation of fixed funding—in which our results differ from those found in prior literature.

II. Three policy mechanisms for promoting biodiversity

One proposed policy mechanism (Venter et al., 2009; Strassburg et al., 2010) for promoting biodiversity in REDD+ would reallocate some fraction of REDD+ finance for the reduction of emissions from high-biodiversity forests. Previous studies of climate and biodiversity have considered a case in which a central decision maker with a constrained budget can "acquire" forest at its opportunity, and must prioritize its acquisitions across carbon and biodiversity (Nelson et al., 2008; Venter et al., 2009). These studies have found a strict tradeoff between acquiring higher-carbon forest and acquiring higher-biodiversity forest, implying that achieving improved biodiversity outcomes comes at the expense of reducing additional carbon emissions. But importantly, the compensation payment that an international REDD mechanism provides to participating forest countries or regions is unlikely to equal to the provider's opportunity cost, but rather would be proportional to the service provided (e.g. a global carbon price measured in \$/tCO2e) (Gregersen et al, 2010). If we consider a REDD+ mechanism in which forest countries or localities can choose to sell forest-based climate change mitigation at a global carbon price, is there still a strict tradeoff between carbon and biodiversity outcomes, or can climate goals be advanced – rather than hindered – by a set-aside of finance for forest biodiversity?

In a second possible policy mechanism, countries or donors interested in biodiversity could simply purchase additional REDD+ credits. By increasing the financial support for REDD+, greater provision of biodiversity would result alongside greater provision of carbon (Busch et al, revise and resubmit).

In a third possible policy mechanism, biodiversity interests could supplement REDD+ payments with biodiversity payments proportional to the biodiversity value of forest where avoided deforestation occurs. For every carbon credit a forest country sells to the REDD+ market, a separate funding mechanism could offer a "biodiversity matching payment."

IV. A simple forest conservation fund

We present a very simple illustrative model of forest conservation under REDD+. This model allocates payments from a fixed fund to forest sites that avoid deforestation. In one payment system, payments are equal to opportunity cost; in a second payment system, payments are proportional to the carbon or biodiversity service provided by avoided deforestation. In the second system, three supplemental policies are introduced—reallocating funding from carbon payments to biodiversity payments; increasing payments for carbon; and supplementing carbon payments with payments for biodiversity. The results of each policy are presented graphically.

Let there exist $i \in [1, n]$ forest sites of equal size that are about to be deforested completely with certainty. Each site i has an agricultural rental value, a_i, a biodiversity value, b_i, and a carbon value, c_i. For illustrative purposes, let n=1000 and let parameters a_i, b_i, and c_i be independent and randomly drawn from the following continuous distributions: $a_i \in [0,\$1000]$, $b_i \in [0,100]$, $c_i \in [0,100]$.

A forest conservation fund of fixed size F offers payments to sites in exchange for avoided deforestation. These payments are offered under one of two alternative payment systems. In the first payment system, the fund makes payments to sites equal to the sites' opportunity cost, and then in turn all sites to which payments are made avoid deforestation. The fund makes payments to sites in the order of highest to lowest benefit-to-cost ratio until the fund is exhausted. The benefit-to-cost ratio equals $(\alpha b_i + (1-\alpha)c_i) / a_i$, where α represents the relative weight placed by the fund on biodiversity benefits relative to carbon benefits.

In the second payment system, the fund makes payments to sites proportional to the service provided if the site avoids deforestation. The forest conservation fund chooses a carbon price, p_c, and a biodiversity price p_c. Forest sites respond with avoided deforestation if $p_b b_i + p_c c_i - a_i > 0$. Total biodiversity benefit, B, is equal to the sum of biodiversity value in sites which avoid deforestation: $B = \sum_i b_i \mid p_b b_i + p_c c_i - a_i > 0$. Total carbon benefit, C, is equal to the sum of carbon value in sites which avoid deforestation: $C = \sum_i c_i \mid p_b b_i + p_c c_i - a_i > 0$. Total funding for biodiversity, F_b, is equal to the sum of payments for biodiversity to sites which avoid deforestation: $F_b(p_b + p_c) = \sum_i p_b b_i \mid p_b b_i + p_c c_i - a_i > 0$. Total funding for carbon, F_c, is equal to the sum of payments for carbon to sites which avoid deforestation: $F_c(p_b + p_c) = \sum_i p_c c_i \mid p_b b_i + p_c c_i - a_i > 0$. Prices p_b and p_c are chosen such that the pool of funding for forest conservation F is exhausted, that is $F_b(p_b, p_c) + F_c(p_b, p_c) = F$. The portion of funding spent on biodiversity is $\beta = \frac{F_b}{F_b + F_c}$.

In the payment system where avoided deforestation payments are equal to opportunity cost, a strict tradeoff is found between conserving carbon and biodiversity (Figure 1).

Additional carbon benefits can not be achieved by reallocating fixed funding toward biodiversity, i.e. $\frac{\partial C}{\partial \propto} < 0\ \forall \propto.$, but only by increasing the fund size, i.e. $\frac{\partial C}{\partial F} > 0\ \forall F$. This is consistent with the findings of previous literature.

However, in the payment system where avoided deforestation payments are proportional to the service provided, conditions exist such that a policy of reallocating a fraction of fixed funding from carbon payments to biodiversity payments would result in both greater carbon benefits and greater biodiversity benefits, i.e. $\frac{\partial C}{\partial \beta} > 0\ for\ some\ \beta$ (Figure 2). In the case where F=$750,000 illustrated in Figure 2, the maximum carbon benefit is achieved when the proportion of total funding spent on biodiversity, β, equals 0.16, while total biodiversity benefit can be increased without decreasing total carbon benefit for β as high as 0.39.

