On trade, land-use, and biodiversity

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Abstract
We combine a Ricardian trade model with a species-area curve to derive the effects of trade on biodiversity conservation. We find that specialization in production tends to drive specialization in ecosystems and their associated biodiversity. Consequently, when trading partners contain similar species in autarky, trade has little effect on global biodiversity, though it may cause declines in local biodiversity. On the other hand, with high endemism, specialization can cause significant declines in both local and global biodiversity. If preferences for biodiversity conservation are sufficiently high, overall utility can decline with a move toward free trade. In many cases, the inadvertent bundling of exotic species with traded products exacerbates this effect.

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1 Introduction

Human actions have been linked to a rapid increase in the rate of species extinctions and loss of biodiversity (e.g., Wilson 1988, Levin 1999). Though it is difficult to establish extinction rates with much precision, most estimates find an increase of several orders of magnitude in the current rate of extinction above the historical rate (NRC 1995, Pimm et al. 1995). Human activities threaten biodiversity in a number of ways including habitat loss, the introduction of exotic species, changes in climate and biogeochemical cycles, pollution, and over-harvesting. Of these, habitat loss and the introduction of exotic species are blamed for the causing the vast majority of current biodiversity loss (Wilson 1992, Wilcove et al. 1998).

Patterns of trade affect both habitat loss and the introduction of exotic species. Habitat loss is driven by the conversion of land for human use in agriculture (crops and grazing), forestry and expansion of urban areas. Conversion of natural habitat into agricultural fields, managed forests or other human dominated land use will occur where it is profitable to do so. Profitability of activities is affected by prices which are, in turn, affected by trade. Trade can impact biodiversity by changing the magnitude and geographical location of production and land use, thereby determining which lands are converted and which are maintained as natural habitat. Trade has a direct impact on the rate of introduction of exotic species. Seeds and organisms hitchhike in shipments of traded goods. Larger trade volume increases the probability of introduction of intruders. A fraction of these intruders will find suitable environments
and become successful invaders, often driving out native biodiversity.

In this paper we analyze the effects of trade on land use and the introduction of exotic species and trace the likely effects of these on biodiversity conservation. In section 2 we present a simple two-good two-country Ricardian trade model. The two goods in the model, grain and timber, are each produced by a fixed ratio of labor and land. Only certain lands (habitat types) are capable of producing each good. Land not converted for production remains as natural habitat capable of supporting species. How many species remain is determined by a species-area curve relationship (MacArthur and Wilson 1967). In section 3, we compare equilibrium production, consumption, and land use in autarky versus free trade. We show that the increased specialization associated with trade can have important consequences for patterns of habitat conversion. Specialization in production, because it requires heavy use of certain habitat causes a decline in species conserved within a country. Depending upon the degree of overlap of species between the two countries, global biodiversity can either increase or decrease with specialization. With a high degree of endemism (i.e., low overlap of species across countries), trade that results in increased specialization will cause a decline in global species conserved. Though trade will necessarily increase the production of goods and the utility of consumption, it may lead to a decline in overall utility. This result occurs when trade leads to large reductions in species conservation, either locally or globally, and such losses factor heavily into the utility function. Section 4 considers regulating trade to maximize utility where a regulator takes account of species concerns. We show that taking species conservation concerns into account can reduce specialization and may reduce the overall level of production.
in order to leave more habitat intact. In section 5, we address the loss of biodiversity from the unintentional introduction of exotic species. Although local species counts may increase or decline with the introduction of exotic species, global biodiversity is unambiguously decreased when invasive species cause extinction of native endemic species. The negative consequences of specialization-driven trade are only exacerbated when exotic species are unintentionally bundled with traded commodities. Section 6 contains concluding comments.

2 A Simple Trade-Conservation Model

We combine a simple Ricardian model of trade with basic ecological principles. The economic and ecological model is as follows.

2.1 Production

We assume the simplest possible production structure. Each country \( i \), \( i = 1, 2 \), has a fixed endowment of labor that may be employed in harvesting either grain, \( X \), or timber, \( Y \). Denote by \( \bar{L}_i \) the country’s total endowment of labor, which we assume also equals the population of country \( i \), and by \( L_{Fi} \) the amount of labor allocated to harvesting timber and by \( L_{Gi} \) the amount of labor allocated to harvesting grain.

We assume that in order for each worker to produce grain or timber she requires exclusive access to one unit of converted land. Producing timber requires one unit of converted forest land. Producing grain requires one unit of converted grassland. Denote each country’s fixed endowment of forest and grassland respectively by \( T_{Fi} \) and \( T_{Gi} \). Let the output of a worker in country \( i \) be \( a_i \) units of \( X \) if she works on
forest land and $b_i$ units of $Y$ if she works on grassland.

