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Master Thesis

Estimating the Contribution of Nature and Biodiversity in Production Functions

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Executive Summary

Context and Research Problem. This thesis examines the integration of natural capital into contemporary economic models, addressing the ecological urgency created by global industrialization. While humanity has become a geological force capable of climate modification and species extinction, natural capital per capita has declined by 40% since 1992, despite a 13% increase in human capital and a doubling of produced capital (Managi and Kumar, 2018).

Conceptual Evolution. The perception of nature in economics has undergone a paradigmatic transformation. Prior to 1950, nature was considered an essential production factor alongside capital and labor. Following World War II, economic models relegated nature to the status of an externality, often perceived as unlimited. This evolution has created a critical disconnect between economic development and environmental sustainability.

Theoretical Framework: The Dasgupta Model. The framework developped by Dasgupta (2021) constitutes the theoretical foundation of this research, proposing an augmented production function that integrates natural capital as a distinct productive factor. The macroeconomic model considers the economy as embedded within the biosphere, challenging the assumption of infinite nature substitution. The impact inequality quantifies the imbalance between human demand for ecosystem services and the biosphere's regenerative capacity.

Methodological Challenges and Proposed Solutions. The empirical estimation of natural capital's role in production presents major econometric challenges, particularly endogeneity bias and the absence of reliable firm-level data. This thesis explores two innovative methodological approaches: Ackerberg, Caves, and Frazer (2015) (ACF) method and Structural Equation Modeling (SEM). The ACF method, adapted for estimating nature-augmented production functions, improves parameter identification by accounting for dynamic input choices and unobserved productivity shocks. SEM, proposed as a promising alternative, allows for the incorporation of latent ecological variables and captures dynamic relationships between economic and ecological systems, including feedback loops crucial for understanding human-nature interactions.

Preliminary Empirical Application. An empirical estimation using European agricultural data (30 countries, 2013-2020) was conducted, where natural capital is proxied by arable land area multiplied by unit price per hectare. Preliminary results suggest that produced capital is systematically overestimated in traditional accounting frameworks, confirming the importance of explicitly integrating natural capital. These results are however not robust, and should be considered more as a toy application of ACF method rather than key take-aways or insights from research.

Contributions and Perspectives. This thesis establishes a conceptual and methodological framework for quantifying the role of natural capital in economic production. SEM is particularly suited for analyzing complex human-nature systems, enabling the modeling of latent variables such as "ecosystem health" and their relationships with observable economic indicators.

Lessons learned from the thesis. The integration of natural capital into economic models represents a scientific and political imperative for ensuring intergenerational sustainability. This thesis serves as a preliminary contribution to bridging the gap between economic theory and ecological reality by proposing methodological tools adapted to the complexity of economy-biosphere interactions. Future developments must deepen the empirical application of these methods to inform sustainable development policies and improve measures of productivity and social welfare.

Note de Synthèse

Contexte et Problématique. Ce mémoire examine l'intégration du capital naturel dans les modèles économiques contemporains, répondant à l'urgence écologique créée par l'industrialisation mondiale. Alors que l'humanité est devenue une force géologique capable de modifier le climat et d'exterminer des espèces, le capital naturel par habitant a diminué de 40% depuis 1992, malgré une augmentation de 13% du capital humain et un doublement du capital produit (Managi and Kumar, 2018).

Évolution Conceptuelle. La perception de la nature dans l'économie a connu une transformation paradigmatique. Avant 1950, la nature était considérée comme un facteur de production essentiel aux côtés du capital et du travail. Après la Seconde Guerre mondiale, les modèles économiques ont relégué la nature au statut d'externalité, souvent perçue comme illimitée. Cette évolution a créé un décalage critique entre le développement économique et la durabilité environnementale.

Cadre Théorique : Le Modèle de Dasgupta. Le cadre développé par Dasgupta (2021) constitue la base théorique de cette recherche, proposant une fonction de production augmentée qui intègre le capital naturel comme facteur productif distinct. Le modèle macroéconomique considère l'économie comme intégrée dans la biosphère, remettant en question l'hypothèse de substitution infinie de la nature. L'inégalité d'impact quantifie le déséquilibre entre la demande humaine pour les services écosystémiques et la capacité régénérative de la biosphère.

Défis Méthodologiques et Solutions Proposées. L'estimation empirique du rôle du capital naturel dans la production présente des défis économétriques majeurs, notamment le biais d'endogénéité et l'absence de données fiables au niveau des entreprises. Cette thèse explore deux approches méthodologiques innovantes : la méthode d'Ackerberg, Caves, and Frazer (2015) (ACF) et la modélisation par équations structurelle (SEM). La méthode ACF, adaptée pour estimer les fonctions de production augmentées par la nature, améliore l'identification des paramètres en tenant compte des choix d'entrée dynamiques et des chocs de productivité non observés. Les SEM, proposés comme alternative prometteuse, permettent d'incorporer des variables écologiques latentes et de capturer les relations dynamiques entre les systèmes économiques et écologiques, incluant les boucles de rétroaction cruciales pour la compréhension des interactions humains-nature.

Application Empirique Préliminaire. Une estimation empirique utilisant des données agricoles européennes (30 pays, 2013-2020) a été réalisée, où le capital naturel est proxifié par la surface de terres arables multipliée par le prix unitaire par hectare. Les résultats préliminaires suggèrent que le capital produit est systématiquement surestimé dans les cadres comptables traditionnels, confirmant l'importance d'intégrer explicitement le capital naturel. Ces résultats ne sont toutefois pas robustes.

Contributions et Perspectives. Cette recherche établit un cadre conceptuel et méthodologique pour quantifier le rôle du capital naturel dans la production économique. La SEM est particulièrement adaptée pour analyser les systèmes complexes humains-nature, permettant de modéliser les variables latentes telles que la "santé des écosystèmes" et leurs relations avec les indicateurs économiques observables.

Enseignements tirés de ce mémoire. L'intégration du capital naturel dans les modèles économiques représente un impératif scientifique et politique pour assurer la durabilité intergénérationnelle. Ce mémoire est le préliminaire d'un travail de recherche contribuant à combler le fossé entre la théorie économique et la réalité écologique en proposant des outils méthodologiques adaptés à la complexité des interactions entre l'économie et la biosphère. Les développements futurs devront approfondir l'application empirique de ces méthodes pour informer les politiques de développement durable et améliorer les mesures de productivité et de bien-être social.

"We have broken the old silent agreement —we take, but we do not reciprocate. The balance has tipped into domination and extraction, rather than coexistence. [...] We have broken the tacit contract that bound man to nature."

Michel Serres (1990) *The Natural Contract* [1]

[1] In *The Natural Contract*, Michel Serres, a French ecological philosopher, argues that for most of human history, there was an unspoken, unconscious balance between humans and the natural world, namely a *tacit* contract. Humans took from nature, but they did not yet possess the power to truly alter or destroy it on a planetary scale. With industrialization, fossil fuels, technology, and global expansion, humanity has become a geological force capable of altering the climate, exterminating species, and reshaping ecosystems. Recent empirical evidence from the overview IPBES (2019) support this rationale. Serres highlights that we are no longer merely inhabitants of Earth we are now agents affecting its very functioning.

Contents

1 Introduction

Nature is indispensable for sustaining any form of life on Earth and, by extension, any form of economic activity. Nature provides not only a flow of provisioning services —such as timber, water, and genetic material—that enter directly into the production process, but also a stock of regulatory and maintenance services that underpin the stability and resilience of production itself. These include climate regulation, water purification, pollination, and soil fertility, among others. Production depends both on the immediate extraction and harvesting of natural resources and on the continued functioning of ecosystems that maintain the conditions under which production is even possible. Yet, considerations of nature remain conspicuously absent from the formal production apparatus in much of modern economic analysis. While the prevailing production framework conceives firms as mobilizing physical capital, human capital, and technology to generate output, it systematically omits a foundational input: the biosphere and the services it provides.

Evidence of a growing disconnect between economic development and environmental sustainability is striking. Managi and Kumar (2018) report that since 1992, human capital per capita has increased by 13%, and produced capital has doubled, while natural capital per capita has declined by 40%. This depletion of natural capital highlights a critical blind spot in contemporary economic thought and underscores the urgency of integrating ecological considerations into economic models.

The disconnection between the biosphere and economic sphere however appears as recent. Warburton (1928) proposes a review of the work and thoughts of early-20th Century American and British economics. What is striking is that produced capital, workers and nature were the three requisites of any form of production, all three indispensable factors of production for any economist of the pre-1950s period. WWII comes as a disruption. In the post-war period, dominant economics (Solow, 1956; Arrow and Debreu, 1954; Lucas, 1988) emphasized growth, efficiency and equilibirum models in which nature was often treated as an externality or taken for granted as an unlimited sink or source. Nature began re-entering economics (Meadows et al., 1972; Georgescu-Roegen, 1975), but as an heterodox movement. By the 1990s and still today mainstream neoclassical journals, namely the so-called Top 5 economic journals,[2] had made critical ecological analyses "heretical", forcing them into niche ecological and heterodox outlets (Baveye, 2014 ; Kish and Farley, 2021). In spite of the unpopularity of the topic, major economists have still tried to contribute to the theoretical framework of nature's re-introduction into the economic thinking (Costanza et al., 1997; Rockström et al., 2009a ; Pearce and Moran, 2013 ; Dasgupta, 2021).

Recent works such as the reviews of Pearce and Moran (2013) and Dasgupta (2021) participated in demonstrating that the omission of the biosphere from the formal core of macro and microeconomics is not benign. It reflects a conceptual lacuna in which the biosphere has been treated, at best, as an external backdrop rather than as an integral factor of production since the 1950s.

(Re-)incorporating biodiversity into economic models of production is methodologically challenging but necessary. Dasgupta (2021) offered a major contribution in accounting for nature in macroeconomic modeling. The Review notably developed the following macroeco-

[2] The *American Economic Review* (AER), *Econometrica*, the *Journal of Political Economy* (JPE), the *Review of Economic Studies* (REStud), and the *Quarterly Journal of Economics* (QJE)

nomic equation

$$Y = A.S^{\beta}.K^{a}.H^{b}.R^{1-a-b}$$

accounting for both the stock of nature used in the production, S, which reflects the contribution of biosphere's maintenance and regulating services to the production, and the flow of nature used in the production, R, which depicts the provisioning services. The role of A, K, and H are more common and account respectively for the technological and institutional scaling parameter, the produced capital and the human capital.

The main innovation in Dasgupta's model is the introduction of S^{β} in the measure of the total factor productivity (TFP). While environmental and resources economics had already suggested to account for biosphere's provisioning services [3], the state of the world and biosphere's processes were considered exogenous. Yet, the authors argue that they do affect productivity. Hence, in this framework, TFP is no longer A but $A \times S^{\beta}$, emphasizing that national accounts in their current form tend to overestimate TFP. However, despite the conceptual significance of their innovation, the authors acknowledge a key limitation: the absence of an empirical strategy for estimating the proposed production function.

This thesis seeks to discuss methods to address that gap by providing a tractable estimation framework. It first explores the possibility to build on Ackerberg, Caves, and Frazer (2015) (ACF) estimation procedure to estimate the nature-augmented production function presented above from firm-level data, and then discusses the use of Structural Equation Modeling (SEM) for the estimation purpose.

ACF's method consists in addressing longstanding identification issues in the estimation of production functions, particularly those related to simultaneity bias between input choices and unobserved productivity shocks. While traditional approaches, such as those by Olley and Pakes (1996) (OP) and Levinsohn and Petrin (2003) (LP), use investment or intermediate inputs as proxies for unobserved productivity, they often rely on restrictive timing and monotonicity assumptions that limit their empirical applicability. The ACF methodology refines and extends this line of work by explicitly modeling the firm's input choice process under more flexible conditions. Specifically, ACF introduces a control function approach that separates input choice equations from the productivity evolution equation, enabling consistent estimation of production function parameters even when productivity is correlated with input choices. This is particularly important when estimating the contribution of unpriced or unobserved inputs —such as ecosystem services—to output, since such inputs are unlikely to be orthogonal to firm-level productivity shocks.

By building on the ACF framework, this paper tries to extend the production function to explicitly include natural capital —both as a flow input and as a stock that affects productivity dynamics. My empirical strategy leverages the control function approach to isolate the marginal contribution of natural capital, while addressing the endogeneity concerns that arise from firms' adaptive input decisions in response to their environmental and productivity conditions.

In doing so, I provide a tractable and estimable model of production that incorporates the biosphere not only as a theoretical necessity but as an empirically grounded input. This allows us to make progress on a central challenge highlighted by Dasgupta (2021): how to bring the

[3] Solow (1974), Solow (1978), Stiglitz (1974), Stiglitz (1976) were major contributions to account for limited natural resources. Yet, as already underlined by Georgescu-Roegen (1975), their model did not account for thermodynamics and bio-physical processes. Dasgupta's model tries to correct for this gap in his model by including the factor S in the production function.

natural environment into the measurable domain of economic production, thereby laying the groundwork for better-aligned metrics of productivity, growth, and sustainability.

