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Implications of Climate Change and Ecosystem Services Degradation for Macroeconomic and Financial Stability

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Introducing Natural Capital in Macroeconomic Modeling*

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Biodiversity loss is now widely perceived as a potential source of significant economic and financial instabilities.[1] This is intuitive since biodiversity loss is not only a risk for the environment and a direct threat to nonhuman species but also a menace to human civilization, which relies on Nature to produce goods and services essential to its livelihood. More impactfully, *"ecosystem services"* are what makes human life possible. Among the most obvious services are food, water, plant materials that generate fuel, infrastructure materials, and drugs. Less visible but certainly not less essential, ecosystem services include climate regulation and natural defenses from natural forces provided by forests, carbon sequestration, or the pollination of crops by insects. Less directly apparent services also include culture, inspiration, and the sense of purpose that living in a healthy and thriving natural world gives humans every day.

Problematically, the major drivers of biodiversity loss are "byproducts" of economic material growth and production[2] This conundrum might seem particularly acute in developing economies, where the Environmental Kuznet Curve (EKC) paradigm has taken

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1. See NGFS (2023).

2. See IPES (2016).

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a hold, suggesting that there is an inescapable road that links economic development to environmental degradation (in this case via pollution). Despite the popularity in the economic profession and public discourse, there is however very weak (if at all) sound statistical work pointing out that such relationship in fact exists.[3] Recognizing that EKCs might be an artifact resulting from bad econometrics is undoubtedly encouraging, as it points to an absence of determinism in the way societies can develop materially while, at the same time, avoiding unsustainable deterioration of the natural environment.

If it is indeed realistic to think about paradigms that allow for sustainable development, one question is then why the economic profession (macroeconomists in particular) has been so quiet on the issue. In fact, while the study of how we should be addressing climate change has been at the forefront of debates and analysis since the early 1990s,[4] the notion of biophysical limits to growth has not yet taken root in modern macroeconomics.[5] As a result, prevalent macroeconomic theory still assumes that economic agents have access to boundless natural resources and bottomless sinks for waste products, thereby eliminating the need for an explicit discussion of economic growth within a natural world.

In this paper, we will first discuss how economic models have been slowly expanded to account for natural resources, and then present an analytical section describing how to set up a "bio-economic" dynamic stochastic general equilibrium (DSGE) model, also showing some simulation results. This latter section primarily builds on the work of Batini and Durand (2024), where biodiversity (equivalently referred to as "Natural capital" or "Nature" *tout court*) is defined as "the world's stocks of natural assets, which include geology, soil, air, water, and all living things" (following the definition of the *Convention on Biological Diversity*). In a final section, we will then summarize three macro-themes that could guide further modeling extensions, with an eye on topics that are relevant for macroeconomists working at central banks and other policy institutions.

3. See Stern (2017).

4. See Nordhaus (1991).

5. While economic activities that produce CO_2 tend to also directly affect the environment, the overlap is partial—for example, mineral extraction does not generate significant CO_2 emissions and yet it is responsible for significant ecosystem services degradation; the same goes for agricultural monocoltures.

1. Macroeconomics of Nature

Modern growth models, like the Solow-Swan neoclassical growth model,[6] do not consider the natural foundation of production. Accordingly, capital goods and labor are combined to produce commodity output, but no land is required as a site, no materials are needed from which to form commodities, and no energy is required to drive the process of commodity production and exchange. As Solow himself remarked, *"The production function is homogeneous of first degree. This amounts to assuming that there is no scarce nonaugmentable resource like land."*

In the 1970s, in response to emerging resource constraints from global energy price shocks and rising pollution, attempts were made to integrate natural resources (as distinct from natural capital) among factors of production and growth in economic models. Initial efforts focused on augmenting traditional input factors with a "nonrenewable resource" factor devising prescriptions for the exploitation of natural resources compatible with constant per capita consumption into the indefinite future.[7] This literature built on the insights from Hotelling (1931), who first showed that, in a competitive market assuming constant marginal extraction costs, extraction of the exhaustible resource should be such that the increase in price minus marginal costs equals the rate of discount (while marginal revenue minus marginal costs should rise at the rate of discount in the case of a monopolistic market).

In the 1980s, mounting environmental pressures and rising temperatures, coupled with expanding federal budget deficits in the United States, contributed to the emergence of a literature centered on the use of environmental levies to address fiscal deficits and on the possible use of environmental regulation to generate revenues that could in turn be used to compensate for other pre-existing distortionary taxes (such as on capital and/or labor). Pearce (1991) might be the first one to refer to the term "double-dividend" to express the idea of using carbon levies to finance reductions in other incentive-distorting taxes. The hypothesis was at the center of a rich debate, with works such as Bovenberg and De Mooij (1994) and Bovenberg and Goulder (1996) arguing that environmental taxes exacerbate rather than alleviate

6. See Solow (1956).

7. See Solow (1974), Stiglitz (1974), Dasgupta and Heal (1974), Dasgupta and others (1978), and Hartwick (1977).

pre-existing tax distortions. Overall, as lucidly pointed out by Fullerton and Metcalf (1997), the validity of the hypothesis cannot be settled as a general matter, as it depends on specific circumstances ultimately requiring case-by-case assessments.

Further attempts gradually expanded the concept of "natural resources" in economic models, moving towards notions better aligned with ecological economics definitions of natural capital. This stream of research included efforts to embed limits to sustained growth from increased pollution (seen as a phenomenon degrading the natural environment) through pollution-reducing technological change.[8] While most of these works concern pollution flows and abatement technologies, some begin to embed natural processes that can regenerate through time—"environmental quality" in the words of Acemoglu and others (2012). In these latter cases, there is a significant departure from previous work on nonrenewable resources, and the Hotelling condition is now expanded to also account for the intrinsic growth rates of the resource stock and the size of the stock relative to its long maximum size. Both concepts are at the core of the management of natural capital.

Along this line of work, Brander and Taylor (1997) analyzed the dynamic system of population interactions with natural resources, finding that an excessive rate of exploitation of stocks of resources tends to generate cycles in both population and natural capital. Dalton and others (2005) extended the model to technological change dependent on institutional parameters showing, for example, that institutions that favor strong property rights tend to bias technological change toward resource conservation rather than encourage or enable resource depletion.

Others have tried to model natural capital as a renewable resource[9] examining how to link material production and consumption to the pace of anthropogenic degradation of natural capital or, in some other cases, studying the impact on trade[10] and the inter-generational aspects of its exploitation[11] and, more recently, also emphasizing

8. See, for example, Tahvonen and Kuuluvainen (1991), Bovenberg and Smulders (1995), Howitt and Aghion (1998), and more recently, Brock and Taylor (2010), Acemoglu and others (2012), and Hassler and others (2016).

9. See Costanza and Daly (1992), Hinterberger and others (1997), Bringezu and others (2003), Comolli (2006), Fischer-Kowalski and others (2011).

10. See Karp and others (2001), also following environmental reforms by Karp and others (2003).

11. See Mourmouras (1991).

political economy aspects.[12,13] This literature stands in contrast with mainstream approaches, which are usually focused on the role of natural resources, and instead emphasizes the creation of ecosystem services. These works generally share the assumption that there can only be limited substitutability between natural capital and other forms of capital, which in turn implies a form of strong sustainability[14] meaning, at a minimum, that over the long run the economy must converge to a state where the total stock of natural capital remains constant over time. This is different from what is referred to as "weak sustainability" (or also "Solow sustainability",[15] which posits constant consumption per capita through time. Also, these models are distinctive in that they start to embed the possibility that there is some boundary usage of nature which, when crossed, provokes large changes in ecosystems behavior. This latter characterization is well aligned with the latest findings in ecological sciences showing both the presence and the possible self-reinforcing effects between separate tipping points, such as those from an Amazon dieback, Arctic sheet meltdown, and collapse of the ocean circulation pattern.

With a growing recognition of the urgency of accounting for ecosystem services degradation and their impact on human welfare came new studies, including Albagli and Vial (2023), who tried to disentangle the role of economic growth and population in driving biodiversity losses, proposing alternative growth pathways that would ensure conservation. One conclusion is that population growth dominates the negative impact of economic growth on biodiversity. This research follows the ecological economics footsteps pointing to limits to growth, for example by Schumacher (2011). Meadows and others (1972), Meadows and others (2004), and Costanza and Daly (1992) suggest that it is necessary to dematerialize growth to decouple production from resource use to ensure that the use and consumption of natural capital remains sustainable.

A difficulty behind these prescriptions is that both empirical evidence and theoretical work suggest that decoupling economic growth from the growth of material and energy use is unprecedented on the scale and time needed to stabilize the Earth system and might

12. See Karp and Rezai (2014).

13. Subsequent interpretations tried to define natural capital more comprehensively equating it to the sum of the stock of renewable, nonrenewable, replenishable, and cultivated natural capital. See, for example, Aronson and others (2007).

14. See Hediger (1997).

15. See Common (1997).

well be unfeasible.[16] This is further emphasized by Jackson (2016) who argues that even though there is historical evidence of relative decoupling, that is of a decline in the material intensity of economic output, absolute decoupling, defined as the situation where material use declines in absolute terms, remains so far a mirage, as CO_2 emissions keep increasing together with the overall material footprint of production (including mineral resources extraction).

As of today, there are continuing efforts made to integrate Nature within macroeconomic models. An example of such efforts is Kornafel and Telega (2020), who embedded natural capital intended as a renewable resource in a neoclassical growth closed-economy model to explore whether it is possible to sustain economic growth even if material consumption increases alongside.[17] They assume that produced goods and natural capital are complements in the sense that economic growth increases the material demand, which means greater depreciation of natural capital. They find stable equilibria when: (i) the stock of natural capital is large enough to begin with even if no investment in natural capital is made; (ii) the growth rates of capital and technological progress are strong enough given the assumed elasticity of material intensity of production relative to the elasticity of material intensity of technology; (iii) investments in natural capital are large enough to maintain the stock of natural capital at a level compatible with the complementarity requirements of continuous production given assumed technologies.

