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«Agriculture Production versus Biodiversity

Protection : what Role for North-south

Unconditional Transfers»

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Agriculture production versus biodiversity protection: what role for north-south unconditional transfers?

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Abstract

In developing countries, biodiversity is often threatened by the development of agricultural production because natural habitats are destroyed by the conversion of forests, wetlands or natural pastures into arable land. There is a trade-off between revenues generated by agricultural production and services supplied by unspoilt natural capital (ecological services, possibility to develop biodiversity-related tourism activities). Whereas agricultural profits are private, biodiversity produces various types of benefits, some of them have global public good characteristics – they benefit all nations without exclusion and without rivalry– while others are regional public inputs in the natural asset-based production activities of neighbouring countries. The purpose of this paper is to explore whether international income transfers can improve the global level of biodiversity and global social welfare by changing the relative contributions to biodiversity-protection and to agricultural production. Because of the public good nature of biodiversity, Warr’s neutrality theorem suggests that such transfers may have no effects at all (Warr, 1983). A simple model is developed, based on the simplifying assumption that northern countries have little biodiversity whereas southern countries are endowed with natural capital in the form of unspoilt biodiversity-rich land. Southern countries allocate optimally land and capital to two competing productive activities, agriculture and eco-tourism. When transfers are organized from the North to the South, we show that Warr’s neutrality theorem collapses except under restrictive hypothesis concerning the characteristics of the eco-tourism and agricultural production functions. We also demonstrate that Pareto-improvements can be obtained even with reductions in the level of biodiversity.

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1 Introduction

Biodiversity conservation produces benefits which have a global public good dimension: they are non rival and non excludable at the international level. For example, the protection of the Amazonian forest contributes to mitigate the effects of global warming. The conservation of traditional crop varieties constitutes a useful gene pool in case of catastrophic crop failure associated with a new pathogen. Countries have therefore engaged into coordinated policies in order to preserve biodiversity: the Convention on Biological Diversity (CBD) was signed by 150 government leaders at the 1992 Rio Earth Summit. Almost 15 years later, it is widely acknowledged that the impact of the CBD on biodiversity is relatively limited, since it rests mostly on voluntary commitments made by signatory parties, with neither reliable means of control nor credible sanctions. The only interstate incentive mechanism is provided by the Global Environmental Fund (GEF) which allocates grants to assist developing countries and transition countries in adopting measures for the protection and conservation of biodiversity. Such grants are conditional transfers: they are calculated so as to compensate for the "agreed full incremental costs" (CBD, Art.20(2)) and are paid on the condition that the recipient complies with a certain behaviour or expected outcome. However the GEF not only has very limited financial resources, but it is also plagued by ineffectiveness and slowness associated with huge control costs to monitor compliance of recipient countries (Deke, 2004) . An alternative solution is to investigate more thoroughly the effectiveness of international redistributive policies - unconditional transfers - on the global level of biodiversity and on global welfare. Although this is a question which is regularly invoked in the debt-for-nature swap debate by environmental and development non governmental organizations, theoretical contributions are relatively scarce.

At first sight, this is explained by the fact that redistributive policies are generally designed to achieve equity goals, rather than efficiency or biodiversity conservation. Nevertheless, they raise a number of important conceptual issues. In a context of environmental externalities like biodiversity it is generally not possible to separate out efficiency and equity goals: the second welfare theorem does not hold here, which means that lump sum transfers may have an effect on social efficiency. But would they modify behaviors in the right direction? If so, they could be considered a simpler and less costly instrument, in terms of transaction costs, that deserves further attention. Of course, the ambition

would then be restricted to improving changes, rather than achieving a first best outcome. But compared to more sophisticated incentive mechanisms, lump sum transfers do not have to cope with informational obstacles, nor do they have to deal with monitoring and compliance issues, since they are unconditional by definition. Those transfers exist anyway, and one may simply want to know, beyond their effects on equity, what consequences they may have on biodiversity and welfare.

Because of the public good nature of biodiversity, the theoretical literature actually suggests that such transfers may have no effect at all, neither on the level of biodiversity, nor on welfare. Indeed, Warr (1983) has demonstrated that the private provision of a public good is unaffected by a marginal redistribution of income between contributors, despite differences in their marginal propensities to contribute to the public good. In other words, an international policy which would induce some higher-income countries to contribute to a multilateral fund with the view to transfer revenues to lower-income countries would not enhance the supply of the global public good biodiversity. The reason is that donor countries would then reduce their voluntary contribution to the public good to the amount of their lost income and would rely instead on contributions made by others. This "crowding out" phenomenon is known as the "neutrality" theorem: redistributive policies amongst voluntary contributors are useless¹. This result only holds for a public good whose technology of production is purely additive: each contribution to the public good adds identically and cumulatively to the overall level of public good.

The impact of international transfers on global environmental issues has been studied in the specific context of consumption externalities by Ono (1998). Following Buchholz and Konrad (1994), Ono shows that lump-sum transfers between two types of countries, contributing industrial countries and non contributing developing countries, can improve global environmental quality and welfare. It is also shown, quite counterintuitively, that it might be Pareto-improving - under certain conditions - to organize transfers from poor countries to rich countries.

The objective of the paper is to revisit the Warr's "neutrality" theorem and Ono's results when the public good under consideration is biodiversity. A first challenge is to design a conceptual framework that captures important specific dimensions of the problem. From the many dimensions of biodiversity, we single out three. We first argue that biodiversity generates in fact two types of public benefits: global benefits associated with the option value of the gene pool preserved; and regional benefits associated with ecosystem services (amenities, flood protection by a wetland, reduction of erosion by a forest, etc.), which have the characteristics of regional public goods shared by several neighbour countries. We then define two types of countries: ecosystem-rich countries can

¹Warr's demonstration holds for marginal transfers between agents who remain contributors after the change. It has been extended in Bergstrom et al (1986) and Cornes and Sandler (1985) who have been able to identify how large transfers can be before they change the set of contributors and do have an effect. Itaya et al (1999) offer an analysis of such large and non neutral transfers.

contribute to biodiversity conservation by preserving their natural ecosystems instead of converting them for higher return activities; ecosystem-poor countries cannot preserve biodiversity "at home" and cannot therefore enjoy the local benefits of biodiversity but they can contribute financially to improve the global benefits of biodiversity (i.e. by financing more research on biotechnologies and creating more knowledge on the value of genetic resources). To sum-up, we assume that biodiversity is both a global public good, which is an argument of the utility function of all countries, and a local input, - when it is used by ecosystem-rich countries in activities based on natural assets such as eco-tourism.

The aggregation function of countries' contributions to biodiversity conservation is therefore more complex than in Warr's generic model: the biodiversity framework described here is a multiple inputs / multiple outputs technology, instead of multiple inputs / single output process. Even if basic linearity assumptions are maintained², as in Warr (1989), it is not clear whether the neutrality theorem still holds.