Yet, facing data limitation issues, most notably the lack of firm-level reporting on the use of nature in production processes, my extension of the ACF estimation method could not be empirically validated and had to remain at a conceptual stage. Beyond this empirical barrier, further reflection revealed deeper conceptual limitations in applying the ACF-based estimation procedure to nature-related economic questions. Specifically, several of its core assumptions, such as the observability and firm-level control over all relevant inputs, become difficult to uphold when attempting to model the role of ecological systems. These challenges motivated an exploration of alternative estimation strategies that could better accommodate both the empirical constraints and the theoretical structure of ecological macroeconomic models, as surveyed by Hardt and O'Neill (2017). Among these, Structural Equation Modeling (SEM) emerges as a particularly promising approach, with the potential to fill key methodological gaps in current stock-flow consistent (SFC) and broader ecological macroeconomic frameworks (notably, Dafermos et al., 2017 for the most advanced applications to date).

SEM is a widely used statistical method in psychology, sociology, and other social sciences, but remains underutilized in macroeconomics[4]. Nonetheless, it offers a powerful and flexible framework particularly suited to the complexities of ecological-economic systems (Grace, 2006). Unlike conventional regression-based techniques, which require direct measurement of all inputs, SEM can incorporate latent variables, such as biodiversity health, ecological resilience, or ecosystem services, that are not directly observed but influence multiple measurable indicators. This capability is crucial when dealing with natural capital, whose contributions to production are often diffuse, spatially heterogeneous, and unpriced. Furthermore, SEM enables the estimation of simultaneous relationships and feedback loops between variables, capturing dynamic interdependencies that lie at the heart of ecological macroeconomic reasoning. These features make SEM particularly well aligned with the modeling needs of systems where the economy is embedded in, and co-evolves with, the biosphere. In this sense, SEM can be understood not only as an empirical workaround but also as a conceptual bridge between micro-level production theory and macro-level ecological models. It supports the development of empirical tools compatible with recent advances in macroeconomic thinking that challenge neoclassical assumptions of separability between the economy and the environment. By enabling the empirical estimation of nature-augmented production functions, even in the presence of imperfect data and latent ecological structures, SEM complements the structural insights offered by models such as those proposed by Dasgupta (2021) and embedded in post-Keynesian SFC modeling traditions. However, while they provide important insights into monetary and financial dynamics, they are often not fully satisfactory for empirical applications, as they typically remain non-estimated, lack structural underpinnings, and abstract from anticipations or explicit microfoundations. These limitations shall be considered when considering this modeling approach and should try to be overcome.

This thesis is structured as follows. I first trace a brief timeline of the treatment of nature in macroeconomic modeling from the late 19th century to the present and elaborate on the macroeconomic modeling of Dasgupta, which serves as the basis for the conceptual contribution presented in this thesis (Section 2). I then propose an econometric approach to estimate the

[4]The limited use of SEM in macroeconomics is a general issue, not specific to environmental or natural resource economics, and is largely attributable to the difficulty of obtaining high-quality aggregate data over sufficiently long time horizons.

contribution of nature to production, building on Dasgupta's framework and adapting the ACF estimation method (Section 3). Both the conceptual and empirical limitations of this approach, including a preliminary and inconclusive application using aggregated European agricultural data, are discussed in the same section. These findings motivate the exploration of SEM in Section 4, where I argue for SEM as a credible and flexible set of tools for estimating nature's role in production and empirically operationalizing ecological macroeconomic models. Section 5 concludes and explains how this thesis serves as a first cornerstone for my forthcoming PhD.

2 A Brief Chronology of Nature in Macroeconomic Thinking and Modeling (Late 19th Century to Today)

The interplay between economic development and environmental sustainability has garnered increasing attention over the past few decades, particularly as evidence mounts regarding the detrimental effects of economic growth on natural capital. This section suggests a short timeline that tracks the evolution of the treatment of nature in macroeconomic thinking and modeling from the late 19th century to the present.

It highlights how early economic theorists conceived of the natural environment as a foundational factor of production alongside labor and capital, and how this view was gradually displaced during the post–World War II rise of neoclassical macroeconomics, which emphasized growth, equilibrium, and substitution between capital and resources. The marginalization of ecological constraints within mainstream models persisted through the late 20th century, even as heterodox thinkers and ecological economists raised alarm about the physical and thermodynamic limits of economic expansion. The 1990s brought a growing awareness of sustainability, yet ecological perspectives remained largely peripheral in elite economic publications. In the 21st century, however, new conceptual advances and policy imperatives have begun to reinsert the biosphere into macroeconomic reasoning. In particular, the Dasgupta (2021) has emerged as a landmark effort to reconceptualize nature as an asset class, central to wealth, risk, and intergenerational equity.

The final part of this section outlines the inclusive growth modeling framework proposed in Dasgupta's review, which serves as a foundational reference for the theoretical developments proposed in this thesis.

2.1 Early Economic Thought and the Inclusion of Nature (Late 19th Century–1945)

From the classical period through the early 20th century, economic thought consistently treated nature not merely as an implicit background condition but as a foundational and indispensable factor of production, on par with labor and capital. In Smith (1776)'s *Wealth of Nations*, land and natural resources were integral to the generation of wealth. *"The annual produce of the land and labour of every nation"* was then understood as the ultimate source of economic prosperity. David Ricardo (1817), in his *Principles of Political Economy and Taxation*, introduced the theory of diminishing returns to land, wherein economic rent emerged due to the differing fertility of land, highlighting the centrality of natural scarcity in distributional outcomes. Similarly, John Stuart Mill (1848) recognized ecological limits in his writings on the *"stationary state"*, positing a future equilibrium in which further material growth would be neither possible nor desirable due to environmental exhaustion and moral considerations.

Beyond being treated as productive assets, land and raw materials were also considered as limiting factors. This emphasis persisted in early neoclassical economics. Marshall (1890) while pioneering marginalism, continued to emphasize land and nature as key determinants of long-run supply, writing that *"nature's action must be reckoned with in the production process"*.

Though increasingly abstract in form, early neoclassical models remained grounded in the idea that economic systems were physically embedded in the natural world. Indeed, Leon Walras (1874), one of the founders of general equilibrium theory, included *"free goods"* (e.g., air, water) and *"appropriable goods"* (e.g., land) in his broader conception of economic value, indicating an early formal recognition of environmental inputs.

By the turn of the 20th century, this tripartite —capital, labor, and land—framework remained central. As reflected by Warburton (1928) in the American Economic Review, nature was commonly understood by economists in both the United States and Britain as an essential input to economic activity, rather than a disposable or substitutable background condition. The review notes that *"Produced capital, workers and nature are the three requisites of any form of production, all three indispensable factors."* signaling the conceptual entrenchment of nature within the production function of the time. Such views were echoed by Frank Knight (1921), who in his critique on *Risk, Uncertainty and Profit*, noted that *"production depends upon control over natural forces and materials"*, a clear acknowledgment of environmental dependence even in early discussions of capital and entrepreneurship.

Furthermore, the emergence of early resource economics in the 1930s, particularly through the work of Harold Hotelling (1931), continued to treat nature as central to economic modeling. Hotelling's rule, published in the Journal of Political Economy, established an intertemporal model of resource extraction, illustrating how the scarcity of exhaustible resources influences prices over time. This work is one of the few pre-war contributions that both modeled and problematized natural resource use in a formal dynamic framework, setting an intellectual precursor to later sustainability debates.

Overall, the classical and early neoclassical traditions did not perceive the environment as a peripheral concern but as integral to economic structure and dynamics. Nature was seen as both a source of wealth and a constraint upon its accumulation. As Dasgupta (2021) later reflects, this period operated with an "ecological grammar" of economic, one in which the economy was not a self-contained mechanism but a subsystem embedded in the biosphere. The severance of this relationship would come only after the Second World War, with the advent of growth theory and formal general equilibrium frameworks that abstracted away from ecological constraints.

2.2 Post-War Economic Dominance and the Marginalization of Nature (1945–1970s)

The post-World War II period marked a paradigmatic shift in macroeconomic modeling, characterized by a deep commitment to formalism, mathematical rigor, and a narrowing focus on growth, efficiency, and equilibrium. This transformation embodied in the neoclassical revolution led to the systematic marginalization of nature within mainstream economic theory. Economists such as Robert Solow, Kenneth J. Arrow, Gerard Debreu, Paul Samuelson, Milton Friedman, and Robert E. Lucas established influential models in which the biosphere was effectively treated as external to the economic system. In these frameworks, natural resources and natural capital were either presumed abundant or implicitly substitutable by human-made capital and technological progress —assumptions that undercut the ecological embeddedness of production and consumption.

The seminal Solow (1956) growth model, published in The Quarterly Journal of Economics, offered a concise and elegant representation of long-run economic growth driven by capital accumulation and exogenous technological progress. Though Solow acknowledged in later work the relevance of natural resource limits (Solow, 1978), his foundational model excluded environmental factors from the production function. This omission created a conceptual architecture in which economic growth could proceed indefinitely, independent of ecological constraints. As

Solow (1974) himself remarked in a retrospective piece in American Economic Review, *"the world can, in effect, get along without natural resources"*. This view, though nuanced in his full analysis, reflects the intellectual climate of the time: nature was increasingly viewed as a residual factor or a correctable market failure rather than a structural component of economic systems.

In parallel, Arrow and Debreu (1954) developed a general equilibrium model that redefined economic analysis through axiomatic foundations and mathematical completeness. Published in Econometrica, their framework achieved internal logical consistency but abstracted entirely from biophysical processes and environmental feedbacks. The economy was portrayed as a closed, frictionless system, devoid of material or energetic throughput. Within this framework, environmental degradation, if it appeared at all, was treated as an externality, correctable through pricing mechanisms or Pigouvian taxes, rather than as a systemic constraint.

By the 1970s, this approach was further entrenched by Lucas (1972, 1988) and the rational expectations school, which emphasized human capital, expectations, and technology as the key drivers of macroeconomic performance. In Lucas's Journal of Monetary Economics and later contributions in the Journal of Political Economy, the biosphere is entirely absent, replaced by a model of the economy governed by optimization and dynamic efficiency. The absence of environmental limits in these models reflected a growing disciplinary epistemology of abstraction, wherein economic systems operated in isolation from natural systems.

The neoclassical turn also coincided with institutional dynamics that narrowed the scope of acceptable inquiry. As Dasgupta (2021) notes, *"Nature was progressively removed from economics, not because it was unimportant, but because it was inconvenient for the formal models then in vogue"*. Top economic journals prioritized methodological rigor over empirical realism, leading to the marginalization of ecological analyses that did not fit the dominant modeling framework. However, the econometric revolution associated with Christopher Sims and others brought macroeconomics closer to data, particularly through the widespread use of vector autoregressions (Sims, 1980 in Econometrica). Yet, this empirical turn did not extend to the integration of environmental variables, largely because long-run, high-quality ecological and natural capital data remained scarce and difficult to align with aggregate macroeconomic series. The consequences of this shift were profound. As models and policy prescriptions based on them proliferated, the disconnect between economic growth and environmental sustainability widened. While some early critiques emerged (Hotelling, 1931; Pigou, 1920) these were sidelined by the dominant growth and equilibrium paradigms. By treating nature as an external backdrop rather than a constitutive force, post-war macroeconomics laid the groundwork for decades of ecological blind spots in both theory and policy.

2.3 Heterodox Reactions and the Emergence of Ecological Economics (1970s–1990s)

The 1970s marked a profound intellectual turning point in the relationship between economics and the environment. As environmental degradation, resource depletion, and pollution became increasingly visible, a new set of critiques emerged that challenged the neoclassical paradigm's treatment of nature as either an externality or an infinite sink. The publication of the Meadows et al. (1972) report served as a catalytic moment. Using a systems-dynamics model to simulate global interactions between population, industrial output, resource use, and environmental pollution, the study projected ecological collapse under conditions of continued exponential growth. Though heavily criticized by mainstream economists for methodological reasons, the report highlighted an intellectual schism: while neoclassical models emphasized substitutability and equilibrium, ecological economists stressed biophysical limits and non-linear feedbacks.

In parallel, Nicholas Georgescu-Roegen introduced a foundational critique of neoclassical economics grounded in thermodynamics. Georgescu-Roegen (1975) seminal work, *Energy and Economic Myths*, argued that economic activity is inherently entropic, that is a dissipative process that transforms low-entropy natural resources into high-entropy waste. This entropic framing challenged the neoclassical emphasis on reversible processes and perpetual growth, asserting that economic theory had fundamentally ignored the laws of physics. *"The neoclassical paradigm treats nature as an infinite sink —an assumption in contradiction with the laws of physics"*, he wrote, calling instead for a bioeconomic paradigm rooted in the constraints of natural systems.

