Economic growth and biodiversity: a sectoral model

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Abstract

Many scientists are claiming that the Sixth Mass Extinction of species is underway. On top of the direct negative impacts on human well-being, one reason to worry is that biodiversity provides numerous ecosystem services that are essential to the economy. Therefore, this paper proposes a global macroeconomic growth model that takes into account the dynamics of biodiversity and the ecosystem services it provides. To do this, I bring together the latest advances in biology on the "Species-Area" and "Biodiversity-Ecosystem Functioning" relationships. I also put forward a new method for estimating sectoral production functions, using input-output tables and their environmental extensions. Importantly, preferences are non-homothetic: there is a minimum subsistence food level. My main results focus on optimal land use on a macroeconomic scale. I show that this value is determined by the trade-off between the total marginal costs and marginal benefits of agricultural production. The costs are broken down into the direct costs of land conversion and the social (productive) costs associated with the loss of ecosystem services. Because of the need for water supply (regulated by biodiversity) in the industrial sector and the non-homothetic preferences, the optimal land use significantly decreases with the development stage of an economy. Its optimal level is half as high (18% vs. 39%) in a developed country as in a less developed one.

JEL Codes: O13, O41, O44, Q57

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1 Introduction

Many scientists are claiming that the Sixth Mass Extinction of species is underway. Almost all types of life on Earth are concerned, especially within the plant and animal kingdoms. For animals, both vertebrates (Ceballos et al., 2020) and invertebrates (Cowie et al., 2022) are facing estimated extinction rates that far exceed the criterion of a mass extinction (a loss of around 75% of species in less than 3 million years (Bradshaw et al., 2021)). According to the IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services), a reason to worry is that biodiversity provides numerous so-called ecosystem services that are essential to the economy, from material provision to regulation and maintenance services (Brondizio et al., 2019). Until now, economists have done relatively little to disentangle the potential interactions of this mechanism with Macroeconomics (Salin and Kedwards, 2024). Until now, two types of approach have been adopted in an attempt to model the interactions between nature and the (macro)economy. The first is based on the concept of natural capital, incorporated into growth models (Dasgupta, 2021; Bastien-Olvera and Moore, 2021). The second involves coupling computed general equilibrium (CGE) models or partial equilibrium models with biophysical ecosystem service models (e.g. Johnson et al., 2023). This class of models was used by the World Bank[1] to estimate how certain ecosystem services impact the economy, and leads to quite limited aggregate impacts.

This paper proposes a biodiversity-integrated growth model with non-homothetic preferences to study the interaction between land use, biodiversity, and economic development. The model seeks to synthesize the two branches of modeling described above. It moves away from the notion of natural capital (which is well detailed in Heal, 2020), which seems to be too abstract to result in "reliable" calibrations. On the other hand, contrary to CGE models, I come up with a model that has the flavor of a stylized growth model, which is not simply the collection of local biophysical dynamics but rather a model of the global economy. The idea here is to avoid the black-box phenomenon generated by IAMs with many sectors and ecosystem services, and rather to highlight the key mechanisms.

[1]https://www.worldbank.org/en/topic/environment/publication/the-economic-case-for-nature

The model is inspired by Dasgupta's methodological proposal (Dasgupta, 2021) emphasizing on the embeddedness of the economy in nature. To do so, I take into account the side sides of the interaction between the economy and biodiversity. On the one hand, the change in land use necessary for economic activity is leading to a fall in biodiversity. Indeed, according to the IPBES, natural habitat conversion is the first pressure on biodiversity worldwide. On the other hand, the economic activity relies on some ecosystem services, themselves depending on biodiversity. Thus, I rework the production function of Dasgupta: (i) concrete ecosystem services, namely the supply of biomass and water, are directly included in the production process, and (ii) the economy is divided into three sectors (agriculture "a", industry "i" and services "s") in order to better reflect its interactions with nature. The economic dynamics are simple and mimicking a Ramsey-Cass-Koopmans model.

The calibration of the model relies on three key ingredients: the quantification of (i) the impacts of human activities on biodiversity dynamics, (ii) the relationship between biodiversity and ecosystem services, and (iii) the dependence of production on ecosystem services. The two first ingredients are taken from the literature in biology. In 1980, the economist Jan Tinbergen stated that "a major problem which ecologists are facing is that of measurement at the macro-level" and that "the type of aggregation into macro-figures which is applied in technological and economic research has still to be developed [in ecology]"[2]. More than forty years later, I take advantage of the successive advances in ecology literature, even if the effort in developing macro-ecology is still ongoing. I select two relationships that can reasonably be generalized at a biome scale, which is the closest to the macro scale. First, the "Species-Area" relationship states that there is a concave relationship between the number of species (called species richness) of a natural habitat and its size, and enables to describe the impacts of human activities on biodiversity dynamics through land conversion. Second, I use the "Biodiversity-Ecosystem Functionning" relationship for two ecosystem services, the supply of water and biomass. In order to quantify the dependence of production on ecosystem services, I propose an *ad hoc* estimation method. Assuming the three sectoral production (agriculture, industry and services) are Cobb-Douglas functions of productivity, ecosystem services, capital, labor and land use, I run a "growth accounting" estimation

[2]Economic Growth and the Biosphere, Tinbergen and Kuenen

exercise. I estimate the different elasticities of the Cobb-Douglas functions using the input-output table GLORIA (Lenzen et al.,2022) and its environmental extensions. I show that agriculture is the only sector significantly relying on land use (with a very low elasticity of $\theta_a \approx 0.025$). Moreover, both the agriculture and industry depends on water supply, with quite high elasticities (0.05 and 0.08, respectively). Finally, agriculture also relies on the supply of biomass.

My main results focus on the optimal land use at a macroeconomic scale. I show that this value is determined by the trade-off between the total marginal costs and marginal benefits of agricultural production. Costs are broken down into the direct costs of land conversion and the social (productive) costs associated with the loss of ecosystem services. The non-homothetic preferences for agricultural, industrial and services goods leads to a key result: the optimal land use significantly decreases with the development stage of an economy. Indeed, the higher the level of development, the higher the weight of industrial consumption relative to agricultural consumption: the social planner is willing to decrease its level of land use in the agricultural sector to spare biodiversity and benefit from more of its ecosystem services in the industrial sector.

More generally, this paper relates to the literature on growth and the environment. The environmental problem of climate change has already been widely addressed by macroeconomists since Nordhaus (1991), with the question of the timing of action at the heart of the discussions (Stern,2006; Acemoglu et al., 2012). The problem of limited resources, whether renewable or exhaustible, was tackled even earlier (Smith, 1968; Dasgupta and Heal, 1974). This paper seeks to tackle an environmental problem that has received little attention from growth economists: that of biological diversity and its contribution to production. It seems to me that the delay in the inclusion of the biodiversity issue in macroeconomic models stems from its purely local appearance, whereas the climate immediately appears to be a global problem (in particular because of the perfect dilution of greenhouse gases in the atmosphere). The collapse of biodiversity was actually understood as a global problem much later than climate change, as shown by the fact that the IPBES was created in 2012, 24 years after the Intergovernmental Panel on Climate Change (IPCC) was created in 1988.

By conducting an in-depth literature review, Salin and Kedwards (2024) "show how both theoretical assumptions and structural constraints in those applied neoclassical models impede the analysis of nature-economy interactions from a complex systems perspectives" (Levrel et al., 2023, also draw this conclusion). By building a neoclassical model, the aim of this paper is also to bring out very precisely the salient points of the difficulty of neoclassical models in capturing certain ecological dynamics, nonetheless identifying how these models could be useful for biodiversity economics.

The remainder of the article is organized as follows. Section 2 details the key features of the interplay between economy and biodiversity and proposes some methods to calibrate this interplay. Section 3 builds a *biodiversity*-integrated sectoral growth model. Section 4 highlight the main mechanisms at play for optimal growth. Section 5 concludes.

2 On the interplay between the economy and biodiversity

In this section, I detail three key ingredients for including biodiversity in a macroeconomic model: (i) the quantification of the impacts of human activities on biodiversity dynamics, (ii) the relationship between biodiversity and ecosystem services, and (iii) the dependence of production on ecosystem services. Once combined, these three ingredients make it possible to build a model (Section 3) in which economic dynamics are deeply embedded in biological dynamics.