In order to disentangle the role played by the above dimensions of biodiversity, we carry the analysis following a progressive sophistication approach. Section 2 starts with a simple resource allocation problem, cast as a two input-two output model. A southern country allocates optimally land and capital to two productive activities, one induces a destruction of biodiversity, the other one is based on its preservation. Let us say, to fix ideas, that these two activities are intensive agriculture and eco-tourism respectively. The eco-tourism production function is based on unspoiled land (forests, wetlands, etc.) which carries biodiversity, whereas agricultural production requires land to be converted into pasture and arable land with neither local nor global biodiversity value. This is of course a caricature of reality since tourism can also contribute to destroy biodiversity when it leads to overcrowding or excessive waste production. If social utility is defined as a strictly concave separable function of revenue and biodiversity, then we show that an increase in the country's wealth can either induce more land conservation -and therefore more biodiversity- or more land conversion -and therefore less biodiversity-, depending on the relative marginal productivity of land and capital in the two competing activities³. Therefore this model provides a renewed interpretation of the Kuznets' environmental curve, based on production economics instead of consumer choice economics. Although necessarily simplistic, such model echoes the debates taking place in biodiversity-rich countries on trade-offs between agricultural production and preservation of their ecosystems. It was calculated in 1995 that the opportunity costs of biodiversity conservation in Kenya, in terms of net returns forgone from agriculture, due to parks, forests and reserves, represented 2.8% of GDP and that the combined revenues from wildlife tourism and forestry were insufficient

²The framework does not fall either in the typology initially established by Hirshleifer (1983) and Cornes and Sandler (1984) who distinguish the *weakest link* and the *best shot* technologies

³We assume in the rest of the paper that arable land can be returned to its original state. There are no irreversible change.

to compensate such losses (Norton-Griffiths and Southey, 1995).

In Section 3, the same result is obtained when the local benefits of land conservation are a local public good shared between two identical neighbouring countries, which use it as an input into their tourism production function. The neutrality of positive income shocks for the two countries is only observed when there are no substitution nor complementarities effects between land and capital in the two activities.

Section 4 then assesses the impact of income transfers from an ecosystem-poor country (the North) to two ecosystem-rich countries (the South) sharing a common ecosystem. Warr's neutrality property generally collapses. When income redistribution induces an increase of biodiversity, we demonstrate that there are cases for which it is a Pareto-improving policy. Less intuitively, it is shown that Pareto improving transfers are still possible even when they induce the south to settle for a lower level of biodiversity. In the current context favouring conditional transfers, that is payments made in proportion to conservation efforts, this result indicates that lump-sum transfers between countries might be viewed as policy instruments which are worth investigating since they can provide the incentives to move forward in the right direction with neither control nor monitoring costs.

2 Biodiversity and agriculture-tourism trade-off in a simple one-country model

Consider a southern country endowed with a naturally biodiversity-rich land (natural pastures, wetlands, forests) supplying a number of ecological services such as flood protection or climate regulation and providing amenities which also essential assets for developing green tourism activities. This land area I , normalized to unity by an adequate choice of units, is potentially convertible (ploughing, deforestation, drainage) into arable land and let s_n denote the unconverted natural land (also called *natural capital*). By definition, $s_n + s_a = 1$. The country is also endowed with an exogenous national wealth w ; a share $x \in [0, 1]$ of w can be used as monetary expenditures in tourism, R_T , the remaining part $(1 - x)$ being then used as monetary expenditures in agriculture, R_A . Of course $R_T + R_A = wx + (1 - x)w = w$.

The production technology in the touristic sector, $\bar{T}(s_n, R_T)$, requires two inputs, unspoilt land and monetary investments, whereas the agricultural technology, $\bar{A}(s_a, R_A)$, combines farmland, which does not carry any valuable biodiversity, with money. Both functions are increasing, twice differentiable and strictly concave with respect to each of their arguments.

Without loss of generality, units of outputs, in each sector, are chosen so that unit prices are both equal to one. Therefore the total revenue from production is simply $\bar{T}(s_n, R_T) + \bar{A}(s_a, R_A)$. With linear costs, the profits in the two sectors are

$T(s_n, R_T) = \bar{T}(s_n, R_T) - c_n s_n - r_T R_T$ and $A(s_a, R_A) = \bar{A}(s_a, R_A) - c_a s_a - r_A R_A$, where c_n and c_a are the unit costs of natural land and arable land; respectively r_T and r_A are the unit opportunity costs of monetary expenditures in tourism and in agriculture. Then the net total revenue is $y = T(s_n, R_T) + A(s_a, R_A)$. We shall assume that the costs of inputs are sufficiently low, so that $T(\cdot)$ and $A(\cdot)$ are increasing functions in each of their arguments. Four technical assumptions regarding profits are made to rule out corner decisions throughout the whole analysis:

$$\mathbf{A1} \quad \frac{\partial}{\partial s_n} T(0, R_T) - \frac{\partial}{\partial s_a} A(1, R_A) > 0, \quad \forall R_T, R_A \in [0, w],$$

$$\mathbf{A2} \quad \frac{\partial}{\partial s_n} T(1, R_T) - \frac{\partial}{\partial s_a} A(0, R_A) < 0, \quad \forall R_T, R_A \in [0, w],$$

$$\mathbf{A3} \quad \frac{\partial}{\partial R_T} T(s_n, 0) - \frac{\partial}{\partial R_A} A(s_a, w) > 0, \quad \forall s_n, s_a \in [0, 1],$$

$$\mathbf{A4} \quad \frac{\partial}{\partial R_T} T(s_n, w) - \frac{\partial}{\partial R_A} A(s_a, 0) < 0, \quad \forall s_n, s_a \in [0, 1].$$

Finally, the country's utility is $U(y, s_n)$, a differentiable function, strictly increasing in each argument and globally concave. Clearly natural land is both a consumption good - associated with the biodiversity value of land -, and a productive input - in the tourism production function.

The country chooses s_n and x in order to maximize total utility:

$$\max_{s_n \in [0, 1], x \in [0, 1]} U(y, s_n)$$

The first-order conditions for interior solutions are written:

$$\frac{\partial U}{\partial s_n} = U_1(T_1 - A_1) + U_2 = 0 \iff T_1 - A_1 = -\frac{U_2}{U_1} = -MRS, \quad (1)$$

$$\frac{\partial U}{\partial x} = wU_1(T_2 - A_2) = 0 \iff T_2 = A_2, \quad (2)$$

where MRS is the *marginal rate of substitution between net revenue and natural capital*, and where $U_1 = \frac{\partial U}{\partial y}$ and $U_2 = \frac{\partial U}{\partial s_n}$ are the partial derivatives of the utility function with respect to y and s_n respectively, $T_1 = \frac{\partial T}{\partial s_n}$, $T_2 = \frac{\partial T}{\partial R_T}$, $A_1 = \frac{\partial A}{\partial s_a}$, $A_2 = \frac{\partial A}{\partial R_A}$ are partial derivatives of the sectoral profit functions with respect to s_n , R_T , s_a , and R_A .

This is a model of optimal allocation of factors between two activities. The vector of optimal decisions $d^* = (s_n^*, x^*)$ is reached when the difference in land marginal revenue is equal to the marginal rate of substitution (1) and when marginal revenue of monetary expenditures are equal in the two production sectors (2).