In a report prepared following an invitation from the Chancellor of the Exchequer of the UK government, Dasgupta (2021) proposed a similar but alternative modification to the model of economic growth that includes natural capital (alongside man-made and human capital), providing a complete capital theoretic account of human activities, from source to sink. In the global economy, natural capital features in an otherwise traditional production function in two forms: as a flow of extracted provisioning service (like oil, timber, fish etc.) and as a stock supplying ecosystem services which are essential to production (like carbon and nitrogen cycles, disease control, climate regulation, soil regeneration etc.)—a modeling device to capture the fact that "the human economy is embedded in the

16. See Ward and others (2016) and Parrique and others (2019).

17. In their model, which features no behavioral equations and no direct role for Nature in the production function, natural capital is distinct from the 'normal' renewable resource, which is intended only as a factor of production, because it plays a positive social function through the provision of recreational and similar services.

biosphere."[18] This setup is fully aligned with the ecological literature—to that effect, it assumes that the net regeneration rate of natural capital is bounded and, if natural capital falls below a certain limit (a "tipping point"), the economy collapses. It also assumes that ecosystem services are complementary to each other in certain ways, and this set bounds on the efficiency with which services from natural capital can be converted into output, implying that global economic growth is bounded. Optimizing agents demand goods produced using the various kinds of capital and value natural capital in their utility function. The main result of this analysis is that, when natural capital is assumed to have an intrinsic value, multiple stationary equilibria exist for different combinations of various types of capital (man-made, human, and natural), but these will depend on the current size of such stocks.

Dasgupta (2021)'s report marked a significant moment for ecological economics and macroeconomics more generally, as it put, for the first time, the issue of sustainable development and limits to growth front and center in the policy arena. The report sparked a wave of newly found interest, with networks and activities recognizing the essential role that Nature plays in economic systems (such as the *Network for Greening the Financial System*, bringing together central banks and financial supervisory institutions together on matters of green finance). The topic is undoubtedly gaining momentum with more policy organizations joining in the conversation, resulting in new landmarks such as the The Kunming-Montreal Global Biodiversity Framework and the establishment of international working groups focused on Nature-related risks to the financial systems.

Taking stock of these previous theoretical advances, in the next section we describe a novel model that was built to help policymakers evaluate the long-run effects of natural resources exploitation and conservation. The model is general enough to allow for a broad characterization of Nature and lends itself well to further fine-tuning and explorations.

2. Introducing Natural Capital in a Macroeconomic Model

In what follows, we proceed by presenting the work of Batini and Durand (2024), which introduces natural capital in a DSGE model

18. See page 144 in Dasgupta (2021).

of the type used to help inform policy analyses. We chose to keep the model-specific economic description qualitative, focusing instead on the quantitative aspects of Nature modeling with an emphasis on its integration within a macroeconomic model.

The framework assumes an infinite horizon in discrete time, with each period corresponding to five years, and a world economy composed of two blocs or regions. The framework assumes that Natural Capital (K_N) is unevenly distributed, displays critical thresholds or "tipping points" beyond which the ecosystem is irreversibly altered, and can contribute to the evolution of total factor productivity via an externality. Specifically, a larger stock of natural capital provides more abundant ecosystem services, which in turn expand the output that can be produced for each unit of labor and man-made capital, given the underlying rate of technological progress.

The two regions, Home (H) and Foreign (F), are populated by infinitely lived households and firms. The blocs trade with each other and differ in size and production structure. Importantly, only H is endowed with natural capital.[19] H produces both "green" and "brown" intermediate goods, which require natural capital as an input of production; both blocs must buy these goods to produce. Both blocs also produce final goods combining the purchased (and then aggregated) intermediate goods with hired labor and rented man-made capital. The technologies used to aggregate the intermediate goods and produce the final good are symmetric between the two regions. We assume that producing green goods (e.g., harvesting forest food) does not dent the stock of natural capital, while producing brown goods (e.g., extracting timber from a forest unsustainably) does. In this sense, the model is assuming that it is possible to "invest" in natural capital through ecosystem conservation, which basically requires ensuring that natural capital is protected from excessive extractive uses or man-made degradation.

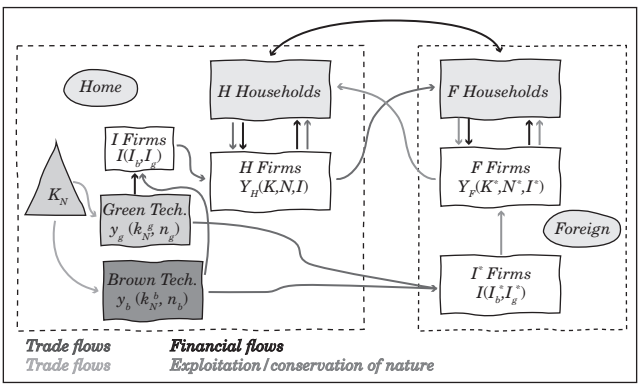
The model is free from nominal and real friction. Financial markets are complete. Finally, both blocs have a fiscal authority that collects taxes (distributes subsidies) and rebates the proceeds (collects the resources) lump-sum to (from) the households. Figure 1 graphically summarizes the structure of the model, showing the various agents and the (main) economic linkages among them. We refer the reader to Batini and Durand (2024) for a detailed algebraic description of the

19. This assumption is simplifying but helps mimic the world's uneven distribution of natural capital.

various economic relationships, together with the associated resulting optimality conditions.

In the next sections, we review how natural capital is modeled. In line with Dasgupta and Mäler (2004), D'Alessandro (2007), and Kornafel and Telega (2019), there are two basic alternative specifications: one with an exogenous and known critical threshold and one without a critical threshold. These two versions have a well-established tradition in the study of fisheries management[20] and conservation more in general,[21] and allow for conceptualizing the dynamic resource-harvesting problem that economic agents face when deciding how much of the natural resource to exploit for production and how much to keep in place for (possible) future use. We also review a third specification for Nature, which assumes that the critical threshold is unknown to the economic agents and is endogenous to the amount of natural capital depletion (that is, the probability of crossing the threshold increases as more natural capital is consumed and, in any given time, the agents do not know *ex-ante* whether a given depletion of resources is bound to set in motion the tipping point). We review each one of the three versions in turn below.

Figure 1. Diagram of the Two-Bloc Model



Source: Batini and Durand (2024).
Notes: The figure shows a stylized representation of the two-bloc model of Batini and Durand (2024). Starred variables refer to F bloc variables. K refers to physical capital; N, n_g, n_b refer to labor employed by the final good and intermediate goods sectors, respectively; I refers to the intermediate aggregate good; y_b, y_g refer to the intermediate brown and green inputs; Y_H, Y_F denote the final H, F produced output; K_N is the stock of Nature.

20. See Clark (2006).
21. See Clark (2010).

2.1 Natural Capital with no Critical Threshold

In the first version, the stock of natural capital can always recover to its original carrying capacity level, no matter what amount of depletion occurs between periods. In particular, in this version, the beginning-of-period stock of natural capital ($K_{N,t}$) depends nonlinearly on its "background" or "natural" regeneration rate, which in turn depends on how far the existing stock is from its carrying capacity level CC, as well as on the amount that is exploited for production:

$$K_{N,t+1} = K_{N,t} + r_N K_{N,t}\left(1 - \tfrac{K_{N,t}}{CC}\right) - K^b_{N,t}, \tag{1}$$
$$A_{N,t} \equiv r_N K_{N,t}\left(1 - \tfrac{K_{N,t}}{CC}\right)$$

where r_N is a parameter denoting the intrinsic regeneration rate, and $K^b_{N,t}$ refers to the amount of natural capital that is destroyed and used as an input in the production of the brown intermediate goods. We call the rate at which natural capital accumulates (or decumulates) through the impact of its own regeneration, given the beginning-of-period existing stock the *Accumulation rate* ($A_{N,t}$). It is important to note that, given this specification, the rate of accumulation also depends on the carrying capacity, CC, and that the rate of accumulation diminishes as the stock of natural capital approaches CC.

2.2 Natural Capital with an Exogenous and Known Critical Threshold

Since the ability of natural capital to recover may change when natural capital is less than a certain Critical Threshold (CT), we also consider a second version of the general specification, which makes the evolution of natural capital dependent on such threshold. Assuming that the level of CT is fixed and known to the agents in the economy, the equation for natural capital under this specification becomes:

$$K_{N,t+1} = K_{N,t} + r_N K_{N,t}\left(1 - \tfrac{K_{N,t}}{CC}\right)\left(\tfrac{K_{N,t}}{CT} - 1\right) - K^b_{N,t} \tag{2}$$
$$A_{N,t} \equiv r_N K_{N,t}\left(1 - \tfrac{K_{N,t}}{CC}\right)\left(\tfrac{K_{N,t}}{CT} - 1\right),$$

In this case, once $K_{N,t} < CT$, the existing stock of natural capital converges progressively to zero (an "environmental disaster" that would not allow life on earth). In other words, in the presence of a

critical threshold, the rate at which natural capital accumulates/decumulates depends not only on CC and r_N but now also on CT.

2.3 Natural Capital with an Endogenous and Unknown Critical Threshold

In our third, more realistic, specification for the evolution of natural capital we assume that i) the level of the CT is unknown to the agents of the economy, and ii) that crossing the CT does not imply a complete progressive depletion of natural capital but rather a permanent re-adjustment of its carrying capacity, towards an impaired, lower level.