These contributions laid the groundwork for what would later coalesce into the field of ecological economics, formally established in the late 1980s. Ecological economics sought to re-embed the economy within the biosphere, drawing from systems ecology, thermodynamics, and steady-state theory. Scholars such as Herman Daly, Robert Costanza, and Joan Martinez-Alier extended Georgescu-Roegen's insights into critiques of GDP, sustainability metrics, and the valuation of ecosystem services.

Despite the intellectual significance of these contributions, their impact on mainstream economics remained marginal. The Top 5 economic journals continued to favor formal, equilibrium-based models that seldom engaged with ecological dynamics. Although some notable exceptions exist in leading economics journals —such as Forster (1972) on pollution and capital theory in the Journal of Economic Theory, and Dasgupta and Heal (1974) on resource depletion in the Review of Economic Studies —these remained isolated and typically couched within neoclassical optimization frameworks.

As Baveye (2014) documents, between 1970 and 2010, articles addressing ecosystem degradation or the integration of ecological principles appeared in fewer than 0.1% of papers published across Top 5 journals. Kish and Farley (2021) similarly observes that ecological critiques, despite their growing empirical relevance, were systematically filtered out by editorial priorities favoring abstraction and tractability over ecological realism. On a personal experience, when searching for a literature review in the use of natural capital in the American Economic Review, I noted that the most recent mention of "natural capital" was made in 1928, in the review of Clark Warburton cited above. This disciplinary exclusion gave rise to a dual-track development: ecological economics flourished in alternative journals such as *Ecological Economics*, *Environment and Development Economics*, and *Environmental Values*, while mainstream macroeconomics remained largely ecologically silent.

The 1970s-1990s thus reflects a deeper epistemological and institutional divide: ecological economists sought to reorient economics around planetary boundaries and biophysical constraints, while neoclassical macroeconomics remained focused on optimization, substitution, and growth, often assuming environmental limits could be overcome through technological progress or market pricing mechanisms. The legacy of this divide continues to shape the reception and integration of ecological insights in macroeconomic modeling today, where environmental degradation due to human economic activity is still considered an externality.

2.4 The Sustainability Turn and Continued Marginalization (1990s –2010s)

The 1990s ushered in what appeared to be a potential turning point in the relationship between economics and the environment. Triggered by rising global concern over biodiversity loss, climate change, and ecological degradation, this period witnessed the formal emergence of sustainability economics and attempts to quantify natural capital and ecosystem services. Yet, despite growing empirical evidence of environmental limits, mainstream macroeconomic modeling continued to marginalize nature, as ecological concerns remained largely external to the core frameworks published in leading economics journals.

One major intellectual advance during this period was the articulation of natural capital theory and the valuation of ecosystem services, as reflected in Costanza et al. (1997), which estimated the annual value of global ecosystem services in the range of US$16-54 trillion, with an average of US$33 trillion per year, representing then nearly double global GDP. Although this article appeared in Nature, a cornerstone of scientific publishing known for its rigorous peer-review process yet not among the Top 5 economic journals, its impact reverberated across disciplines. Nonetheless, as Pearce and Moran (2013) later observed, these insights had limited influence on neoclassical macroeconomic modeling, especially within top-tier economics journals.

Within the mainstream, contributions to sustainability were often framed within neoclassical growth models and optimization techniques. For example, Acemoglu et al. (2012), in the American Economic Review, introducing endogenous and directed technical change in a growth model with environmental constraints, while differentiating between the use of *"dirty"* and *"clean"* inputs in the production of final goods. Their work examined how environmental policy could steer innovation toward clean technologies in a directed technical change framework. While insightful, these models typically retained assumptions of infinite substitutability and smooth environmental damage functions, failing to account for ecological thresholds and irreversible losses.

Another line of mainstream research focused on the economics of climate change. Nordhaus (1993)'s DICE model, first published in the American Economic Review, emerged as the dominant integrated assessment framework. Although Nordhaus's work was published in top journals, widely cited, and awarded a Nobel Prize in 2018, critics pointed to its discounting of long-term ecological risks, underestimation of tipping points, and the treatment of climate damages as a smooth function of GDP loss. As Stern (2007) and others have argued, this reflected a bias in mainstream macroeconomics toward market efficiency and optimization, often at the expense of ecological realism.

During the same period, the concept of weak versus strong sustainability gained traction. Articles such as Dasgupta and Mäler (2000) introduced formal models of inclusive wealth that incorporated natural capital into national accounting frameworks. Yet, even here, assumptions about the substitutability of ecological functions with human-made capital often prevailed. As a result, macroeconomic theory continued to treat environmental degradation as a correctable market failure, rather than as an existential threat to economic systems.

Overall, while the sustainability discourse gained global traction, macroeconomics remained largely impervious to its implications. The treatment of nature continued to be peripheral, and attempts to re-center it within the discipline often had to find outlets in interdisciplinary or heterodox journals. This persistent disconnection between ecological science and macroeconomic theory set the stage for the more systemic critique of economic reasoning found in later works such as Dasgupta (2021) and the planetary boundaries literature (see the corpus of Johan Rockstörm and co-authors Rockström et al., 2009b, Rockström et al., 2009a, Steffen et al., 2015, and Richardson et al., 2023).

2.5 Contemporary Perspectives and Future Directions (Dasgupta's Review 2021 and its legacy)

The publication of *The Economics of Biodiversity: The Dasgupta Review* (Dasgupta, 2021) marked a watershed in the intellectual treatment of nature within economics. Commissioned by the UK Treasury and authored by Partha Dasgupta, the review challenged the prevailing macroeconomic orthodoxy by arguing that economic models systematically neglect the biosphere as a foundational input to all economic activity. Dasgupta contends that *"nature is not a luxury; it is our ultimate asset"*, and that *"the economy is embedded within, not external to, the biosphere"*. Central to the review is the assertion that the current economic grammar, centered on produced and human capital, must be revised to incorporate natural capital as a core component of wealth and inter-generational well-being.

While Dasgupta's framework draws heavily on ecological economics and earlier bioeconomic thinking (e.g., Georgescu-Roegen, 1975), its ambition is to recenter these concerns within the core of mainstream policy economics. The Review formalizes a macroeconomic model of inclusive wealth that integrates natural capital, population dynamics, and social discounting, offering both a critique of prevailing discounting practices and a roadmap for reforming national accounting and investment appraisal.

The Review's macroeconomic model (Chapters 4 and 4*) embeds the global economy within the biosphere, challenging the conventional assumption that nature is an infinite or substitutable input. Dasgupta argues that conventional economic growth models—such as Solow or Ramsey-Cass-Koopmans frameworks—fail to account for the critical role of natural capital in sustaining productive and regenerative processes. In contrast, his model introduces nature as a core input to production and well-being, alongside produced and human capital. This integration leads to an augmented form of the production function:

$$Y(t) = F\Big(K(t), H(t), N(t)\Big) \tag{1}$$

where $Y(t)$ denotes output at date t, $K(t)$ produced capital, $H(t)$ human capital (encompassing labor $L(t)$), and $N(t)$ natural capital. Natural capital N is further decomposed into regulating and maintenance services S, and provisioning services R, both essential to sustaining economic activity. Assuming a Cobb–Douglas specification and the suggested decomposing of natural capital, the production function in Equation (1) can be written as:

$$Y = A.S^{\beta}.K^{a}.H^{b}.R^{1-a-b} \tag{2}$$

where A denotes TFP and the parameters β, a, and b represent the output elasticities associated with ecosystem regulating services, produced capital, and human capital, respectively. Crucially, the model does not assume perfect substitutability among these inputs. On the contrary, it emphasizes ecological complementarity through the idea that produced and human capital are unable to replicate essential ecosystem functions once critical natural capital is lost or crosses biophysical thresholds.

Building on this augmented framework, the Review introduces the concept of the *"Impact Inequality"*, which formalizes the imbalance between human demand for nature's services and the biosphere's regenerative capacity. Let $\mathcal{I}(t)$ denote humanity's aggregate ecological impact at time t, and $\mathcal{N}(t)$ the biosphere's ability to regenerate. Then the *Impact Inequality* is written as:

$$\mathcal{I}(t) = \frac{P(t) \times y(t)}{\alpha(t)} \geq \mathcal{N}(t) \tag{3}$$

where $P(t)$ is global population, $y(t) = \frac{Y(t)}{P(t)}$ is per capita output, and $\alpha(t)$ is the efficiency with which output is converted into ecological impact, in other words the inverse of the decoupling rate. Equation (3) captures the fundamental unsustainability of current global economic trends. As both population and per capita income rise, unless α falls sufficiently (through green technologies or behavioral change), the economy's total impact will exceed nature's regenerative limits.

To close this inequality and remain within the Earth's *"safe operating space"* (Rockström et al., 2009a), the Review identifies three levers: reducing the population P, reducing consumption y, or reducing the impact intensity α. However, only the latter is consistent with improving human well-being without sacrificing development. Yet, as Dasgupta emphasizes, decoupling output from nature is subject to diminishing returns and biophysical constraints—especially when ecosystem functions exhibit threshold dynamics or tipping points.

This biophysical embedding has profound implications for intertemporal welfare theory. Whereas conventional growth models evaluate social welfare via consumption utility paths, the Review adopts an inclusive wealth framework (Dasgupta and Mäler, 2000 ; Arrow, Dasgupta, and Mäler, 2003), in which sustainable development requires the non-declining value of total capital assets—including natural capital. Let $W(t)$ denote inclusive wealth, then sustainability implies:

$$\dot{W}(t) \geq 0 \tag{4}$$

where W includes produced, human, and natural capital stocks, each weighted by their respective accounting prices, derived from their marginal contributions to social welfare. In this framework, a decline in natural capital N that is not offset by gains in other forms of capital implies a reduction in long-run well-being, even if GDP increases. Moreover, because many ecosystem services are irreplaceable or imperfectly substitutable, their accounting prices rise as they become scarcer, reinforcing the urgency of conservation.

Finally, the model incorporates the endogenous dynamics of natural capital through a law of motion:

$$\dot{N}(t) = G(N(t)) - \phi(Y(t)) \tag{5}$$

where $G(N(t))$ represents nature's regenerative function and $\phi(Y(t))$ the degradation or waste associated with economic output. When $G(N) < \phi(Y)$, natural capital depreciates, leading to a contraction of the productive base and reinforcing the *Impact Inequality*. This ecological feedback mechanism illustrates that growth cannot be sustained independently of the state of the biosphere.

The intellectual realignment presented in *The Dasgupta's Review* has found partial resonance in recent theoretical contributions published in top-tier economic journals. For instance, Golosov et al. (2014) in Econometrica offers a dynamic stochastic model of optimal carbon taxation that internalizes the long-term damages of climate change, suggesting that relatively simple policy rules can approximate optimal outcomes in climate-economy models. More broadly, macroeconomic models incorporating tail risks, originally formalized by Barro (2009) in the context of wars and economic catastrophes, and subsequently extended by Farhi and Gabaix (2016), employ rare-disaster frameworks that can be adapted to account for ecological collapse as a source of systemic risk.

Despite these advances, the institutional mainstream remains largely resistant to fully endogenous treatments of ecological limits. The marginalization is not merely editorial but conceptual: even recent dynamic models tend to treat the biosphere as a perturbation to optimal growth paths, rather than as a binding and co-evolving constraint.

Nonetheless, signs of epistemic convergence are emerging. Economists such as Nicholas Stern, Joseph Stiglitz, and Johan Rockström have called for reimagining macroeconomics under planetary boundaries (Richardson et al., 2023). On an institutional perspective, signs of a better understanding of the urgency of considering nature and biodiversity in macroeconomic and financial modeling are showing: Banque de France has launched a consortium on Biodiversity and Nature-related risk in June 2025 ; the Bank of England has introduced natural capital in their national accounts, following the recommendation of the World Bank, since 2022 (see the UK's Office of National Statistics); the European Central Bank (ECB) and the Network for Green Sustainable Finance (NGFS), with ECB Executive Board Member and Supervisory Board Vice-President Frank Elderson as a central figure, show an increasing will to return to a nature-embedded economic reasoning.

> *"Nature isn't just the roots and shoots of biologists... a thriving natural environment provides vital benefits that sustain our well-being and serve as a crucial driving force for the global economy."*

Frank Elderson, 22 May 2025, Leiden - Naturalis Biodiversity Center.

As Dasgupta concludes, the path forward requires a *"new grammar"* of economics, one that can articulate a meaningful conception of prosperity compatible with the biophysical realities of the 21st century. Whether the field will adapt its core modeling paradigms accordingly remains an open and urgent question. My work humbly tries to contribute to answering it.