2.1 Monetary transfers and resources allocation

Let the country's utility function be $U(y, s_n) = y + \varepsilon N(s_n)$, with $\varepsilon > 0$ a strictly positive parameter and $N(\cdot)$ a continuous function, increasing and concave with

respect to s_n that converts an area of natural land into a biodiversity index. For instance, if the biodiversity index is the α -biodiversity, that is the number of species in the area under conservation, then the functional form is usually written: $N(s_n) = bs_n^z$, with $b > 0$ and $z \in [0, 1]$. Note that, with this choice of utility function, $MRS = \frac{U_2}{U_1} = \varepsilon N'$.

A monetary transfer to the country (in the form of a lump-sum subsidy from an international organization, or bilateral aid) increases its wealth w . In the appendix, we show that it will induce a marginal change in the optimal allocation of land which is:

$$\left. \frac{ds_n}{dw} \right|_{d=d^*} = \frac{A_{12}T_{22} - A_{22}T_{12}}{[T_{11} + A_{11} + \varepsilon N''][T_{22} + A_{22}] - [T_{12} + A_{12}]^2} \quad (3)$$

where $A_{11} = \frac{\partial A_1}{\partial s_a} < 0$, $A_{22} = \frac{\partial A_2}{\partial R_a} < 0$, $T_{11} = \frac{\partial T_1}{\partial s_n} < 0$, $T_{22} = \frac{\partial T_2}{\partial R_T} < 0$, $A_{12} = \frac{\partial A_1}{\partial R_a}$, $T_{12} = \frac{\partial T_1}{\partial R_T}$ are the second order partial derivatives of the net revenue function.

From expression (3), one can readily deduce the conditions under which a monetary transfer has no effect (marginally) on the natural capital. At the most general level, neutrality is obtained when the numerator is zero, that is:

$$A_{12}T_{22} - A_{22}T_{12} = 0 .$$

A priori, this general condition encompasses five subcases: *i*) $A_{12} = A_{22} = 0$, *ii*) $T_{22} = T_{12} = 0$, *iii*) $T_{22} = A_{22} = 0$, *iv*) $A_{12} = T_{12} = 0$, *v*) $A_{12}T_{22} = A_{22}T_{12}$ with $A_{12}, T_{22}, A_{22}, T_{12} \neq 0$. Possibilities *i*) – *iii*) are ruled out by the assumptions of strict concavity made so far on the production technologies. Let us discuss the two last ones. Possibility *iv*) depends only on the technologies in the two sectors, whereas possibility *v*) is more subtle as it may also depend on the way resources are re-allocated after a change in w .

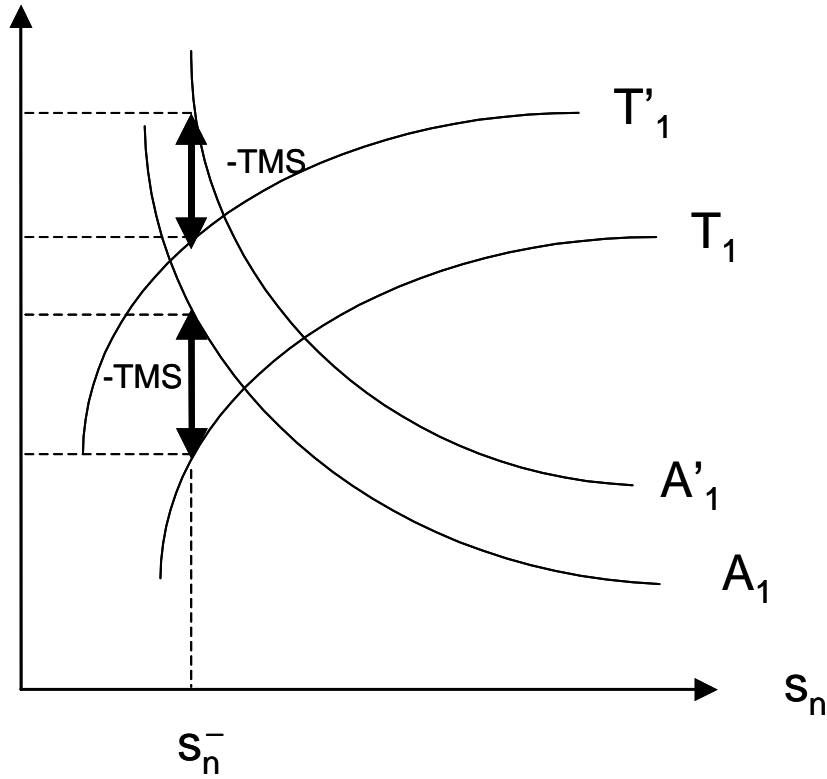
Proposition 1 *If there are no complementary nor substitution cross effects between land and monetary expenditures, i.e. $A_{12} = T_{12} = 0$, then a financial transfer to the country has no impact on natural capital, $\left. \frac{ds_n}{dw} \right|_{d=d^*} = 0$.*

This property does not mean that the second decision variable x is unaffected. Actually a change in the initial wealth induces a change in the allocation of monetary expenditures (a change in x), which is:

$$\left. \frac{dx}{dw} \right|_{d=d^*} = - \frac{xT_{22} - A_{22}(1-x)}{w(T_{22} + A_{22})} . \quad (4)$$

But, by assumption this has no effect whatsoever on the marginal revenues T_1 and A_1 , therefore no effect on the optimal s_n as can be deduced from the first order condition (1).

Proposition 2 *if $A_{12}T_{22} = A_{22}T_{12}$ with $A_{12}, T_{22}, A_{22}, T_{12} \neq 0$, then a financial transfer to the country has no impact on natural capital, $\left. \frac{ds_n}{dw} \right|_{d=d^*} = 0$*



This second case exists even when $A_{12}, T_{22}, A_{22}, T_{12} \neq 0$ are not constants. When those second derivatives vary with the level of natural capital and the level of monetary investments, Proposition 2 singles out the case where the monetary transfer induces a reallocation of monetary expenditures such that the first order condition $T_1 - A_1 = -\frac{U_2}{U_1}$ is verified at the unchanged optimal level of natural capital s_n (see figure 1):

Incidentally, this situation supposes that the cross partial derivatives have the same sign: either land and monetary expenditures are complementary in both sectors, or they are substitutes in both sectors.

Those particular cases excepted, natural capital either increases or decreases with income. With a slight abuse of language we shall borrow two notions from the consumer theory and say that natural capital is a *normal good* when $\frac{ds_n}{dw}|_{d=d^*} > 0$, and an *inferior good* when $\frac{ds_n}{dw}|_{d=d^*} < 0$.⁴

It is worth interpreting those results in the light of the Kuznets' environmen-

⁴The choice of term "normal good" or "inferior good" is partially inexact since s_n is not only a consumption good (in the second part of the utility function) but also an input in the net revenue functions.

tal curve hypothesis (KEC). The KEC is an empirical statistical result showing an inverted U-shaped relationship between per capita income and environmental degradation. It tends therefore to indicate that beyond a turning point, economic growth can lead to environmental improvement. The usual intuitive explanation for this phenomenon is that the pure scale effect (production growth leads to an increase in pollution and resource exploitation) is compensated by improvements in green technologies driven by a higher demand for environmental quality (Stern, 2004). However, the KEC is a controversial result: an increasing number of econometric studies show that there are no regularities in the revenue-environment relationship, especially when one looks at resource depletion rather than pollution concentration (see Koop and Tole, 1999 for a study on deforestation). Surprisingly, there is relatively little formal modelling exploring the micro-economic foundations of the KEC, although this could be very useful to explain the different curves observed empirically. Bulte and van Soest (2001) propose a household model of optimal allocation of work and investment when natural capital is an input in production, and show that under the imperfect market hypothesis the U-shaped relation between natural capital stock and income can be generated.