This idea reflects the fact that, in environmental sciences, the level at which a tipping point is reached is typically unknown, but it is observed that crossing a tipping point usually switches the ecosystem into a possibly stable but less productive and/or healthy state. The case of the Atlantic rainforest is in point, in the sense that, as shown by research, the forest itself, when in a self-sustainable state, can recycle much of the rain that falls on it, generating a self-preserving cycle. Research suggests that removing as little as 30 percent of the forest cover can impede this self-perpetuating stabilizing cycle. Without this active restoration system in place, the system could flip to another state, such as a savannah grassland.[22] The specification that we adopt is reminiscent of the modeling of tipping points in climate change.[23] In our case, however, regime shifts are triggered by a reduction in the stock of Nature below a certain tipping point level. In particular, we assume that, conditional on not having crossed a tipping point at time t, there is a probability $h(K_{N,t}, K_{N,t+1})$ of crossing that point between time t and $t + 1$, depending on the stock of natural capital that is left after exploitation occurring at time t.

Formally, at the beginning of time t, conditional on not having crossed the threshold yet, the evolution of natural capital is uncertain.

$$\begin{aligned} K_{N,t+1} = {} & \left[1 - h\left(K_{N,t}, K_{N,t+1}\right)\right]\left(1 + r_N\left(1 - \tfrac{K_{N,t}}{CC}\right)\right)K_{N,t} \\ & + h\left(K_{N,t}, K_{N,t+1}\right)\left(1 + r_N^0\left(1 - \tfrac{K_{N,t}}{CC_0}\right)\right)K_{N,t} - K_{N,t}^b \end{aligned} \tag{3}$$

where $h(\bullet)$ denotes the probability of crossing the critical threshold between periods, CC is the current level of carrying capacity, and

22. See Nepstad and others (2007), Salati (1987), Farley (2008).
23. See Lemoine and Traeger (2014).

CC_0, r_N^0 are the alternative levels of carrying capacity and intrinsic regeneration rate towards which the system adjusts if the critical threshold is crossed. In the above expression, $K_{N,t+1}$ reflects uncertainty as of time t, its actual value only being revealed at the beginning of time $t + 1$, depending on whether the threshold has been crossed or not, given the exploitation/conservation choices made as of time t. In the following discussions, we will always assume that $CC_0 \leq CC$ and $r_N^0 \leq r_N$, meaning that activating the tipping point can reduce the carrying capacity of Nature, and/or its intrinsic regeneration rate.

The probability of crossing the threshold, which we call the *hazard ratio,* is endogenous and given by

$$h\left(K_{N,t}, K_{N,t+1}\right) = \max\left(0, \frac{max\left(K_{N,t+1}, \overline{K}_N\right) - K_{N,t}}{\overline{K}_N - K_{N,t}}\right) \tag{4}$$

where $\overline{K}_N$ corresponds to the level of K_N at which point crossing happens with probability 1.[24] This expression defines the hazard of crossing. As the economy consumes more stock of natural capital without crossing the threshold, the agents infer that the tipping point is somewhere below the current stock of natural capital. Importantly, as more depletion occurs, the probability of crossing increases. In this scenario, the critical threshold is unknown, and could be well above: in fact, every level of natural capital between $K_{N,t}$ and the value of $\overline{K}_N$ has an equal chance of being a critical threshold (e.g., the critical threshold is uniformly distributed between the initial existing stock of natural capital and $\overline{K}_N$).

2.4 Accumulation Rates

To help understand what these alternative specifications entail for K_N in practice, Figure 2 plots the rate at which natural capital evolves (that is, its accumulation rate A_N) with or without CT, normalizing the value of CC to 1.[25] In line with the above discussion, the figure shows that, in the absence of a critical threshold, the accumulation rate of natural capital is always positive and increases before decreasing

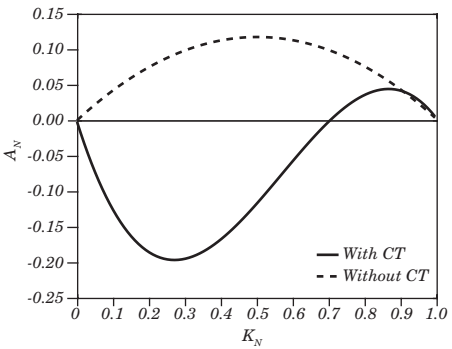
24. In a simpler specification it would be possible to consider the $h(\bullet)$ as exogenous, while still capturing the uncertainty associated with crossing the critical threshold.

25. The case with an endogenous CT is similar to the case without a CT since both the pre-tipping and post-tipping natural capital dynamics follow the specification assumed in the model without a CT.

in proximity of natural capital's maximum sustainable level, CC—namely, A_N is always above zero in the interval (0, 1), increasing for $K_N < CC/2$ and decreasing for $K_N > CC/2$. Conversely, in the presence of a critical threshold, A_N is negative for values below CT, but positive and increasing for a range of values between CT and CC before converging to zero as K_N approaches CC.

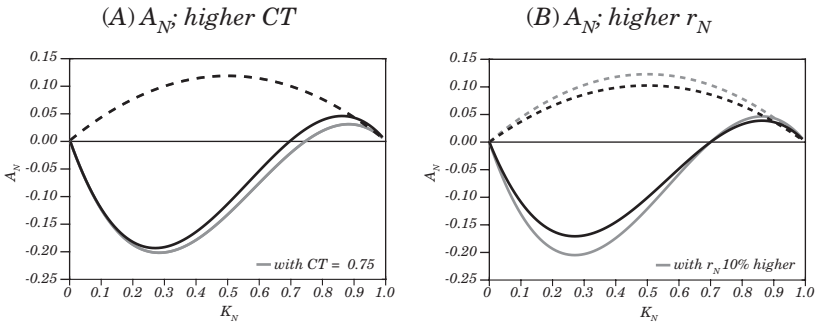
It is instructive to compare how the accumulation rate changes depending on the assumed values of the CT and regeneration rate, r_N, both of which are assumed exogenous and fixed in the setup. To this end, panel (A) in Figure 3 shows that a marginally higher critical threshold compresses the region where there is positive accumulation of K_N and impairs the regeneration rate when K_N is close to the CT, while panel (B) evidences an upward shift in A_N following an increase in r_N.

Figure 2. Nature Accumulation Rates (A_N)



Source: Authors' calculations.
Notes: $CC = 1$, $CT = 0.7$. $r_N = 1.4$ when assuming a CT, and $r_N = 0.4$ otherwise.

Figure 3. Nature Accumulation Rates (A_N) Counterfactual



Source: Authors' calculations.
Notes: Note: In the baseline, we set CC = 1, CT = 0.7. r_N = 1.4 when assuming a CT, and r_N = 0.4 otherwise. In counterfactual (A), CT = 0.75, while in counterfactual (B), r_N is increased by 10%. Counterfactuals are shown with grey lines.

2.5 Adding Uncertainty over the Regeneration Rate

In practice, under all three scenarios, the accumulation rate of natural capital remains uncertain because parametric shocks to each specification may affect the evolution of natural capital. To capture this, we go one step further in modeling K_N and postulate that there are shocks that affect multiplicatively the accumulation rate. Specifically, we define a stationary shock process:

$$ln\left(z_{t+1}\right) = \rho^N \, ln\left(z_t\right) + \sigma_\epsilon \epsilon_{t+1} \tag{5}$$

where $\sigma_\epsilon > 0$, $|\rho^N| \leq 1$ and $\epsilon_{t+1} \sim N(0, 1)$. We thus rewrite the law of motion of natural capital (in the absence of a critical threshold) as:

$$K_{N,t+1} = K_{N,t}\left(1 + z_t r_N \left(1 - \frac{K_{N,t}}{CC}\right)\right) - K^b_{N,t}, \tag{6}$$

We adopt the same approach when modeling natural capital in the presence of a critical threshold (both exogenous and endogenous). The multiplicative assumption implies that the greater A_N, the larger the uncertainty that the agents (or social planner) face when making optimal decisions, due to the higher impact that the shocks can have. Importantly, the (log) formulation of the shock implies that the accumulation rate cannot turn negative following the realization of a bad shock. This implies that it is always possible to compress exploitation of Nature enough so as to gradually allow

Nature to recover following a bad shock, even if close to the *CT*. This is a simplifying assumption, which we adopt to contain the studied equilibria within the economically sustainable region (to the right of the *CT*).