3 Estimating Nature's Role in Production: An Ackerberg et al. (2015)-Based Econometric Approach and Its Limits

Although Dasgupta (2021) provides a valuable macroeconomic framework for modeling biodiversity, particularly through Equation (1) discussed at the end of Section 2, the author acknowledges the absence of a robust empirical estimation methodology to quantify the contribution of natural capital. This includes both its role in regulating and maintaining ecosystem services, as well as provisioning services within the production process.
A benchmark in the field of production function estimation is the proxy-based method developed by Ackerberg et al. (2015). This section explores the potential for adapting the ACF framework to the production function proposed by Dasgupta. Specifically, this involves incorporating natural capital, denoted as S in Dasgupta's formulation, as a fixed input, and potentially treating natural resource use, R, as a variable input.
A preliminary empirical application using European agricultural data is proposed. However, due to significant data constraints, notably the widespread absence of firm-level measurements of biosphere-related assets, the empirical results remain limited.
Nonetheless, it is hoped that the growing recognition of the biosphere's finite capacity and its essential role in economic production will lead to improved data collection at the firm level. Such advancements would enhance the applicability and relevance of the framework proposed here.

3.1 A Brief Review of Production Functions Estimation Literature

Understanding the production process at the firm level has long been a central objective in empirical economics. Production function estimation serves as a foundational tool to quantify the relationship between inputs (typically capital, labor, and materials) and output. This estimation plays a vital role in measuring firm-level productivity, evaluating policy impacts, and informing industrial organization and development economics. However, the task is fraught with econometric challenges, most notably the endogeneity of input choices, driven by unobserved productivity shocks known to the firm but unobservable to the econometrician. This simultaneity leads to biased and inconsistent parameter estimates, thereby compromising the reliability of any inference drawn from standard production function models.

Addressing Simultaneity Bias: The Evolution of Proxy-Based Estimators. Understanding the determinants of firm-level productivity has been at the heart of economic research for decades. Traditional models of production posit that output is generated through the combination of two primary inputs, namely capital and labor, whose quantity and quality are assumed to be the key drivers of productivity. Yet, beginning with the seminal insights of Marschak and Andrews (1944) published in Econometrica, economists have recognized a critical econometric challenge in estimating production functions: the potential endogeneity arising from the correlation between input choices and unobserved firm-specific productivity shocks. Firms observe their own productivity in real time and adjust their input decisions accordingly —allocating more capital, labor, or materials when they anticipate higher productivity levels. However, because the econometrician does not observe these productivity shocks, standard estimation methods, such as ordinary least squares (OLS), treat input levels as exogenous, resulting in biased and inconsistent estimates of the production function parameters.

As first highlighted in Griliches and Mairesse (1998), traditional solutions to this endogeneity problem included fixed effects or first-differencing methods, which attempt to purge time-invariant firm-level heterogeneity. Yet, these methods fail to address the within-firm, time-varying productivity shocks that drive input choices. As such, they often yield misleading conclusions about input elasticities and total factor productivity (TFP).

In response, a wave of methodological innovations introduced proxy-based estimators that leverage observable variables, which are assumed to be correlated with the unobserved productivity shock, as control functions. The seminal contribution by Olley and Pakes (1996), published in Econometrica, pioneered this approach. Their method relies on the firm's investment decision as a proxy for productivity. The key insight is that if, conditional on the capital stock, investment is a strictly increasing function of productivity, it is possible to invert the investment function and recover productivity nonparametrically. This approach enables consistent estimation of the production function without requiring productivity to be directly observed or instrumented.

However, the Olley-Pakes approach comes with limitations. Investment data is often irregular, lumpy, or zero for a nontrivial number of observations, especially in developing country settings or industries with high adjustment costs. To overcome this limitation, Levinsohn and Petrin (2003) proposed in Econometrica to use intermediate inputs, such as materials or energy consumption, as a smoother and more ubiquitous proxy. Because intermediate inputs are typically adjusted more flexibly and more frequently than capital or labor, the Levinsohn-Petrin estimator is more widely applicable across empirical contexts. Their approach follows the same logic as Olley-Pakes, that is treating intermediate inputs as a monotonic function of productivity that can be inverted to recover the unobserved term, but avoids reliance on investment data.

Despite its greater empirical applicability, the Levinsohn-Petrin method introduced new identification issues. Specifically, as noted by Ackerberg, Caves, and Frazer (2015) (ACF) in Econometrica, Levinsohn-Petrin's first-stage regression can suffer from insufficient variation in input choices if firms set labor before observing the productivity shock. This timing assumption critically affects the identifiability of the labor coefficient. If labor is chosen based on past information, and the proxy (materials) is a function of productivity and contemporaneous labor, then labor may be collinear with the proxy, leading to a failure of functional independence and rendering the estimator under-identified.

The influential work of ACF addressed this problem by reconsidering the timing structure of input decisions and by allowing for greater flexibility in the sequence of input choice and information revelation. ACF introduced a refined two-stage estimation procedure that preserves the semiparametric structure of Olley-Pakes and Levinsohn-Petrin while resolving their key limitations. In their framework, inputs like capital and labor can be chosen in different periods (dynamic vs. static inputs). The proxy variable (materials) is still assumed to be strictly increasing in productivity, conditional not only on the capital stock as in Olley-Pakes but also on labor. Crucially, their method imposes minimal restrictions on the functional forms of the production function or the proxy relationship, relying instead on timing and monotonicity assumptions for identification.

As a result, the ACF estimator has become the dominant paradigm in modern production function estimation. It offers improved robustness, a more transparent identification strategy, and greater flexibility in handling different data structures. Its widespread adoption in empirical research reflects both its theoretical appeal and its practical tractability.

Nonetheless, the reliance on proxies comes with trade-offs. All proxy-based methods require strong assumptions about monotonicity, timing, and the absence of measurement error in proxy variables, which may not hold in all empirical settings. Moreover, these approaches typically abstract from other sources of firm heterogeneity that are increasingly recognized as crucial in explaining firm performance, such as differences in management practices, market structure, or environmental factors.

ACF's framework in detail: Assumptions and Mechanisms. The ACF framework is grounded in a model of dynamically optimizing firms operating in discrete time. Firms are assumed to be price-takers in both input and output markets, and their production decisions are subject to a series of assumptions that govern behavior and observability. The model retains the core features of OP and LP but modifies the structure to enhance identification.

The five primary assumptions underlying the ACF approach are as follows:

Assumption 1 (Information Set). *The firm's information set at t, I_t, includes current and past productivity shocks $\{\omega_{i\tau}\}_{\tau=0}^{t}$ but does not include future productivity shocks $\{\omega_{i\tau}\}_{\tau=t+1}^{\infty}$.*

Assumption 2 (First Order Markov). *Productivity shocks evolve according to the distribution*

$$p\left(\omega_{it+1}|I_t\right) = p\left(\omega_{it+1}|\omega_t\right)$$

This distribution is known to firms and stochastically increasing in ω_{it}.

Assumption 3 (Timing of Input Choices). *Firms accumulate capital according to*

$$k_{it} = \kappa(k_{it-1}, i_{it-1}) \tag{6}$$

where investment i_{it-1} is chosen in period $t-1$. Labor input l_{it} has potential dynamic implications and is chosen at period t, period $t-1$ or period $t-b$ (with $0 < b < 1$).

Assumption 4 (Scalar Unobservable). *Firms' intermediate input demand is given by*

$$m_{it} = f(k_{it}, l_{it}, \omega_{it}) \tag{7}$$

Assumption 5 (Strict Monotonicity). *f is strictly increasing in its third-argument, that is $f(k_{it}, l_{it}, \omega_{it})$ is strictly increasing in ω_{it}.*

Assumptions 1 and 2 are informative about the behavior of productivity shocks and straightforward: a firm can only observe a productivity shock ω_{it} once realized but knows about the distribution of future shocks. Assumption 3 precises that the current level capital is dynamically chosen at period $t-1$ according to the previous level of capital and an investment process. The policy function that defines a firm's investment decision, i_{it}, is the result of a dynamic optimization problem. Labor can be chosen at a period $t-b$ (where $0 \leq b \leq 1$)[5], that is that labor is chosen under incomplete information. This incompleteness induces variations in l allowing

[5] Noting that if $b = 0$, then labor is non-dynamic and a function only of I_{it}, and therefore LP's procedure does not pose identification problem. On the other end, if $b = 1$, then as for capital, $l_{it} \in I_{it}$ and therefore identification moments conditions shall include both l_{it} and l_{it-1}

for its identification. Assumption 4 states that intermediate inputs are a function of the state variables k_{it}, l_{it}, ω_{it}, that is that the choice of m_{it}, is conditional on the choices of inputs and of the unobservable productivity shock. As pointed out by Griliches and Mairesse (1998), this assumption places strong restrictions on the underlying model, ruling out unobserved heterogeneity across firms in the output markets. Assumption 5 is a consequence of assumption 2 and allows to invert ω_{it} as function of observables —that is $\omega_{it} = f^{-1}(k_{it}, l_{it}, m_{it})$.

Unresolved Issues and New Frontiers: The Role of Environmental Factors. Despite the notable advances made by proxy-based estimators, several critical dimensions remain underexplored. One such aspect is the role of environmental factors—including climate conditions, pollution, water availability, and other forms of natural capital—in shaping the production process. Standard models, including Olley-Pakes, Levinsohn-Petrin, and ACF, implicitly assume that the production environment is homogeneous across firms or that environmental conditions are orthogonal to input choices and productivity. This is a strong and potentially unrealistic assumption, particularly in the context of firms located in climate-vulnerable or resource-constrained regions.

Environmental factors can influence production both directly—by affecting the productivity of labor and capital—and indirectly, by shaping the input choice behavior of firms. For instance, high temperatures may reduce labor productivity or increase depreciation rates of capital equipment, while water scarcity may constrain input availability or limit production scale. These interactions are likely endogenous and heterogeneous across firms, necessitating more sophisticated econometric tools and richer data to properly model them.

A growing literature in environmental and development economics has begun to recognize these dynamics. Studies have documented the non-trivial impact of environmental stressors on firm survival, investment behavior, and output volatility, suggesting that current production function estimators may systematically overestimate productivity by failing to account for these omitted factors. Incorporating environmental variables into the estimation framework thus represents an important extension of existing methodologies, and a necessary step to improve the external validity of productivity estimates.

Thesis Contribution. The work presented in this thesis contributes to this evolving literature by proposing an extension to the ACF framework that explicitly incorporates environmental variables into the production function estimation. I aim to relax the implicit assumption of environmental homogeneity and model how local environmental conditions interact with input choices and productivity shocks. By doing so, I seek to provide a more accurate and policy-relevant understanding of the determinants of firm performance, particularly in developing country contexts where environmental challenges are pervasive.

3.2 A Conceptual Estimation Framework to Account for Nature in Production Function Estimation

I adapt Dasgupta (2021) macroeconomic model for production —presented at the end of section 2—to a firm-level analysis that will allow an identification of the parameters through ACF's procedure.

Specifically, I consider Equation (1),

$$Y = A.S^{\beta}.K^{a}.H^{b}.R^{1-a-b}$$

which extends the classical Cobb–Douglas production function (Cobb and Douglas, 1928) by allowing for a non-zero elasticity of social infrastructure ($\beta \neq 0$) and relaxing the assumption of perfect substitutability among inputs (i.e., $a + b \neq 1$). As noted in ACF, their methodology can accommodate multiple fixed inputs (such as produced capital K) as well as multiple freely variable inputs (e.g., differentiated labor types, such as skilled versus unskilled labor). Given these characteristics, the application of the ACF framework to my firm-level setting emerges as a natural and conceptual consistent extension.

Modeling Simplification. We consider here, as a first application, a simplified version of Dasgupta's model as it only accounts for natural capital, that is, regulating and maintaining services used by the firm rather than provisioning services.

While oversimplifying, the decision to focus exclusively on the version featuring only regulating and maintenance services within natural capital is grounded in emerging empirical and theoretical literature that identifies these services as the primary ecological underpinning of biodiversity conservation. Unlike provisioning services which are more directly tied to market transactions and subject to substitution, regulating services are critical to maintaining ecosystem stability and resilience.

A growing body of ecological-economic research demonstrates that the degradation of regulating services is more closely associated with long-term biodiversity loss than the depletion of provisioning services. For instance, Wei et al. (2020) examined three key regulating ecosystem services —carbon storage, water yield and soil retention—and two key provisioning ecosystem services —crop and livestock production. Using correlation and factor analysis, they found that protected areas exhibited healthier carbon storage, water yield, and soil retention compared with other areas, while livestock production did not differ significantly between conserved and non-conserved areas. Another illustrative study is Le Provost et al. (2023) , who employed structural equation modeling (SEM) to examine how larger-scale biodiversity dynamics contribute to ecosystem service delivery. Their results provide a comprehensive picture of which services —among sixteen cultural, provisioning and regulating services—[6] depend most strongly on biodiversity, and at which spatial scales. Using 150 European agricultural grassland plots, they found that both plot-level and surrounding plant diversity significantly influence cultural and aboveground regulating services, whereas provisioning and belowground regulating services are more strongly determined by field-level management and abiotic factors.