2.1 The impact of human activities on biodiversity dynamics

In 2019, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) published its global assessment report (Brondizio et al., 2019), in which it pinpoints the five main drivers of change in nature. From the largest global impact to the least, these drivers are: changes in land and sea use, direct exploitation of organisms, climate change, pollution and invasion of alien species. In this paper, I focus on the first pressure, and more specifically land use change. According to the IPBES, agricultural expansion is the main cause of land use change: crop and livestock farming now cover more than a third of the terrestrial land surface.

For a macroeconomic modelling purposes, it would be ideal to have an aggregate or "universal" relationship linking biological diversity and land use change. Does such a relationship exist? Put another way, this question was at the heart of biological research from a very early stage, guided by the search for a relationship between the number of species and the size of a natural habitat. From the end of the 18th century, scientists observed that the number of species increased with area, but it wasn't until 1921 that the first mathematical description (Arrhenius, 1921) was proposed by Olof Arrhenius[3]. Based on the observation of 14 communities of the islands of Stockholm, he derived a

[3]the son of the famous Swedish chemist Svante Arrhenius, first to describe the mechanisms of the atmospheric greenhouse effect

well-fitted empirical relationship called the "Species-Area Relationship" (SAR):

$$S = cA^z \tag{1}$$

where S is the number of species, A the area, c and z constants. z ranges from 0.08 to 0.4 depending on the community observed. The relationship has remained the benchmark to this day. Papers demonstrating its existence in a variety of contexts have proliferated (Preston, 1962; Rosenzweig, 1995). In Section 3, I will use this relationship for the benchmark model.

The S used in the SAR actually describes long-term equilibrium biological diversity. In 1972, Diamond highlighted the phenomenon of relaxation: a change in environmental conditions does not have an immediate influence on the number of species, but modifies its long-term dynamics. As modelled by Lafuite and Loreau (2017) and Augeraud-Véron et al. (2019), the actual number of species B tends to the long term equilibrium biodiversity S estimated by the SAR, according to the formula:

$$\dot{B} = -\epsilon(B - S) \tag{2}$$

where ϵ is the relaxation rate. Some have tried to estimate this parameter in different biological contexts (e.g. Brooks et al., 1999). Lafuite and Loreau (2017) shows that this parameter can play a key role in socio-ecological dynamics. However, in the benchmark case of this paper, I assume that there is an instantaneous adjustment of the species richness to environmental changes such that, at any time t: $B(t) = S(t)$.

Recent work has built much more complex and granular models to determine the impact of land use (or climate change) on different functional groups (Kim et al.,2018; Newbold et al., 2020). However, this type of work does not easily fit into a macroeconomic model, although it is very useful for better understanding the impact of man on biodiversity.

2.2 The Biodiversity-Ecosystem Functioning relationship (BEF)

Economic production is not based on biodiversity itself, but rather on the ecosystem services it provides. The IPBES classifies these services into three main categories: provisioning (water, food, timber, bioenergy...), regulation and maintenance (pollination, climate regulation, soil quality, flood protection...), and cultural services (amenities...). Since the early 1990s (Schulze and Mooney, 1994), the study of the relationship between biodiversity and ecosystem services has become a field of biology on its own, and has continued to make progress ever since, both theoretically and experimentally. The question is whether there is a general equation that links the state of biodiversity to the quantity of ecosystem services provided, whatever the scale of the ecosystem considered. Loreau (1998) has carried out a number of theoretical studies showing that, under certain conditions, there is a positive and concave relationship between the biological diversity of plants and biomass production. Experiments (Tilman et al., 2014) suggest that this concave relationship may hold for many ecosystem services, even when excluding unrealistic communities (Jochum et al., 2020).

Thus, a very stylized relationship between biodiversity (B) and ecosystem services (ES) is:

$$ES = B^{\sigma} \tag{3}$$

Constrained by data availability (in the next section), I use only two ecosystem services in my benchmark model: biomass production and the supply of blue water. van der Plas (2019) shows that most of the studies of the BEF relationships point to a positive and concave impact of biodiversity on biomass production (also shown by O'Connor et al., 2017). However, the meta-analysis does not mention the supply of blue water as an ecosystem service. For this service, I rely on Tilman et al. (2014), who depicts a concave relationship between biodiversity and drought resistance in experimental conditions. I also make the assumption that there is only one functional group ($n = 1$). Introducing several groups requires extending work on group-specific SARs.

2.3 The sensitivity of production to ecosystem services

The Dasgupta's Bounded Global Economy Model (BGEM) proposes to use one single aggregate production function written down as:

$$Y = AS^{\beta}K^{a}H^{b}R^{(1-a-b)} \tag{4}$$

where Y is the output, A the productivity, K the produced capital and H the human capital. S is "as a stock supplying regulating and maintenance services [that should be designated as] biosphere and natural capital interchangeably" and R is "a flow of extracted provisioning service". At no point in its methodological sections (chapters 4* and 13*) does Dasgupta propose a method for calibrating his aggregate production function (Equation 4). It seems to me that using the notion of natural capital weakens the possibility of calibration. Indeed, to my knowledge, there is no database of the stock of primary producers (used as a proxy for natural capital in Dasgupta, 2021) that would allow this exercise to be carried out.

In my model, I prefer to focus on the integration of ecosystem services as such in the production function. I still distinguish provision, on the one hand, and regulation and maintenance services, on the other hand. For the latter, it seems to me that the most natural inclusion is to model them as mitigators of the variance of the production function and not as factors of production as such, as in Augeraud-Véron et al. (2019). As far as I do not use a stochastic model in this paper, I thus decide to only include provision services in the production function. However, as depicted by Dasgupta, "the multiplicative factor S^{β} [regulating and maintenance services], absent from nearly all contemporary models, captures the fact that the human economy is embedded in the biosphere, like a family sheltered in their home." In order to keep the embeddedness of the economy, I conserve the idea that production should have an impact on future ecosystem services, but in my case, only provision services are impacted (conversely to the Dasgupta version). To do so, I incorporate land as a factor of production and build on sections 2.1 and 2.2 to endogenize ecosystem services. The idea is to ground the production function in biological stylized fact : production does not directly hinder biodiversity (as proposed in Dasgupta, 2021) but requires to stimulate some pressures (among them land use change) that in turn endanger species diversity, as described in section 2.1.

As far as economic sectors may actually have very different dependencies on land and provision services, I split my economy into 3 different “macro-sectors”: Agriculture (subscript “a”), Industry (“i”) and Services (“s”). For each of these 3 macro-sectors $j \in \{a, i, s\}$, I calibrate a Cobb-Douglas production function of the following form:

$$Y_j = A_j \times \prod_{l=1}^{m} ES_{jl}^{\gamma_{l,j}} \times K_j^{1-\alpha_j-\theta_j} L_j^{\alpha_j} \times T_j^{\theta_j} \tag{5}$$

where, Y is the output, A the level of productivity, ES the ecosystem services (m of them), K the capital produced, L the labor, and T the land. As long as capital is not given in the input output matrix, I deduce its share by assuming a constant return to scale with labor and land.

2.3.1 An estimation method

The aim of this section is to propose a method for estimating the Equation 5. In recent years, the number of environmental extended multi-regional input-output tables (EEMRIO) has soared: GLORIA, Exiobase, Eora26, OECD... These databases provide an opportunity to calibrate the above-mentioned production functions, as they associate the production factors (especially labor force) of numerous economic sectors with their environmental dependencies (certain ecosystem provision services, land use, water consumption, etc.). As a benchmark, I use the GLORIA input-output table (Lenzen et al.,2022) that encompasses 164 regions in the world and 120 economic sectors (in each region, that is, 19680 sectors in total). I classify these 120 sectors to match my three “macro-sectors”: Agriculture (23 sectors), Industry (76 sectors) and Services (21 sectors). The detailed list is given in Appendix 5.2.

The estimation strategy sums up to one single equation, estimating simultaneously the elasticities of production to labor force, to some provision services and to land:

$$\log(Y_{k,r}) = \sum_{j\in\{a,i,s\}} \alpha_j \log(L_{k,r}) \times 1_{k\in\text{sector}\, j} + \sum_{l=1}^{m} \sum_{j\in\{a,i,s\}} \gamma_{l,j} \log(ES_{l,k,r}) \times 1_{k\in\text{sector}\, j}$$
$$+ \sum_{j\in\{a,i,s\}} \theta_j \log(T_{k,r}) \times 1_{k\in\text{sector}\, j} + \sum_{j\in\{a,i,s\}} \mu_j \times 1_{k\in\text{sector}\, j} + f_r + \epsilon_{k,r} \quad (6)$$

$X_{k,r}$ is the value of variable X for the $k-$th sector of region r. $1_{k\in\text{sector}\, j}$ takes the value 1 if sector k is in the macro-sector j, 0 either. μ_j are macro-sectoral fixed effect and f_r are regional fixed effect to capture the productivity heterogeneity between the different countries.