### 2.2 Species Assemblages

We assume that once land is converted to a productive use, it is incapable of supporting native biological diversity. While certainly an oversimplification, this assumption helps maintain clarity and is not entirely unrealistic. For example, the tall grass prairies of the midwestern U.S. once supported large assemblages of native species; statewide declines in tallgrass prairie from historical area coverage range from an 82.6% decline (Kansas) to a 99.9% decline (Illinois, Indiana, Iowa, North Dakota, Wisconsin) (Samson et al. 1998). Subsequent conversion to crop monocultures supports very low biological diversity; as of 2001, 740 plant species had been listed as either threatened or endangered under the U.S. Endangered Species Act, though only 26 plant species are known to have gone extinct (USFWS, 2002). In our model, land not in production remains as natural habitat capable of supporting species. Define natural forest and grassland habitat in country $i$ as $T_{NF_i} = T_{Fi} - L_{Fi}$ and $T_{NG_i} = T_{Gi} - L_{Gi}$, respectively.

A widely utilized first-principle in ecological theory is the relationship between the size of habitat and the number of species it can support (MacArthur and Wilson 1967). The “species area curve” describes the number of species surviving in each habitat type. Denote by $S_{Fi}$ the number of forest land species in country $i$ and by $S_{Gi}$ the number of grassland species; then

$$S_{Fi} = \phi_i(T_{NF_i})$$

$$S_{Gi} = \gamma_i(T_{NG_i})$$
where $\phi_i(\cdot)$ and $\gamma_i(\cdot)$ are the species-area functions in country $i$ for forest and grassland ecosystems, respectively. Species-area curves have declining marginal returns to area so $\phi_i' > 0$, $\gamma_i' > 0$ and $\phi_i'' < 0$, $\gamma_i'' < 0$. Although biological diversity can be measured in many ways (see for example, Solow and Polasky 1994, Weitzman 1992, and Faith 1992), we will focus attention only on species richness. The number of species conserved in country $i$ is therefore $S_i = S_{Fi} + S_{Gi}$. Define $S$ to be the number of species conserved globally.

2.3 Citizen-consumers

We round out the model by assuming that consumers in each country have identical Cobb Douglas preferences over timber and grain and additively separable utility over consumption goods and species conservation: $U(x_\alpha y^{1-\alpha}, S_i, S)$ where $\alpha \in (0,1)$ and $x_i$ and $y_i$ are per capita consumption levels. Optimization by atomistic consumers yields relative demand for timber $\frac{x_d}{y_d} = \frac{\alpha}{1-\alpha}P$ where $P$ is the local relative price of timber.

Note that the utility function admits both local species conserved and global species conserved to be valued. Local species conservation may be valued because people place value on observing wildlife (e.g., birdwatching) or because species contribute to the production of valued ecosystem services. Increasing diversity has been linked to increased ecosystem productivity, nutrient retention, stability and other ecosystem functions that may produce valued ecosystem services (Tilman and Downing 1994, Naeem et al. 1994, Tilman et al. 1996, 1997, 2001, Naeem and Li 1997, Hector et al. 1999, Loreau et al. 2001). Global species conservation may be of value.
because people may wish to preserve the evolutionary potential of species, to preserve the genetic material of the species for bioprospecting purposes (Simpson et al. 1996), or because people place existence value on species that is unrelated to any present or future potential use value of the species. Of course, people may also care about other attributes of biodiversity that are not closely linked to either local or global species richness. For example, people may place great value on specific species (e.g., charismatic megafauna) and little value on other species (e.g., charismatically challenged invertebrates with no known economic use). We return to the issue of alternative values of biodiversity briefly in the final section of the paper.

3 Results

In this section we highlight the relevant results from trade theory and to derive outcomes for both species assemblages and consumer utility in conditions of autarky and free trade. Our objective is to derive the effect of trade on biodiversity and overall utility.