Our optimal production model provides the theoretical basis for an explanation of the KEC rooted in production economics. We have shown above how natural capital can decrease or increase with wealth depending on the relative concavity parameters of our production functions for tourism and agriculture ($A_{11}, A_{22}, A_{12}, T_{12}$). The intuition is the following: when agricultural production increases, therefore driving up income, the relative marginal productivity of land and monetary investments in this sector decline, making it more profitable to invest in tourism and protect natural capital. We intend, in a subsequent version of this paper, to introduce examples of production functions which could illustrate the KEC and more generally reproduce the results found in Koop and Tole (1999) in the case of deforestation .

2.2 Monetary transfers and total utility

Changes in utility associated with monetary transfers are written:

$$\begin{aligned} \frac{dU}{dw} \Big|_{d=d^*} &= U_1 \frac{dy}{dw} \Big|_{d=d^*} + U_2 \frac{ds_n}{dw} \Big|_{d=d^*} , \\ &= U_1 \left[(T_1 - A_1) \frac{ds_n}{dw} \Big|_{d=d^*} + (wT_2 - wA_2) \frac{dx}{dw} \Big|_{d=d^*} + xT_2 + (1-x)A_2 \right] \\ &\quad + U_2 \frac{ds_n}{dw} \Big|_{d=d^*} . \end{aligned}$$

Using the first order conditions (1) and (2), this expression simplifies to:

$$\frac{dU}{dw} \Big|_{d=d^*} = A_2 \geq 0.$$

As the intuition suggests, total utility increases when wealth increases.

3 The local public good dimension of biodiversity in the two-country model

It is often the case that natural capital has in fact cross-border spillovers. For example, a large forest area, or wetlands, will presumably benefit neighbouring countries by preserving wildlife habitats and landscapes and therefore will increase the attractiveness of the whole region for tourism. Conversely, if a country chooses to reduce the quality and size of its preserved land, it will probably harm the whole region as well by reducing ecological services and amenities. Therefore, in many cases, s_n is a regional public good: countries in the same region benefit from it without exclusion nor rivalry in consumption. Examples abound: lake Victoria in East Africa, the Amazon forest in South America, the mangroves in South East Asia.

Let us assume that the southern country described in the previous section is split into two identical sovereign countries sharing a common border ($i = 1, 2$). Each country has an initial endowment in natural capital $I^i = 1/2$ and an initial level of wealth $w^i = w/2$.

Production functions and utility functions are unchanged. Each country i has to choose the optimal allocation of land (s_{ni}) and monetary expenditures (x_i) between the two activities, tourism and agriculture. There are two differences with the previous basic model. Firstly, $s_n = \sum s_{ni}$ is a regional public good. Each country benefits from it both as an input in the tourism production function and as a consumption good. Secondly and consequently, there are now strategic interactions.

3.1 Monetary transfers and resource allocation

Non cooperative decisions $d_i = (s_{ni}, x_i)$, $i = 1, 2$ are conceptualized as a Nash equilibrium. Each country selects its contribution s_{ni} to the public good/*input* and the allocation x_i of monetary expenditures between tourism and agriculture in order to maximize its utility, taking as given the decision variables of the other country. Formally, country i 's problem reads as:

$$\max_{s_{ni} \in [0, 1/2], x_i \in [0, 1]} U^i(y^i, s_{ni} + s_{nj})$$

where

- $y^i = T(s_{ni} + s_{nj}, R_T^i) + A(\frac{1}{2} - s_{ni}, R_A^i)$ is country i 's total net revenue,
- $R_T^i = \frac{1}{2}wx_i$ and $R_A^i = \frac{1}{2}w(1-x_i)$ are the monetary expenditures dedicated respectively to tourism and agriculture,
- and s_{nj} and x_j are considered as exogenously given.

The first-order conditions for $i = 1, 2$ are:

$$\begin{aligned}\frac{\partial U^i}{\partial s_{ni}} &= U_1^i(T_1 - A_1) + U_2^i = 0 \iff T_1 - A_1 = -\frac{U_2^i}{U_1^i} = -MRS^i, \\ \frac{\partial U^i}{\partial x_i} &= \frac{1}{2}wU_1^i(T_2 - A_2) = 0 \iff T_2 = A_2.\end{aligned}$$

Definition 3 *A interior symmetric Nash equilibrium (ISNE) for the two-country economy is a profile of decisions $\bar{d} = (\bar{s}_{n1}, \bar{s}_{n2}, \bar{x}_1, \bar{x}_2) = (\frac{1}{2}\bar{s}_n, \frac{1}{2}\bar{s}_n, \bar{x}, \bar{x})$, such that countries simultaneously solve their decision problems given the decisions of the other country.*

Note that, at such a symmetric outcome, $MRS^1 = MRS^2 = MRS$.

For $U^i(y_i, s_n) = y_i + \varepsilon N(s_n)$, we can calculate the impact of a change in wealth on x and on s_n , evaluated at an ISNE:

$$\left. \frac{dx}{dw} \right|_{d=\bar{d}} = -\frac{2T_{21} + A_{21}}{w(T_{22} + A_{22})} \left. \frac{ds_n}{dw} \right|_{d=\bar{d}} - \frac{xT_{22} - (1-x)A_{22}}{w(T_{22} + A_{22})} \quad (5)$$

$$\left. \frac{ds_n}{dw} \right|_{d=\bar{d}} = \frac{A_{12}T_{22} - A_{22}T_{12}}{(2T_{11} + A_{11} + 2\varepsilon N''(T_{22} + A_{22}) - (T_{12} + A_{12})(2T_{21} + A_{21}))} \quad (6)$$

Results are comparable to those found in the first section. An increase in the wealth of both countries can either lead to a higher s_n or to a lower s_n . Under specific conditions, and in particular when cross effects of inputs are nil, then a financial transfer to both countries has no impact on total natural capital.