Building on the satellite accounts of the Release 055 of the GLORIA global environmentally-extended multi-region input-output database, I allocate, to each sector k in each country r, a quantity of ecosystem services for the production of biomass and blue water consumption, by adding the satellite account listed in Table 4, in Appendix. Provision services modulate total factor productivity (TFP).

2.3.2 Results of the estimation

The results of the estimation of Equation 6 are shown in Table 1. Elasticities for Industry and Services are given as differences to the elasticities for Agriculture.

Land. The estimation leads to a very low land elasticity of the agricultural production of 2.4%. In their benchmark model, Ashraf et al. (2008) also use land as a fixed factor in a Cobb-Douglas production function. By arbitrary setting the labor and capital share to 0.6 and 0.3, they choose a land share of 0.1, in order to have constant return to scale. To my knowledge, my calibration is thus the first one to propose a non-arbitrary method to compute the land share in a Cobb-Douglas production function. Lanz et al. (2018) are using a constant elasticity of substitution (CES) function with a capital-labor composite and land. Their calibration of this function relies on the literature on fixed factors. Land elasticity of industrial production seems to be close to 0 ($= 0.024 - 0.023$), while land elasticity of services production is not computed (and equal to 0) because not a single service in the database uses land as an input.

Biomass. Agriculture significantly depends on biomass production, with an elasticity of 3%. For the Industry sector, adding the interaction coefficient leads to a value close to zero ($= 0.030 - 0.044$).

Blue water. For this provision service, both Agriculture and Industry sectors show significant estimates of their blue water elasticity of production, respectively equal to 5.1% and 7.5%.

Table 1: Regression Results (all variables in log, omits regional fixed effect)

	Dependent variable:
	Added value
Employment in agriculture	0.412***
	(0.017)
Employment in industry (difference with agriculture)	0.231***
	(0.018)
Employment in services (difference with agriculture)	0.145***
	(0.026)
Land in agriculture	0.024***
	(0.004)
Land in industry (difference with agriculture)	-0.023***
	(0.009)
Land in services (difference with agriculture)	
Biomass in agriculture	0.030***
	(0.005)
Biomass in industry (difference with agriculture)	-0.044***
	(0.007)
Biomass in services (difference with agriculture)	
Blue water in agriculture	0.051***
	(0.008)
Blue water in industry (difference with agriculture)	0.024***
	(0.009)
Blue water in services (difference with agriculture)	-0.064***
	(0.010)
Energy in agriculture	0.019**
	(0.009)
Energy in industry (difference with agriculture)	0.002
	(0.010)
Energy in services (difference with agriculture)	
Industry constant (difference with agriculture)	-0.728
	(0.488)
Services constant (difference with agriculture)	4.087***
	(0.304)
Constant in agriculture	6.034***
	(0.810)
Observations	19,661
R^2	0.601
Adjusted R^2	0.598
Note:	*p<0.1; **p<0.05; ***p<0.01

2.3.3 Robustness of the method

The proposed method also produces consistent results in terms of employment, energy and productivity.

Employment. If we were in a decentralized equilibrium, assuming perfect competition and that factors are paid to their marginal products, the elasticity of production with respect to labor can be identified to the labor share (because of the Cobb-Douglas form). From the estimation, the labor share varies widely from one macro-sector to another. Surprisingly, the industrial labor share fits perfectly its usual estimates (Grossman and Oberfield, 2022) with a value of 0.64 ($= 0.41 + 0.23$). This is all the more surprising as usual estimation of labor shares through Cobb Douglas production function are made thanks to datasets at the firm level (Mollisi and Rovigatti, 2017) and not the sectoral level. In the Agriculture and Services sectors, the labor shares fall down to 0.41 and 0.56, respectively.

Energy. Energy elasticity of agricultural and industrial productions are estimated to be similar, around 2%. This is in line with Keen et al. (2019): using energy in a Cobb-Douglas production function, on an equal footage with labor and capital, leads to unrealistically low energy shares. For sake of simplicity, I do not use energy as an input factor in my baseline model. However, it would be interesting to build an integrated biodiversity-energy model in further work, with a special emphasis on bioenergy, for which data is available in GLORIA.

On the Total Factor Productivity. When we look at the estimates of country fixed effects, this theoretically provides a proxy for ranking countries according to their TFP. As shown in Figure 1, the calibration seems to produce a realistic ranking of countries, in which the Top 30 features a lot of OECD countries.

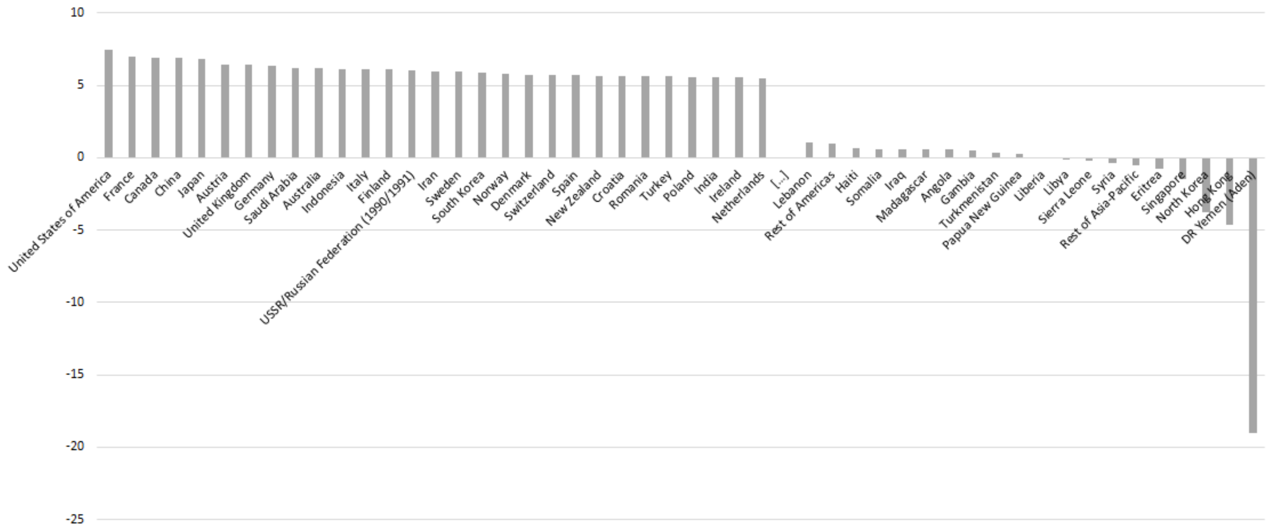

Figure 1: Total Factor Productivity ranking, estimated by the calibration (30 first regions and 20 last regions)

3 A *biodiversity*-integrated sectoral growth model

3.1 Overview

Figure 2 provides a schematic representation of the model. A mass L of agents can work for and consume goods from three sectors: agriculture, industry and services. The industrial good is split between consumption and investment in capital. On top of this usual multisectoral growth model structure, I add three blocks (in dark green) which endogenise the ecological dynamics linked to the loss of biodiversity. Land use is necessary to produce the agricultural good, but hinders biodiversity through the Species-Area relationship (SAR). Ecosystem services depend on the level of biodiversity (Biodiversity-Ecosystem Functioning relationship, BEF) and contributes to both the agricultural and industrial production. It should be noted that the production of services is not directly dependent on nature, but only indirectly through its dependence on industrial capital, which relies on ecosystem services in its production process.