3.1 Autarkic Equilibrium

Denote autarkic values by superscript 0. Using known results for the Ricardian model with Cobb-Douglas preferences, in autarky equilibrium requires \( P^0_i = \frac{b_i}{a_i} \) and \( L^0_{Fi} = \alpha \bar{L}_i \) and so \( X^0_i = a_i \alpha \bar{L}_i \) and \( Y^0_i = b_i [1 - \alpha] \bar{L}_i \). This implies that the number of forest species present in country \( i \) will be \( S^0_{Fi} = \phi_i (T_{Fi} - \alpha \bar{L}_i) \) and the number of grassland species present will be \( S^0_{Gi} = \gamma_i (T_{Gi} - [1 - \alpha] \bar{L}_i) \). And finally, these autarkic values imply that the utility of any one of country \( i \)'s \( \bar{L}_i \) citizens is \( U^0_i = \)
$$U(u_i^0, \phi_i(T_{F_i} - \alpha \bar{L}_i) + \gamma_i(T_{G_i} - [1 - \alpha] \bar{L}_i), S)$$ where $u_i^0 = \alpha^a[1 - \alpha]^{1-a}a_i^aq_i^{1-a}$ is the (sub-) utility that a citizen of country $i$ obtains from consumption of grain and timber in autarky.

### 3.2 Free Trade

We now consider the equilibrium allocations of labor across industries when countries are open to free trade (denoted by $^*$). We assume, without loss of generality, that country 1 has a comparative advantage in production of timber while country 2 has comparative advantage in the production of grain: $\frac{b_2}{a_2} > \frac{b_1}{a_1}$. Consider the case in which each country is specialized in the free trade equilibrium.\(^1\) When each country is specialized then country 1 allocates all of its labor to extraction of timber while all workers in country 2 are employed in the production of grain: $L_{F_1} = \bar{L}_1$ and $L_{G_2} = \bar{L}_2$.

Then the number of species in each country will be

$$S_{F_1}^* = \phi_1(T_{F_1} - \bar{L}_1)$$
$$S_{G_1}^* = \gamma_1(T_{G_1})$$
$$S_{F_2}^* = \phi_2(T_{F_2})$$
$$S_{G_2}^* = \gamma_2(T_{G_2} - \bar{L}_2)$$

and so the total number of species in each country is

$$S_1^* = \phi_1(T_{F_1} - \bar{L}_1) + \gamma_1(T_{G_1})$$
$$S_2^* = \phi_2(T_{F_2}) + \gamma_2(T_{G_2} - \bar{L}_2).$$

This gives overall utility of

$$U_1^* = U(u_1^*, \phi_1(T_{F_1} - \bar{L}_1) + \gamma_1(T_{G_1}), S)$$

\(^1\) This result will occur if $\frac{a_2}{a_1} \leq \frac{[1-\alpha]L_1}{\alpha L_2} \leq \frac{b_2}{b_1}$, $\bar{L}_1 \leq T_{F_1}$ and $\bar{L}_2 \leq T_{G_2}$. 

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in country 1 and
\[ U^*_2 = U(u^*_2, \phi_2(T_{F2}) + \gamma_2(T_{G2} - \bar{L}_2), S) \]
in country 2 where \( u^*_1 = \alpha a^1 b^1 L_1^{1-a} L_2^{a-1} \) and \( u^*_2 = [1 - \alpha] a^2 b^2 L_1^{1-a} L_2^{a-1} \).\(^2\)

### 3.3 Does trade with unregulated production make citizens better off?

We now ask whether trade with unregulated production makes consumers better off.

On one hand, it is well known that opening up to trade unambiguously increases (sub)-utility from consumption of private goods. On the other hand, if opening up to trade causes biodiversity decline, consumers may, in the end, have been better off in autarky. We trace out the effects on local biodiversity, global biodiversity, and overall utility, in turn.

#### 3.3.1 “Local” biodiversity

Whether the number of native species surviving in country 1 is higher or lower in the free trade equilibrium depends on whether

\[ S_1^0 = \phi_1(T_{Fi} - \alpha \bar{L}_i) + \gamma_1(T_{Gi} - [1 - \alpha] \bar{L}_i) \geq \phi_1(T_{F1} - \bar{L}_1) + \gamma_1(T_{G1}) = S_1^* . \]

Because country 1 specializes in timber production, fewer forest species but a greater number of grassland species are present in the trading equilibrium. Whether the gain in grassland species is sufficient to offset the loss in forest species depends on parameters of the model. Take, for example the simplest case in which labor and land are equal across ecosystems and countries \((\bar{L}_i = \bar{L} \text{ and } T_{ji} = T \text{ for } j \in \{F, G\}, i \in \{1, 2\})\), but that the species area relationships differ between countries and ecosys-

\(^2\) These values follow from the free trade equilibrium price \( P^* = \frac{\alpha b^2 \bar{L}_2}{(1 - \alpha) a^1 \bar{L}_1} \).
tems according to a multiplicative scaling factor: $\phi_i(\cdot) = c_i \phi(\cdot)$ and $\gamma_i(\cdot) = d_i \phi(\cdot)$ for $i = \{1, 2\}$. Whether trade tends to increase or decrease biodiversity depends critically on how productive their ecosystems are in producing species. If countries have symmetric species area relationships, trade unambiguously reduces local biodiversity. On the other hand if the species area relationships across countries are sufficiently asymmetric, trade may increase local biodiversity. These results are summarized in the following proposition:

**Proposition 1** When countries are symmetric in their endowments of land and labor, but their species area relationships differ up to a scaling parameter, we obtain the following results:

- For any $c_1$ there exists a unique $\tilde{d}_1(c_1)$ satisfying $c_1 < \tilde{d}_1(c_1) < \infty$ such that if $d_1 \begin{cases} < \\ > \end{cases} \tilde{d}_1$, local biodiversity is $\begin{cases} \text{decreased} \\ \text{increased} \end{cases}$ with free trade. And,

- For any $c_2$ there exists a unique $\tilde{d}_2(c_2)$ satisfying $0 < \tilde{d}_2(c_2) < c_2$ such that if $d_2 \begin{cases} < \\ > \end{cases} \tilde{d}_2$, local biodiversity is $\begin{cases} \text{increased} \\ \text{decreased} \end{cases}$ with free trade.

**Proof.** We prove the result for country 1. A similar proof exists for country 2. The difference in local biodiversity under autarky and free trade is:

$$S^0_1 - S^*_1 = c_1 \phi(T - \alpha \bar{L}) + d_1 \phi(T - (1 - \alpha) \bar{L}) - (c_1 \phi(T - \bar{L}) + d_1 \phi(T)) \quad (3)$$

First we show how the difference in local biodiversity in autarky and local biodiversity under free trade changes with $d_1$:

$$\frac{d(S^0_1 - S^*_1)}{d(d_1)} = \phi(T - (1 - \alpha) \bar{L}) - \phi(T) < 0. \quad (4)$$

This expression is negative because $\phi' > 0$. Therefore, for any $c_1$, there exists at most one $\tilde{d}_1(c_1)$ such that $S^0_1 = S^*_1$, and by the sign of equation (4), if $d_1 \begin{cases} > \\ < \end{cases} \tilde{d}_1(c_1)$, $S^0_1 \begin{cases} < \\ > \end{cases} S^*_1$. 

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We now show that $\tilde{d}_1(c_1)$ lies strictly between $c_1$ and $\infty$. Solving (3) explicitly for the $d$ for which $S_1^0 = S_1^*$ (i.e. for $\tilde{d}_1(c_1)$), we obtain:

$$\tilde{d}_1(c_1) = c_1 \left[ \frac{\phi(T - \bar{L} + (1 - \alpha)\bar{L}) - \phi(T - \bar{L})}{\phi(T) - \phi(T - (1 - \alpha)\bar{L})} \right].$$

(5)

The arguments of $\phi$ in (5) have been rearranged to show that the difference in the arguments of $\phi$ in both the numerator and denominator is $(1 - \alpha)L$. Therefore, since $\phi$ is both concave and increasing, the bracketed term in (5) is greater than 1 and $\tilde{d}_1(c_1) > c_1$. Furthermore, the numerator is always finite and the denominator is always positive, so $\tilde{d}_1(c_1) < \infty$. □

The assumption that species area curves are identical up to a scaling parameter is widely accepted in ecology. The usual form of the species-area curve is that species equals $wL^z$, where $w$ is ecosystem-specific, but $z$ is constant across ecosystems (often, $z = 0.25$ is used).

Proposition 1 shows that unless the habitat type that is increasing in area is sufficiently more productive ecologically than the ecosystem that is reduced in area, then free trade will lower local biodiversity. The intuition for this result is as follows: Trade that causes specialization in production also causes specialization in habitats. Owing to the concavity of the species area relationship, the decline in habitat to produce the good in which the country specializes tends to cause a steep decline in biodiversity, while the increase in habitat toward complete restoration moves along a flatter portion of the species area curve and consequently tends to cause a small increase in biodiversity. With asymmetric species area relationships, specialization also causes a decrease in biodiversity unless the restored habitat is significantly more productive ecologically. The more concave is the species area relationship, the stronger is this effect.

We further note that intuitively, one may expect a positive relationship between $a_i$ (productivity of forest land for timber products) and $c_i$ (productivity of forest land for producing species) and similarly between $b_i$ and $d_i$. Given that country 1 specializes in
forest production, this typically, but not always, implies \( c_1 < d_1 \) and \( c_2 > d_2 \), in which case, moving to free trade unambiguously reduces local biodiversity in both countries.