How do we explain this somewhat counterintuitive result that reallocating fixed funding away from carbon can result in greater carbon benefit? Wouldn't carbon payments acquire additional carbon more directly and more cost-effectively than biodiversity payments? This is true, but only at first—eventually carbon payments face diminishing returns. Achieving additional carbon benefit through carbon payments requires raising the carbon price to outcompete the opportunity cost of the marginal carbon provider. In a payment system where avoided deforestation payments are proportional to the service provided, this increase in the carbon price must be paid not only to the marginal carbon provider, but to all other providers as well (Figure 3). So, $\frac{\partial C}{\partial F_c} > 0$ while $\frac{\partial^2 C}{\partial {F_c}^2} < 0$. On the other hand, biodiversity payments provide some amount of carbon benefit as well, $\frac{\partial C}{\partial F_b} > 0$, and conserve forest without raising the carbon price. Biodiversity payments in fact lower the marginal cost of achieving carbon benefit through carbon payments, $\frac{\partial^2 C}{\partial F_b F_c} < 0$, by subsidizing carbon payments. When combined with biodiversity payments, carbon payments can conserve sites of forest where carbon payments alone would be insufficient to outcompete opportunity cost and achieve conservation. So beyond a certain level of finance, additional carbon benefit can be more cost-effectively achieved by providing additional funding for biodiversity payments rather than carbon payments (Figure 4).

This result that carbon benefit can be increased by reallocating funding from carbon to biodiversity is more likely to hold when total funding is greater, when the initial portion of funding for biodiversity is smaller, when the carbon price increases rapidly as funding is spent on carbon, relative to a slower increase in carbon price and biodiversity price as money is spent on biodiversity. Appendix I presents an analytical proof of these conditions.

Naturally, increasing the available finance for avoided deforestation would increase both the biodiversity benefit and the carbon benefit. A policy of increasing payments for carbon would result in substantially greater carbon benefits and somewhat greater biodiversity benefits ($\frac{\partial C}{\partial F_c} \gg 0$ and $\frac{\partial B}{\partial F_c} > 0$), while a policy of increasing payments for biodiversity would result in substantially greater biodiversity and somewhat greater carbon benefits ($\frac{\partial C}{\partial F_b} > 0$ and $\frac{\partial B}{\partial F_b} \gg 0$).

V. A simulated global REDD mechanism

In addition to the simple illustrative model, we present a simulation of land use in 85 countries under an international REDD+ mechanism. We supplement an international mechanism for reducing emissions from deforestation based on a global carbon price with one of three alternative policies for promoting biodiversity benefits. Relative impacts on climate and biodiversity benefits are compared.

We applied the Open Source Impacts of REDD+ Incentives Spreadsheet model ("OSIRIS"; Busch et al. 2009; Busch et al. 2010; Busch et al. revise and resubmit) to simulate national participation, deforestation, and species extinction rates under REDD+ across 85 tropical or developing countries thought to be potentially eligible for REDD+. OSIRIS is a single-period partial equilibrium model for a single commodity—the composite output of agriculture, including a one-time timber harvest, produced on one hectare of land cleared from the tropical forest frontier. Countries participated voluntarily in REDD+, choosing to "opt in" only if the national economic surplus from forest carbon exceeded the foregone national economic surplus from agriculture and one-time timber harvest. Otherwise countries chose to "opt out." Countries with higher national reference levels had a greater financial incentive to opt in to REDD+. After opting in to or out of REDD+, countries chose a rate of deforestation to maximize their aggregate national economic surplus from forests and agriculture.[1] Leakage of

[1] While this opportunity cost framework offers a starting point for comparing impacts across reference level designs and countries, it oversimplifies reality in two respects. First, countries' decisions to participate in REDD are likely to be more complex than a simple comparison of earnings from agriculture and earnings from REDD. Poverty alleviation, traditional values, political economy, ecological services and biodiversity are likely to factor into countries' land use decisions. Second, some promising methods for reducing emissions from deforestation do not

deforestation occurs endogenously in the model, as a reduction of deforestation in one country led to a higher price for frontier agriculture and increased pressure to deforest in other countries. The model was parameterized using spatially explicit global data on potential agricultural revenue (Fischer et al. 2000; Naidoo & Iwamura 2007; Strassburg et al. 2009), national average forest biomass (Ruesch & Gibbs 2008) and soil carbon (GSDTG 2000) within forests (Schmitt, 2008), national-level tabular data on returns to one-time timber harvest (Sohngen & Tennity 2004), forest cover and forest cover change (FAO 2010)[2], and a global average management and transaction cost (James 2001). Reference levels were based on average deforestation rates during a 1990-2005 reference period and applied to a 2005-2010 implementation and crediting period. This analysis used many of the same set of illustrative parameter values as Busch et al (2009).

Consistent with the UNFCCC decision that national reference levels for REDD+ should be "based on historical data, adjusted for national circumstances" (UNFCCC, 2009b), we applied a REDD+ design in which national reference levels are a weighted average of national and global historic average deforestation rates (Strassburg et al. 2009). The weight on global average deforestation rates, 0.20, was set to maximize climate-effectiveness and cost-efficiency under default parameter values.[3] We examined three levels of annual finance for REDD+ ($5

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involve directly outcompeting opportunity cost at a site—notably, removal of perverse agricultural subsidies, moratoria on road construction, increased capacity to enforce forestry laws, and improved fire management (Busch et al. 2009).

[2] For an in depth critique of using FAO Forest Resource Assessment rates for REDD reference levels, see Olander *et al* (2008).

[3] Default parameter conditions used in OSIRIS v3.4 (data, model and country-by-county outputs may be downloaded at http://www.conservation.org/osiris) were as follows, unless otherwise indicated: Permanence reduction scale = 1.00 (no withholding to ensure permanence); exponential demand for frontier agriculture with

billion/year; $10 billion/year; $15 billion/year), consistent with either fund or market financing for REDD+.

Species-area relationships were applied to national deforestation rates to estimate the extinction rate of nationally endemic forest-dependent amphibian (Schipper et al. 2008), bird (Birdlife International, 2010) and mammal (Stuart et al. 2004) species (hereafter referred to as "endemic forest species"), as described in greater detail in Busch et al (revise and resubmit).