2.6 Optimal Management of Renewable Resources

The macroeconomic model (which we will also refer to as a "bio-economic", or Nature-economy model equivalently), once appropriately calibrated, can be used to analyze the optimal management of renewable natural resources. We refer the reader to the original paper for a discussion of the calibration and associated challenges. To streamline the presentation, in the following discussion, we omit possible externalities from the stock of Nature, meaning that the analysis can equally apply to a competitive equilibrium allocation or a social planning problem.[26]

Batini and Durand (2024) highlight that there are significant differences in economic and natural dynamics depending on whether the initial stock of Nature is abundant or not and also on whether Nature´s evolution is influenced by the existence of a critical threshold. A main result is that in the case of an initially quasi-pristine environment, and independently of the existence of a *CT*, it is always optimal to gradually decrease the stock of Nature. However, there are differences regarding the final steady-state level at which the economy converges in the long run. This happens because otherwise a large portion of K_N must be kept aside for conservation, which in turn implies reducing substantially the production of brown goods both presently and in the future, and brown goods are the dominant input in the production structure of the economy of aggregate intermediate goods. Importantly, the tradeoff between conservation and exploitation becomes larger as K_N is closer to its *CC* because, as K_N approaches its pristine level, the rate at which K_N accumulates if left untouched approches zero (even more, for levels of K_N above *CC*, it turns negative). In fact, for a level of $K_N = CC$, there is no natural regeneration, absent human interventions. This means that, to conserve the full stock of Nature, there should not be any level of brown production, an outcome

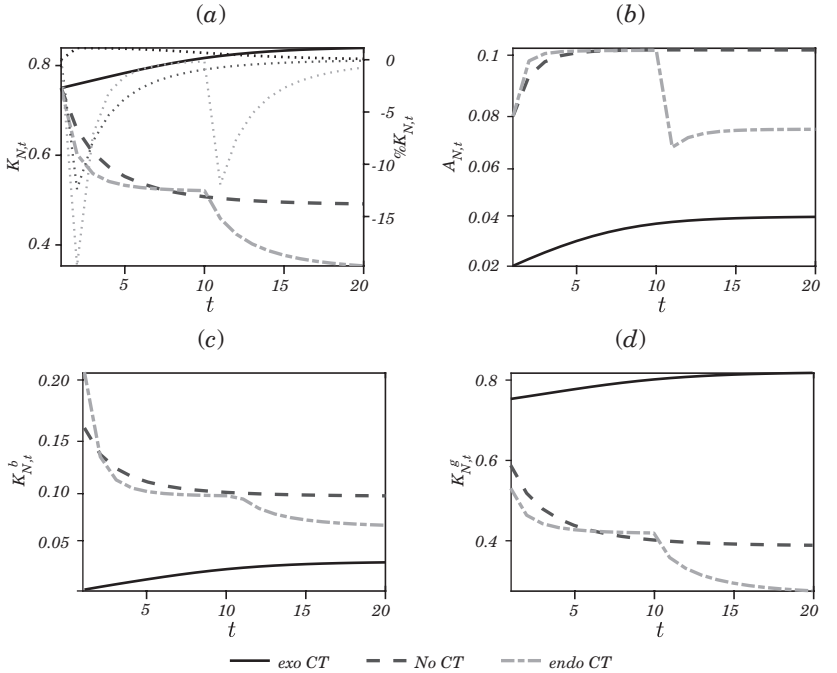
26. The possibility of externalities from the stock of Nature opens the door to a study of economic policies as the social planner and competitive equilibrium allocations would then differ; we refer the reader to the original paper for an exercise that involves subsidizing green production, including a welfare analysis.

that is clearly incompatible with life on earth. Starkly different results appear when an economy starts with a stock of Nature very well below its pristine level and possibly close to its (exogenously given) CT (when assumed). Figure 4 summarizes how K_N should be optimally managed in this case over the long run (we report the first 100 years), contrasting the three ecological modeling choices presented in the previous sections and assuming $K_{N,t0} = 0.75$, with an exogenous CT level equal to 0.7. The latter value is aligned with ecological findings—for instance, while some scientists go as far as to argue that already a 10 percent loss in biodiversity might be considered unsafe,[27] others are much less pessimistic, setting safe limits as low as 30 percent of the original biodiversity richness,[28] which is what we are going to assume moving forward.

Specifically, when assuming an exogenous CT, it becomes optimal to gradually conserve more natural assets than when the economy starts in an abundant K_N state. Incremental additions to K_N then allow for *both* more exploitation and conservation (K_N^b, K_N^g, respectively). A result of Batini and Durand (2024) is that, as the economy moves away from the CT, brown output can expand allowing for an overall increase in consumption through time from the initial levels. This happens because, with K_N initially close to CT, it is optimal at first to reduce brown output and divert labor resources to green production in order to raise the level of K_N from its critically depleted state. But as the economy moves away from its tipping point, it becomes increasingly inefficient to sacrifice brown production to favor green production, which only has a marginal role in total production. Despite this relocation of labor resources away from the green sector, the overall rate of decline in green production is muted, which is possible because when moving away from CT the rate at which Nature can regenerate itself increases, thus raising the endogenous accumulation rate, which in turn allows to count on more natural capital in the future while still allowing for more K_N accumulation in the near-term (as also shown in the top right panel of Figure 4).

27. See Newbold and others (2016).
28. See Steffen and others (2015).

Figure 4. Optimal Evolution of Natural Capital



Source: Authors' calculations.
Notes: $CC = 1$, $CC_0 = 0.7$, $r_N = r_N^0 = 0.4$. When modeling the case with an endogenous CT, we assume that the threshold is crossed over at $t = 10$. In the shown simulations, realizations of the shocks are set to 0.

When considering the case of an endogenous and unknown tipping point, the results are aligned with those from the model without CT, albeit with two major distinctions, as also highlighted in Figure 4.[29] First, the possibility of crossing the tipping point makes it optimal to eventually converge to a steady-state value of K_N, which is relatively higher as compared to the one in the simple model without a CT.[30]

29. We fix the lower threshold of the tipping probability, $K_N = 0.4$, a relatively low value. This parametrization implies that starting from a level of $K_{N,t0} = 0.75$ a 10% reduction of natural capital is tantamount to an approx. 21% probability of moving to the low-carrying capacity world.

30. Even though the initial drawdown is relatively stronger, since agents do not know which regime will be in place in the next period, and in case the post-tipping scenario materializes, having conserved too much Nature as compared to what is technologically efficient is costlier the farthest away from $CC_0/2$—the level at which the accumulation rate is maximized—the stock turns out to be.

Second, if the tipping point is crossed during the transition to the long-run steady state (which in the figure is assumed to happen at $t = 10$), the accumulation rate drops, as the law of motion of K_N is now regulated by CC_0 with $CC_0 < CC$ (we assume that $r_N = r_N^0$ for simplicity). This, in turn, contributes to an initially strong drawdown of Nature starting at $t = 11$, until convergence to the lower long-run stock compatible with the post-tipping carrying capacity level. This latter result arises because the carrying capacity in the post-tipping world is below that of the pre-tipping environment, so that the level of K_N that maximizes the accumulation rate is also relatively lower.

Having described how natural capital should be efficiently managed under our three alternative specifications, a further interesting question is the role that uncertainty plays in our setup. Up until now, the discourse assumed that all realizations of the shocks were equal to zero, which is convenient when emphasizing long-run dynamics, but this does not need to be the case. In truth it is more realistic to assume that the realizations of the shocks are different from zero, making the accumulation rate respond to nonmodeled factors, following the specification in Equation (5). This latter dynamic assumes that $\rho^N = 0.95$, a fairly high value which underscores that environmental events might have large persistence over Nature's future evolution.

We then propose the following exercise: the economy starts with a stock of Nature close to its exogenous CT (if assumed) and experiences a sequence of (positive and negative) shocks (ϵ_t), starting with a negative shock at $t = 2$. This means that z_t, which regulates the intrinsic regeneration rate of Nature, falls below 1 at $t = 2$. The shock, while not pushing the ecological system beyond the tipping point (by construction—see our discussion on uncertainty), still incapacitates Nature's ability to regenerate itself over time. How, then, does the evolution of consumption differ from a scenario where all shocks are set to zero, especially with regard to the case where there is an exogenous CT?

Figure 5 summarizes the simulations from this exercise, showing the impacts on consumption, green labor, and the accumulation rate of K_N. Dashed lines represent the scenario where all realizations of the shocks are zero, while solid lines refer to the case where shocks can vary over time. Macroeconomic variables are expressed in percentage deviations from their initial (t_0) levels. As discussed above, the optimal management of K_N leads to a gradual increase in

consumption (independently of the presence of a *CT*) and a gradual increase (decrease) in green labor in the scenario without (with) a *CT*.[31]

Importantly, the figure also illustrates that when introducing a negative shock to z_t, the presence of a *CT* requires keeping consumption approximately constant at its initial level. This happens because the agents are efficiently conserving more Nature and also shifting more labor resources to the green sector (as also highlighted in the figure by the smaller decline in green labor, as compared to the scenario without shocks), which however contributes much less to the production of the final home goods.

We repeat the exercise, this time comparing the case without a *CT* together with the case where there is an endogenous and unknown *CT*, which, in this case, is never crossed over throughout the simulation. Hence, in both scenarios, the underlying ecological process of Nature remains the same over time. Figure 6 summarizes the results, which highlight how the possibility of crossing the threshold dramatically changes the efficient evolution of consumption and labor dedicated to the green sector, over the next 25 years (e.g., five periods in the model). In particular, while in the absence of a *CT* it is efficient to sustainably increase consumption for several periods, as more Nature is exploited, this is no longer the case when agents rationally internalize that more exploitation increases the probability of tipping over the edge of Nature. This is also well reflected in the difference in accumulation rates, which shrinks as the economy precautionarily settles over time at a steady state further to the right of $CC/2$ (the stock of Nature that maximizes the ecological accumulation rate, as also shown in Figure 2).

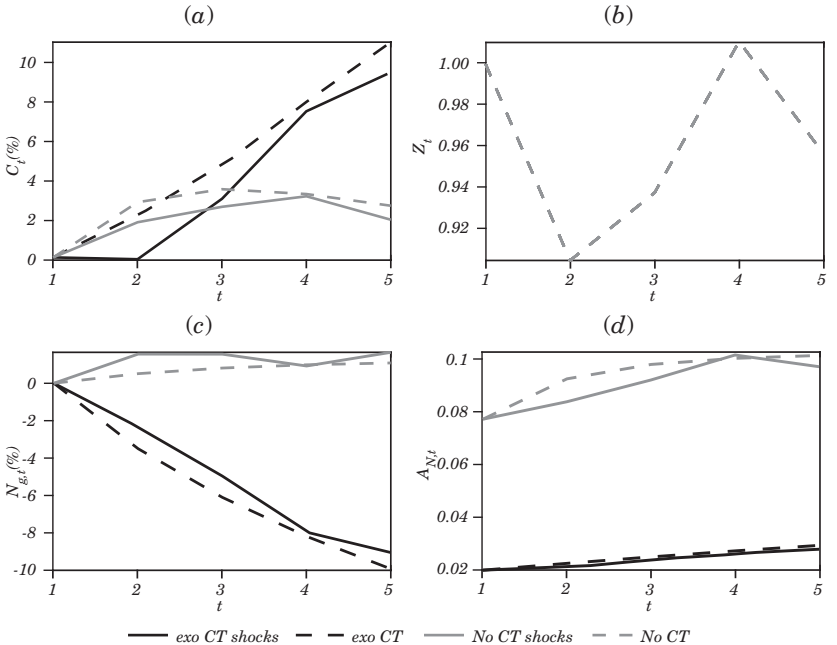
3. Studying the Green Transition using the Bio-Economic Model

The analytical framework presented in this chapter can be used as a foundation to a multitude of analyses and exercises. In particular, central banks and other policy institutions can benefit from a deeper understanding of how nature degradation interacts with the financial system and the economy at large,[32] especially with an eye on the green transition.