### 3.3.2 “Global” biodiversity

The effect of trade on global biodiversity depends on the degree to which species in each country are endemic. In this section we explore two extreme cases: (1) all species in each country are endemic (no species overlap) and (2) all species are represented in both countries (complete species overlap). More generally, we can think of species in each country providing services that enter a consumer’s utility function. In that case, the question is whether those services are uniquely provided by species in each country. For example, even though species of sedges occur throughout the world, they are primarily valued for their capacity to filter water in wetland ecosystems, which confers primarily a local benefit. Therefore, although the sedge species itself may not be endemic, the services it provides has primarily a local benefit, and utility should be measured accordingly. On the other hand, many cases exist in which one replica of the species (or population) is sufficient to satiate utility over that good. For example, if people care only that the worldwide chimpanzee population is viable, then a viable population in the Congo is redundant to a population in Cameroon (ignoring the possibility that redundant populations have value as risk mitigation).

Although the degree of endemism varies throughout the world, most countries share a significant proportion of their biodiversity with other countries. Of the 21 most widely recognized “biodiversity hot spots” around the world, the percent of endemic species varies from 9% (Brazil’s Cerrado has 1268 bird, mammal, reptile, and amphibian species, only 117 of which are endemic) to 78% (Madagascar has 987 vertebrate species, 771 of which are endemic) (author’s calculations based on Myers et al. 2000). To the extent that trade is
driven by differences in endowments or technologies across countries, we may expect little overlap between species in countries 1 and 2. On the other hand, the above arguments suggest that the services provided by those species may be similar in the two countries, even if the species themselves are unique. In determining the effect of trade on worldwide biodiversity, we consider both extremes.

When all species are endemic, worldwide biodiversity \( S \) is simply \( S^0_1 + S^0_2 \) in autarky and \( S^*_1 + S^*_2 \) under free trade. We can use proposition 1 to derive the conditions under which free trade decreases local biodiversity in both countries, which in this case means that global biodiversity declines. Under many reasonable conditions, free trade reduces global biodiversity when there is little or no overlap in species between trading countries.

But what is the effect of free trade on global biodiversity when few species are endemic? The answer sharply contradicts the result when there exists high endemism. With complete species overlap, the effects of free trade are as follows. The change in global forest and grassland biodiversity with free trade are given by:

\[
S_F = \max\{\phi_1(T_{F1} - \alpha L_1), \phi_2(T_{F2} - \alpha L_2)\} - \max\{\phi_1(T_{F1} - \bar{L}_1), \phi_2(T_{F2})\} \quad (6)
\]

\[
S_G = \max\{\gamma_1(T_{G1} - (1 - \alpha)\bar{L}_1), \gamma_2(T_{G2} - (1 - \alpha)\bar{L}_2)\} - \max\{\gamma_1(T_{G1}), \gamma_2(T_{G2} - \bar{L}_2)\} \quad (7)
\]

Under the assumptions of proposition 1 and with symmetric ecosystems across countries, worldwide biodiversity is unambiguously increased under free trade. Since countries are symmetric, specialization causes local species declines in one sector, but local species increases in the other. Since each country specializes in a different good, and under the assumption of no endemism, worldwide biodiversity is greater (but more specialized). In this case, we would expect to see high global biodiversity, but species existing in only one country, where they previously occurred in multiple countries.

This result raises a question of the timing of trade policies. Moving from pristine condi-
tions to autarky causes local extinctions (extirpation). If trade is subsequently introduced, extirpated species may not be able to recolonize the local ecosystem, in which case, global biodiversity would be unchanged when moving from autarky to free trade.

### 3.3.3 When are citizens better off?

To determine the overall effect on citizen’s utility, we must more explicitly define the utility function. For simplicity, we assume that species conservation enters the utility function as a simple separable and linear function, as follows:

$$U_i = x^\alpha y^{1-\alpha}_{ai} + \mu S_i + \theta S_v_{vi}$$  \hspace{1cm} (8)

In this section, we explore the difference in $U_i$ under autarky and free trade, assuming that countries are symmetric in their endowment of labor and land and each country has symmetric ecosystems ($c_i = d_i = 1$).