Furthermore, provisioning services are often produced at the expense of biodiversity and the integrity of ecological functions, reflecting a fundamental trade-off between immediate economic gains and long-term ecosystem stability. Intensification of agriculture, deforestation, or overfishing can increase outputs of crops, timber, or fish in the short term, but these activities frequently degrade habitats, reduce species diversity, and impair regulating services such as carbon sequestration, water purification, and soil retention. This trade-off underscores the ecological centrality of regulating services, which sustain the resilience and productivity of ecosystems over time and provide the foundational support upon which provisioning services

[6] *Cultural ecosystem services*: Acoustic diversity, Birdwooking potential, Total flower cover ; *Aboveground regulating services*: Pollination, Natural enemy abundance, Lack of pathogen infection, Herbivores, Decomposition ; *Aboveground provisionning services*: Shoot biomass, Forage quality ; *Belowground regulating services*: Soil aggregation, Phosphorous retention, Nitrogen retention, Groundwater recharge, Soil carbon stocks, Nitrification

ultimately depend (Balvanera et al., 2006 ; Faith et al., 2010).
By isolating these services in the production function, my approach better intends to capture the non-market dimensions of natural capital that are essential for firm productivity but poorly reflected in traditional input measures. This simplification serves as a necessary first step toward a more comprehensive economic representation of nature in firm-level analysis.

A second rationale for abstracting from provisioning services in this simplified version of the model is rooted in the econometric challenges associated with identification. In particular, incorporating provisioning services, namely R in Dasgupta's specification, risks conflating these services with traditional intermediate inputs M in the estimation procedure. As highlighted in LP and ACF frameworks, intermediate inputs are frequently used as proxies for unobserved productivity shocks under the control function approach. However, many provisioning services (timber, water, fossil fuels, or other extractive resources) are themselves embodied in intermediate inputs commonly used by firms. This introduces a confounding identification problem: the econometrician cannot easily disentangle whether variation in M reflects firm productivity or the consumption of nature-based provisioning services. Including R explicitly in the production function alongside M could therefore violate the exclusion restrictions or monotonicity conditions required for consistent estimation, particularly if the two inputs are colinear or jointly determined. To mitigate these risks and ensure credible identification of the production parameters in this initial stage, I opt to exclude provisioning services from the model, focusing instead on regulating and maintenance services that are less likely to be embodied in standard intermediate inputs and more amenable to separate measurement or approximation. A tentative of including R without conflicting with M is an avenue left for further research. A first early-stage and high-level reflexion on this question is proposed in the Appendix (see 6.1).

Considering the limitations and caveats mentioned above, I start with the following specification:

$$Y_{it} = S_{it}^{\beta_s} L_{it}^{\beta_l} K_{it}^{\beta_k} M_{it}^{\beta_m} \exp(\omega_{it} + \epsilon_{it}) \tag{8}$$

where Y_{it} represents the production of the firm i at period t, S_{it} the natural capital it mobilizes, and K_{it}, L_{it} and M_{it} represent produced capital,[7] labor,[8] and intermediate inputs used in the firm's production, respectively. The productivity shock is captured by $\exp(\omega_{it})$.

About the natural capital input. S_{it} provides a structural tool for quantifying the productive contribution of nature in economic processes and analyzing the consequences of environmental degradation on business productivity. It represents a synthetic aggregate of maintaining and regulating ecosystem services that support the firm's production, typically without being directly controlled or owned by the firm. From an economic standpoint, S_{it} reflects the ecological support environment relevant to the firm's operations, that is the degree to which natural systems underpin production processes.
This form of natural capital enters the production function as a distinct input, emphasizing

[7] In this basic model, by construction, I make the simple assumption that natural capital and produced capital are perfectly interchangeable. This assumption can and will be questioned (Discussion 3.4).

[8] When compared to Daguspta's specification, human capital was replaced by labor to avoid the complication on the definition and accounting for human capital. An extension of the model accounting for the level of qualification of the labor force and for the firm's investment in training could be developed. Yet, I decided to opt for this simplification as my main focus was on the consideration of nature and biodiversity in production functions.

that total factor productivity depends not only on produced and human capital, but also on the integrity of the surrounding natural systems. Unlike provisioning services (i.e., R), S is non-extractive: it supports production without being consumed, but can still degrade through overuse or neglect.
S_{it} evolves dynamically, influenced by natural degradation (e.g., biodiversity loss, water stress) or, in some contexts, regeneration (e.g., soil recovery). Like produced capital K_{it}, the nature-based capital, S_{it}, is a function of the firm's investment i_{it} chosen at date $t-1$. The firm can, in principle, allocate a share α_{it} of its investment i_{it} to maintaining or enhancing S_{it}. However, because the benefits of S are non-rival and non-excludable, individual firms lack the incentive to invest. Consequently, α_{it} would often be close to zero. In this sense, S behaves like a global externality: essential, but typically underpriced or ignored by market actors. In other words, S would no longer be firm-specific but regional or global, leading to $S_{it} = S_t$
Considering the regeneration process of natural capital, its depletion, and the firm's investment in its maintenance or restoration, I define a discrete-time dynamic equation for the stock of natural capital in logarithm ($s_{it} = \log(S_{it})$) as suggested in Dasgupta (2021):

$$s_{it} = s_{it-1} + g(s_{it-1}) - d_{it} + h(\alpha_{it} i_{it}) \tag{9}$$

with $g(.)$, the natural regeneration function —that is the ecological recovery—that is shared across firm; d_{it}, the degradation of natural capital due to the firm's activities; $\alpha_{it} i_{it}$, firm's investment in natural capital maintenance or restoration ; and $h(.)$, the impact of maintenance and restoration investment on natural stock's dynamics. A discussion on the possible shape of $g(.)$ and $h(.)$ is offered in the Appendix (see 6.2).

Log-linearizing Equation (8), I get:

$$y_{it} = \beta_0 + \beta_s s_{it} + \beta_l l_{it} + \beta_k k_{it} + \beta_m m_{it} + \omega_{it} + \epsilon_{it} \tag{10}$$

where $x = \log(X)$ for all variables X in Equation (8).

The addition of the natural capital S_{it} as a factor of production requires some adjustments of ACF's model Assumptions 3, 4, and 5. Assumptions 1 and 2 remain unchanged as they are not affected by the introduction of S_{it} in the model.

Assumption 3′ (Timing of Input Choices)**.** *Firms accumulate produced capital according to*

$$k_{it} = \kappa(k_{it-1}\ , (1-\alpha_{t-1}) \times i_{it-1}) \tag{11}$$

and natural capital according to

$$s_{it} = s_{it-1} + g(s_{it-1}) - d_{it} + h(\alpha_{it} i_{it}) \tag{12}$$

where investment i_{it-1} and the share of investment the firm wants to dedicate to natural capital, α_{t-1}, are chosen in period $t-1$. Labor input l_{it} have potential dynamic implications and is chosen at $t-b$ (with $0 \leq b \leq 1$).

Assumption 4′ (Scalar Unobservable with nature)**.** *Firms' intermediate input demand is given by*

$$m_{it} = \tilde{f}(k_{it}, l_{it}, s_{it}, \omega_{it}) \tag{13}$$

Assumption 5′ (Strict Monotonicty with nature). *$\tilde{f}$ is strictly increasing in its fourth-argument, that is $\tilde{f}(k_{it}, l_{it}, s_{it}, \omega_{it})$ is strictly increasing in ω_{it}.*

Assumption 3′ slightly modifies the capital accumulation law from assumption 3 by introducing the firm's trade-off between investing in natural and produced capital, allowing firms to dynamically adjust their preferences for nature depending on their expectation about future degradation of natural capital and (through the multiplier α). It also precises the accumulation process of natural capital used in the production process. Natural capital, as it is a capital, is chosen at the same moment than k.
Assumption 4′ underlines that the model I suggested is a natural extension of ACF's framework. It simply adds natural capital, s_{it}, into the state space, in the same fashion that they introduced labor to control for unobserved productivity when adjusting OP and LP's work. The logic of the functional dependence of m_{it} on s_{it} can be explained through two main channels, namely an effective productivity channel suggesting that a higher stock of regulating and maintenance services (e.g., climate stability, water quality, pollination) may enhance the productivity of intermediate inputs, thereby reducing the quantity of m required per unit of output ; and a cost-quality channel reflecting that when natural capital is degraded, firms may need to substitute natural ecosystem services with market-based inputs (e.g., water treatment chemicals, artificial pollination), thereby increasing demand for m. Conversely, a rich natural capital base may reduce reliance on costly intermediates.
Assumption 5′ is the necessary assumption for the inversion, keeping m_{it} as a non-dynamic input to apply LP's invertibility proof, just like ACF did when integrating l_{it} in the controls.

Model Estimation Procedure. Given these assumptions, I can follow LP and ACF procedure by first inverting produced intermediate input demand, $\omega_{it} = \tilde{f}^{-1}(k_{it}, l_{it}, s_{it}, m_{it})$, and then substituting the result into the log-production function (Equation (10)), that is:

$$\begin{aligned} y_{it} &= \beta_0 + \beta_l l_{it} + \beta_k k_{it} + \beta_m m_{it} + \beta_s s_{it} + \tilde{f}^{-1}(k_{it}, l_{it}, s_{it}, m_{it}) + \epsilon_{it} \\ &= \tilde{\Phi}(k_{it}, l_{it}, s_{it}, m_{it}) + \epsilon_{it} \end{aligned} \tag{14}$$

with $\tilde{\Phi}(k_{it}, l_{it}, s_{it}, m_{it}) = \beta_0 + \beta_l l_{it} + \beta_k k_{it} + \beta_m m_{it} + \beta_s s_{it} + \tilde{f}^{-1}(k_{it}, l_{it}, s_{it}, m_{it})$.
Following again ACF, $\tilde{f}^{-1}$ is estimated nonparametrically, performing an OLS regression of y_{it} on a high-order polynomial in $(k_{it}, l_{it}, s_{it}, m_{it})$. This first stage results in the first stage moment condition

$$\mathbb{E}[\epsilon_{it}|I_{it}] = \mathbb{E}\left[y_{it} - \tilde{\Phi}(k_{it}, l_{it}, s_{it}, m_{it})\,|I_{it}\right] = 0 \tag{15}$$

and in an estimate $\widehat{\tilde{\Phi}}(k_{it}, l_{it}, s_{it}, m_{it})$ of $\tilde{\Phi}(k_{it}, l_{it}, s_{it}, m_{it})$. Inspired by ACF, I propose estimating β_s using the second stage conditional moment condition:

$$\begin{aligned} \mathbb{E}\big[\xi_{it-1} + \epsilon_{it-1} \mid I_{it-1}\big] = \mathbb{E}\big[\, & y_{it} - \beta_0 - \beta_k k_{it} - \beta_l l_{it} - \beta_s s_{it} \\ & - g\big(\tilde{\Phi}(k_{it}, l_{it}, s_{it}, m_{it})\big) \mid I_{it-1}\big] = 0. \end{aligned} \tag{16}$$

The composite function $\tilde{\Phi}(k_{it}, l_{it}, s_{it}, m_{it})$ already contains the input s_{it} and its coefficient β_s. Hence, with no other source of variation, it is not possible to identify β_s solely from $\tilde{\Phi}$. Therefore, just like in any IV regression where the number of instruments needs to match or exceed the number of endogenous variables, the addition of natural capital in the production function requires an additional moment condition to estimate the four production function parameters (β_0, β_k, β_l, β_s) and the auto-regressive parameter ρ:

$$\mathbb{E}\left[\xi_{it-1} + \epsilon_{it-1} \,\middle|\, I_{it-1}\right] = \mathbb{E}\Big[y_{it} - \beta_0 - \beta_k k_{it} - \beta_l l_{it} - \beta_s s_{it} - \rho\big(\tilde{\Phi}(k_{it}, l_{it}, s_{it}, m_{it}) - \beta_0 - \beta_k k_{it} - \beta_l l_{it} - \beta_s s_{it}\big) \otimes \begin{pmatrix} 1 \\ k_{it} \\ l_{it-1} \\ s_{it} \\ \tilde{\Phi}(k_{it-1}, l_{it-1}, s_{it-1}, m_{it-1}) \end{pmatrix} \,\Big|\, I_{it-1}\Big] = 0. \tag{17}$$

3.3 A Tentative of Empirical Estimation, from European Agriculture Data

This subsection presents a preliminary empirical application of the conceptual extension outlined above, with the aim of assessing the contribution of natural factors within a production framework. Specifically, we estimate firm-level production functions using an adapted version of the model from Dasgupta (2021), extending the ACF methodology to explicitly account for natural capital alongside conventional factors (produced capital and labor).