3.2 Monetary transfers and social welfare

Let us consider an utilitarian social welfare function for the two countries considered together:

$$W = U^1(y_1, s_n) + U^2(y_2, s_n)$$

At an ISNE we have:

$$\left. \frac{dW}{dw} \right|_{d=\bar{d}} = 2 \left. \frac{dU^i}{dw} \right|_{d=\bar{d}} = 2 \left[U_1^i \left. \frac{dy}{dw} \right|_{d=\bar{d}} + U_2^i \left. \frac{ds_n}{dw} \right|_{d=\bar{d}} \right] = 2 \left[\left. \frac{dy}{dw} \right|_{d=\bar{d}} + \varepsilon N' \left. \frac{ds_n}{dw} \right|_{d=\bar{d}} \right], \quad (7)$$

where:

$$\left. \frac{dy}{dw} \right|_{d=\bar{d}} = T_1 \left. \frac{ds_n}{dw} \right|_{d=\bar{d}} + \frac{1}{2}xT_2 - \frac{1}{2}A_1 \cdot \left. \frac{ds_n}{dw} \right|_{d=\bar{d}} + \frac{1}{2}(1-x)A_2, \quad (8)$$

$$= \left(T_1 - \frac{1}{2}A_1 \right) \left. \frac{ds_n}{dw} \right|_{d=\bar{d}} + \frac{1}{2}A_2. \quad (9)$$

Therefore

$$\begin{aligned} 2 \frac{dy}{dw} \Big|_{d=\bar{d}} &= (T_1 + T_1 - A_1) \frac{ds_n}{dw} \Big|_{d=\bar{d}} + A_2, \\ &= (T_1 - \varepsilon N') \frac{ds_n}{dw} \Big|_{d=\bar{d}} + A_2. \end{aligned} \quad (10)$$

Plugging back expression (10) into expression (7), one obtains:

$$\frac{dW}{dw} \Big|_{d=\bar{d}} = T_1 \frac{ds_n}{dw} \Big|_{d=\bar{d}} + A_2. \quad (11)$$

The marginal variation of social welfare depends on the behaviour of $\frac{ds_n}{dw} \Big|_{d=\bar{d}}$. Remember that in an economy with a single country, the utility increases after a positive shock to income. By contrast, in a two-country world, expression (11) shows that the variation of each country's utility is ambiguous.

Proposition 4 *If $\frac{ds_n}{dw} \Big|_{d=\bar{d}} = 0$, i.e. a change in total income produces no change on the public good production, then $\frac{dW}{dw} \Big|_{d=\bar{d}} = A_2 > 0$.*

In this case, when one of the two conditions for $\frac{ds_n}{dw} = 0$ is met (cf. sections 2.1 and 3.1), then an exogenous increase of income always ends up in an improvement of social welfare, although it has no effect on the public good provision. This is due, as in Section 3.1, to an optimal reallocation of investments between the two economic activities. In all other cases, when $\frac{ds_n}{dw} \neq 0$, the two following clear-cut properties hold:

Proposition 5 *If s_n is a normal good, then $\frac{dW}{dw} \Big|_{d=\bar{d}} > 0$.*

Proposition 5 singles out a sufficient, easy-to-interpret and empirically testable condition (normality), for a positive social welfare impact. But the necessary and sufficient condition is:

Proposition 6 *$\frac{dW}{dw} \Big|_{d=\bar{d}} \geq 0$ iff $\frac{ds_n}{dw} \geq -\frac{A_2}{T_1}$.*

Therefore there can be Pareto improving transfers even if s_n is akin to an inferior good, provided that $\frac{ds_n}{dw} < 0$ is not too small. To put it differently, the variation of social welfare depends on the sign of $\frac{ds_n}{dw}$; and it depends on its scale (when $\frac{ds_n}{dw} < 0$).

Finally, it is worth highlighting that there are cases when monetary transfers have a negative impact both on the conservation of natural capital and on welfare: when $\frac{ds_n}{dw} < -\frac{A_2}{T_1} < 0$ then $\frac{dW}{dw} < 0$

This is an interesting counterintuitive proposition, suggesting that the taxation of these countries would help improve their level of welfare and biodiversity.

4 Adding the global public good dimension of biodiversity

4.1 A simple north-south model

A wetland spreading over two neighbouring countries is a local public good; it delivers ecological services (water storage, water purification etc.) benefitting without rivalry to the citizens of both countries. It is also a public input providing amenities to both countries and therefore entering as an argument in their tourism production functions. In addition, the preservation of the wetland ecosystem contributes to improve the quality of global biodiversity and generates world-wide benefits. From a general perspective, those global benefits should be taken into account. Following this idea, we add a northern distant country in the conceptual framework. This third country does not share the regional benefits of the wetland because of geographical distance but it shares the benefits of the gene pool conservation and of its existence value.

Formally, a three-country economy, $i = 1, 2, 3$ allows to add to the model the global public good dimension to the natural capital. This global public good is denoted: $G = G(s_{n1}, s_{n2}, g_3) = N(s_n) + g(g_3)$ where g_3 is the financial contribution of the third country to biodiversity (ie monetary contributions to R&D efforts that convert genetic diversity into pharmaceutical innovations, which in turn are beneficial for public health; funds to finance gene banks etc.) and g is the production function of global public good associated with expenses g_3 . The functions N and g are both continuous, increasing and concave. Note the heterogeneity of the inputs: in the model, the natural area is localized in the first two countries; the third countries is not endowed with the natural potential for conservation, but it can offer financial contributions to increase the benefits of biodiversity. We assume that N and g are additive and separable in the production function of the global opublic good G . In other words, even if both southern countries destroyed entirely their natural asset, $s_{n1} = s_{n2} = 0$, the northern country could still contribute to the global public good, ie through the financing of ex-situ conservation.

As in the previous section, the focus shall be on the effect of income transfers on the Nash equilibrium, therefore on the equilibrium trade-off between the two activities of tourism and agriculture, with one difference though: transfers are not considered as exogenous income shocks anymore; they shall be organized from the northern country towards southern countries. In other words, we finally explore the question of the impact of income redistribution on the level of biodiversity and welfare.

As for country 3, its utility reads as $U^3(c_3, G) = v(c_3) + \sigma G$, where $v(c_3)$ is a concave and increasing function of private good consumption $c_3 = w_3 - g_3$, and $\sigma > 0$ represents a preference parameter for the global public good G . This country has only one decision variable: the level of monetary contribution g_3 to the production of biodiversity. To avoid corner decisions we assume:

A5 $-v'(w_3) + \sigma g'(0) > 0$,

A6 $-v'(0) + \sigma g'(w_3) < 0$.

The utility functions of country $i = 1, 2$ is now $U^i(y_i, G) = y_i + \varepsilon G$. Southern countries have the same preference for the global public good.

Definition 7 *A interior symmetric Nash equilibrium (ISNE) for the three-country economy is a profile of decisions $\hat{d} = (\hat{s}_{n1}, \hat{s}_{n2}, \hat{x}_1, \hat{x}_2, \hat{g}_3)$, such that countries simultaneously solve their decision problems given the decisions of the other countries.*

More precisely, on a non cooperative basis each country takes as given rival decisions and uses its own decisions to maximize its utility:

- for $i = 1, 2$:

$$\max_{s_{ni} \in [0, 1/2], x_i \in [0, 1]} U^i(y_i, G(s_{n1}, s_{n2}, g_3))$$

subject to $y_i = T(s_n, R_T^i) + A(I/2 - s_{ni}, R_A^i)$. At an interior Nash equilibrium for $i = 1, 2$, we have:

$$T_1 - A_1 = -\frac{U_2}{U_1} = -TMS = -\varepsilon N'(s_n) , \quad (12)$$

$$T_2 = A_2 . \quad (13)$$

- and for $i = 3$:

$$\max_{g_3 \in [0, w_3]} U^3(w_3 - g_3, G(s_{n1}, s_{n2}, g_3))$$

The first order condition for an interior decision is:

$$-U_1^3 + U_2^3 g' = 0 \quad (14)$$

It should be noted that this system of five equations is decomposable into two independent blocks: the first one is a system of four equations for four unknown $(s_{n1}, s_{n2}, x_1, x_2)$ and the second block is made of a single equation for g_3 . By differentiating the last equation with respect to g_3 and w_3 , we can deduce the marginal impact of income on the third country's contribution:

$$\Leftrightarrow (U_{11}^3 - U_{12}^3 g' - U_{21}^3 g' + U_{22}^3 (g')^2 + U_2^3 g'') dg_3 + (-U_{11}^3 + U_{21}^3 g') dw_3 = 0$$