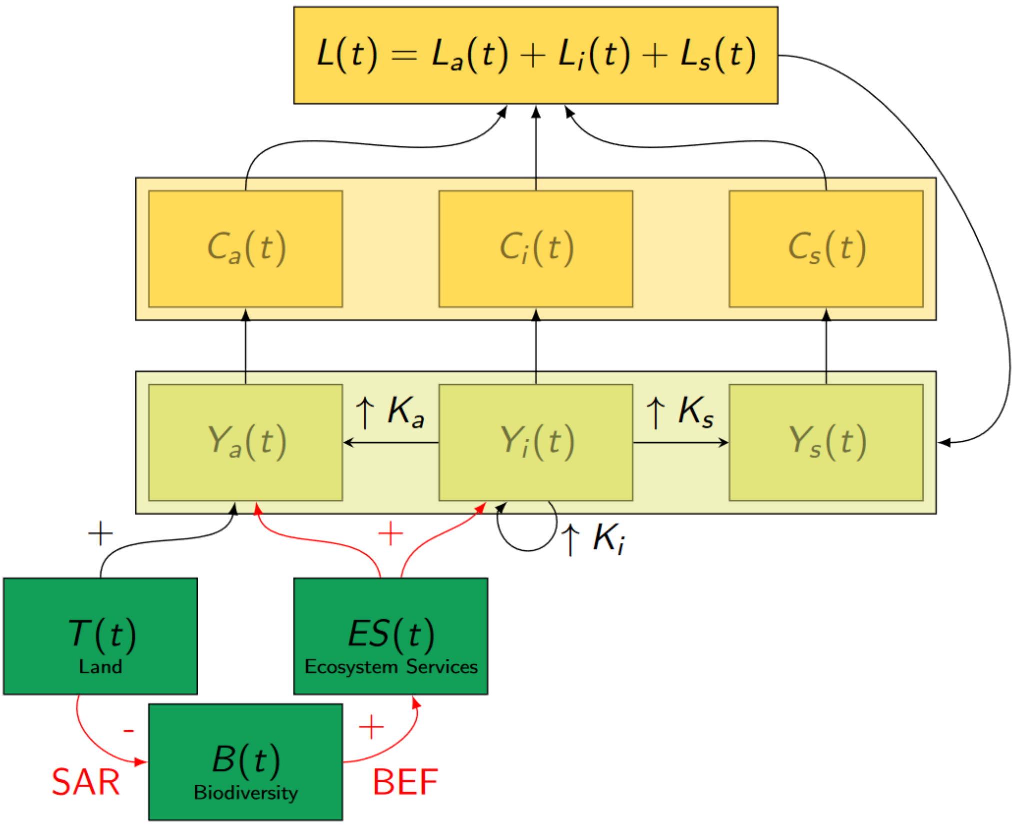

Figure 2: An overview of the model

3.2 Preferences

The objective function is the discounted sum of the utility derived from consumption by a representative household of mass L_t, the total population[4]:

$$\max_{(C_a,C_i,C_s)} \sum_{t=0}^{\infty} \beta^t \left(L_t U \left(\frac{C_{at}}{L_t}, \frac{C_{it}}{L_t}, \frac{C_{st}}{L_t} \right) - pT_t \right) \tag{7}$$

The household consume three different goods (from agriculture, industry and services), with non-homothetic Stone-Geary preferences, as in Matsuyama (1992), for all t:

$$U(c_{at}, c_{it}, c_{st}) = \phi_a \log(c_{at} - \bar{c}_a) + \phi_i \log(c_{it}) + \phi_s \log(c_{st}) \tag{8}$$

where $\bar{c}_a$ is the subsistence level of food consumption, and ϕ_j are high-income shares of sectoral consumption with $\sum_{j\in\{a,i,s\}} \phi_j = 1$. Non-homothetic production structures (Figure 3) can be observed when looking at sectoral shares of the GDP as a function of the GDP per capita of countries (using GLORIA database).

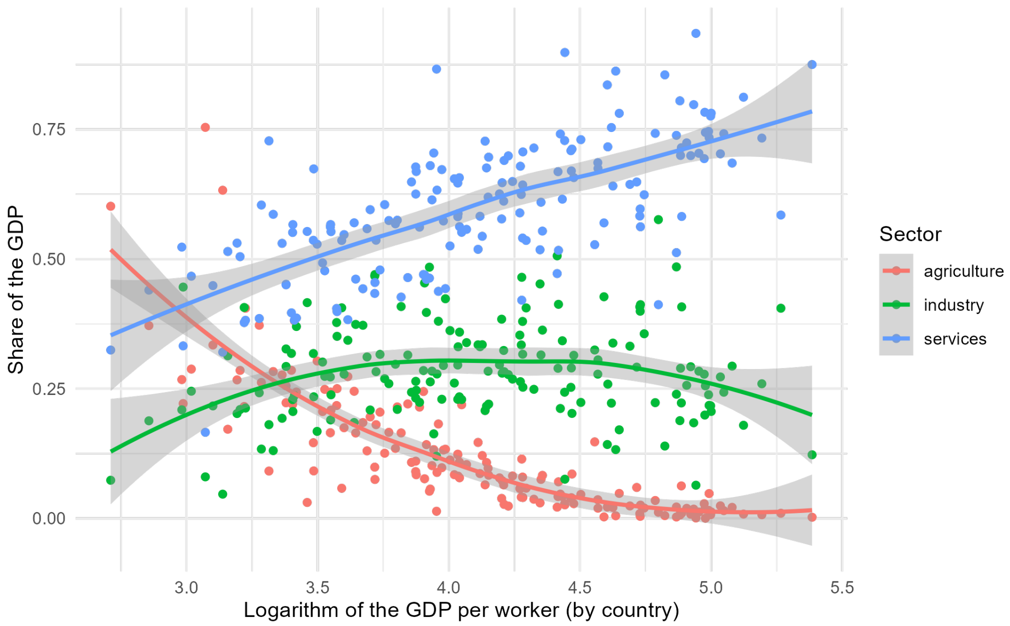

Figure 3: Sectoral shares of GDP as observed in GLORIA (2020)

Note: Shares are calculated by aggregating the added value of sectors according to the classifacation of Section 5.2. Smoothed curves are obtained by using the method "loess" of function ggplot2 in R.

[4]The total population corresponds to the workforce that can be allocated without friction to work int the three sectors $L_t = L_{t,a} + L_{t,i} + L_{t,s}$

We can clearly state that low income countries are dedicating higher shares of their production to agriculture. I make the assumption that this actually reflects preferences of a representative consumer of each country. For a range of revenue between 1 and 100, I choose my parameters ($\bar{c}_a = 0.5$; $\phi_a = 0.02$; $\phi_i = 0.23$; $\phi_s = 0.75$) in order to mimic the graph of Figure 3, as displayed in Figure 4.

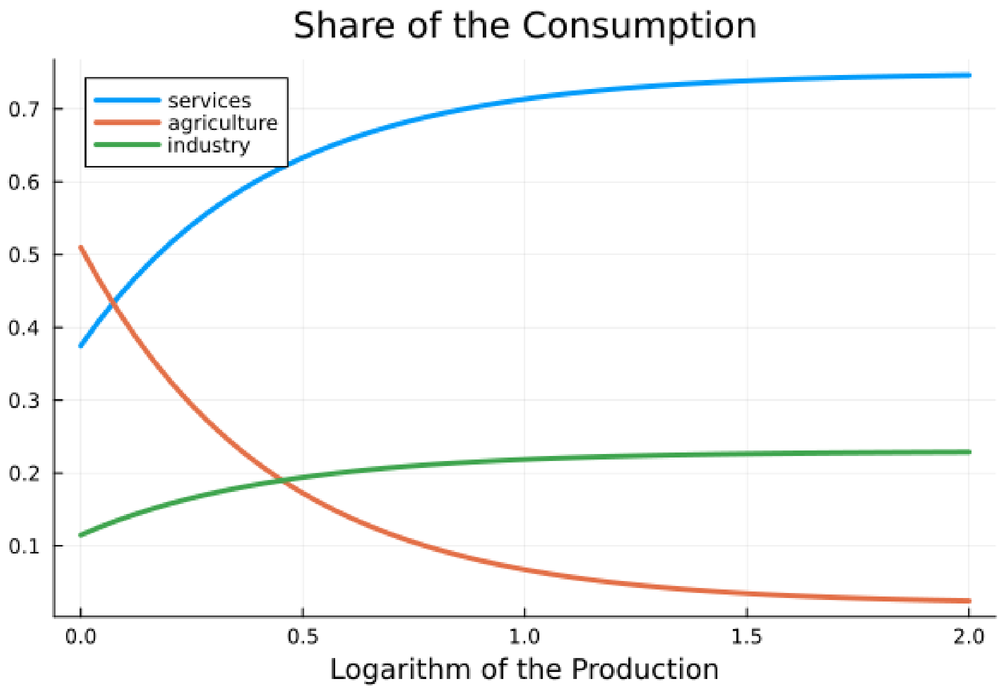

Figure 4: Simulated allocation of the production (ranging from 1 to 100) when the utility function is specified as in Equation 8 with ($\bar{c}_a = 0.5$; $\phi_a = 0.02$; $\phi_i = 0.23$; $\phi_s = 0.75$)

Also, I assume that there is a linear disutility of land use (measured by p) which encompasses both the costs of land conversion and the non-productive amenities from natural habitats.