As we discussed in section 3.3, the difference in sub-utility from goods consumption is unambiguously higher under free trade. The corresponding difference in utility from species existence depends on whether species are all endemic (equation (9)) or are shared between both countries (equation (10)), as summarized below:

$$v_1^0 - v_1^* = (\mu + 2\theta)(\phi(T - \alpha \bar{L}) + \phi(T - (1 - \alpha)\bar{L}) - (\phi(T - \bar{L}) + \phi(T)))$$  \hspace{1cm} (9)

$$v_1^0 - v_1^* = (\mu + \theta)(\phi(T - \alpha \bar{L}) + \phi(T - (1 - \alpha)\bar{L})) - (\mu(\phi(T - \bar{L}) + \phi(T)) + 2\theta(T))$$  \hspace{1cm} (10)

Whether citizens obtain higher utility under autarky or free trade depends on how heavily they weight consumption of timber and grain relative to species conservation. It also depends on the extent to which consumers value local versus global biodiversity. Suppose, for example that only global biodiversity is valued ($\mu = 0, \theta > 0$), and further that species are shared between the two countries. Then consumers are unambiguously better off under
free trade than under autarky (globally, more species exist under free trade in this case). At the other extreme, consider the case in which only local biodiversity matters ($\mu > 0$, $\theta = 0$). Then consumers receive lower utility from species conservation under free trade, but they receive higher utility from private goods consumption. Whether they ultimately receive higher, or lower, overall utility under autarky or free trade depends on the relative strength of their preferences for species conservation, versus consumption of private goods.

We have shown that even though utility from consumption must increase with free trade, overall utility may decline. Specialization leads to a decline in the number of species in each country and may decrease species globally, depending on the degree of endemism. The loss of utility from species decline may more than offset the increase in utility from consumption gains meaning that free trade can lead to lower welfare.

4 The Socially Optimal Pattern of Production

In both autarky and free trade, the welfare effects of production on species conservation are ignored. Because of this both autarky and free trade equilibria are inefficient. Here we analyze the socially optimal pattern of production and land use and compare this outcome to that under autarky and free trade.

A social planner wishing to maximize utility of individuals across the two countries (and
assuming equal weights attached to each individual) faces the following problem:

\[
\begin{align*}
\max & \quad (\bar{L}_1 + \bar{L}_2)X^\alpha Y^{1-\alpha} + \bar{L}_1\mu S_1 + \bar{L}_2\mu S_2 + (\bar{L}_1 + \bar{L}_2)\theta S \\
\text{s.t.} & \quad X = X_1 + X_2, \quad Y = Y_1 + Y_2 \\
& \quad X_1 = a_1L_{G1}, \quad X_2 = a_2L_{G2}, \quad Y_1 = b_1L_{F1}, \quad Y_2 = b_2L_{F2} \\
& \quad L_{Gi} + L_{Fi} \leq \bar{L}_i \quad i = 1, 2 \\
& \quad S = S_1 + S_2 \\
& \quad S_i = S_i^G + S_i^F \quad i = 1, 2 \\
& \quad S_i^G = \gamma_i(T_{Gi} - L_{Gi}) \quad i = 1, 2 \\
& \quad S_i^F = \phi_i(T_{Fi} - L_{Fi}) \quad i = 1, 2 \\
& \quad 0 \leq L_{Gi} \leq T_{Gi}, \quad 0 \leq L_{Fi} \leq T_{Fi} \quad i = 1, 2
\end{align*}
\]  

Let \( \lambda_i \geq 0 \) represent the Lagrange multiplier on the constraints that labor applied not exceed population: \( L_{Gi} + L_{Fi} \leq \bar{L}_i \). Let \( \eta_i \geq 0 \) represent the multiplier on the non-negativity constraint on \( L_{Gi} \) and \( \psi_i \geq 0 \) represent the multiplier on the non-negativity constraint on \( L_{Fi} \). Define aggregate consumption as \( c = X^\alpha Y^{1-\alpha} \). Then, the first order conditions for an optimal solution are as follows:

\[
\begin{align*}
\frac{\alpha a_i c}{X} & - \left[ \frac{\bar{L}_i}{L_1 + L_2} \mu + \theta \right] \gamma_i(T_{Gi} - L_{Gi}) - \lambda_i + \eta_i = 0 \quad i = 1, 2 \\
\frac{(1 - \alpha)b_i c}{Y} & - \left[ \frac{\bar{L}_i}{L_1 + L_2} \mu + \theta \right] \phi_i(T_{Fi} - L_{Fi}) - \lambda_i + \psi_i = 0 \quad i = 1, 2
\end{align*}
\]  

Note that ignoring the effect of species on utility is equivalent to setting \( \mu \) and \( \theta \) equal to zero. In this case, terms relating to species conservation drop out and the social planner maximizes the utility of consumption alone. With \( \mu = \theta = 0 \) and with different comparative advantage in the two countries, i.e., \( \frac{a_1}{b_1} \neq \frac{a_2}{b_2} \), equations (12) and (13) necessarily imply specialization (in at least one country) and complete utilization of labor. These results can
be shown as follows. Assuming that no specialization occurs, i.e., that $L_{G_i}$ and $L_{F_i}$ are all strictly positive, which implies that $\eta_i$ and $\psi_i$ are zero, $i = 1, 2$, generates a contradiction when comparing the ratio of the two first order conditions for production in each country. Also, because the first terms in equations (12) and (13) is strictly positive, we must have $\lambda_i$ strictly positive, which implies the labor constraint is binding.