According to our assumption of additive separability of utility functions, $U_{12}^3 = U_{21}^3 = 0$, and $U_{22}^3 = 0$. We get:

$$(U_{11}^3 + U_2^3 g'') dg_3 - U_{11}^3 dw_3 = 0$$

and

$$\left. \frac{dg_3}{dw_3} \right|_{d=\hat{d}} = \frac{U_{11}^3}{(U_{11}^3 + U_2^3 g'')} > 0 \quad (15)$$

Expression (15) confirms, under particular assumptions, the intuition that a contribution to a public good increases when income increases. Besides, one can observe that $0 < \left. \frac{dg_3}{dw_3} \right|_{d=\hat{d}} < 1$ because $g'' < 0$, $U_{11}^3 < 0$ and $U_2^3 > 0$: a reduction of the northern country's income by one dollar is followed by a less than proportional reduction in the contribution to biodiversity, whereas the private good consumption is reduced by a greater amount.

4.2 Welfare effect of a lump sum transfer between countries

When welfare is accounted for by the utilitarian criterion

$$W = U^1(y_1, G) + U^2(y_2, G) + U^3(c_3, G) ,$$

what is the welfare effect of a lump sum income redistribution from the North to the South, given the complex public good nature of biodiversity? Let us study a transfer from country 3 that is shared equally by country 1 and country 2.

Proposition 8 *A lump sum transfer is welfare improving, $\left. \frac{dW}{dw} \right|_{d=\hat{d}} > 0$, iff $A_2 + [T_1 + (3\varepsilon + 2\sigma) N'] \frac{ds_n}{dw} > 4\varepsilon g'(g_3) \frac{dg_3}{dw_3} + 2v'(c_3)$.*

Proof. Appendix B. ■

Despite its complicated form, the above inequality has an easy interpretation: its right hand side is the welfare impact of the change in the Northern country's decision variables (g_3 and c_3) after the transfer. When $dw_3 < 0$, this welfare impact is negative. The left hand side displays the welfare effect of a change in the local trade-offs in southern countries. It is unambiguously positive when the natural capital is a normal good (that is when $\frac{ds_n}{dw} > 0$). Overall, the expression reveals the conditions for a global positive welfare effect: the adjustments in the south must compensate the negative welfare effect from the adjustment in the north. Presumably, it is more likely to be the case when the natural capital is a normal good. When s_n is an inferior good, then a necessary (but not sufficient) condition is that the positive impact on agricultural income of an increase in wealth exceed the negative impact on welfare of the reduction of s_n .

Otherwise, $\frac{dW}{dw} < 0$, and it would be justified, from the point of view of efficiency, to organize transfers from the South to the North! The logic that explains this possibility is not difficult to grasp, but this is a rather provocative and hard to admit conclusion. As a mitigation, one should bear in mind that transfer policies are primarily designed to pursue equity goals rather than efficiency goals.

There is a simple policy implication from this section: before any income transfer, an empirical study which should not be limited to an estimation of

whether s_n is an inferior good, would be welcome. Those results suggest that a precise knowledge of production technologies in sectors destroying or using biodiversity is valuable if decision-makers wish to use unconditional transfers as a policy instrument to improve the protection of biodiversity and to increase global welfare. This knowledge must be sufficiently precise about the cross effects between land and investments (T_{12}, A_{12}) in production technologies, about the extent of decreasing returns $(T_{11}, T_{22}, A_{11}, A_{22})$ and about the marginal products (T_1, T_2, A_1, A_2) . In addition, we have shown that the additivity of the production technology for the public good is not sufficient for the robustness of Warr's neutrality theorem. Indeed, the welfare variation is generally not null after an income redistribution between the three countries, even if the redistribution does not change the set of contributors.

4.3 Extensions

Beyond showing how fragile the neutrality property can be in the complex context of biodiversity, the previous results also reveal the important role played by some sort of complementarity assumptions. This suggests an *addendum* to the scope of this paper: we propose to investigate the robustness of a positive effect on the protection of biodiversity of an increase in wealth, when there exists complementarities between the agricultural sector and the tourism sector. More precisely, the goal of this subsection is to make four jumps in one shot; namely by decreasing order of importance: *i*) to allow for non infinitesimal redistributions of income, *ii*) to dispense with interior decisions, *iii*) to allow for any number of countries, both in the north and in the south, *iv*) to give up all symmetry assumptions, except for the way income is redistributed in the south. The first two limitations come from the use, so far, of the implicit function theorem. But under specific conditions, akin to complementarity assumptions, supermodularity theory can prove a much more powerful tool to perform some comparative statics. As we now show, this approach is indeed fruitful to strengthen our previous results -though not all.

From now on, we drop Inada conditions $(A_1$ to $A_4)$. There are now p countries in the south, and q countries in the north. Previous specific forms for utility functions are maintained but we allow for heterogeneity (we previously assumed symmetry in the south). In the south, utility functions are:

$$U^h(y_h, G) = y_h + \varepsilon^h G, \quad h = 1, \dots, p.$$

And, in the north, utility functions are:

$$U^h(c_h, G) = v^h(c_h) + \sigma^h G, \quad h = p+1, \dots, p+q.$$

The global public good technology is therefore:

$$G = G(s_{n1}, s_{n2}, \dots, s_{n_p}, g_{p+1}, \dots, g_{p+q}) = N(s_n) + g(g_{p+1} + \dots + g_{p+q}).$$

As before, the functions N and g are both continuous, increasing and concave.

Each southern country now has specific concave technologies for its two sectors, $T^h(s_n, R_T^h)$ and $A^h(s_a, R_A^h)$, that may differ from the technologies in the other southern countries. We however assume:

A7 $A_{12}^h < 0, T_{12}^h + A_{12}^h > 0, h = 1, \dots, p.$

A8 $T_{11}^h = N'' = 0.$

Those assumptions ensure increasing best reply functions in the south (see Appendix C). For this reason, we call this particular extended model the *partially supermodular north-south model*. Intuitively, in such a strategic situation, a change in southern income fosters the marginal incentives to scale up the share of natural capital in the total land endowment: indeed, because $A_{12}^h < 0$, the relative interest to allocate more land to the agricultural sector, compared to the tourism sector, is reduced. As far as the decision to allocate money between the two sectors is concerned, concavity in the agricultural sector (A_{22}^h) also increases the incentive to invest more in tourism. Finally, because of some complementarity between the different trade offs ($T_{12}^h + A_{12}^h > 0$), all those partial effects reinforce each other. We can therefore expect an overall increase of natural income. This property can indeed be established very simply.