We extended the OSIRIS model to enable biodiversity payments in addition to carbon payments. Whereas the carbon payment made to each country was proportional to the country's area of avoided deforestation scaled for those areas' carbon values, the biodiversity payment made to each country was proportional the country's area of avoided deforestation scaled for those area's biodiversity values. That is, $F_c = p_C * [f(\sum_i d_i' c_i) - \sum_i d_i c_i]$ and $F_b = p_b * [f(\sum_i d_i' b_i) - \sum_i d_i b_i]$, where d_i' represents site-specific deforestation rate during a reference period, and *f()* represents a formulaic adjustment to historical deforestation emissions. The same reference rates of national deforestation used to calculate national reference levels of greenhouse gas emissions are used to calculate reference rates of biodiversity loss. The biodiversity value per hectare used here was the number of endemic forest species in a country divided by the country's forest area. This metric was selected to be illustrative and due to its relationship with extinction from forest habitat loss; clearly alternative

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price elasticity = 2.00 (2% decrease in supply leads to 1% increase in price); fraction of soil carbon credited under REDD = 0.10; social preference for agricultural revenue relative to carbon revenue = 1.00; management and transaction cost = 2001 US$3.50 ha−1 yr−1; fraction of national average timber rent included = 1.00; reference level design = weighted average of national and global historical deforestation rates; weight on national historic rates = 0.80; reference period = 1990–2005.

metrics of biodiversity value could be used. Since the per-hectare biodiversity values of countries' forests ranged across four orders of magnitude using this metric, a maximum biodiversity payment of $10,000 per hectare was imposed to prevent the inefficient concentration of biodiversity funding in a small handful of countries.

Reallocation of funding toward biodiversity increased biodiversity benefits. In principle reallocation of funding toward biodiversity has the potential to increase climate benefits as well, as shown above, but in this simulation this occurred over only a very limited range (when F=$15B/yr, carbon benefit is maximized when the portion of total funding spent on biodiversity, β=0.02; Figure 5).[4] Additional REDD+ payments directly support additional climate benefits, while indirectly improving biodiversity benefits. Biodiversity matching payments increase biodiversity benefits nearly as much as reallocation of funding, while always improving climate benefits.

The OSIRIS model was constructed to compare impacts across REDD+ policy options under a common set of data and assumptions, rather than to predict the magnitude of impacts of an international REDD+ mechanism with certainty. This lack of certainty arises because no prior implementation of a global REDD+ mechanism exists against which to calibrate parameters or validate model performance, global data were aggregated from sources of varying quality, and parameters to which the model is sensitive such as elasticity of demand for frontier agriculture have uncertain values. For this reason we tested the robustness of the

[4] The data set used in our model employs within-country variability in agricultural rental value, but uses national average values for biodiversity value and carbon value. A model of land use and REDD+ based on a data set with variability in biodiversity value and carbon value in addition to agricultural rental value could be expected to have returns to carbon value diminish more quickly relative to agricultural rental value. This would produce a greater range of values for which reallocating funding from carbon toward biodiversity increases climate benefits.

range under which reallocating fixed payments toward biodiversity can increase climate benefits to alternative parameter assumptions (Table 1). Though we refer to REDD+ throughout this paper, we only examined mechanism incentives related to deforestation and forest carbon stock conservation. We did not examine the impacts of incentives related to forest degradation, sustainable management of forests or carbon stock enhancement.

VI. Discussion

The United Nations Framework Convention on Climate Change (UNFCCC) REDD+ mechanism is being designed primarily to deliver climate change mitigation benefits from forests. Other fora developing for international REDD+ transfers (REDD+ partnership; Norway bilateral agreements; Governor's Climate and Forest Forum) are also likely to focus primarily on climate change mitigation. But forests not only store carbon; they also provide habitat for over two-thirds of known terrestrial species (Raven 1988) and provide other environmental services. Thus REDD+ payments have the potential to substantially contribute to biodiversity conservation as well. Supplemental mechanisms for biodiversity, if developed, have the potential to increase biodiversity benefits even further. The political feasibility of implementing such supplemental mechanisms depends on whether they would advance or hinder the delivery of climate benefits.

Previous studies have considered one such mechanism, the reallocation of fixed funding from carbon to biodiversity in an avoided deforestation payment program, and have posited a strict tradeoff between conserving biodiversity and storing carbon. However, these studies have considered a mechanism for REDD+ in which payments are equal to opportunity costs. Such a payment mechanism appears unrealistic in the context of international climate policy discussions.[5] If as is currently considered in international REDD+ discussions, REDD+ payments are proportional to services based on a global carbon price, then a tradeoff between climate and biodiversity benefits no longer binds. It is possible under certain theoretical conditions to reallocate a portion of carbon funding towards biodiversity and obtain both more biodiversity and more carbon. In our simulation of a global REDD+ mechanism, reallocation of funding increases climate benefits over only a very limited range, but this result will vary by region, country or landscape considered, depending on the heterogeneity of agricultural rental value, carbon and biodiversity.

Individual countries will have greater flexibility than the UNFCCC in designing their national REDD+ programs. National REDD+ programs can potentially be integrated with payment programs for biodiversity, freshwater provision, or other ecosystem services. National REDD+ decision makers should consider the possibility that a modest shift in funding toward biodiversity has the possibility of advancing both carbon and biodiversity goals. Future research at the level of countries' landscapes can improve knowledge on the spatial variation of carbon, biodiversity and opportunity costs, with a view to supporting climate, biodiversity and economic outcome-improving allocations of funding.

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[5] Payment programs which only pay opportunity cost and no more face two criticisms (see Gregersen et al 2010). First, such programs would provide no additional producer surplus to forest countries or communities, negating the economic incentive of these countries to produce and sell emission reductions to REDD+ rather than continue with alternative land uses. Second, mechanisms to elicit forest countries' private knowledge of willingness-to-accept rely for their efficacy on a lack of full information by reduction providers. Given full information, strategic behavior on the part of a rational reduction provider would be to announce a willingness to accept that is as high as that of the marginal reduction provider.