31. The gradual (but temporary, as suggested by the figure, showing a reversion starting in period 5) increase in consumption in the no-*CT* scenario arises because the speed of physical disinvestment is faster than the speed at which output declines, which in equilibrium allows for greater consumption.

32. See ECB (2023).

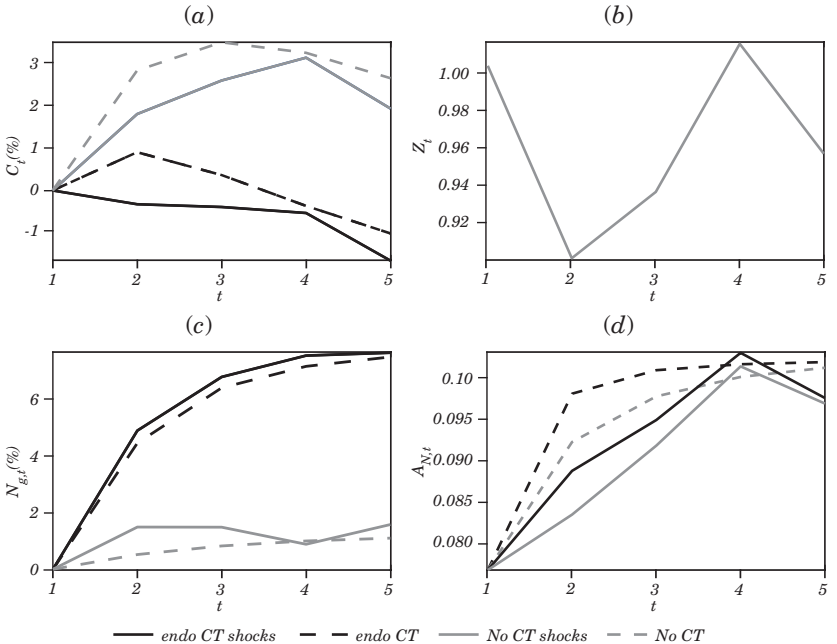
Figure 5. Evolution of Selected Variables



Source: Authors' calculations.
Notes: $CC = 1$, $CT = 0.7$, $K_{N,t0} = 0.75$. Light solid (dashed) lines refer to the *No-CT* case with (without) shocks, while dark solid (dashed) lines refer to the *CT* case with (without) shocks. Each macroeconomic variable is expressed in terms of the percentage change with respect to its initial level at $t0$. The variable $N_{g,t}$ refers to labor employed by the green sector, and the variable C_t to consumption.

This section builds on the previous discussions and results and summarizes how the bio-economic model just presented can be adapted for such purposes. The green transition should be understood as a gradual shift toward an economy that is less based on over-exploitation of natural resources and that instead relies relatively more on sustainable activities aligned with the concept of the circular economy, including the adoption of polyculture and regenerative land and ocean farming, conservation activities, and sustainable forest management. We will structure our discussion of the transition around three broad thematic analyses, namely, the short-run macroeconomic impacts on quantity and prices, the importance of distinguishing between local versus global environmental policies, and the structural shifts in preferences, technologies, and mutating ecological dynamics that will arise along the way.

Figure 6. Evolution of Selected Variables



Source: Authors' calculations.
Notes: $CC = 1$, $CT = 0.7$, $K_{N,t0} = 0.75$. Light solid (dashed) lines refer to the *exo-CT* case with (without) shocks, while dark solid (dashed) lines refer to the *endo-CT* case with (without) shocks. Each macroeconomic variable is expressed in terms of the percentage change with respect to its initial level at $t0$. The variable $N_{g,t}$ refers to labor employed by the green sector, and the variable C_t to consumption.

3.1 Short-Run Macroeconomic Effects of a Green Transition

As ecological systems degrade, supply-side disruptions are expected to become more frequent, generating potential uncertainty that economic forecasters and policymakers need to take into account when making decisions. Ecological phenomena in particular are increasingly being considered as relevant drivers of output loss and inflation, for example through droughts that cause a reduction in agricultural output.[33] As stressed by the World Bank, the economic cost in terms of GDP loss due to a partial collapse of ecosystem services would be large, with the majority of countries in the analyzed sample potentially

33. See Barnes and Bosch (2024).

suffering an economic decline larger than that caused in 2020 by the Covid-19 lockdowns.[34] From an economic policy perspective, these predictions point to far-reaching effects via economic and financial markets. One example in this direction is Burke and others (2025), who propose analyzing how ecological collapse can affect sovereign borrowing through changes in credit ratings. Another case in point is Pinto-Gutiérrez (2023), who documents that droughts increase mining companies' loan spreads and influence financial institutions' premiums on loans granted to mining companies. Similarly, Giglio and others (2023) find that the returns of an equity portfolio long in industries with low biodiversity risk exposures and short in industries with high biodiversity risk exposures is positively correlated with an aggregate index of biodiversity risk, which suggests that financial markets participants are pricing in the risk of ecosystem degradation when valuing companies.

On the monetary front, while there is uncertainty over the final qualitative impact on headline inflation (for example, because risk-adverse consumers might cut back on consumption when faced with more frequent environmental shocks, which partly compensates price pressures), there seems to be a consensus that worsening ecological dynamics do lead to an increase in price variability.[35] From a monetary policy perspective, some of the challenges that are usually discussed in the context of climate change are also relevant when looking at biodiversity losses; specifically, central bankers need to adapt their toolkits taking into account the impact of physical risks and transition risks on the conduct of monetary policy. For example, changes in the natural interest rate, which could be falling in the context of lower productivity and increased risk aversion, might reduce the space for conventional instruments used when fighting inflation. Also, supply shocks that lower economic activity while increasing prices might worsen the typical tradeoff with price stability.[36] In this context, it is reasonable to argue that, even from a strictly financial standpoint, a gradual shift away from carbon-intensive activities that exacerbate the effects of natural hazards and extreme weather events is justified.[37]

34. See World Bank (2021).

35. See Ciccarelli and others (2023).

36. The NGFS Macroeconomic Modeling Handbook (NGFS, 2024) presents a comprehensive survey on how economic frameworks, including neoKeynesian setups, should adapt to take into account these challenges in the context of climate change.

37. See Saco and others (2021).

The two-bloc Nature-economy model provides a useful platform to analyze these issues at large. For instance, introducing nominal stickiness as in Calvo (1983) could be easily done by assuming that the brown and green intermediate inputs are characterized by monopolistic competition, giving rise to some degree of price rigidity. Also, some degree of nominal wage stickiness could be assumed, as done for example, in García and others (2019). Importantly, the distinction between intermediate green and brown inputs allows to capture that the prices of the latter are generally relatively less sticky than those of the former[38] and also the imperfect substitutability of both inputs for production of the final consumption goods. This is essential since, when inputs cannot be freely substituted for, there is a tradeoff from transitioning, as brown taxes do increase marginal costs for the rest of the economy. In particular, price rigidity combined with downward rigidity in nominal wages can lead to a "green-transition-led" recession. The recession is deeper when an inflation-targeting central bank reacts to the increase in headline and core inflation, both of which tend to increase. According to Del Negro and others (2023), these dynamics are however short-lived to the extent that the central bank does not respond to the increase in inflation and remains committed to closing the output gap, arguably without a loss in credibility. These macroeconomic effects seem supported also by empirical analysis[39] and other modeling work,[40] even though further analysis is needed in the context of emerging and developing countries, where monetary policy frameworks are on average relatively weaker[41] and where deviations (albeit temporary) from an inflation-targeting regime coupled with a drop in local economic activity might give space to instabilities and nonlinear effects, via capital flows.[42]

In the Nature-economy model, the possibility of a tipping point further adds a layer of complexity to the analysis since the closer the economy is to its ecological critical threshold, the lower the accumulation rate of Nature. This means that if, when transition policies are first introduced (for example via a tax on brown activities), the economy is close to its *CT*, one of the factor inputs (Nature) cannot change much despite shifting sectoral demand for green goods. This is a simple point, yet it has important implications.

38. See Del Negro and others (2023).
39. See Konradt and Weder di Mauro (2023).
40. See Olovsson and Vestin (2023).
41. See IMF (2023).
42. See Batini and Durand (2021).

In fact, in the limit, the natural production factor is fixed, since as shown in Equation (2), $limK_{N,t \to CT} A_{N,t} = 0$, that is, the accumulation rate goes to zero. One important implication is that this impairment in the capacity of Nature to grow in the short-term also reduces the scope for greater productivity enhancements that would otherwise be expected to materialize through a reduction in any pre-existing negative externality on productivity.