The initial objective of this exercise is two-fold. First, we aim to empirically test the feasibility of integrating natural capital, proxied by land, into the structural estimation procedure proposed by ACF. Second, we compare the estimated output elasticities of labor and capital under two model specifications: one that does not account for natural capital, and another that explicitly incorporates them. This comparison allows us to evaluate the extent to which the omission of nature biases standard productivity estimates.

In trying to apply the proposed estimation method, I sought access to firm-level data detailing the use of natural capital in production processes. However, significant data limitations were encountered. In particular, such data do not appear to be publicly available. While the European Commission does conduct surveys on firms' use of land, natural intermediate inputs, and related factors, access to the micro-level survey data was denied upon request. Similarly, private data providers (including Wharton Research Data Services (WRDS), Iceberg Data Lab, and Bloomberg) do not appear to offer firm-level datasets capturing the exploitation of natural capital in production activities.

These data limitations, which are further discussed in Subsection 3.4, have therefore precluded the implementation of the conceptual extension of the ACF estimation framework outlined in Subsection 3.2 using firm-level data.

To nevertheless explore the viability of this approach, I rely on aggregated, country-level agricultural data made available by the European Commission through Eurostat and the Agri-food Data Portal. Before presenting the dataset and empirical results, it is important to acknowledge several critical caveats. The use of aggregated data significantly deviates from the ideal conditions assumed in the structural estimation framework. Key modeling assumptions, such as the common input and output prices, and the availability of firm-level variation, are violated. As such, the resulting estimates are likely to be non-robust and biased.

These methodological limitations are addressed in more detail in the subsequent discussion. The empirical exercise presented here should therefore be interpreted as a preliminary and illustrative attempt, a conceptual "toy test" of the method, rather than as a definitive or policy-relevant estimation. Future work conducted during the course of the PhD will focus on addressing these data and methodological challenges through improved empirical design and expanded data access.

Bearing in mind the previously mentioned caveats and limitations, I propose to implement the suggested estimation procedure on country-level agricultural data collected through Eurostat. To mitigate the challenges associated with limited time-series observations in aggregate data, I exploit a cross-sectional dimension by including 30 countries (27 European Union countries, the United Kingdom, Norway, and Iceland) over three survey years —2013, 2016, and 2020—corresponding to the years in which the European Commission collected agricultural sector data. In this setup, each entity i is a country and each time period t is a year in the set. Leveraging multiple countries in the estimation increases the effective number of observations, providing more variation to identify the relationships between variables while maintaining the analysis at the aggregate level. The correspondence between the variables of interest and the proxies used is displayed in Table 1. For natural capital, S, since there are no account for natural capital, I had to find a possible valuation for nature input. As recommended in nature valuation method that use market prices as proxies for setting a price on nature assets (see Mendelsohn, Nordhaus, and Shaw, 1994; Costanza et al., 1997; Goulder and Kennedy, 2000; Greenstone and Hanna, 2014; and more recently Dasgupta, 2021), I used the arable land surface used in the overall agricultural industry (in hectares), that we denote by F, multiplied by the unit price of an hectare of arable land, that we denote p_F. The natural capital proxy, S, is then the product of the two ($S = F \times p_F$).

Variable	Proxy	Eurostat Data Serie Code
Y	Overall agricultural industry output	agr_r_accts / item_nwa 1800
K	Agricultural gross fixed capital formation	agr_r_accts / item_nwa 34000
L	Total agricultural labor	aact_ali01 item_nwa 40000
L_1	Paid agricultural labor	aact_ali01 item_nwa 41000
L_2	Unpaid agricultural labor	aact_ali01 item_nwa 41000
M	Total agricultural intermediate consumption	agr_r_accts / item_nwa 19000
F	Arable Land Surface in hectare	ef_lus_main / 'crops' = 'ARA'
p_F	Arable Land Price per hectare	apri_lprc / 'agriprod' = 'ARA'
S	$S = p_F \times F$	-

Table 1: Data Used for the EU Agricultural Sector Preliminary Estimation

Once the data collected, I used the R package `prodest`, and more specifically the function `prodestACF`, developed by Gabriele Rovigatti[9] to estimate the eslaticities of labor, produced capital and natural capital in the production function. Two main estimation were made, one that includes S and one that doesn't account for it. In the results displayed below, only total

[9]Find Gabriele Rovigatti's work in his Github repository and further documentation on the Comprehensive R Archives Network (CRAN) Project

labor L was considered. A further refined estimation that distincts between paid and unpaid labor (respectively L_1 and L_2) is presented in the Appendix (see 6.3).

Estimation Model	**Without S**		**With S**		
	K	**L**	**K**	**S**	**L**
Estimate	0.591	0.063	0.024	0.043	0.091
Std. Error	(0.651)	(0.426)	(0.199)	(0.162)	(0.488)
N	42		42		
Bootstrap repetitions	5		5		
1st Stage Parameters	NA	NA	NA	NA	NA
Optimizer	optim		optim		
Elapsed Time	0.01 mins		0.01 mins		

Table 2: Production Function Estimation Summary

The presented results suggest that the contribution of produced capital is overestimated in traditional accounting frameworks. Yet, as expected, the results are not significant (the p-values are way above any statistical level) and non-robust, likely due to small-sample specification. Therefore, any interpretation of these results could be misleading. Further work could focus on exploring the data to find significant results in this estimation process. However, a take-away from this experiment, that could be optimistically seen as a win, is that, once we find better data, the structure of the code and the method can be immediately used. Due to the influence of the method (well-published ACF method and influential review from Dasgupta), we hope that further development of this method could make a significant contribution to the literature.

3.4 Discussion

The conceptual extension of the ACF framework and the preliminary empirical estimation presented here are subject to several critical limitations, most notably concerning data availability. Chief among these challenges is the severe lack of reliable and comprehensive data on the use of natural capital in production at the firm level.

Despite extensive efforts to identify suitable data sources, both public and private, I was unable to find firm-level datasets that adequately capture the role of nature in production processes. One potentially promising source was the Environmental, Social, and Governance (ESG) database available through WRDS, compiled by MSCI. This dataset includes ESG indicators for a wide range of firms in multiple sectors and countries. Among its environmental metrics is a variable pertaining to firms' reported use of natural resources. However, upon downloading and inspecting the dataset, I found that out of more than three million firms, only two firms had reported any measurable use of natural capital and thus were assigned a rating for their interaction with the biosphere. This striking absence of reporting strongly suggests that natural capital is still largely treated as a free or exogenous input in economic activity, acknowledged in rhetoric, but not captured in firm-level accounting systems or datasets. Further attempts to obtain more detailed data were equally unfruitful. I identified potentially relevant firm-level surveys conducted by the European Commission, notably those referenced in Eurostat and the Agri-Food Data Portal. These surveys reportedly include micro-level information on agricultural production, including land use and other nature-related inputs, collected triennially across EU member states. However, access to these firm-level microdata is restricted. I submitted two formal data requests to the corresponding authorities, both of which were denied. In the absence of access to suitable microdata, I was left with no alternative but to rely on country-level aggregated data to carry out the empirical estimation. While this strategy allows for a tentative test of the conceptual extension and the underlying code, it comes at a clear cost. Aggregate data obscure within-country heterogeneity, limit the identification of firm-specific productivity shocks, and violate several of the structural assumptions required for consistent estimation in the ACF framework. These limitations are acknowledged and discussed further in the subsequent sections. Nevertheless, this preliminary exercise serves as a conceptual proof-of-approach, which can be refined and strengthened in future work as better data become available.

That said, promising avenues for future research do exist. In particular, the increasing availability of high-frequency geographical data on precipitation, river flows, and groundwater stocks could allow for more precise characterization of local ecological constraints, especially when linked to economic outcomes. In the French context, the *Centre d'Accès Sécurisé aux Données* (CASD) provides detailed firm-level and establishment-level information that could, in principle, be combined with hydrological indicators to study how water availability and shocks affect productivity, investment, and resilience. Pursuing this line of research would not only enrich ecological macroeconomics but also help bridge the gap between environmental sciences and applied economic analysis.

This empirical try also revealed that most available measurements related to nature and ecosystem services are produced at the geographical or macro level, rather than at the firm level. In light of these findings, and given both the urgency of understanding nature's role in economic systems and the current limitations in firm-level data availability, it may be more appropriate, at this stage, to adopt macro-level estimation approaches. Such methods are better suited to capturing the aggregate dynamics of the biosphere, including its state, degradation, and regenerative capacity, and can complement micro-level models by providing broader ecological context. While these approaches come with their own trade-offs, they offer a viable path forward for empirically integrating nature into production analysis, especially until improvements in environmental accounting and firm-level reporting allow for more granular estimations.

Secondly, regarding the conceptual framework itself, several key assumptions of the ACF methodology may not hold when it is extended to the assessment of nature's contribution.

One critical assumption in ACF is the existence of common input prices across firms. However, when natural capital, particularly land, is included, as in the empirical application discussed above, this assumption becomes problematic. Land is inherently heterogeneous, and its value varies significantly across regions due to differences in soil fertility, climatic conditions, water availability, and broader ecological characteristics. In addition, factors such as land use regulation, property rights, and regional market dynamics further distort the comparability of input prices. Weather variability and exposure to climate-related risks also affect expected productivity and, consequently, the implicit value of land. These spatial and environmental heterogeneities introduce significant measurement challenges and undermine the validity of the common input price assumption. As a result, caution is warranted when interpreting the estimated coefficients on natural inputs within the ACF framework. It may be necessary to explore extensions or modifications to the original framework that can explicitly accommodate input price heterogeneity or leverage instruments and control strategies tailored to the specificity of natural capital.

The framework assumes that firms choose input levels in a context of partial information, but with some knowledge about the productivity process and state variables. However, when it comes to natural capital, firms often make decisions under substantial uncertainty regarding the state of the surrounding biosphere. As Dasgupta emphasizes in the opening chapter of the *Review*, *"Nature is (i) mobile, (ii) invisible, and (iii) silent."* This implies that the quality and functionality of ecosystem services are not readily observable or predictable at the moment firms make production decisions. For example, the regenerative capacity of soil, the resilience of nearby ecosystems, or the availability of pollinators and groundwater are often unknown or poorly understood. This disconnect between the timing of input decisions and the delayed, diffuse, or hidden feedbacks from nature challenges the validity of the timing structure assumed in ACF. Incorporating natural capital thus calls for a deeper treatment of uncertainty, imperfect information, and ecological lags in production processes, dimensions that are not fully captured by conventional proxy-variable methods.

Overall, the conceptual extension of the ACF framework and the preliminary empirical attempts undertaken in this thesis underscore significant constraints, both empirical and theoretical, in capturing the role of nature within firm-level production analysis. Empirically, the scarcity of firm-level data that explicitly account for biosphere-dependent services severely limits the applicability of conventional micro-econometric methods. Conceptually, the ACF framework rests on assumptions of observable, firm-specific inputs and relatively stable, homogenous market prices. Yet, the characteristics of natural capital, such as spatial heterogeneity, non-excludability, and uncertain regenerative dynamics, are fundamentally at odds with these premises.

These constraints suggest a broader methodological and epistemological limitation: conventional production function estimations, even when extended to include ecological variables, struggle to reflect the embeddedness of economic activity within complex natural systems. This insight necessitates a shift from firm-centric econometric modeling toward approaches that are more compatible with system-level thinking, that is approaches that can capture latent, indirect, and nonlinear interactions between the economy and the biosphere. In this context, Structural Equation Modeling (SEM) emerges not merely as an econometric alternative, but as a transitional method toward macro-level modeling paradigms in ecological economics.

SEM offers a flexible framework for incorporating latent ecological variables (e.g., ecosystem health, biodiversity integrity, environmental resilience) that are central to ecological macroeconomic models but are rarely directly observable nor measurable. Furthermore, its capacity to model simultaneous equations and feedback mechanisms makes it particularly suitable for representing bi-directional causalities, such as those between economic output and ecological degradation or regeneration. These features align closely with the core dynamics embedded in recent ecological macroeconomic frameworks, including Dasgupta's inclusive wealth model and the broader modeling landscape reviewed by Hardt and O'Neill (2017).

Importantly, SEM provides a conceptual and methodological bridge between the empirical demands of micro-based production theory and the integrated systems perspective of ecological macroeconomics. While ACF-style methods allow for a granular analysis of production dynamics under specific econometric assumptions, SEM offers a way to scale this analysis upward, enabling the construction of macro-level empirical models that remain grounded in theory but are more responsive to the invisible and systemic properties of natural capital. In other words, SEM facilitates the movement from estimating partial equilibrium relationships toward analyzing general system behaviors—a transition that is essential for embedding the economy within planetary boundaries.