At either the international and national level, purchasing additional REDD+ credits will certainly increase biodiversity benefits, while directly improving climate benefits as well. This would require no additional institutional infrastructure. Yet even better for increasing biodiversity benefits would be supplemental payments for biodiversity. Such finance would increase biodiversity benefits nearly as directly as reallocating finance from carbon payments, while always improving climate goals as in the purchase of additional REDD+ credits.

Various methods are possible for financing supplemental biodiversity payments. First, existing buyers of REDD+ may be willing to pay a price premium for emission reductions known to originate from more biodiverse forests. This price premium could be considerable on the part of certain public or private buyers, although the magnitude of finance available through price premiums would be fundamentally limited by the scale of existing REDD+ demand. Second, a pool of biodiversity buyers distinct from carbon buyers could provide additional upfront financial support for investing in reducing deforestation in especially biodiverse forests, and then countries or communities could sell the resulting carbon abatement to the REDD+ mechanism. Third, biodiversity buyers could purchase emission reductions through the REDD+ mechanism from especially biodiverse forests above market price, and then sell the reductions back into the market at market price. In this way the buyers would have paid only the incremental price premium for the biodiversity value. Fourth, biodiversity buyers could establish a biodiversity matching fund, which would pay a “biodiversity matching payment” to countries or communities selling emission reductions to the REDD+ mechanism from especially biodiverse forests.

To implement any of these supplemental biodiversity finance methods, three additional global institutional investments would be useful. First, a registry identifying the spatial origin of emission reductions would allow potential buyers of biodiversity to decide which forests are so valuable for biodiversity as to merit paying a price premium for their conservation. This registry may be an important feature of international or national REDD+ programs even in the absence of supplemental biodiversity finance. Second, a standardized, accepted system for quantitatively differentiating forests' relative biodiversity value would relieve individual buyers of the cost of information-gathering on biodiversity value. This analysis has considered only one possible metric of relative biodiversity value—average number of nationally endemic forest-dependent amphibian, bird and mammal species per hectare of forest nationally—with a view to reducing vertebrate species extinctions. But other metrics of relative biodiversity value are certainly possible, including richness, threat, range size rarity or flagship species. Importantly, a site's biodiversity value must be independent of the status or condition of other sites, ruling out conservation value metrics based on complementarity or substitutability. Efficiency in reducing extinctions would likely be improved through the development of biodiversity value metrics at a finer spatial scale. Arriving at appropriate and accurate metrics for biodiversity value need not be the burden of the UNFCCC, but should result from a transparent and science-based process. Geographic differentiation of the relative value of other services provided by forests, such as clean water, could enable matching payments for further services as well. Third, supplemental biodiversity payments would benefit from a facility to consolidate demand for the biodiversity benefit of avoided deforestation from many potential small and geographically dispersed sources.

Why would biodiversity conservation groups be interested in devoting scarce financial resources to supplementing REDD+, rather than investing in other activities? Because by doing so, transaction costs and startup costs could be far lower than in traditional project-by-project initiatives. Conservationists would be able to guide market demand for forest conservation activity toward high-biodiversity forests by leveraging the vast institutional infrastructure being put in place to support REDD+. This infrastructure includes monitoring, reporting and verification of deforestation, and accounting, finance and governance systems necessary to channel billions of dollars worth of international demand for climate change mitigation towards compensating developing countries for reducing deforestation.

Recoverable international finance for forests' biodiversity is potentially considerable. Historically, payments for biodiversity have comprised a large share of international willingness-to-pay for forests, in the form of conservation projects and bilateral and multilateral budget support for protected areas. Estimates of current international expenditure on biodiversity conservation have ranged from $1.5 billion annually (Halpern et al, 2006) to $3.5 billion annually (Castro and Hammond, 2009) up to $5 billion annually (Gutman and Davidson, 2008). We hypothesize that funding for biodiversity would increase further if a REDD+ mechanism establishes an efficient payment vehicle for forest conservation.

VII. Conclusion

At the international level, all parties to REDD+ have an interest in facilitating supplemental payments for biodiversity, which would increase finance available to sellers of reduced deforestation, lower the marginal cost to buyers of achieving emission reductions, and advance the delivery of climate benefits. The burden on the UNFCCC or its Parties could be limited to maintaining a registry of the geographic origin of emission reductions. Quantitatively differentiating forests' biodiversity value and consolidating supplemental demand for forest biodiversity could be led by external institutions. At the national level, countries that are interested in designing national REDD+ programs to promote multiple forest benefits should recognize that in some cases, climate benefits can be achieved most cost-effectively through a mixture of financial support for carbon and biodiversity. In this Year of Biodiversity, developing the institutions to supplement REDD+ with biodiversity payments would bring the Convention on Biological Diversity and the UNFCCC together in complementary and mutually enforcing efforts for climate change mitigation and biodiversity conservation.