3.3 Production, consumption, capital accumulation and labor allocation

Agricultural output is given by a Cobb-Douglas production function:

$$Y_{t,a} = A_{t,a} \times ES_{t,a}^{\gamma_a} \times K_{t,a}^{\alpha_a} L_{t,a}^{1-\alpha_a-\theta} T_t^{\theta} \tag{9}$$

where $Y_{t,a}$ is real agricultural output at time t, $A_{t,a}$ is an index of productivity in agriculture, $ES_{t,a}$ the quantity of ecosystem services useable by agriculture,

$K_{t,a}$ is capital allocated to agriculture, $L_{t,a}$ is the agricultural workforce and T_t the converted land (bounded by $\overline{T}$, the total amount of land). All parameters are calibrated following the process described in Section 2.3. Only a fraction of the agricultural production is consumed because of food waste and loss (FWL, see Section **??**):

$$c_{t,a} = (1-\omega)Y_{t,a} \tag{10}$$

where ω is the share of food wasted or lost, reaching 30% in 2022 according to UNO[5].

Services production is represented by a standard Cobb-Douglas production function:

$$Y_{t,s} = A_{t,s} \times K_{t,s}^{\alpha_i} L_{t,s}^{1-\alpha_s} \tag{11}$$

that is fully consumed:

$$Y_{t,s} = c_{t,s} \tag{12}$$

Finally, industrial production is given by:

$$Y_{t,i} = A_{t,i} \times ES_{t,i}^{\gamma_i} \times K_{t,i}^{\alpha_i} L_{t,i}^{1-\alpha_i} \tag{13}$$

Industrial output is split between industrial consumption and investment:

$$Y_{t,i} = c_{t,i} + I_t \tag{14}$$

Investment enables to accumulate capital that depreciate at a standard rate $\delta = 0.075$:

$$K_{t+1} = (1-\delta)K_t + I_t \tag{15}$$

Capital is split between the three sectors without any frictions:

$$K_t = K_{t,a} + K_{t,i} + K_{t,s} \tag{16}$$

Similarly, the workforce is divided between the three sectors and grows at rate g:

$$L_0 e^{gt} = L_t = L_{t,a} + L_{t,i} + L_{t,s} \tag{17}$$

[5]https://www.un.org/en/observances/end-food-waste-day

3.4 Ecological dynamics

As described in Section 2.1, long-term biodiversity S_t is determined by the Species-Area relationship (SAR):

$$S_t = c(\overline{T} - T_t)^z$$

Without loss of generality, I assume that $c = 1$. In the benchmark model, I make the assumption that there is no relaxation time, that is, that the actual biodiversity level reaches its long-term level immediately $B(t) = S(t)$.

Moreover, each ecosystem service depends on biodiversity according the Biodiversity-Ecosystem Functioning relationship so that $\forall j \in \{a, i\}$, $\forall t$:

$$\prod_{l=1}^{m} ES_{l,t,j}^{\gamma_{l,j}} = \prod_{l=1}^{m} B_t^{\sigma\gamma_{l,j}} = B_t^{\sigma \sum_{l=1}^{m} \gamma_{l,j}} = (\overline{T} - T_t)^{z\sigma \sum_{l=1}^{m} \gamma_{l,j}} = (\overline{T} - T_t)^{z\sigma\gamma_j}$$

by denoting $\gamma_j = \sum_{l=1}^{m} \gamma_{l,j}$. This equation closes the ecological feedback loop by internalizing land conversion in production functions.

3.5 Parameterization of the model

Table 2 gives a summary of all the parameters used in the model.

Table 2: Benchmark parameter values

Ecology			
Curvature of the Species-Area relationship	z	0.25	Preston (1962)
Curvature of the BEF relationship	σ	0.25	O'Connor et al. (2017)
Initial stock of converted land	$land_0$	0.33	Brondizio et al. (2019)
Economy			
Disocunt factor	β	0.99	Lanz et al. (2018)
Subsistence level of food consumption	$\bar{c}_a$	0.50	author
High income secoral shares	ϕ_a, ϕ_i, ϕ_s	0.02,0.23,0.75	author
Initial value for TFP in agriculture	A_a	1.00	author
Initial value for TFP in industry	A_i	1.00	author
Initial value for TFP in services	A_s	1.00	author
Elasticity of ES in agricultural production	γ_a	0.08	author
Elasticity of ES in industrial production	γ_i	0.08	author
Elasticity of ES in services production	γ_s	0.00	author
Share of capital in agriculture	α_a	0.565	author
Share of capital in industry	α_i	0.36	author
Share of capital in services	α_s	0.44	author
Share of land in agriculture	θ	0.025	author
Depreciation rate	δ	0.075	standard
Initial capital stock	K_0	1.00	author
Initial population stock	L_0	1.00	author
Population growth rate	g	0.00	author
Wasted food share	ω	0.30	UNO (2022)

4 Results

4.1 The optimal share of natural habitat

Deriving the first-order condition of the maximization problem of Equation 7, I get an instantaneous arbitrage condition on land use:

$$\phi_a \left(\theta \frac{1}{T^*} - z\sigma\gamma_a \frac{1}{\overline{T} - T^*} \right) \frac{c_a^*}{c_a^* - \overline{c}_a} - \phi_i z\sigma\gamma_i \frac{1}{\overline{T} - T^*} - p = 0 \tag{18}$$

By denoting $C_a^* = \frac{c_a^* - \overline{c}_a}{c_a^*}$ (the stage of development) and normalizing $\overline{T} = 1$, the arbitrage can be plotted as in Figure 5.

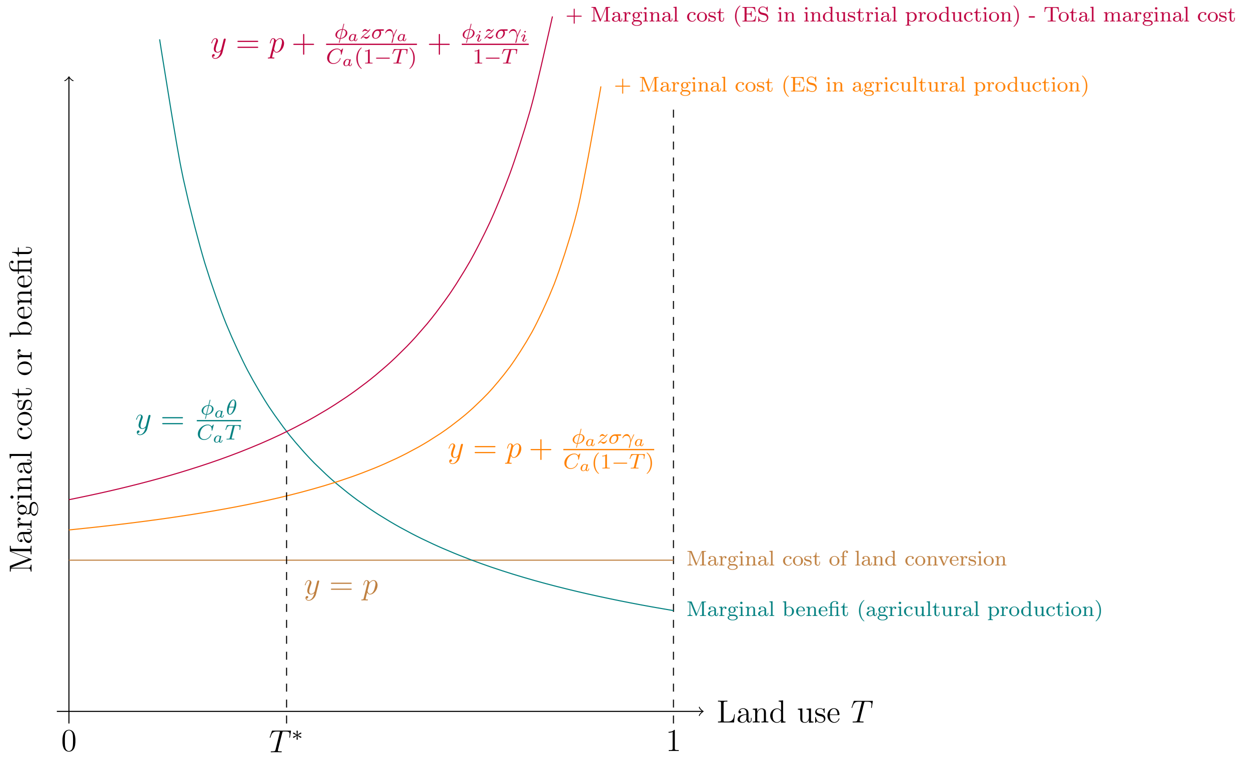

Figure 5: Optimal land use for a fixed level of development (C_a^*)

Figure 5 shows that the optimal land use is determined by the trade-off between the total marginal costs and marginal benefits of agricultural production. The costs are broken down into the direct costs of land conversion and the social (productive) costs associated with the loss of ecosystem services.