Importantly, however, neither the specialization nor full use of labor results hold when species conservation effects on utility are included. First note that if $\mu_i$ or $\theta_i$ is large, the second term in equations (12) and (13) is large and negative. Therefore, $\lambda_i$ need not be positive but can be zero, which implies that the labor constraint need not bind. The intuition for this result is straightforward. When the disutility from species loss is large, natural habitat is of greater value than is the utility from increased consumption that can be gained by using labor and converting habitat for production of grain or timber. Next, note that it is possible for it to be optimal for each country to produce some amount of both goods. There is an opportunity cost of production of each good in each country, which is caused by the loss of species from habitat loss. Therefore, it may be optimal to use a little of each type of habitat, moving along the relatively flat part of the species-area curve relationship, but not to use a great deal of any type of habitat as would be required by specialization, thereby avoiding moving down the steep part of the species area curve.

Implementing an optimal solution requires knowledge of the terms in equations (12) and (13). In other words, it requires knowledge of the marginal utility of conserving a species and the species-area curve. If these relationships are known (or can be roughly approximated) an optimal solution can be implemented in a decentralized equilibrium by imposing a tax/subsidy program on land use or employment. The optimal solution may well include paying some workers to remain idle thereby retaining more natural habitat.
5 Effects of Invasive Species

Thus far we have focused attention on the effects of trade on land use and the consequent change in biodiversity. We now turn attention to invasive species which have been implicated in the decline of 400 of the 958 species listed as threatened or endangered under the Endangered Species Act (Pimentel et al. 2000). International commodity trade is the primary cause of unintentional exotic species invasions. In this section, we focus on the exotic species that are unintended consequences of trade, and are transported as hitchhikers in packing materials or on commodities themselves. For simplicity, we further assume that species inhabiting the forest ecosystem are only imported if timber products are imported, similarly for grassland species.

There is an enormous literature addressing the requirements for an exotic species to invade and cause damage in a foreign country. For example, the “tens” rule (coined by Williamson and Fitter (1996)) is a rule of thumb positing that about 10% of introduced species become established in a host environment and that about 10% of those become pests. Brown (1989) notes that similarity between physical environments in the home and host countries increases the probability that an introduced species will become established, and that invasion is aided when the host environment has been disturbed, in particular by human activity.

5.1 Effects of Invasives on Local Species Counts

The unintentional bundling of exotic species with traded products may increase, or decrease the number of extant species in any one country. Exotic species that become established but do not displace native species—for example exotics that occupy an ecological niche previously unoccupied in that country—will increase the number of extant species in a
region, raising $S_i$ relative to the case with no invasives. For example, 1023 of the 5867 known plant species in the California are alien species (Hickman 1996). More likely, however, is the case where established exotics do displace native species. If they displace native species at a higher than one-for-one ratio then local biodiversity will suffer from trade to an even greater extent than that suggested in section 3.

However there is also the question of whether biological “hitchhikers” will become established in the first place. Revisiting the analysis by Brown (1989) and others, rates of establishment depend on the characteristics species and the host and home countries. When the two countries have similar physical environments (for example a “dry” country trading with another “dry” country), trade volume and invasiveness of species may have offsetting effects. On one hand, similarity in physical environments tends to make exotic hitchhikers more likely to establish free populations in the host country once introduced. But on the other hand, similarity in physical environments suggest that the basis for trade in our model—international differences in the harvesting capabilities of labor—may be absent, so there may be little incentive to trade to begin with. We should point out though that there are bases for trade between nations with similar geographic characteristics other than those implicit in a Ricardian model of trade. For example differences in relative endowments of productive factors, as in the factor proportions model of trade, and imperfectly competitive output markets, both serve as bases for trade, bases that are likely to persist between countries of similar climate and geography, raising again the specter of biological invasions amongst open economies of similar geographic types.

If we continue to assume that exotic species displace native species, but that trading partners have different physical environments (a “wet” country trading with a “dry” country), we obtain a similar result, for the opposite reason. That is, while the incentive to trade
is substantial (owing to differences in physical conditions driving comparative advantage), invasives are less likely to take hold once they arrive. Again, these effects are, in part, offsetting.