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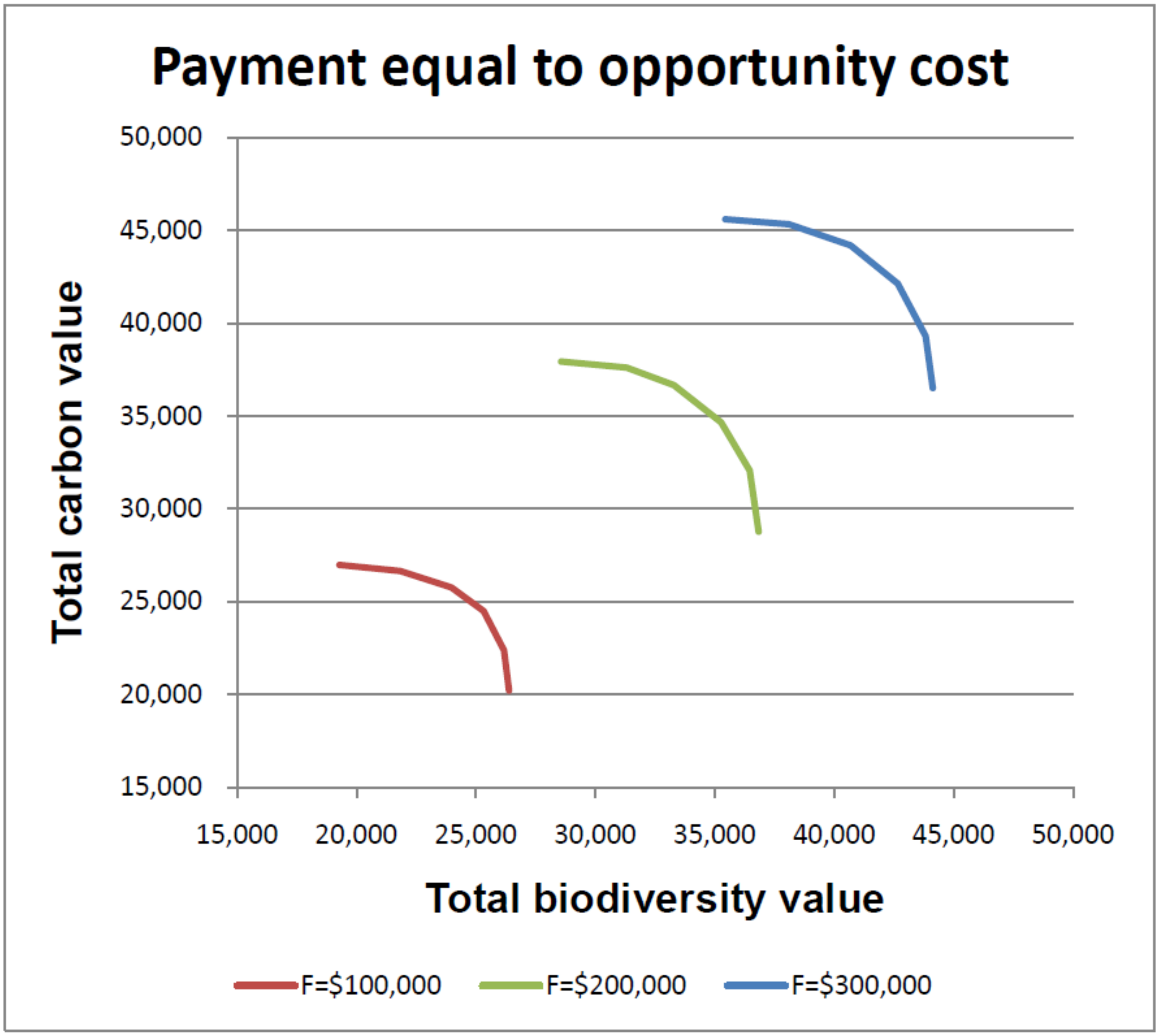

Figure 1 – Carbon and biodiversity value produced by a simple forest conservation fund when payments are equal to landusers' opportunity costs. Curves represent feasible outcomes at any level of funding, where the funding priority is shifted along carbon-biodiversity continuum. Curves slope downward, indicating that a strict tradeoff exists between obtaining greater biodiversity value and obtaining greater carbon value from the area of land on which avoided deforestation is purchased.