A *feasible* redistribution of income from the north to the south is a vector $(\Delta w_1, \dots, \Delta w_p, \Delta w_{p+1}, \dots, \Delta w_{p+q})$ with positive p first elements and the following q elements negative. Of course

$$\sum_{i=1}^{p+q} \Delta w_i = 0,$$

and, in addition, a feasible redistribution is such that it does not put donor agents into bankruptcy, which means $w_i + \Delta w_i \geq 0, i = p + 1, \dots, p + q$. Actually, within the set of feasible redistributions, attention is restricted to those redistributions offering the same increments to all the southern countries: $\Delta w_1 = \Delta w_2 = \dots = \Delta w_p = \Delta w$.

Proposition 9 *Under Assumptions A7 and A8, in the partially supermodular north-south model a feasible redistribution of income*

$$(\Delta w, \dots, \Delta w, \Delta w_{p+1}, \dots, \Delta w_{p+q})$$

from the rich north to the developing south has a non negative impact on the natural capital, hence on biodiversity.

Proof. Appendix C. ■

5 Conclusion

How do those results compare with those established by Warr ? This author shows that income transfers between contributors are neutral on the private

provision of public goods which are produced via an additive technology. When dealing with biodiversity, a multidimensional public good, we have shown that the assumption of additive technology does not guaranty the neutrality property. Indeed, the non neutrality is the rule while neutrality is the exception. Here the input dimension of the public good plays a key role, as well as its regional dimension. Furthermore, the nature of the public good biodiversity, i.e. normal good or inferior good, is helpful in assessing the welfare effect of marginal income redistributions. Normality makes a stronger case in favor of lump sum transfers as a tool for the protection of biodiversity. However, it should be reminded that Pareto improvements can be obtained without modification, or even with a reduction of the level of biodiversity. When both the local dimension and the global dimension of the public good are considered, the effects of income redistribution are complex and their assessment require a good knowledge of the production technologies for which natural capital is an essential input, since cases when transfers from the North to the South reduce global welfare cannot be excluded. Under such conditions, recomandations for Pareto-improving policies should - in theory - include South-North transfers. This latest finding converges with Ono's results (1998) when the issue at stake is consumption externalities. Of course, it should be interpreted with care since such analysis does not include equity concerns but it could feed the debates on transfers taking place on various international negotiation arena. Southern biodiversity-rich countries are increasingly vocal about the financial aid they wish to obtain from industrial countries in compensation for their efforts to protect biodiversity. The like-minded group of megadiverse countries created in 2001 by biodiversity-rich countries such as Bolivia, Brazil, China, or the Philippines argues in favour of massive transfers to the South for the preservation of ecosystems. There is scope, however, to conduct a more careful analysis of the potential impact - on biodiversity- of such transfers.

However, biodiversity protection is not limited to the North-South issue. The paper's results are also relevant when dealing with decisions at a federal level. There are several sites in Europe which are close to the situation described in the model. For example, the Prespa Lake is one of the largest remaining wetlands in the Northern part of the Mediterranean Sea. It is located across Macedonia (candidate to the EU), Albania (candidate to the EU) and Greece (EU member) . Prespa Lake and its associated wetlands are an important economic zone for the three countries both in terms of agricultural production (apple production especially) and ranging, fishing activities, and in terms of tourism which increased rapidly since the creation of the Prespa Park in 2000. Prespa Lake is also listed as a Ramsar site and part of the site is either registered as national monument or park or Natura 2000 site for bird protection. Despite these protection zones, Prespa Lake is increasingly threatened by economic development in the three countries. Indeed, the Prespa Lake, as in our first model, is at the same time an input for many of the local activities (agriculture, fishing, tourism), a local public good preserved for local biodiversity and ecological services, and a global public good as it has been identified as a site of European interest (Natura 2000) and international interest (Ramsar Convention) for biodiversity

conservation. Financial transfers already exist between European countries to contribute to biodiversity conservation, most of them being conditional. The theoretical conclusions of our model could provide a first basis of discussion at the European Commission level to link redistributive policies amongst EU members and biodiversity protection.

Appendix

A Variation of the conservation effort in an economy with a single country - Section 2

Starting from the optimal decision vector $d^* = (s_n^*, x^*)$ and differentiating the first order conditions with respect to w , s_n and x , it follows:

$$\begin{cases} [xT_{12} - (1-x)A_{12}]dw + [T_{11} + A_{11} + \varepsilon N'']ds_n + [wT_{12} + wA_{12}]dx = 0, \\ [xT_{22} - (1-x)A_{22}]dw + [T_{21} + A_{21}]ds_n + [wT_{22} + wA_{22}]dx = 0. \end{cases}$$

After dividing each of those expressions by dw , one obtains:

$$\begin{cases} [T_{11} + A_{11} + \varepsilon N'']\frac{ds_n}{dw} + [T_{12} + A_{12}]w\frac{dx}{dw} + [xT_{12} - (1-x)A_{12}] = 0 \\ [T_{21} + A_{21}]\frac{ds_n}{dw} + [wT_{22} + wA_{22}]\frac{dx}{dw} + [xT_{22} - (1-x)A_{22}] = 0 \end{cases}$$

From the second equation:

$$\frac{dx}{dw} = -\frac{[T_{21} + A_{21}]}{w[T_{22} + A_{22}]} \frac{ds_n}{dw} - \frac{[xT_{22} - (1-x)A_{22}]}{w[T_{22} + A_{22}]} \quad (16)$$

Plugging expression (16) into the first equation of the system, we have:

$$\begin{aligned} & [T_{11} + A_{11} + \varepsilon N'']\frac{ds_n}{dw} - \frac{[T_{12} + A_{12}][T_{21} + A_{21}]}{[T_{22} + A_{22}]} \frac{ds_n}{dw} \\ & - \frac{[T_{12} + A_{12}][xT_{22} - (1-x)A_{22}]}{[T_{22} + A_{22}]} + [xT_{12} - (1-x)A_{12}] = 0 \end{aligned}$$

$$\begin{aligned} & \frac{[T_{11} + A_{11} + \varepsilon N''] [T_{22} + A_{22}] - [T_{12} + A_{12}][T_{21} + A_{21}]}{[T_{22} + A_{22}]} \frac{ds_n}{dw} \\ & - \frac{[T_{12} + A_{12}][xT_{22} - (1-x)A_{22}] - [T_{22} + A_{22}][xT_{12} - (1-x)A_{12}]}{[T_{22} + A_{22}]} = 0 \end{aligned}$$

and therefore:

$$\begin{aligned} \left. \frac{ds_n}{dw} \right|_{d=d^*} &= \frac{[T_{12} + A_{12}][xT_{22} - (1-x)A_{22}] - [T_{22} + A_{22}][xT_{12} - (1-x)A_{12}]}{[T_{11} + A_{11} + \varepsilon N''] [T_{22} + A_{22}] - [T_{12} + A_{12}][T_{21} + A_{21}]} \quad (17) \\ &= \frac{A_{12}T_{22} - A_{22}T_{12}}{[T_{11} + A_{11} + \varepsilon N''] [T_{22} + A_{22}] - [T_{12} + A_{12}]^2} \end{aligned}$$

The simplification of expression (17) is reported in Section 2.1 (expression (3)).