From an economic standpoint this implies that, for a given level of productivity, the closer the economy is to $A_{N,t} = 0$, the greater the amount of labor that needs to shift from the brown and final consumption goods sectors to the green intermediate sector in order to reach a certain level of production of green goods (and under usual assumptions regarding production, such as constant returns to scale, we know that the marginal product of labor, for a given fixed amount of the other factors inputs, is decreasing). Of course, at the optimum, there is a tradeoff which balances the decrease in the production of H and b intermediates (from lower labor dedicated to these sectors and also less exploited natural resources) against the marginal costs from keeping the g intermediate production at its pre-transition level. In equilibrium, the tradeoff determines the efficient decline in the production of the aggregate intermediate input that maximizes economic welfare. Overall, these nuances suggest that in the bio-economic model, the "policy-induced" recession might be more protracted in time if implemented too late (that is when the economy is already reaching its tipping point) and when not accompanied by changes in technology and/or production paradigms that reduce the reliance on brown inputs, as we will further explore below.

3.2 Global Policies, Local Policies, and Political Economy Considerations

The overall economic effect of a green transition on the world economy also depends on whether the policies are enacted globally or locally, and also on how each (local) authority responds to other authorities, including on whether there is some degree of policy coordination across the various regions of the world. The bio-economic model is rich enough to make all these distinctions and carry out a comprehensive analysis. For instance, global policies could be introduced *via* a tax/subsidy on all intermediate brown production, while local policies could be modeled via a tax/subsidy on brown imports that are purchased by the foreign bloc (or similarly on brown

goods that are purchased by the home bloc). Policy coordination could be easily introduced, assuming that each bloc either sets the tax/subsidy as a Nash equilibrium outcome (for example, via a National Social Planner), taking as given the other bloc's policy, or instead as a solution to a worldwide planning problem where a single social planner sets the optimal instruments.

While existing climate economy models emphasize that emerging markets, being the major producers of brown (CO_2-emitting) goods,[43] are unlikely to initiate by themselves sufficient climate and environmental policies,[44] our setup allows for a more pragmatic discussion of the issue. In particular, by underscoring the dual use of the stock of Nature—as an input required to carry out exploitative activities and also as an input in conservation activities—our model suggests that it is possible for emerging markets to (at least in part) shift their prevailing economic modes of production toward sustainability without necessarily compromising long-run economic development. In fact, our framework suggests quite the opposite, which is that it is more efficient to start out implementing the policy when the stock of Nature is still abundant, permitting an alignment between private and social marginal values from the get-go, rather than in an environment where a previously inefficiently high production of brown goods ultimately led the economy relatively closer to a tipping point. Then it requires reorienting a relatively larger amount of resources toward the green sector, to avoid crossing the *CT*. Importantly, crossing the *CT* is not optimal as it puts in motion a decline in the natural stock independently of what economic policies are implemented thereafter (that is, in our framework, both tipping-points specifications are built following a "point of no return" paradigm). In this sense, as compared to traditional climate economy models where small countries/regions might see higher temperatures as exogenous to domestic environmental policies, our model infuses a local, self-interested, rationale to enact green policies sooner rather than later (or never).

Our assumption that it is possible to produce goods and services without harming the environment is backed by solid evidence and increasing support from policymakers. As an illustrative example, consider the case of Virunga National Park located in the Democratic Republic of Congo, and which dedicates resources to conservation efforts. Virunga's estimated total annual economic value in 2013,

43. See Cole and others (2021).
44. See Minesso and Pagliari (2023).

despite the significant fragilities afflicting the country, was approximately USD 48.9 million, 41 of which correspond to direct-use values such as fisheries and tourism.[45] According to the same report, in a stable situation conducive to economic growth and tourism, the park's total economic value could be higher than USD 1.1 billion per year and could be the source of more than 45,000 jobs. Several other examples in more stable geographic regions confirm the vast economic potential that derives from the sustainable use of the stock of Nature.[46] In another case in point, demonstrating the strong support that conservation is attracting among policy institutions, the European Investment Bank argues that investing in forests can enhance economic growth in rural communities.[47]

Distinguishing between the geographic location where green policies are enacted is also fundamental from a political economy standpoint. For instance, advanced economies' push to introduce sustainability requirements affecting international trade (via for example carbon border adjustments) and also their objective to swiftly and rapidly embark on a net zero transition[48] might be perceived as an example of "regulatory imperialism", which could ultimately lead to a worsening of trade relationships and less willingness to embrace sustainability as a long-term development paradigm. As an example of such brooding attacks, Almeida and others (2023) argue how the European Green Deal should be interpreted as "a regime imbricated in colonial and neocolonial motivations viewing peripheral countries and societies as policy deficient, climatically unambitious, and in need of 'capacity-building' for sustainability and development". Along the same lines, Zografos and Robbins (2020) underscore that, despite its good intentions, the Green New Deal will generate new "sacrifice zones", meaning geographic areas in the Global South that will be negatively affected by "the sourcing, transportation, installation, and operation of solutions for powering low-carbon transitions, as well as end-of-life treatment of related material waste". In fact, aside from the rhetoric, mounting evidence suggests that it is already happening, as convincingly documented by Pitron (2020) for the case of China (for example, in the Nancheng county, Jiangxi province). In a similar vein, Meijaard and others (2020) discuss the role of palm oil, from which the

45. See WWF (2013).
46. See Chidakel and others (2020).
47. See EIB (2022).
48. See Almeida and others (2023).

majority of biodiesel is produced, in deforestation, suggesting that oil palm expansion directly contributed to regional tropical deforestation with values ranging from 3 percent in West Africa to 50 percent in Malaysian Borneo. As a result, several once populous species, including the orangutan, the tiger, and the white rhino, have become critically endangered.

In parallel to these concerns, other critics argue that some of the green actions and frameworks embraced by the North are no more than a *façade*: firms' practical actions deviate from their Environmental and Social Governance (ESG) disclosures, environmental tax reform significantly increases greenwashing of highly polluting companies, and firms facing rising tax costs associated with environmental standards tend to reduce green innovation.[49] All this seems to suggest that studying sustainability and finding solutions that emphasize "the local" rather than "the global" side of the equation could be given more prominence and might ultimately prove to be of great effect in shaping tomorrow's world.

3.3 Long-Run Structural Changes of a Green Transition

A realistic analysis of a green transition should account for the fact that, as time passes, the very foundations of our production system are also evolving. A similar argument applies in the case of the natural world, whose dynamics are endogenously mutating depending on the ecological pressures exerted upon it. Unfortunately, current macroeconomic research generally sidesteps these realities and tends to assume that, while technology might mutate and policies might change, the foundations of the economy are immutable.[50] In technical terms, this happens because standard DSGE models assume that the policy functions, which map the states of the economy (and of the natural world) to the actions of the agents within the model, are stationary; that is, there is time homogeneity in the Markov decision functions. Of course, this class of models could be adapted without resorting to a nonstationary framework by simply gluing together a sequence of stationary model simulations, one for each period of time, and solving each one of these fundamentally different models one by one, independently of one another. While this shortcut allows

49. See Hu and others (2023).

50. See Airaudo and others (2023), Olovsson and Vestin (2023), Konradt and Weder di Mauro (2023).

to construct, by connecting each decision function, a time path of optimal choices that are specific to the structure of the economy in each period, it would still neglect the connections that exist between different time periods, including uncertainty and anticipatory effects, which are arguably essential to an analysis of the transition.[51]

In this respect, our framework innovates as compared to the majority of the existing macroeconomic literature in the sense that it can be easily extended to allow for both uncertainty and time-dependent scenarios, both of which are required to represent economic and natural nonstationary changes. The reason behind such flexibility is that the bio-economic model solution technique directly borrows from Maliar and others (2020), which assumes time-inhomogeneous (nonstationary) policy choice functions. Different from the time-homogeneous model, where all parameters are time invariant and known to the agents since the beginning of time, in our setup, scenarios can be time-dependent and future values of the parameters unknown to the agents, or known only up to a certain probability. In the next paragraphs, we review two relatively easy examples that could be integrated into the bio-economic model to better represent real-world dynamics.

The first example assumes that the law of motion of natural capital is subject to state-dependent shocks. In this case, we could consider that σ_ϵ (or ρ) in Equation (5) is time-varying. Instead of modeling the volatility parameter as an ARCH process,[52] it could be assumed that, as the stock of Nature approaches the *CT* of the economy, the variability in the size and persistence of the shocks associated with the regeneration rate becomes larger due, for example, to more frequent and large extreme natural events.[53] This modeling would strengthen the argument to reduce natural capital exploitation, since as the economy embraces more sustainable means of production and moves away from its *CT*, the ecological process of accumulation becomes over time more stable and less subject to serpentine changes. This might have relevant welfare implications for developing and poor countries where climate risk insurance is often lacking or insufficient.[54]

Another direct example is the case of structural economic changes and/or technical advancements. This could involve a shift in the

51. See Fried and others (2022).
52. See Bollerslev and others (1994).
53. See Silva and others (2023).
54. See Madaki and others (2023).

parameters regulating the share and/or the elasticity of substitution between green and brown intermediate inputs. As a practical example, consider the share of green intermediate goods that are used to produce the final inputs—let's call it $\omega_{G,t}$. This parameter can gradually increase as time passes and also make sudden jumps. This evolution could be anticipated or not, and could also be embedded within a Markov transition matrix, with exogenously given probabilities. The simulated paths could reflect changes in policies, technological changes, or shifting preferences (for instance, agents might become more sensitive to sourcing sustainably produced inputs that originate from polyculture and regenerative land and ocean farming, conservation activities, and sustainable forest management).