The upshot is that local species counts can either be increased (if exotic species do not substantially impact native species), or decreased (if exotic species negatively impact native species). In cases where exotic species require disturbance in order to take hold, they may not have an appreciable effect on local biodiversity since specialization leaves one ecosystem in nearly pristine condition while heavily exploiting the other. When exotics instead have the ability to invade pristine ecosystems, the biodiversity loss associated with trade will be exacerbated by unintentional exotic species introductions.

5.2 Effects of Invasives on Global Biodiversity and Utility

The preceding section focused on the effects of invasive species on local species counts. Although we argue that cases exist in which local species counts may even increase with exotic introductions, we must account for the effect on global biodiversity in order to measure the overall effects on utility. In the case where all species are endemic to both countries, trade unambiguously decreases global biodiversity. The possibility of exotic species introductions can only exacerbate this problem because whenever an exotic species displace a native species, $S$ necessarily falls. This highlights the error inherent in assuming a constant relationship between global biodiversity—measured here by $S$—and local biodiversity. In particular, as openness generates trade flows which serve as platforms for biological invasions by non-native species, relationships between local and global species counts that may have been appropriate in autarky change as the world’s ecosystems become homogenized.
6 Conclusions and Discussion

In this paper, we developed a simple two-country two-good Ricardian trade model linked with species-area curves to demonstrate the effects of trade on the pattern of production across countries, habitat conversion, species assemblages, consumption and utility. Trade can have adverse consequences for biodiversity for precisely the reason it is attractive: exploiting comparative advantage resulting in specialization. To the extent that ecosystems are aligned with production systems, specialization in production means that conversion of habitat will be focused on certain types of ecosystems. Because of the concavity of species-area relationships, such specialization can lead to severe declines in the number of species conserved. When there is a high degree of species endemism, or where local biodiversity as opposed to global biodiversity is of greater concern, trade can reduce welfare. On the other hand, when trading partners have large overlap in species and what is of concern is global rather than local biodiversity, trade is unambiguously beneficial. Taking species concerns into account may lead to changes in trade including idling some factors of production to maintain habitat and reducing the extent of specialization, even though both changes reduce the value of production.

We also provide a brief discussion of a secondary channel through which trade influences local and global biodiversity: the facilitation of exotic species introductions. In particular, we note that it is possible that measures of local biodiversity are unchanged or even enhanced by the introduction of exotic species. However, global biodiversity declines when exotics displace native endemic species.

The model we developed in this paper was kept quite simple in order to make clear the basic logic of how trade can affect biodiversity conservation. There are a number of ways in which the model could be enhanced. Land parcels generally are capable of producing
different goods. For example, a forest could be cleared so that crops could be planted. One could specify the capability of each land parcel for producing each particular good rather than assuming it can only produce a single good.

Our model focused on the effect of trade on the location of production across countries, and the importation of exotic species. These effects are surely important but they are not the only effects of trade on biodiversity. Trade can also change demand through an income effect, which may have important environmental consequences. Trade may also influence relative input prices, which can lead to changes in the techniques of production. For example, moving to more intensive agricultural production methods capable of growing more grain per hectare can reduce demand on land and spare natural habitat. Our model assumed fixed factor proportions in production and so cannot analyze this technique effect.

The ecological side of the model could be similarly enhanced. There need not be a one-to-one relationship between habitat and production. The assumption that species can only utilize natural habitat is also too restrictive. Certain species do perfectly fine in managed forests or agricultural fields. Other factors beyond just habitat area, such as habitat quality, fragmentation and connectivity, also matter for species survival probabilities. A more realistic model would involve specifying the survival probability of each species as a function of the pattern of natural and managed habitats.

We have modeled utility as a function of private consumption and local and global species richness. It is equally plausible that alternative measures of biodiversity enter the utility function. For example, individual species or groups of species may be inputs to the production of ecosystem services, which themselves have value. Alternatively, we may be interested in genetic diversity, rather than simply species richness. Including these as arguments of utility would require a different objective function, but would not qualitatively
alter the results of this paper. A third possibility that may have important consequences is that people obtain systematically different utility from different species. Charismatic megafauna, the lions, tigers and bears of the world, often require large tracts of undisturbed habitat and are therefore often the first to be extirpated from ecosystems converted for human use. In that case, even small amounts of conversion can cause large utility declines, a result that tends to favor specialization over diversification of production in each country.

Enriching both the economic and ecological sides of the model could add insights and greater realism to the analysis of the links between trade and biodiversity conservation. Specifically directing policy on the basis of this work will require going beyond the simple model presented here in ways outlined in the prior paragraphs as well as others. These more complex models, however, would still contain the basic insights on how trade can affect biodiversity conservation, either directly through importation of exotic species, or indirectly through the changes in relative returns that affects land use and habitat, that we have emphasized in this paper.

References