Thus, the limitations encountered through the ACF approach are not merely obstacles to estimation, but indicators of a necessary methodological evolution. SEM should not be viewed as a fallback, but rather as a gateway toward macro-modeling tools capable of accommodating ecological complexity, feedback, and uncertainty. By enabling empirical strategies that are consistent with ecological macroeconomic principles, SEM plays a critical role in the ongoing project to develop nature-embedded economic models.

The following section offers a preliminary exploration of how SEM may be applied to estimate the contribution of nature within an extended production function framework. In doing so, it aims to illustrate the potential of SEM not only as a technical tool, but as a foundational component in the broader transition toward ecological macroeconomic modeling.

4 Integrating Structural Equation Modeling into Ecological Macroeconomic Modeling

The growing urgency to integrate the biosphere into economic modeling frameworks has spurred interest in methodologies capable of capturing the complex, latent, and feedback-driven nature of ecological-economic systems. This section explores the potential of Structural Equation Modeling (SEM) as a complementary empirical approach for advancing ecological macroeconomic modeling. Although SEM is widely used in fields such as psychology, natural sciences, and social sciences, it remains underutilized in economics, despite its ability to represent systems characterized by simultaneous, multidirectional, and partially unobservable relationships.

The objective of this section is to establish a conceptual and methodological link between SEM and the broader tradition of ecological macroeconomic models, as reviewed by Hardt and O'Neill (2017), and to demonstrate SEM's relevance for operationalizing macro-level frameworks such as that proposed by Dasgupta (2021). Ecological macro models typically aim to incorporate biophysical boundaries, stocks and flows of natural capital, and non-linear environmental dynamics—features that align closely with the structural and statistical capacities of SEM. These models often rely on post-Keynesian macroeconomic foundations, particularly in the form of stock-flow consistent (SFC) approaches.

In this context, SEM offers the capacity to explicitly model latent constructs such as ecosystem resilience or environmental degradation, while integrating observable proxies and mediating variables across both economic and ecological domains. As highlighted by Yann Dafermos in an interview given to Lukas Hardt and Daniel W. O'Neill (Hardt and O'Neill, 2017), even advanced ecological macro frameworks, such as his own work on stock-flow-fund (SFF) modeling Dafermos et al. (2017), still lack mechanisms to *"integrate feedback effects of the ecosystems on the macroeconomy"* in analogous manner to damage function in climate economics. SEM can help address this empirical gap by allowing for the estimation of hidden ecological processes that influence macroeconomic outcomes but remain unaccounted for in traditional models.

By bridging the methodological gap between data limitations and the systemic complexity of nature–economy interactions, SEM emerges not only as a pragmatic tool for empirical estimation but also as a conceptual bridge toward more integrated and ecologically coherent macroeconomic models. The remainder of this section elaborates on SEM's methodological fit, its alignment with ecological macroeconomic theory, and its potential role in the empirical estimation of nature-augmented production functions, particularly under uncertainty and incomplete information.

4.1 Structural Equation Modeling: A Primer for Ecological Applications

The evolution of SEM is deeply rooted in the development of 20th-century statistical and causal reasoning. Long before its application to ecology or economics, the building blocks of SEM emerged from three distinct but converging research traditions: correlation theory, factor analysis, and path analysis.

Karl Pearson introduced the correlation coefficient and laid the mathematical foundation for Principal Component Analysis (PCA) and regression modeling, two pillars of modern multivariate statistics and precursors to SEM (Pearson, 1901). In parallel, Charles Spearman advanced the idea of general intelligence ("g") as a latent variable, pioneering factor analysis to statistically capture unobservable constructs inferred from multiple indicators, an essential feature in today's SEM applications (Spearman, 1904 ; 1927).

In a landmark contribution, Sewall Wright developed path analysis, a graphical approach to estimating and visualizing causal relationships (Wright, 1921). His framework introduced the notions of direct and indirect effects, and anticipated the causal graph methodology decades before its formal adoption in econometrics and systems modeling. As noted by Kline (2017), these early 20th-century contributions represent the conceptual origins of SEM, even though none of these pioneers used the modern term.

While Pearson and Spearman focused on measurement and data reduction, and Wright on biological causality, these traditions were synthesized in the mid-20th century by social scientists such as Otis Dudley Duncan and Hubert M. Blalock Jr. Duncan (1966, 1975)'s work unified path analysis with latent variable modeling, introducing recursive systems into econometric analysis and helping establish SEM as a formal framework for both measurement theory and causal inference. Blalock (1961, 1964, 1973) further emphasized the role of SEM in modeling theoretical constructs that cannot be directly observed, such as attitudes or institutional structures—a concern that echoes strongly in ecological and macroeconomic modeling, where abstract constructs like "resilience" or "ecological integrity" are central yet unmeasurable by conventional means.

This foundation was further reinforced by Foster et al. (2006), who demonstrated SEM's suitability for handling measurement error, recursive systems, and feedback loops. These characteristics are essential to both economic and ecological systems, yet often inadequately addressed by traditional regression-based techniques.

Despite its social science origins, SEM gained a foothold in ecology in the 1990s and in beginning of the 2000s, largely through the work of Grace (2006). In the introduction to his seminal book *Structural Equation Modeling and Natural Systems*, Grace argues that ecological systems are inherently interdependent, involving multiple processes and feedback mechanisms that cannot be adequately captured by univariate or simple multivariate techniques. He writes:

> *"One of the factors that has limited the advance of ecological science has been the absence of methods for developing and evaluating multivariate theories. [...] Conventional univariate analyses are typically limited to the examination of a single or at most a few processes at a time. [...] Characterizing interacting systems using univariate methods is commonly misleading and often inadequate."*

Grace's perspective has proven influential. By enabling the simultaneous estimation of multiple relationships among observed and latent variables, SEM provides a powerful remedy to the analytical limitations of conventional ecological statistics. It is especially suited to studying systems with feedbacks, mediations, latent effects, and indirect causality, all of which are core features of coupled human-environment systems.

In environmental and ecological sciences, SEM has gained significant traction over the past two decades, largely due to the work of Grace and colleagues. In a comprehensive review, Grace et al. (2016) identified over 140 peer-reviewed ecological studies that applied SEM to topics ranging from species richness to ecosystem services, land use, and climate resilience. The review underscores SEM's ability to capture spatial heterogeneity, nonlinear effects, and mediated interactions between ecological and socio-economic systems.

Moreover, studies such as Tuominen et al. (2022) demonstrate SEM's flexibility in linking biophysical variables, human behavior, and policy interventions within a single modeling framework. These studies mirror the types of systems that ecological macroeconomics seeks to model, making SEM a natural fit for translating conceptual ecological frameworks into empirical models.

While SEM has been extensively used in psychology, sociology, and increasingly ecology, its application in macroeconomics remains limited. This is surprising given that macroeconomic systems, and especially ecological macroeconomics, often involve latent factors (such as "natural capital quality", "ecological risk", "social stability"), multidirectional feedback loops (for instance, environmental degradation reduces productivity, which alters policy, which in turn affects environmental pressures), endogeneity and simultaneity between key aggregates (e.g., GDP, emissions, biodiversity loss).

Ecological macroeconomic models, such as those grounded in SFC frameworks (Dafermos et al., 2017), attempt to capture these dynamics structurally but often lack corresponding empirical estimation tools. The use of SEM could help bridging this gap. Beyond the post-Keynesian SFC literature, SEM offers a methodological contribution that can enrich empirical practice in macroeconomics more generally by empirically modeling the latent structure of ecological-economic systems while remaining consistent with macroeconomic principles.

In particular, SEM is well aligned with the Dasgupta (2021) framework, where production is modeled as a function of reproducible capital, human capital, and natural capital, each of which may interact with and affect the others in complex, nonlinear ways. SEM allows such interactions to be estimated even when some key variables, such as ecosystem services, are unobservable or measured through noisy proxies.

4.2 SEM and the Estimation of Nature's Latent Role in Production

The integration of nature into production functions has become an increasingly urgent challenge in ecological economics, particularly in light of growing recognition that conventional economic models systematically underrepresent the role of natural capital. Dasgupta's framework advanced recalled in Equation (1), which includes nature as a co-equal input alongside produced and human capital, represents a significant conceptual step in that direction. However, efforts to empirically estimate nature's contribution, especially under conditions of incomplete data, are often hampered by the diffuse, unpriced, and spatially heterogeneous nature of ecological inputs. By providing a robust statistical framework for estimating the latent role of natural capital in macroeconomic production systems, SEM appears as a method that can address these empirical challenges.

Conventional estimation approaches, such as production function regressions or growth accounting, typically require observable and well-measured inputs. This is problematic in the case of ecological factors, many of which are not traded in markets, not directly measured in firm or national accounts, and whose effects are mediated through complex feedback loops rather than isolated inputs (Gowdy, 1994 ; Liu, Costanza, Farber, and Troy, 2010). For example, soil fertility, biodiversity, and hydrological integrity may significantly influence agricultural productivity, but these biophysical assets are rarely priced, let alone explicitly recorded, in economic data. SEM allows for the formal incorporation of such latent ecological variables, offering a solution to this longstanding disconnect between economic theory and available data.

In an SEM framework, latent variables (e.g., "ecosystem services", "ecological resilience") are modeled as unobservable constructs that influence a set of observable indicators. For instance, the latent quality of ecosystem services could be inferred from proxies encompassing biophysical conditions (e.g., living stock index, soil acidity, erosion, atmospheric carbon dioxide levels). These observed variables are treated not as direct causes of economic outcomes, but as manifestations of deeper, unmeasured ecological conditions that jointly affect productivity, land use decisions, and output levels.

SEM is uniquely equipped to handle the complexity of coupled human–natural systems because it enables the simultaneous estimation of interdependent relationships, including two-way interactions. These interactions capture the reciprocal causality between ecological and economic processes: ecological conditions (such as biodiversity, soil fertility, or water quality) affect productivity and resource use, while economic activity (through land conversion, input intensification, or pollution) feeds back into ecosystems, reshaping the very processes that sustain production. Such feedbacks can generate virtuous cycles of resilience or vicious cycles of degradation, making them central to ecological macroeconomic analysis.

In an applied setting, SEM can represent these dynamics through latent variables. For instance, ecosystem services may influence agricultural output both directly and indirectly via land productivity and input efficiency, while agricultural practices such as fertilizer use or expansion into new land areas simultaneously degrade ecosystem services. This ability to capture bidirectional feedbacks allows researchers to move beyond the one-directional causality assumed in standard econometric techniques or traditional growth models. Declines in ecosystem services, for example, may reduce yields, triggering more intensive input use that further weakens ecological resilience—a self-reinforcing cycle that SEM can empirically identify and quantify.

By explicitly modeling these interactions, SEM also strengthens the link between ecological macroeconomics and policy analysis. Production incentives such as fertilizer subsidies, carbon pricing, or land-use regulations can be evaluated not only for their immediate economic effects but also for their long-run ecological feedbacks and systemic consequences. Because ecological degradation in turn influences growth, employment, and financial stability, policies that ignore feedback loops risk being systematically miscalibrated. SEM thus provides a rigorous empirical tool for grounding the dynamic, co-evolutionary processes that ecological macroeconomic theory has long emphasized but struggled to operationalize.

To illustrate, consider the hypothetical SEM path model presented in Figure 1. This preliminary conceptual SEM illustrates the causal and recursive relationships between ecological integrity and agricultural-economic performance, emphasizing ecosystem health as a central latent construct mediating multiple systems of interactions. The model captures both biophysical and socioeconomic dimensions, explicitly incorporating feedback loops between natural and economic subsystems.

At the center of the model is the latent variable Ecosystem Health, which is not directly observed but is inferred from multiple measurable biophysical domains. Ecosystem health is conceptualized as a function of:

- Physiochemical Drivers, which encompass:
  - Water Quality, influenced by biochemical oxygen demand (BOD), total phosphorus (TP), and total nitrogen (TN).
  - Soil Chemistry, inferred from indicators such as soil acidity (measured via its pH) and soil organic carbon (SOC).

  - Atmospheric Conditions: Including temperature (Temp.) and atmospheric CO_2 levels.

- Biological Conditions captures ecosystem vitality through biological indicators such as the Normalized Difference Vegetation Index (NDVI), macroinvertebrate community index (MCI), and biomass index (BMI, also called living stock in some papers and data bases).

- Land Use: Represented by land-cover and land-management indicators such as percentage of land under agriculture (% Agri.) or urban (% Urb.) use, erosion levels (Erosion), grazing pressure (Grazing), and both chemical and natural pesticide (respectively, Chem. Pest. and Nat. Pest.) applications.

Each of these components serves as a measurable indicator of stress or resilience in the ecosystem, feeding into the unobserved construct of ecosystem health.

Ecosystem health directly affects three critical agricultural outputs:

- Crop Yield, influenced via mechanisms such as soil fertility, pollination services, and water retention capacities, also encompassed in the concept of ecosystem health.