A more sophisticated version of the Nature-economy model could naturally endogenize such dynamics along the lines explored in Acemoglu and others (2012), where it is assumed that the economy has "scientists" who can move across sectors and, through their discoveries, improve sector-specific productivity. A limited number of available scientists reflects that an improvement in technology in one sector comes at the expense of the other sector, generating a tradeoff (a direct manifestation of scarcity).[55] Technological advancements could allow for economic activities such as textiles, manufacturing, and real estate to reduce their use of virgin materials (for example, through renewable energy production, recycling of material inputs, etc.), thus expanding the potential of a circular economy. Also, while all energy production, including green energy, requires at its origin the exploitation of Nature, new technologies could lower the associated environmental pressure. For example, in the case of the infrastructures needed to produce green energy, which rely on rare earth minerals, new extraction and separation techniques might eventually become less taxing on the environment.[56,57] In modeling terms, this could result in final goods output that is generated by a relatively larger share of green (i.e., nonnatural capital depleting) inputs as opposed to brown inputs. To this end, $\omega_{G,t}$ could be assumed to be an affine function of the level of green technology in place, mimicking what is done by Antosiewicz and Kowal (2016) in the context of sectoral physical capital investments.

55. An equivalent approach is to assume a "technology" menu as in Hassler and others (2021).

56. See He and others (2019).

57. The amount of rare metals required for stationary power storage batteries such as those used in electric vehicle is significant (IEO, 2022); given the current technologies, phasing out fossil fuels seems quite unrealistic.

4. Conclusion

In this paper, we emphasized the importance of accounting for Nature in macroeconomic modeling by first reviewing past and present research that accounts for the material foundations of production (starting from models with nonrenewable resources to frameworks that fully develop the concept of natural capital). We then complemented this literature review by describing a novel framework. The latter extends a standard DSGE setup by embedding natural capital—defined as a variety of ecosystem goods and services essential to economic activity—alongside man-made capital.

The proposed model already features all key ingredients necessary for an informed discussion. To this end, we reviewed how natural capital and economic variables evolved towards their long-run equilibria starting from different states of the world and different assumptions regarding the evolution of natural capital: a world still rich in natural assets and a world in which these assets have been critically depleted; a world where there is no critical threshold and a world where it is possible to permanently alter the way biodiversity can regenerate over time. We also discussed some implications for economic variables and showed the role that uncertainty about some of the ecological parameters driving the stock of Nature plays in transitioning away from an equilibrium close to a tipping point.

The proposed framework opens the doors to further policy-relevant extensions, such as the study of the economic impact of greening the production structure of an economy. The latter is, we believe, an essential step forward, since without allowing the model to account for changes in the way we produce goods and relate to material consumption, any attempt at redistributing labor and human-made capital resources from the traditional sectors to the sustainable sectors in a world dominated by the former is going to prove costly in the short-run and hence without (much needed) political traction. The third part of this study offered a broad discussion of these possible extensions by emphasizing the importance of accounting for the short-run macroeconomic effects of such a transition, the tension that could materialize between local versus global environmental policies—especially when the latter are implemented without sufficient involvement of all stakeholders—, and finally the necessity to extend the framework to allow for time-dependent scenarios that can fully capture shifts in preferences, technologies, and ecological processes.

References

Acemoglu, D., P. Aghion, L. Bursztyn, and D. Hemous. 2012. "The Environment and Directed Technical Change." *American Economic Review* 102(1): 131–66.

Airaudo, F.S., E. Pappa, and H.D. Seoane. 2023. "The Green Metamorphosis of a Small Open Economy." Working Papers No. 219, Centre for Economic Policy Research.

Albagli, E. and J. Vial. 2023. "Biodiversity and Economic Growth: Something Must Give." Technical Report 70, Economic Policy Papers, Central Bank of Chile.

Almeida, D.V., V. Kolinjivadi, T. Ferrando, B. Roy, H. Herrera, M.V. Gonçalves, and G. Van Hecken. 2023. "The "Greening" of Empire: The European Green Deal as the EU First Agenda." *Political Geography* 105: 102925.

Antosiewicz, M. and P. Kowal. 2016. *Memo iii-A Large Scale Multi-Sector DSGE Model.* IBS Research Report 02/2016.

Aronson, J., S.J. Milton, and J.N. Blignaut. 2007. "Restoring Natural Capital: Definitions and Rationale."

Barnes, D. and J.S. Bosch. 2024. *Inflation as an Ecological Phenomenon*. London, UK: *Positive Money*.

Batini, N. and L. Durand. 2021. "Facing the Global Financial Cycle: What Role for Policy." IMF Working Paper No. 2021/171, International Monetary Fund.

Batini, N. and L. Durand. 2024. "Accounting for Nature in Economic Models." Working Paper No. 1014, Central Bank of Chile.

Bollerslev, T., R.F. Engle, and D.B. Nelson. 1994. "Arch Models." *Handbook of Econometrics* 4: 2959–3038.

Bovenberg, A.L. and R.A. De Mooij. 1994. "Environmental Levies and Distortionary Taxation." *American Economic Review* 84(4): 1085–89.

Bovenberg, A.L. and L.H. Goulder. 1996. "Optimal Environmental Taxation in the Presence of Other Taxes: General-Equilibrium Analyses." *American Economic Review* 86(4): 985–1000.

Bovenberg, A.L. and S. Smulders. 1995. "Environmental Quality and Pollution-Augmenting Technological Change in a Two-Sector Endogenous Growth Model." *Journal of Public Economics* 57(3): 369–91.

Brander, J.A. and M.S. Taylor. 1997. "International Trade between Consumer and Conservationist Countries." *Resource and Energy Economics* 19(4): 267–97.

Bringezu, S., Schütz, H., Moll, S. 2003. "Rationale For and Interpretation of Economy Wide Materials Flow Analysis and Derived Indicators." *Journal of Industrial Ecology* 7(2): 43–64.

Brock, W.A. and M.S. Taylor. 2010. "The Green Solow Model." *Journal of Economic Growth* 15: 127–53.

Burke, M., M. Agarwala, P. Klusak and K. Mohaddes. 2024. "Climate Policy and Sovereign Debt: The Impact of Transition Scenarios on Sovereign Creditworthiness." Centre for Applied Macroeconomic Analysis Working Paper 73/2024.

Calvo, G.A. 1983. "Staggered Prices in a Utility-Maximizing Framework." *Journal of Monetary Economics* 12(3): 383–98.

Chidakel, A., C. Eb, and B. Child. 2020. "The Comparative Financial and Economic Performance of Protected Areas in the Greater Kruger National Park, South Africa: Functional Diversity and Resilience in the Socio-Economics of a Landscape-Scale Reserve Network." *Journal of Sustainable Tourism* 28(8): 1100–19.

Ciccarelli, M., F. Kuik, and C.M. Hernández. 2023. "The Asymmetric Effects of Weather Shocks on Euro Area Inflation." Working Papers No. 2798, European Central Bank.

Clark, C.W. 2006. "Fisheries Bioeconomics: Why Is It So Widely Misunderstood?" *Population Ecology* 48(2): 95–8.

Clark, C.W. 2010. *Mathematical Bioeconomics: The Mathematics of Conservation.* Hoboken, NJ: John Wiley & Sons.

Cole, M.A., R.J. Elliott, T. Okubo, and L. Zhang. 2021. "Importing, Outsourcing and Pollution Offshoring." *Energy Economics* 103: 105562.

Common, M. 1997. "Towards an Ecological Economics of Sustainability." In *Economics of Ecological Resources*, Edward Elgar Publishing.

Comolli, P. 2006. "Sustainability and Growth When Manufactured Capital and Natural Capital Are Not Substitutable." *Ecological Economics* 60(1): 157–67.

Costanza, R. and H.E. Daly. 1992. "Natural Capital and Sustainable Development." *Conservation Biology* 6(1): 37–46.

D'Alessandro, S. 2007. "Non-Linear Dynamics of Population and Natural Resources: The Emergence of Different Patterns of Development." *Ecological Economics* 62(3-4): 473–81.

Dalton, T.R., R.M. Coats, and B.R. Asrabadi. 2005. "Renewable Resources, Property Rights Regimes, and Endogenous Growth." *Ecological Economics* 52(1): 31–41.

Dasgupta, P. 2021. "The Economics of Biodiversity: The Dasgupta Review." HM Treasury, 2021.

Dasgupta, P., R. Eastwood, and G. Heal. 1978. "Resource Management in a Trading Economy." *Quarterly Journal of Economics* 92(2): 297–306.

Dasgupta, P. and G. Heal. 1974. "The Optimal Depletion of Exhaustible Resources." *Review of Economic Studies* 41: 3–28.

Dasgupta, P. and K.G. Mäler. 2004. *The Economics of Non-Convex Ecosystems: Introduction*. New York, NY: Springer.

Del Negro, M., J. Di Giovanni, and K. Dogra. 2023. "Is the Green Transition Inflationary?" Staff Report. Federal Reserve Bank of New York.

European Central Bank (ECB). 2023. *The Economy and Banks Need Nature to Survive.*

European Investment Bank (EIB). 2022. *Forests at the Heart of Sustainable Development*.

Farley, J. 2008. "The Role of Prices in Conserving Critical Natural Capital." *Conservation Biology* 22(6): 1399–408.

Fischer-Kowalski, M., F. Krausmann, S. Giljum, S. Lutter, A. Mayer, S. Bringezu, Y. Moriguchi, H. Schütz, H. Schandl, and H. Weisz. 2011. "Methodology and Indicators of Economy-Wide Material Flow Accounting: State of the Art and Reliability across Sources." *Journal of Industrial Ecology* 15(6): 855–76.

Fried, S., K. Novan, and W.B. Peterman. 2022. "Climate Policy Transition Risk and the Macroeconomy." *European Economic Review* 147: 104174.

Fullerton, D. and G.E. Metcalf. 1997. "Environmental Taxes and the Double-Dividend Hypothesis: Did You Really Expect Something for Nothing?" National Bureau of Economic Research Working Paper No. 6199.