Proposition 1. At each time step t, the optimal land used can be expressed as:

$$T^* = \frac{\left(\Theta_a + \Gamma_a + C_a(\Gamma_i + p\overline{T})\right) + \sqrt{\left(\Theta_a + \Gamma_a + C_a(\Gamma_i + p\overline{T})\right)^2 - 4pC_a\Theta_a\overline{T}}}{2pC_a}$$

where $\Theta_a = \phi_a\theta$, $\Gamma_a = \phi_a z\sigma\gamma_a$, $\Gamma_i = \phi_i z\sigma\gamma_i$, and $C_a = \frac{c_a^* - \bar{c}_a}{c_a^*}$.
Proof in Appendix.

The optimal share of natural habitat $(1 - T^*)$ is an increasing function of the curvature of the Species-Area and Biodiversity-Ecosystem Functioning relationships (z and σ), which play a symmetrical role as in Lafuite and Loreau (2017). It is also positively correlated with the ecosystem services elasticity of production. Conversely, the optimal share of natural habitat decreases with the land elasticity of agricultural production.

Proposition 2. Without costs of land restoration, the optimal land use is a decreasing function of the development stage C_a. Proof in Appendix.

In the following analysis, I set the penalty p such that the optimal level of land use without taking into account ecosystem services is constant across the development stages and equal to $\tilde{T} = 0.45\overline{T}$ (which is the current world share of habitable land dedicated to agriculture). The details are in Appendix.

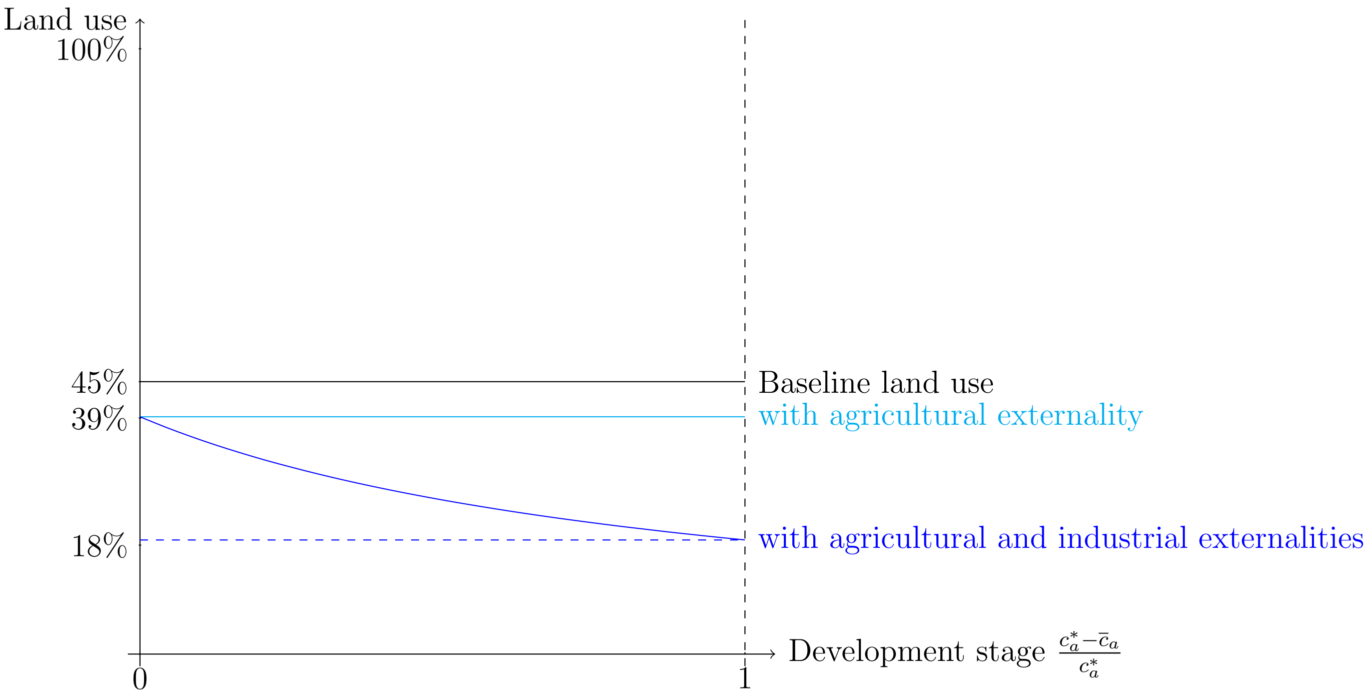

Figure 6: Optimum land use along the development path

Using the parameters of Section 3.5, I plot the optimal land use as a function of the development stage on Figure 6. Only taking into account ecosystem services benefiting for the agricultural lowers the baseline land use by around 13.3% (6/45). This value is very close to the value found in Lanz et al. 2018 ($\approx$ 13.5%). The non-homothetic preferences lead to a key result: the optimal land use significantly decreases with the development stage of an economy. Indeed, the optimal level of land use for agricultural purposes is less than half as high (18% vs. 39%) in the case of a developed country compared with least developed countries ($c_a^* = \overline{c_a}$).

5 Conclusion

In this paper, I introduce the ecological dynamics linked to biodiversity and ecosystem services into a growth model. In particular, taking inspiration from Dasgupta's model, I include ecosystem provisioning services directly in the production function. I calibrate them by proposing an *ad hoc* method based on the GLORIA input-output database and its environmental extensions. To my knowledge, this is the first exercise to quantitatively integrate biodiversity into a macro-model as a production factor. I also draw on the latest advances in ecology to provide a scientific basis for understanding the interactions between biodiversity and the economy. In particular, I use two well-established relationships, namely the Species-Area relationship and the Biodiversity-Ecosystem Functioning relationships.

Then, I build an optimal growth model based on biodiversity. First results show that the optimal share of natural habitat is an increasing function of the curvature of the Species-Area and Biodiversity-Ecosystem Functioning relationships (z and σ), which play a symmetrical role. It is also positively correlated with the elasticity of production of ecosystem services. Conversely, the optimal share decreases with the land elasticity of agricultural production and the share of agriculture in the labor force. My main results focus on the optimal land use at a macroeconomic scale. I show that this value is determined by the trade-off between the total marginal costs and marginal benefits of agricultural production. Costs are broken down into the direct costs of land conversion and the social (productive) costs associated with the loss of ecosystem services. The non-homothetic preferences for agricultural, industrial and services goods leads to a key result: the optimal land use significantly decreases with the development stage of an economy. Indeed, the higher the level of development, the higher the weight of industrial consumption relative to agricultural consumption: the social planner is willing to decrease its level of land use in the agricultural sector to spare biodiversity and benefit from more of its ecosystem services in the industrial sector.