B Welfare effect of a lump sum transfer between countries

The utilitarian social welfare function is given by:

$$W = U^1(y_1, G) + U^2(y_2, G) + U^3(c_3, G)$$

Following a lump sum transfer $-dw_3 = dw_1 + dw_2 = 2dw$, one has:

$$dW = U_1^1 dy_1 + U_2^1 dG + U_1^2 dy_2 + U_2^2 dG + U_1^3 dc_3 + U_2^3 dG \quad (18)$$

where

1. $dy_1 = dy_2 = dy = [(T_1 - \frac{1}{2}A_1) \frac{ds_n}{dw} + \frac{1}{2}A_2]dw$ (according to expression (8) of the previous section),
2. $dG = N' \frac{\partial s_n}{\partial dw_1} dw_1 + N' \frac{\partial s_n}{\partial dw_2} dw_2 + g'(g_3) \frac{\partial g_3}{\partial dw_3} dw_3$,
3. $dc_3 = dw_3 - \frac{\partial g_3}{\partial dw_3} dw_3$..

Plugging back the previous expressions into expression (18), one obtains:

$$\begin{aligned} dW &= U_1^1 dy_1 + U_2^1 dG + U_1^2 dy_2 + U_2^2 dG + U_1^3 dc_3 + U_2^3 dG, \\ &= (U_1^1 + U_1^2) dy + (U_2^1 + U_2^2 + U_2^3) dG + U_1^3 dc_3, \end{aligned}$$

or

$$\begin{aligned} dW &= 2 \left[(T_1 - \frac{1}{2}A_1) \frac{ds_n}{dw} + \frac{1}{2}A_2 \right] dw \\ &\quad + (2\varepsilon + \sigma) \left[N' \frac{\partial s_n}{\partial dw_1} dw_1 + N' \frac{\partial s_n}{\partial dw_2} dw_2 + g'(g_3) \frac{\partial g_3}{\partial dw_3} dw_3 \right] \\ &\quad + v'(c_3) \left(dw_3 - \frac{\partial g_3}{\partial dw_3} dw_3 \right). \end{aligned}$$

Bearing in mind that $dw_3 = -2dw$, this expression simplifies to:

$$\begin{aligned} \frac{dW}{dw} &= 2(T_1 - \frac{1}{2}A_1) \frac{ds_n}{dw} + A_2 \\ &\quad + (2\varepsilon + \sigma) \left[N' \left(\frac{\partial s_n}{\partial w} + \frac{\partial s_n}{\partial w} \right) - 2g'(g_3) \frac{\partial g_3}{\partial w_3} \right] \\ &\quad - 2v'(c_3) \left(1 - \frac{\partial g_3}{\partial w_3} \right). \end{aligned}$$

So, at an ISNE:

$$\left. \frac{dW}{dw} \right|_{d=\hat{d}} = 2(T_1 - \frac{1}{2}A_1) \frac{ds_n}{dw} + A_2 + 2(2\varepsilon + \sigma) \left[N' \frac{ds_n}{dw} - g'(g_3) \frac{dg_3}{dw_3} \right] - 2v'(c_3) \left(1 - \frac{\partial g_3}{\partial w_3} \right).$$

From the first order condition (14), where $-v'(c_3) + \sigma g'(g_3) = 0$, this can be rewritten:

$$\left. \frac{dW}{dw} \right|_{d=\hat{d}} = [T_1 + (3\varepsilon + 2\sigma) N'] \frac{ds_n}{dw} + A_2 - 4\varepsilon g'(g_3) \frac{dg_3}{dw_3} - 2v'(c_3). \quad (19)$$

Equipped with this expression, it is easy to deduce the condition given in Proposition 8.

C Effect on biodiversity of an income transfers in the partially supermodular north-south model

The idea of the proof is to notice the equivalence between the Nash equilibrium of the partially supermodular north-south model on the one hand, and the Nash equilibrium of a fictitious supermodular game on the other hand. Since in the later an increase of the income pushes upwards the equilibrium (by the properties of supermodular games), so does the outcome in the partially supermodular north-south model.

On a non cooperative basis, each country takes as given rival decisions and uses its own decisions to maximize its utility:

- for $h = 1, \dots, p$:

$$\max_{s_{ni} \in [0, I^h], x_h \in [0, 1]} U^h(y_h, G(s_{n1} + \dots + s_{np}, g_{p+1} + \dots + g_{p+q}))$$

subject to $y_i = T(s_n, R_T^i) + A(I^h - s_{ni}, R_A^i)$. The necessary first order conditions, accounting for the possibility of corner decisions, are:

$$T_1^h(s_n, R_T^i) - A_1^h(I^h - s_{ni}, R_A^i) + \varepsilon N'(s_n) \begin{matrix} \leq \\ \geq \end{matrix} 0 \Leftrightarrow s_{nh} \begin{cases} = 0 \\ \in]0, I^h[\\ = I^h \end{cases} \quad (20)$$

$$T_2^h(s_n, R_T^i) - A_2^h(I^h - s_{ni}, R_A^i) \begin{matrix} \leq \\ \geq \end{matrix} 0 \Leftrightarrow x_h \begin{cases} = 0 \\ \in]0, 1[\\ = 1 \end{cases} \quad (21)$$

- and for $h = p + 1, \dots, p + q$:

$$\max_{g_h \in [0, w_h]} U^h(w_h - g_h, G(s_{n1} + \dots + s_{np}, g_{p+1} + \dots + g_{p+q}))$$

Again the first order condition is:

$$-v'(w_h - g_h) + \sigma^h g'(g_{p+1} + \dots + g_{p+q}) \leq 0 \Leftrightarrow g_h \begin{cases} = 0 \\ \in]0, w_h[\\ = w_h \end{cases}$$

Interestingly enough, the set of necessary conditions for the south, under our assumptions, does not depend on the decisions variables of the north, and conversely, the set of necessary conditions for the north does not depend at all on the decisions undertaken in the south. This property turns out to be crucial for the simplicity of the proof.

The trick is to observe that necessary conditions (20) and (21) are also necessary conditions for the fictitious p -player game with payoff functions

$$\pi^i(s_{n1}, \dots, s_{np}, R_T^i) = T^h(s_n, R_T^i) + A^h(I^h - s_{ni}, w - R_T^i) + \varepsilon N(s_n).$$

From Assumptions A7 and A8:

$$\begin{aligned} \frac{\partial^2}{\partial s_{n_h} \partial s_{n_k}} \pi^h &= T_{11}^h(s_n, R_T^h) + \varepsilon N'(s_n) = 0, \\ \frac{\partial^2}{\partial s_{n_h} \partial R_T^h} \pi^h &= T_{12}^h(s_n, R_T^h) + A_{12}^h(I^h - s_{nh}, w - R_T^h) > 0, \\ \frac{\partial^2}{\partial s_{n_h} \partial x_k} \pi^h &= 0, \quad k \neq h, \\ \frac{\partial^2}{\partial s_{n_h} \partial w^h} \pi^h &= -A_{12}^h(I^h - s_{nh}, w - R_T^h) > 0, \\ \frac{\partial^2}{\partial R_T^h \partial w^h} \pi^i &= -A_{22}^h(I^h - s_{ni}, w - R_T^h) > 0. \end{aligned}$$

This means the fictitious game is supermodular. From the properties of such games, the Nash equilibrium decision variables of the fictitious supermodular model are non decreasing functions of the parameter w ; hence, in the partially supermodular north-south model, the amounts of land left for nature by southern countries are non decreasing functions of the income increments.

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