García, B., S- Guarda, M. Kirchner, and R. Tranamil. 2019. "Xmas: An Extended Model for Analysis and Simulations." Working Paper No. 833, Central Bank of Chile.

Giglio, S., T. Kuchler, J. Stroebel, and X. Zeng. 2023. "Biodiversity Risk." National Bureau of Economic Research Working Paper No. 31137.

Hartwick, J.M. 1977. "Intergenerational Equity and the Investing of Rents from Exhaustible Resources." *American Economic Review* 67(5): 972–74.

Hassler, J., P. Krusell, and J. Nycander. 2016. "Climate Policy." *Economic Policy* 31(87): 503–58.

Hassler, J., P. Krusell, and C. Olovsson. 2021. "Directed Technical Change as a Response to Natural Resource Scarcity." *Journal of Political Economy* 129(11): 3039–72.

He, Y., S. Guo, K. Chen, S. Li, L. Zhang, and S. Yin. 2019. "Sustainable Green Production: A Review of Recent Development on Rare Earths Extraction and Separation Using Microreactors." *ACS Sustainable Chemistry and Engineering* 7(21): 17616–26.

Hediger, W. 1997. "Ecological Economics of Sustainable Development." *Sustainable Development* 5(3): 101–9.

Hinterberger, F., F. Luks, and F. Schmidt-Bleek. 1997. "Material Flows vs. Natural Capital: What Makes an Economy Sustainable?" *Ecological Economics* 23(1): 1–14.

Hotelling, H. 1931. "The Economics of Exhaustible Resources." *Journal of Political Economy* 39(2): 137–75.

Howitt, P. and P. Aghion. 1998. "Capital Accumulation and Innovation as Complementary Factors in Long-Run Growth." *Journal of Economic Growth* 3(2): 111–30.

Hu, S., A. Wang, and K. Du. 2023. "Environmental Tax Reform and Greenwashing: Evidence from Chinese Listed Companies." *Energy Economics* 124: 106873.

IMF Independent Evaluation Office (IEO). 2022. "The Market for Rare Metals and Implications for Phasing Out Fossil Fuels: Where Do We Stand?" YouTube, uploaded by IMF, https://youtu.be/mlDga99zgqQ.

International Monetary Fund (IMF). 2023. "Global Recovery Remains Slow, with Growing Regional Divergences and Little Margin for ´Policy Error". *World Economic Outlook*.

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). 2016. "The Assessment Report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services on Pollinators, Pollination and Food Production."

Jackson, T. 2016. *Prosperity Without Growth: Foundations for the Economy of Tomorrow.* London, UK: Routledge.

Karp, L. and A. Rezai. 2014. "The Political Economy of Environmental Policy with Overlapping Generations." *International Economic Review* 55(3): 711–33.

Karp, L., S. Sacheti, and J. Zhao. 2001. "Common Ground between Free-Traders and Environmentalists." *International Economic Review* 42(3): 617–648.

Karp, L., J. Zhao, and S. Sacheti. 2003. "The Long-Run Effects of Environmental Reform in Open Economies." *Journal of Environmental Economics and Management* 45(2): 246–64.

Konradt, M., and B. Weder di Mauro. 2023. "Carbon Taxation and Greenflation: Evidence from Europe and Canada." *Journal of the European Economic Association* 21(6): 2518–46.

Kornafel, M. and I. Telega. 2019. "Natural Capital in Economic Models." *Statistical Review* 65(3): 253–70.

Kornafel, M. and I. Telega. 2020. "Dynamics of Natural Capital in Neoclassical Growth Models." *International Journal of Sustainable Economy* 12(1): 1–24.

Lemoine, D. and C. Traeger. 2014. "Watch Your Step: Optimal Policy in a Tipping Climate." *American Economic Journal: Economic Policy* 6(1): 137–66.

Madaki, M.Y., H. Kaechele, and M. Bavorova, M. 2023. "Agricultural Insurance as a Climate Risk Adaptation Strategy in Developing Countries: A Case of Nigeria." *Climate Policy* 23(6): 747–62.

Maliar, L., S. Maliar, J.B. Taylor, and I. Tsener. 2020. "A Tractable Framework for Analyzing a Class of Nonstationary Markov Models." *Quantitative Economics* 11(4): 1289–323.

Meadows, D.H., D.L. Meadows, J. Randers, and W.W. Behrens III. 1972. *The Limits to Growth: A Report for the Club of Rome's Project on the Predicament of Mankind.* Universe Books.

Meadows, D.H., D.L. Meadows, and J. Randers. 2004. *Limits to Growth: The 30-Year Update*. London, UK: Chelsea Green Publishing.

Meijaard, E., T.M. Brooks, K.M. Carlson, E.M. Slade, J. Garcia-Ulloa, D.L. Gaveau, J.S.H. Lee, T. Santika, D. Juffe-Bignoli, and M.J. Struebig. 2020. "The Environmental Impacts of Palm Oil in Context." *Nature Plants* 6: 1418–26.

Minesso, M.F. and M.S. Pagliari. 2023. "No Country Is an Island. International Cooperation and Climate Change." *Journal of International Economics* 145: 103816.

Mourmouras, A. 1991. "Competitive Equilibria and Sustainable Growth in a Life-Cycle Model with Natural Resources." *The Scandinavian Journal of Economics* 93(4): 585–91.

Nepstad, D.C., I.M. Tohver, D. Ray, P. Moutinho, and G. Cardinot. 2007. "Mortality of Large Trees and Lianas Following Experimental Drought in an Amazon Forest." *Ecology* 88(9): 2259–69.

Newbold, T., L.N. Hudson, A.P. Arnell, S. Contu, A. De Palma, S. Ferrier, S.L. Hill, A.J. Hoskins, I. Lysenko, and H.R. Phillips. 2016.

"Has Land Use Pushed Terrestrial Biodiversity Beyond the Planetary Boundary? A Global Assessment." *Science* 353(6296): 288–91.

Network for Greening the Financial System (NGFS). 2023. "Nature-Related Financial Risks: A Conceptual Framework to Guide Action by Central Banks and Supervisors." Technical Document.

Network for Greening the Financial System (NGFS). 2024. *Macroeconomic Modeling Handbook.*

Nordhaus, W.D. 1991. "To Slow Or Not To Slow: The Economics of the Greenhouse Effect." *The Economic Journal* 101(407): 920–37.

Olovsson, C. and D. Vestin. 2023. "Greenflation?" Sveriges Riksbank Working Paper No. 420.

Parrique, T., J. Barth, F. Briens, A. Kuokkanen, and J. Spangenberg. 2019. "Evidence and Arguments Against Green Growth as a Sole Strategy for Sustainability." European Environmental Bureau.

Pearce, D. 1991. "The Role of Carbon Taxes in Adjusting to Global Warming." *The Economic Journal* 101(407): 938–48.

Pinto-Gutiérrez, C.A. 2023. "Drought Risk and the Cost of Debt in the Mining Industry." *Resources Policy* 83: 103724.

Pitron, G. 2020. *The Rare Metals War: The Dark Side of Clean Energy and Digital Technologies*. Scribe Publications.

Saco, P., K. McDonough, J. Rodríguez, J. Rivera-Zayas, and S. Sandi. 2021. "The Role of Soils in the Regulation of Hazards and Extreme Events." *Philosophical Transactions of the Royal Society B* 376(1834): 20200178.

Salati, E. 1987. *The Forest and the Hydrological Cycle. The Geophysiology of Amazonia*, edited by R.E. Dickeson. Hoboken, NJ: John Wiley & Sons.

Schumacher, E.F. 2011. *Small Is Beautiful: A Study of Economics as If People Mattered.* New York, NY: Random House.

Da Silva, S. F. Brown, A. de Oliveira Sampaio, A.L.C. Silva, N.C.R.S. dos Santos, A.C. Lima, A.M. de Souza Aquino, P.H. da Costa Silva, J.G. do Vale Moreira, and I. Oliveira. 2023. "Amazon Climate Extremes: Increasing Droughts and Floods in Brazil's State of Acre." *Perspectives in Ecology and Conservation* 21(4): 311– 7.

Solow, R.M. 1956. "A Contribution to the Theory of Economic Growth." *Quarterly Journal of Economics* 70(1): 65–94.

Solow, R. M. 1974. "Intergenerational Equity and Exhaustible Resources." *Review of Economic Studies* 41: 29–45.

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., De Vries, W., & De Wit, C. A. 2015. Planetary boundaries: Guiding human development on a changing planet. *Sciencexpress* 347(6223): 1–17. https://doi.org/10.1126/science.1259855

Stern, D. I. 2017. "The Environmental Kuznets Curve after 25 Years." *Journal of Bioeconomics* 19: 7–28.

Stiglitz, J. 1974. "Growth with Exhaustible Natural Resources: Efficient and Optimal Growth Paths." *Review of Economic Studies* 41: 123–37.

Tahvonen, O. and J. Kuuluvainen. 1991. "Optimal Growth with Renewable Resources and Pollution." *European Economic Review* 35(2-3): 650–61.

Ward, J.D., P.C. Sutton, A.D. Werner, R. Costanza, S.H. Mohr, and C.T. Simmons. 2016. "Is Decoupling GDP Growth from Environmental Impact Possible?" *PloS One* 11: e0164733.

World Bank. 2021. "The Economic Case for Nature." Washington, DC: The World Bank.

World Wildlife Foundation (WWF). 2013. "The Economic Value of Virunga National Park." WWF Report.

Zografos, C. and P. Robbins. 2020. "Green Sacrifice Zones, Or Why a Green New Deal Cannot Ignore the Cost Shifts of Just Transitions." *One Earth* 3(5): 543–46.