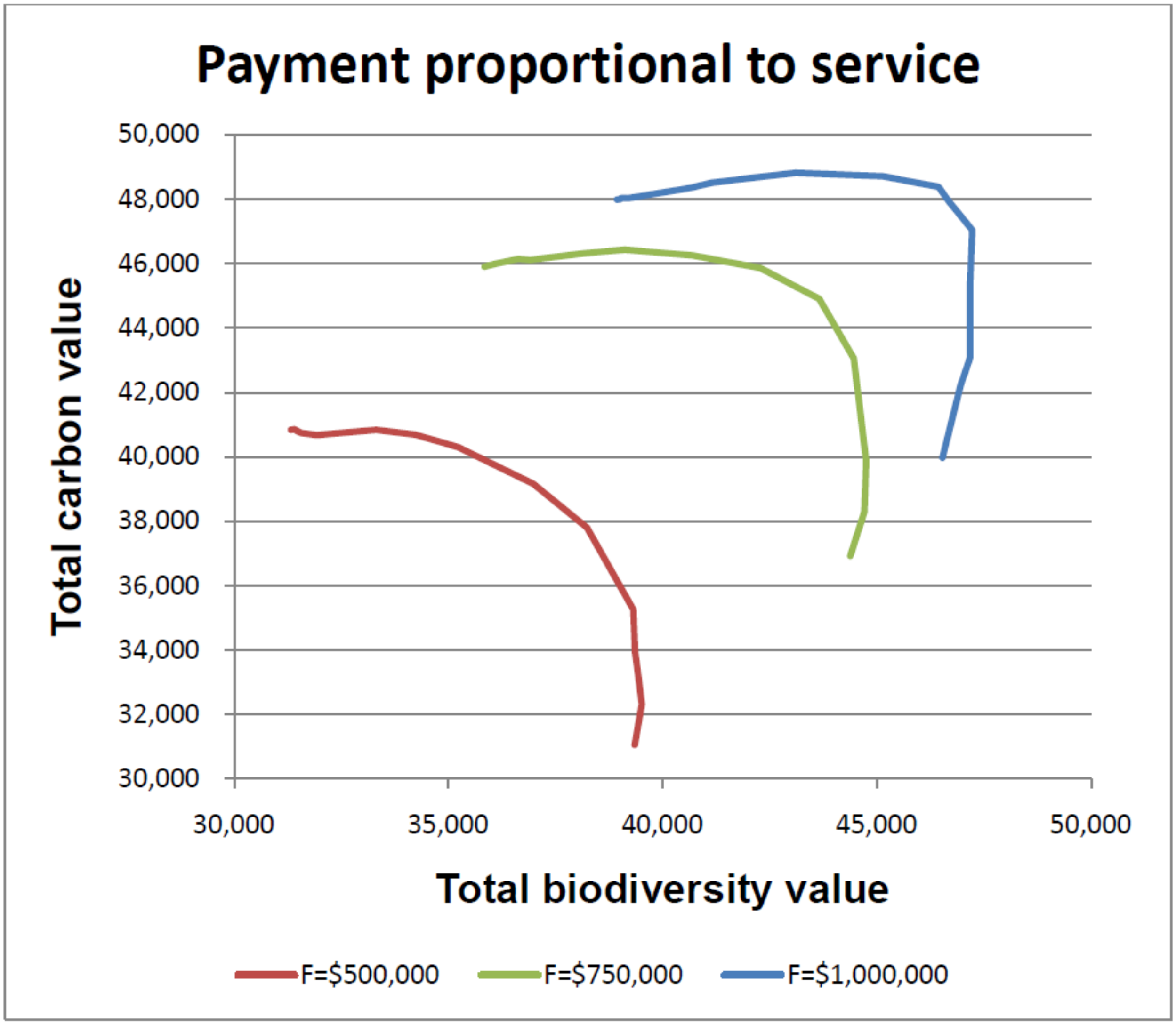

Figure 2 – Carbon and biodiversity value produced by a simple forest conservation fund when payments are proportional to the carbon or biodiversity service provided by avoided deforestation in a given unit of forest. Curves represent feasible outcomes at any level of funding, where the funding allocation is shifted along carbon-biodiversity continuum. Curves bubble outward, indicating that over some portion of the range of possible outcomes it is possible to shift the allocation of fixed funding to obtain both more carbon and more biodiversity.

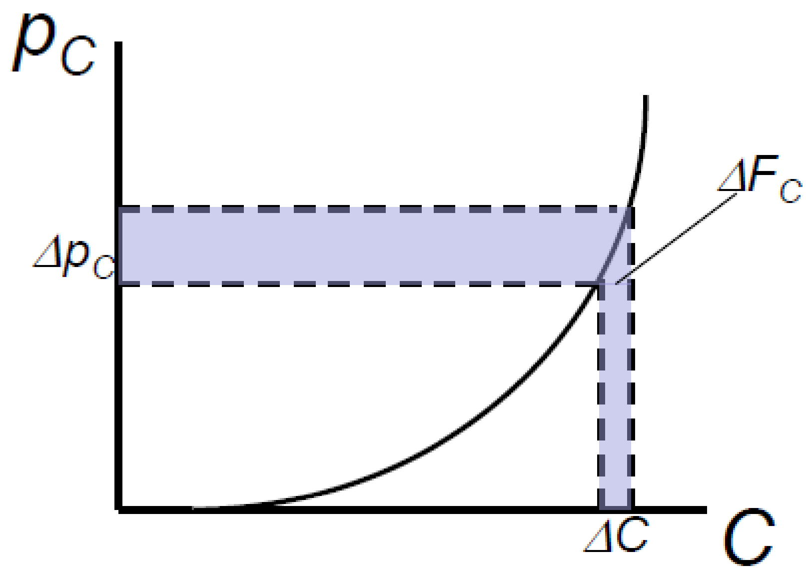

Figure 3 – Returns to carbon benefit, C, are diminishing in the level of funding spent on carbon, F_c. Each additional unit of carbon benefit acquired, ΔC, requires raising the price of carbon by Δp_c, not only for the marginal unit of carbon, but for all previous units as well.

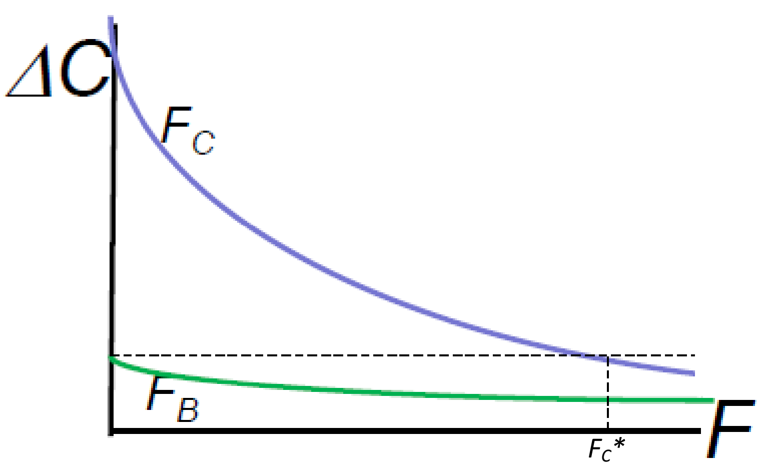

Figure 4 – The level of additional carbon benefits, ΔC, achieved with each additional dollar spent on carbon payments, F_C, is diminishing. Past the point F_C*, more additional carbon benefits can be achieved by spending funding on biodiversity payments rather than carbon payments.