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Appendix A: Proofs

5.1 Proof of Proposition 1

Taking into account Equation 7 and all the constraints, the welfare function can be written as:

$$\begin{aligned} W = \sum_{t=0}^{\infty} \beta^t \Big[& \phi_a \ln\Big((1-\omega)A_{t,a}(\overline{T}-T_t)^{z\sigma\gamma_a} K_{t,a}^{\alpha_a} L_{t,a}^{1-\alpha_a-\theta} T_t^{\theta} - \overline{c}_a\Big) \\ & + \phi_i \ln\big(A_{t,i}(\overline{T}-T_t)^{z\sigma\gamma_i} K_{t,i}^{\alpha_i} L_{t,i}^{1-\alpha_i} - K_{t+1} + (1-\delta)K_t\big) \\ & + \phi_s \ln\big(A_{t,s}(K_t - K_{t,i} - K_{t,a})^{\alpha_s}(L_t - L_{t,i} - L_{t,a})^{1-\alpha_s}\big) - pT_t \Big] \end{aligned} \tag{19}$$

At the optimum, at each time step t, the first order condition with respect to T can be written as, in the case the penalty is linear:

$$\phi_a \left(\theta \frac{c_a^*}{T^*} - z\sigma\gamma_a \frac{c_a^*}{\overline{T}-T^*}\right) \frac{1}{c_a^* - \overline{c}_a} - \phi_i z\sigma\gamma_i \frac{c_i^*}{\overline{T}-T^*} \frac{1}{c_i^*} - p = 0$$

$$\phi_a \left(\theta(\overline{T}-T^*) - z\sigma\gamma_a T^*\right) \frac{c_a^*}{c_a^* - \overline{c}_a} - \phi_i T^* z\sigma\gamma_i - p(\overline{T}-T^*)T^* = 0$$

Let's denote $\Theta_a = \phi_a\theta$, $\Gamma_a = \phi_a z\sigma\gamma_a$, $\Gamma_i = \phi_i z\sigma\gamma_i$, and $C_a = \frac{c_a^* - \overline{c}_a}{c_a^*}$. The second-order polynomial equation can be rewritten:

$$pT^{*2} - \left((\Theta_a + \Gamma_a)\frac{1}{C_a} + \Gamma_i + p\overline{T}\right) T^* + \Theta_a \overline{T} = 0$$

$$C_a p T^{*2} - \left(\Theta_a + \Gamma_a + C_a(\Gamma_i + p\overline{T})\right) T^* + C_a \Theta_a \overline{T} = 0$$

The discriminant of the equation is:

$$\Delta = \left(\Theta_a + \Gamma_a + C_a(\Gamma_i + p\overline{T})\right)^2 - 4pC_a\Theta_a\overline{T}$$

In the case $\Delta > 0$, the roots of the eqaution are:

$$T^*_{+-} = \frac{\left(\Theta_a + \Gamma_a + C_a(\Gamma_i + p\overline{T})\right) \pm \sqrt{\left(\Theta_a + \Gamma_a + C_a(\Gamma_i + p\overline{T})\right)^2 - 4pC_a\Theta_a\overline{T}}}{2pC_a}$$

Let us assume that the current observed level of land use corresponds to the optimal level taking into account the private cost of land use without taking into account its externalities on agricultural and industrial productivity. In that case, optimal values can be expressed as (setting $\overline{T} = 1$):

$$T^*_{+-} = \frac{\left(\Theta_a + C_a p\overline{T}\right) \pm \sqrt{\left(\Theta_a + C_a p\overline{T}\right)^2 - 4pC_a\Theta_a\overline{T}}}{2pC_a}$$

$$T^*_{+-} = \frac{\left(\Theta_a + C_a p\overline{T}\right) \pm \sqrt{\left(\Theta_a - C_a p\overline{T}\right)^2}}{2pC_a}$$

$$T^*_{+-} = \frac{\left(\Theta_a + C_a p\overline{T}\right) \pm \left(\Theta_a - C_a p\overline{T}\right)}{2pC_a}$$

We have that $T^*_- = 1$ and,

$$T^*_+ = \frac{\Theta_a}{pC_a}\overline{T}$$

Let us assume that the cost of land use is a decreasing function of C_a such that pC_a is constant and equal to Θ_a over the observed level of land use $T_o = 0.45\overline{T} = T_o^{\%}\overline{T}$:

$$pC_a = \frac{\Theta_a}{T_o^{\%}}$$

Appendix B

5.2 Calibration

Sector name	Macro sector
Growing wheat	Agriculture
Growing maize	Agriculture
Growing cereals n.e.c	Agriculture
Growing leguminous crops and oil seeds	Agriculture
Growing rice	Agriculture
Growing vegetables, roots, tubers	Agriculture
Growing sugar beet and cane	Agriculture
Growing tobacco	Agriculture
Growing fibre crops	Agriculture
Growing crops n.e.c.	Agriculture
Growing grapes	Agriculture
Growing fruits and nuts	Agriculture
Growing beverage crops (coffee, tea etc)	Agriculture
Growing spices, aromatic, drug and pharmaceutical crops	Agriculture
Seeds and plant propagation	Agriculture
Raising of cattle	Agriculture
Raising of sheep	Agriculture
Raising of swine/pigs	Agriculture
Raising of poultry	Agriculture
Raising of animals n.e.c.; services to agriculture	Agriculture
Forestry and logging	Agriculture
Fishing	Agriculture
Crustaceans and molluscs	Agriculture
Hard coal	Industry
Lignite and peat	Industry
Petroleum extraction	Industry
Gas extraction	Industry
Iron ores	Industry
Uranium ores	Industry
Aluminium ore	Industry

Copper ores	Industry
Gold ores	Industry
Lead/zinc/silver ores	Industry
Nickel ores	Industry
Tin ores	Industry
Other non-ferrous ores	Industry
Quarrying of stone, sand and clay	Industry
Chemical and fertilizer minerals	Industry
Extraction of salt	Industry
Mining and quarrying n.e.c.; services to mining	Industry
Beef meat	Industry
Sheep meat	Industry
Pork	Industry
Poultry meat	Industry
Other meat products	Industry
Fish products	Industry
Cereal products	Industry
Vegetable products	Industry
Fruit products	Industry
Food products and feeds n.e.c.	Industry
Sugar refining; cocoa, chocolate and confectionery	Industry
Animal oils and fats	Industry
Vegetable oils and fats	Industry
Dairy products	Industry
Alcoholic and other beverages	Industry
Tobacco products	Industry
Textiles and clothing	Industry
Leather and footwear	Industry
Sawmill products	Industry
Pulp and paper	Industry
Printing	Industry
Coke oven products	Industry
Refined petroleum products	Industry
Nitrogenous fertilizers	Industry

Non-nitrogenous and mixed fertilizers	Industry
Basic petrochemical products	Industry
Basic inorganic chemicals	Industry
Basic organic chemicals	Industry
Pharmaceuticals and medicinal products	Industry
Dyes, paints, glues, detergents and other chemical products	Industry
Rubber products	Industry
Plastic products	Industry
Clay building materials	Industry
Other ceramics n.e.c.	Industry
Cement, lime and plaster products	Industry
Other non-metallic mineral products n.e.c.	Industry
Basic iron and steel	Industry
Basic aluminium	Industry
Basic Copper	Industry
Basic Gold	Industry
Basic lead/zinc/silver	Industry
Basic nickel	Industry
Basic tin	Industry
Basic non-ferrous metals n.e.c.	Industry
Fabricated metal products	Industry
Machinery and equipment	Industry
Motor vehicles, trailers and semi-trailers	Industry
Other transport equipment	Industry
Repair and installation of machinery and equipment	Industry
Computers; electronic products; optical and precision instruments	Industry
Electrical equipment	Industry
Furniture and other manufacturing n.e.c	Industry
Electric power generation, transmission and distribution	Industry
Distribution of gaseous fuels through mains	Industry
Water collection, treatment and supply; sewerage	Industry
Waste collection, treatment, and disposal	Industry
Materials recovery	Industry

Building construction	Industry
Civil engineering construction	Industry
Wholesale and retail trade; repair of motor vehicles and motor-cycles	Services
Road transport	Services
Rail transport	Services
Transport via pipeline	Services
Water transport	Services
Air transport	Services
Services to transport	Services
Postal and courier services	Services
Hospitality	Services
Publishing	Services
Telecommunications	Services
Information services	Services
Finance and insurance	Services
Property and real estate	Services
Professional, scientific and technical services	Services
Administrative services	Services
Government; social security; defence; public order	Services
Education	Services
Human health and social work activities	Services
Arts, entertainment and recreation	Services
Other services	Services