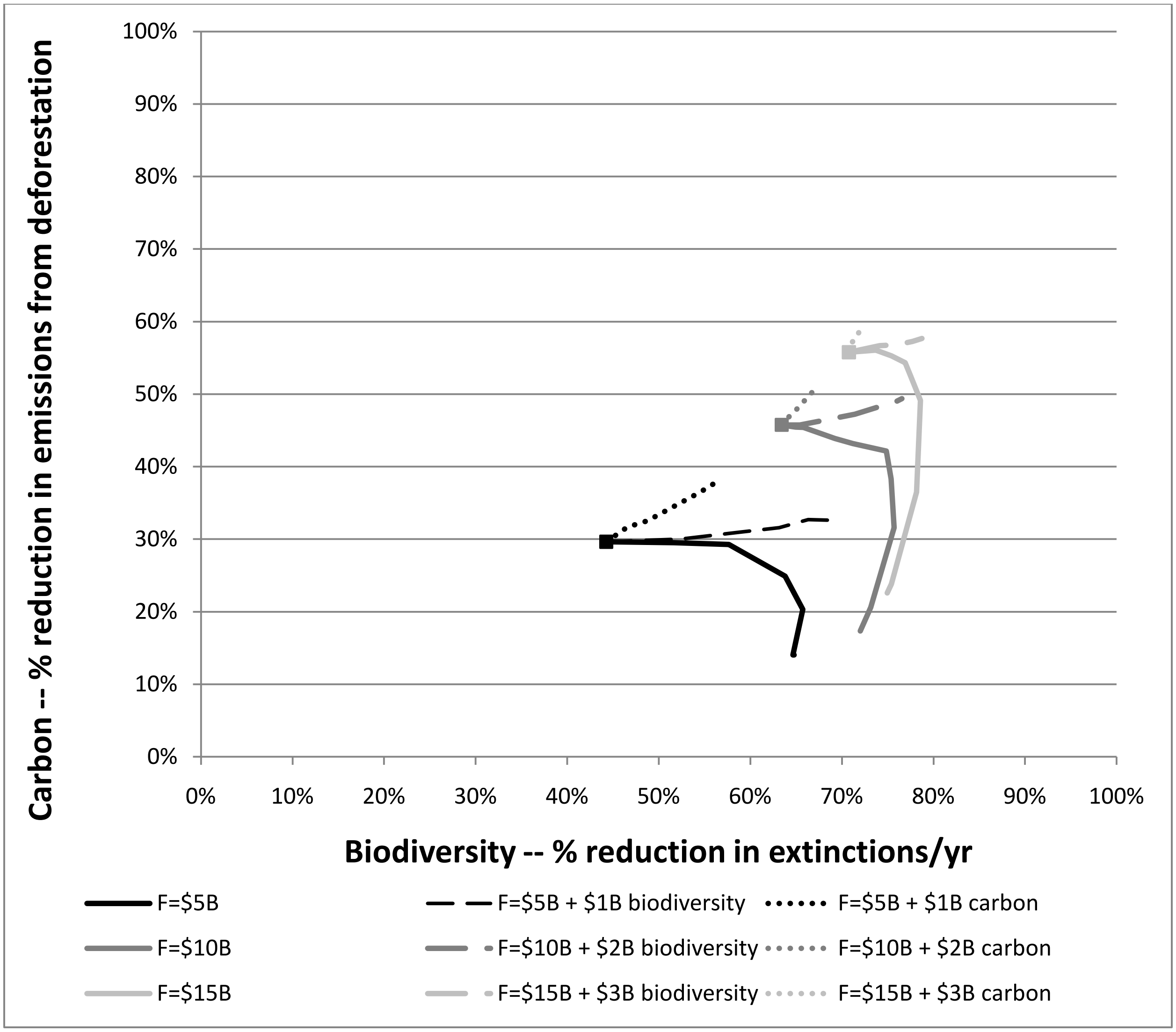

Figure 5 – Carbon and biodiversity value produced by a simulated global REDD+ mechanism when payments are proportional to the carbon or biodiversity service provided by avoided deforestation in a given unit of forest. Square points represent biodiversity and carbon outcomes at a fixed level of REDD+ carbon funding ($5B/yr; $10B/yr; $15B/yr). Solid lines represent outcomes when the fixed level of funding is reallocated from carbon toward biodiversity. Dashed lines represent outcomes when funding is supplemented with supplemental biodiversity payments up to 20% of the initial level of funding. Dotted lines represent outcomes when funding is supplemented with addition carbon payments up to 20% of the initial level of funding.

Table 1

Appendix I – A simple analytical model of forest conservation

When forest is conserved through carbon payments, while holding biodiversity payments constant:

The total area of forest conserved is increasing in the price of carbon: $A(p_c) = a_c {p_c}^i$ where a_c>0, i>0.

The average tons of carbon per unit of forest area conserved, D_c, is decreasing in the total area of forest conserved: $D_c(A(p_c)) = d_c A^j$ where d_c>0, -1>j>0.

The average value of biodiversity per unit of forest area conserved is constant in the total area of forest conserved: $V_c(A(p_c)) = v_c$ where v_c>0.

Total funding for carbon is a function of carbon price:

$$F_c(p_c) = p_c * A(p_c) * D_c(A(p_c))$$

$$= p_c * a_c {p_c}^i * d_c (a_c {p_c}^i)^j$$

$$= {a_c}^{1+j} d_c {p_c}^{1+i+ij}$$

So carbon price as a function of total funding for carbon is:

$$p_c(F_c) = (\frac{F_c}{{a_c}^{1+j} d_c})^{\frac{1}{1+i+ij}}$$

and carbon value as a function of total funding for carbon is:

$$C(F_c) = A\big(p_c(F_c)\big) * D_c\left(A\big(p_c(F_c)\big)\right) = {a_c}^{1+j} * d_c {p_c}^{i+ij}$$

$$= {a_c}^{1+j} d_c (\frac{F_c}{{a_c}^{1+j} d_c})^{\frac{i+ij}{1+i+ij}}$$

$$={a_c}^{\frac{i(1+j)(1+j)}{1+i+ij}} {d_c}^{\frac{1}{1+i+ij}} * {F_c}^{\frac{i+ij}{1+i+ij}}$$

Similarly, when forest is conserved through biodiversity payments, while holding carbon payments constant:

The total area of forest conserved is increasing in the price of biodiversity: $A(p_b) = a_b {p_b}^k$ where a_b>0, *k>0*.

The average value of biodiversity per unit of forest area conserved, V_b, is decreasing in the total area of forest conserved: $V_b(A(p_b)) = v_b A^l$ where v_b*>0, -1>l>0*.

The average tons of carbon per unit of forest area conserved is constant in the total area of forest conserved: $D_b(A(p_b)) = d_b$ where d_b*>0*.

Total funding for biodiversity is a function of biodiversity price:

$$F_b(p_b) = p_b * A(p_b) * V_c(A(p_c))$$

$$= p_b * a_b {p_b}^k * v_b(a_b {p_b}^k)^l$$

$$= {a_b}^{1+l} v_b {p_b}^{1+k+kl}$$

So biodiversity price as a function of total funding for biodiversity is:

$$p_b(F_b) = \left(\frac{F_b}{{a_b}^{1+l} v_b}\right)^{\frac{1}{1+k+kl}}$$

and carbon value as a function of total funding for biodiversity is:

$$C(F_b) = A\big(p_b(F_b)\big) * D_b\Big(A\big(p_b(F_b)\big)\Big) = a_b {p_b}^k * d_b$$

$$= a_b d_b \left(\frac{F_b}{{a_b}^{1+l} v_b}\right)^{\frac{k}{1+k+kl}}$$

$$= {a_b}^{\frac{1}{1+k+kl}} d_b {v_b}^{\frac{-k}{1+k+kl}} {F_b}^{\frac{k}{1+k+kl}}$$

So, carbon value as a function of total funding for both carbon and biodiversity is:

$$C = C(F_c) + C(F_b) = a_c^{\frac{i(1+j)(1+j)}{1+i+ij}} d_c^{\frac{1}{1+i+ij}} F_c^{\frac{i+ij}{1+i+ij}} + a_b^{\frac{1}{1+k+kl}} d_b v_b^{\frac{-k}{1+k+kl}} F_b^{\frac{k}{1+k+kl}}$$

Note that since *i>0; -1>j>0; k>0; -1>l>0*, and therefore since $\frac{i+ij}{1+i+ij}$*>0;* $\frac{k}{1+k+kl}$*>0;* we will always observe $\frac{\partial C}{\partial F_c} > 0$ and $\frac{\partial C}{\partial F_c} > 0$. That is, increasing payments for biodiversity or for carbon will always increase carbon benefits. But more interestingly, we are interested in the conditions under which a reallocation of fixed funding from carbon to biodiversity can increase carbon benefits. That is, when $\beta = \frac{F_b}{F_b+F_c}$, under what conditions are we more likely to observe that $\frac{\partial C(\beta)}{\partial \beta} > 0$?

$$C(\beta) = a_c^{\frac{i(1+j)(1+j)}{1+i+ij}} d_c^{\frac{1}{1+i+ij}} ((1-\beta)F)^{\frac{i+ij}{1+i+ij}} + a_b^{\frac{1}{1+k+kl}} d_b v_b^{\frac{-k}{1+k+kl}} (\beta F)^{\frac{k}{1+k+kl}}$$

$$= a_c^{\frac{i(1+j)(1+j)}{1+i+ij}} d_c^{\frac{1}{1+i+ij}} F^{\frac{i+ij}{1+i+ij}} (1-\beta)^{\frac{i+ij}{1+i+ij}} + a_b^{\frac{1}{1+k+kl}} d_b v_b^{\frac{-k}{1+k+kl}} F^{\frac{k}{1+k+kl}} \beta^{\frac{k}{1+k+kl}}$$

$$\frac{\partial C(\beta)}{\partial \beta} = -\frac{i+ij}{1+i+ij} a_c^{\frac{i(1+j)(1+j)}{1+i+ij}} d_c^{\frac{1}{1+i+ij}} F^{\frac{i+ij}{1+i+ij}} (1-\beta)^{\frac{-1}{1+i+ij}} + \frac{k}{1+k+kl} a_b^{\frac{1}{1+k+kl}} d_b v_b^{\frac{-k}{1+k+kl}} F^{\frac{k}{1+k+kl}} \beta^{\frac{-1-kl}{1+k+kl}}$$

$\frac{\partial C(\beta)}{\partial \beta} > 0$ when:

$$\frac{k}{1+k+kl} a_b^{\frac{1}{1+k+kl}} d_b v_b^{\frac{-k}{1+k+kl}} F^{\frac{k}{1+k+kl}} \beta^{\frac{-1-kl}{1+k+kl}} > \frac{i+ij}{1+i+ij} a_c^{\frac{i(1+j)(1+j)}{1+i+ij}} d_c^{\frac{1}{1+i+ij}} F^{\frac{i+ij}{1+i+ij}} (1-\beta)^{\frac{-1}{1+i+ij}}$$

That is when:

$$\frac{k}{1+k+kl} a_b^{\frac{1}{1+k+kl}} d_b (\frac{1}{v_b})^{\frac{k}{1+k+kl}} F^{\frac{k}{1+k+kl}} (\frac{1}{\beta})^{\frac{1+kl}{1+k+kl}} > \frac{i+ij}{1+i+ij} a_c^{\frac{i(1+j)(1+j)}{1+i+ij}} d_c^{\frac{1}{1+i+ij}} F^{\frac{i+ij}{1+i+ij}} (\frac{1}{1-\beta})^{\frac{1}{1+i+ij}}$$

Recalling that *a_b>0; a_c>0; d_b>0; d_c>0; v_b>0; F>0; 0≤β≤1; i>0; -1>j>0; k>0; -1>l>0*, we know that $\frac{1}{1+k+kl} > 0$; $\frac{k}{1+k+kl} > 0$; $\frac{1+kl}{1+k+kl} > 0$; $\frac{1}{1+i+ij} > 0$; $\frac{i+ij}{1+i+ij} > 0$; $\frac{i(1+j)(1+j)}{1+i+ij} > 0$.

Having observed from numerical examples that $\frac{\partial C(\beta)}{\partial \beta} > 0$ is more common when *F* is large, we can deduce from the exponents on *F* that $\frac{\partial C(\beta)}{\partial \beta} > 0$ is more likely when $\frac{k}{1+k+kl} > \frac{i+ij}{1+i+ij}$, that is when *i* is small;

when *j* is small; when *k* is large; when *l* is small. Furthermore, $\frac{\partial C(\beta)}{\partial \beta} > 0$ is more likely when β is small; when a_b is large, when d_b is large, when a_c is small, when d_c is small, and when v_b is small.

Put differently, reallocating fixed finance from carbon toward biodiversity is more likely to increase carbon benefits in addition to biodiversity benefits when the following conditions hold: larger levels of total finance; smaller initial portion of funding for biodiversity; larger and more rapidly increasing return to carbon from funding spent on biodiversity, relative to smaller and more slowly increasing return to carbon from funding spent on carbon; small and slowly increasing return to biodiversity from funding spent on biodiversity. That is, a rapidly increase in carbon price as funding is spent on carbon, relative to a slower increase in biodiversity price and carbon price as money is spent on biodiversity.