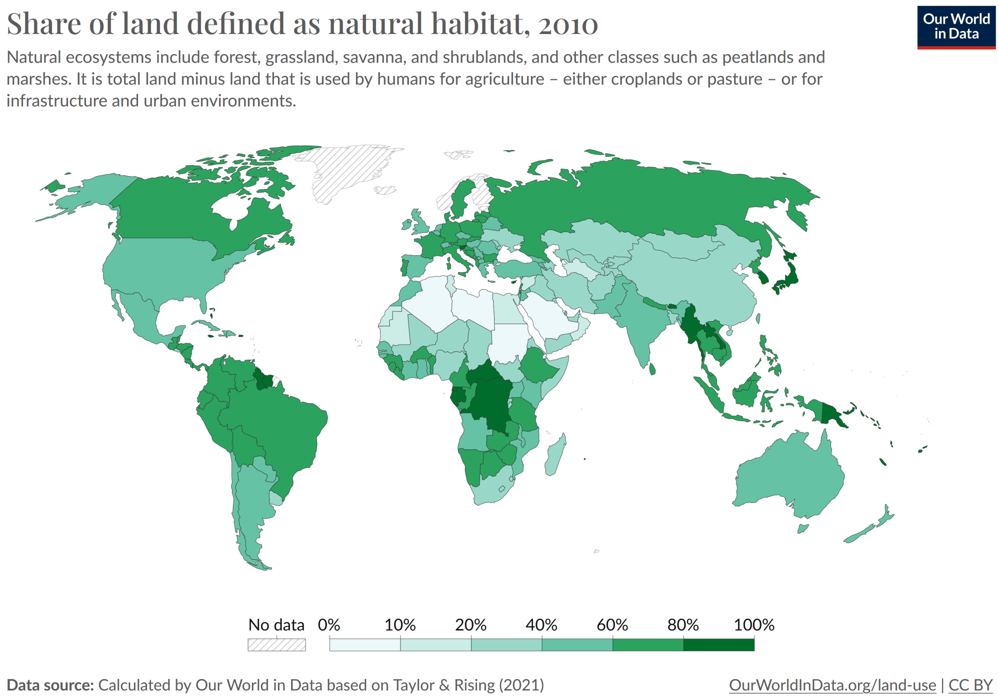

Figure 7: Share of land defined as natural habitat in 2010

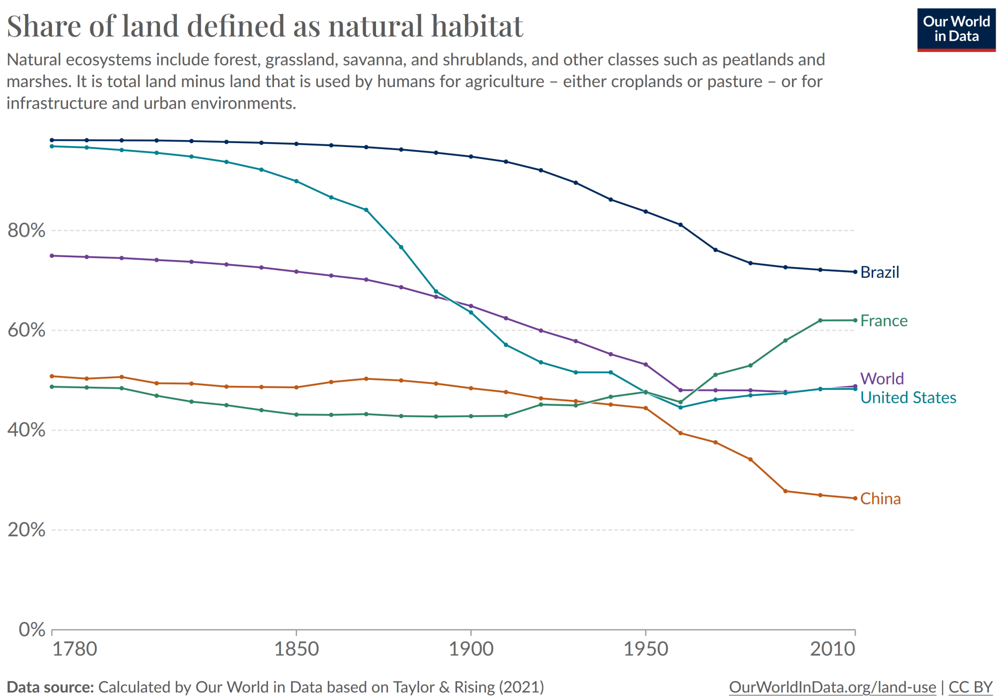

Figure 8: Share of land defined as natural habitat for 4 countries and the world between 1780 and 2010

Table 4: Satellite accounts from GLORIA

Nr	Head indicator	Indicator	Unit	Variable
71	Material	Rice	tonnes CUeq	Biomass
72	Material	Wheat	tonnes CUeq	Biomass
73	Material	Cereals n.e.c.	tonnes CUeq	Biomass
74	Material	Other crops n.e.c	tonnes CUeq	Biomass
75	Material	Spice - beverage - pharmaceutical crops	tonnes CUeq	Biomass
76	Material	Tobacco	tonnes CUeq	Biomass
77	Material	Roots and tubers	tonnes CUeq	Biomass
78	Material	Sugar crops	tonnes CUeq	Biomass
79	Material	Pulses	tonnes CUeq	Biomass
80	Material	Nuts	tonnes CUeq	Biomass
81	Material	Oil bearing crops	tonnes CUeq	Biomass
82	Material	Vegetables	tonnes CUeq	Biomass
83	Material	Fruits	tonnes CUeq	Biomass
84	Material	Fibres	tonnes CUeq	Biomass
85	Material	Straw	tonnes CUeq	Biomass
86	Material	Other crop residues	tonnes CUeq	Biomass
87	Material	Fodder crops	tonnes CUeq	Biomass
88	Material	Grazed biomass	tonnes CUeq	Biomass
89	Material	Timber (Industrial roundwood)	tonnes CUeq	Biomass
90	Material	Wood fuel and other extraction	tonnes CUeq	Biomass
91	Material	Wild fish catch	tonnes CUeq	Biomass
92	Material	All other aquatic animals	tonnes CUeq	Biomass
93	Material	Aquatic plants	tonnes CUeq	Biomass
94	Material	Iron ores	tonnes CUeq	Ores
95	Material	Silver ores	tonnes CUeq	Ores
96	Material	Bauxite and other aluminium ores - gross ore	tonnes CUeq	Ores
97	Material	Gold ores	tonnes CUeq	Ores
98	Material	Chromium ores	tonnes CUeq	Ores
99	Material	Copper ores	tonnes CUeq	Ores
100	Material	Manganese ores	tonnes CUeq	Ores
101	Material	Other metal ores	tonnes CUeq	Ores
102	Material	Nickel ores	tonnes CUeq	Ores
103	Material	Lead ores	tonnes CUeq	Ores
104	Material	Platinum group metal ores	tonnes CUeq	Ores
105	Material	Tin ores	tonnes CUeq	Ores
106	Material	Titanium ores	tonnes CUeq	Ores
107	Material	Uranium ores	tonnes CUeq	Ores
108	Material	Zinc ores	tonnes CUeq	Ores
113	Material	Fertilizer minerals n.e.c.	tonnes CUeq	Fertilizer
133	Employment	Female	k ppl	Employment
134	Employment	Male	k ppl	Employment
138	Land use	Annual_crops	1000 ha	Land
139	Land use	Permanent_crops	1000 ha	Land
140	Land use	Pastures	1000 ha	Land
141	Land use	Intensive_forestry	1000 ha	Land
142	Land use	Extensive_forestry	1000 ha	Land
143	Land use	Urban	1000 ha	Land
144	Energy	Coal and peat	TJ	Energy
145	Energy	Oil and natural gas	TJ	Energy
146	Energy	Nuclear	TJ	Energy
147	Energy	Solid biofuels	TJ	Energy
148	Energy	Captured energy	TJ	Energy
149	Energy	Heat	TJ	Energy
158	Blue water	Agriculture blue water consumption	M m3 H2Oeq	Blue water
159	Blue water	Non-agriculture blue water consumption	M m3 H2Oeq	Blue water

Table 5: Aggregate values of satellite accounts of GLORIA Release 055, per macro sector

Variable	Agriculture	Industry	Services
Added value (million $)	3 685	22 021	55 324
Employment (million ppl)	701	804	1 720
Land (kha)	5 889 516	274 893	0
Biomass (ktonnes CU eq)	24 746 151	709 965	0
Blue Water (M m3 H2O eq)	985 587	139 191	11 154
Energy (TJ)	30 681 733	529 040 813	0
Fertilizer (tonnes CU eq)	0	350 926 309	0
Ores (tonnes CU eq)	0	9 720 132 529	0