- Input Efficiency (or Productivity), determined by ecological services such as natural pest regulation, pollination, and nutrient cycling, which affect how efficiently economic inputs (labor, capital) are converted into outputs, and hence create a direct link between productivity and ecosystem health.

- Land Use Intensity, mediated by ecological constraints on land capacity and the trade-offs between expansion (e.g., deforestation) and intensification. The healthier an ecosystem, the more it will be used, increasing therefore the risk of degradation and depletion. The Amazonian deforestation is one of the most compelling example of this line of thoughts.

These three pathways channel ecological functions into agricultural productivity, thus forming the ecological basis for economic performance.

From the agricultural outputs, the model branches into a set of economic production inputs and outcomes. As seen in Sections 2 and 3, Production is a direct function of Crop Yield, Labor Input, Capital Investment, Intermediate Inputs (e.g., fertilizers, seeds, water...), and Input Efficiency (or Productivity). Production, in turn, affects many aspects of human economic and social life. For instance, it influences Human Well-being, which is operationalized as a composite outcome encompassing Food Security and other benefits of production (e.g., possibility to invest in education, better health and healthcare systems, longevity, etc.).

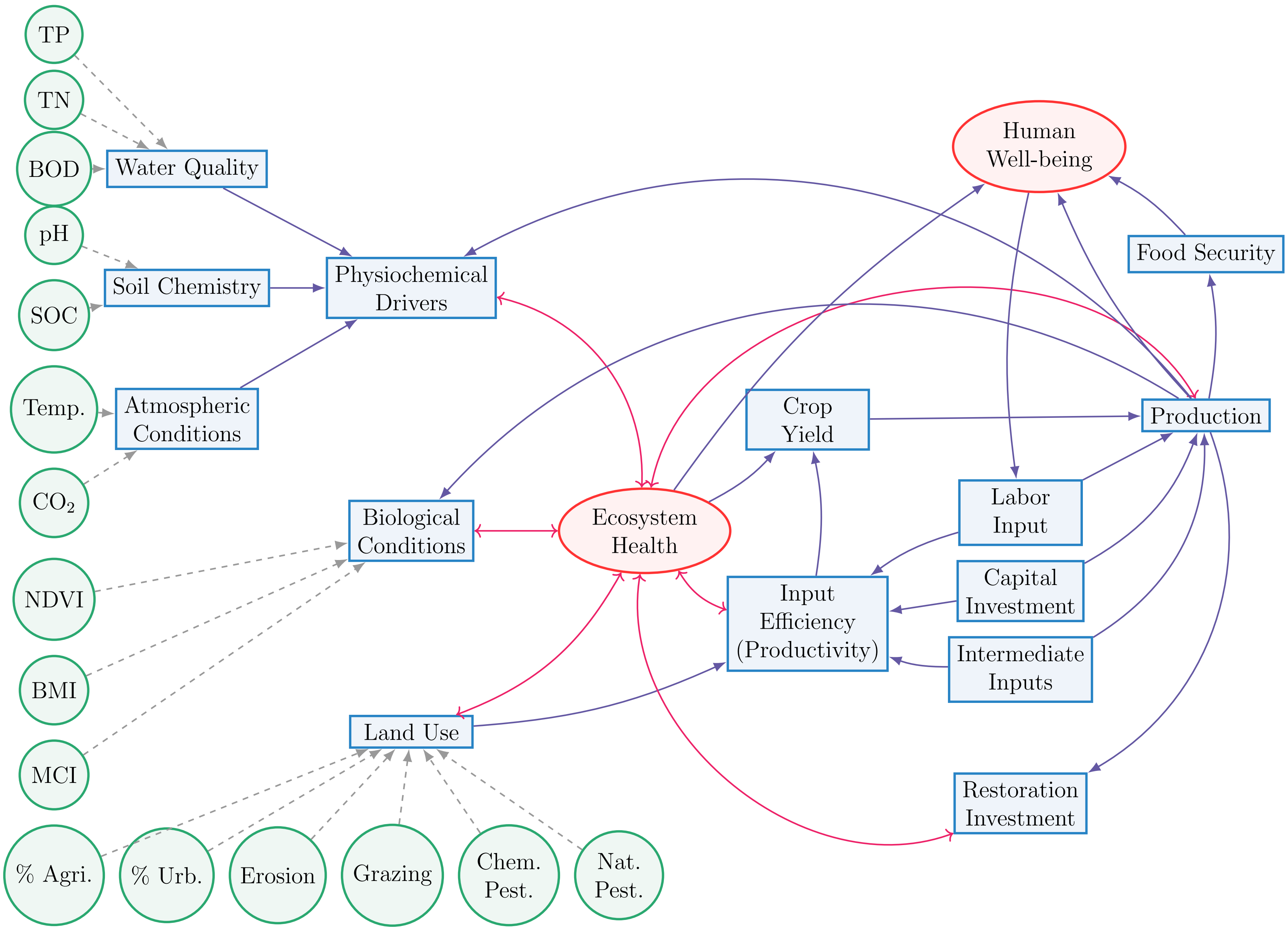
Crucially, the model incorporates multiple feedback loops. Land Use Feedback Loop represents the idea that changes in land use (e.g., intensification, urban expansion, pesticide application) degrade or restore ecosystem health. This forms a recursive loop where land use both results from and influences ecological status. Restoration Investment Feedback Loop graps that restoration investment is influenced by observed declines in productivity or well-being, leading to targeted interventions aimed at improving ecosystem health. This forms a restorative feedback loop, potentially enhancing both ecological and economic resilience. Productivity-Ecosystem Feedback Loop emphasizes that declines in input efficiency may trigger increased reliance on chemical inputs, which in turn negatively affect water and soil quality—further degrading ecosystem health. Conversely, ecological enhancements that increase input efficiency reduce economic dependence on costly or harmful inputs. Production-Ecosystem Health Feedback Loop highlights the already known impact of production on ecosystem health for instance through greenhouse gas (GHG) emissions (Production - Physiochemical Drivers), harvesting and extraction (Production - Biochemical Conditions). The impact of the production on each indicator of the physiochemical drivers and biochemical conditions could be further precise using current evidence drawn from climate economics. This would therefore contribute to reunifying the literature between climate economics and nature economics, to softening the opposition nature-risks versus climate-risks that has been risen over the past decade, and to extending the discussion beyond CO_2 and GHG emissions that dominated environmental economics and green finance.

This preliminary SEM concept reveals several systemic leverage points. First, restoration investment emerges as a critical node for policy intervention, providing a pathway to positively reinforce ecosystem health and stabilize agricultural productivity. Second, land use governance is central to mitigating degradation pathways and aligning agricultural intensification with sustainability objectives. Third, intermediate inputs represent a dual-edged mechanism: while necessary for short-term productivity, their overuse introduces negative feedbacks into the ecological subsystem. Managing these inputs is thus essential for preserving long-term system viability. Last, human well-being as an ultimate dependent variable is shaped not only by economic production but also by underlying ecological integrity, emphasizing that sustainable development goals must integrate ecological considerations into economic planning.

The structure proposed in Figure 1 offers a preliminary systems-based framework for analyzing the interplay between natural capital, agriculture, and economic development. It supports integrated policy design that aligns ecological sustainability with agricultural productivity and human welfare. It enables researchers to (i) estimate direct effects of ecological conditions on productivity (the focus of this thesis), (ii) capture mediated effects via economic variables such as land use, (iii) account for feedback loops between economic activity and ecological integrity, and (iv) model latent ecological constructs using observed environmental indicators.

From an econometric standpoint, SEM is particularly valuable. By linking latent variables to indicators, it allows for the integration of measurement models with structural models, therefore specifying the causal relationships among variables. This dual capacity enables more accurate estimation of ecological contributions even when no single indicator is sufficient on its own, and when indicators are subject to noise or measurement error. Moreover, the model can be estimated using Maximum Likelihood, Partial Least Squares, Covariance-based, or Bayesian-based estimation techniques, depending on data availability and distributional assumptions.

Figure 1: Conceptual SEM - Linking Ecosystem Health to Agricultural and Economic Outcomes



A further advantage of SEM is its flexibility with respect to data structure. Models can be estimated using cross-sectional, panel, or time-series data, and the framework can accommodate both country-level and regional-level macroeconomic datasets. For example, SEM could be applied to Eurostat or FAO data across EU member states to estimate how latent ecological variables shape agricultural productivity at the macro level, even when detailed firm-level data are unavailable. This is particularly pertinent in light of the data limitations discussed in Section 3.4, where attempts to empirically apply ACF-style estimation to micro-level ecological inputs were hampered by severe data gaps.

Finally, SEM facilitates transparency and reproducibility by making explicit the hypothesized causal pathways between ecological and economic variables. Unlike "black-box" machine learning methods, SEM relies on a priori theory to specify model structure, thereby reinforcing conceptual clarity and interpretability —qualities that are particularly important in policy-relevant ecological macroeconomic research and more broadly to show the scientific soundness of considering an embedded-in-Nature world.

In sum, SEM offers a rigorous and adaptable framework for empirically estimating the latent, systemic, and interactive role of nature in production processes. It addresses key limitations in current macroeconomic modeling by (i) including unobservable ecological inputs, (ii) modeling complex causal structures including feedback and mediation, (iii) managing and integrating measurement error and data incompleteness, and (iv) aligning empirical models with theoretical macro frameworks (Dafermos et al., 2017 ; Dasgupta, 2021).

In the next section, we turn to the broader question of how SEM can be conceptually integrated into the architecture of ecological macroeconomic models, moving from a tool of empirical estimation to a structural component of system-wide economic-environmental modeling.

4.3 A Conceptual Integration with Ecological Macroeconomic Models

While Section 4.2 has demonstrated how SEM can serve as a pragmatic empirical tool for estimating the latent role of nature in production, its utility extends beyond empirical estimation. SEM can also be understood as a conceptually compatible and structurally integrative method within the broader landscape of ecological macroeconomic models. In particular, it resonates with the modeling logic of post-Keynesian ecological frameworks, stock-flow models, and biophysical systems thinking that define much of the current frontier in ecological macroeconomics.

Ecological macroeconomic models aim to describe an economy embedded within, and dependent upon, the biosphere. As summarized by Hardt and O'Neill (2017), these models typically integrate three essential features: (i) non-linear feedbacks between economic activity and the environment, (ii) stock and flow dynamics across economic and ecological domains, and (iii) multi-scalar complexity, involving interactions across local, national, and planetary levels. However, despite the increasing sophistication of such models, ranging from dynamic systems approaches to agent-based and stock-flow consistent (SFC) formulations, the empirical side of ecological macroeconomics remains underdeveloped. Most models are theoretical or calibrated using exogenous parameters, with limited capacity for empirically estimating structural relationships, particularly those involving nature's contributions to economic performance.

Here, I propose to look closely at stock-flow models, and in particular Dafermos et al. (2017).

Their model is a stock-flow-funds (SFF) model that integrates natural capital degradation, climate damages, and financial instability within a post-Keynesian macroeconomic structure. Climate change is introduced as an endogenous process, driven by CO_2 emissions that accumulate over time and affect the productive capacity of the economy through damages to natural capital.

Dafermos's model advances the macroeconomic literature by systematically linking the dynamics of economic output, financial variables, and environmental degradation, while also respecting the biophysical foundations of economic activity.

Rooted in the Sraffian and Minskyan traditions,[10] the model explicitly distinguishes between stocks (e.g., physical capital, debt, atmospheric carbon concentration) and funds (e.g., labor and natural ecosystems), the latter of which are required to sustain production but cannot be depleted without systemic consequences. Dafermos departs from neoclassical assumptions of market-clearing behavior and rational expectations, emphasizing instead the role of endogenous money, financial instability, and underemployment.

One of the central innovations in the model is the explicit modeling of environmental degradation as a dynamic stock process, particularly through the accumulation of CO_2 in the atmosphere and its adverse feedback effects on economic growth. The model introduces a climate damage function that reduces productivity as the stock of atmospheric carbon increases. This mechanism provides a non-linear constraint on long-run growth trajectories, reinforcing the case for structural and policy interventions.

Importantly, Dafermos embeds the ecological dimension within a monetary production economy. Households, firms, banks, and the government interact in an integrated system where financial variables, such as private debt and public deficits, have real and ecological consequences. The authors also account for path-dependency and hysteresis effects, highlighting how initial conditions and policy trajectories shape future outcomes in both the economic and ecological domains. Policy analysis within the model suggests that relying solely on carbon pricing or green technological progress is insufficient to ensure ecological sustainability. Instead, the model supports a multiinstrument policy approach that includes public investment, debt restructuring, green industrial policy, and limits to growth. These policy prescriptions echo the theoretical underpinnings of ecological macroeconomics, which emphasize the physical limits to growth and the need for a post-growth or steady-state economy.

While pathbreaking in its integration of ecological and financial dynamics, the Dafermos framework also inherits the usual limitations of post-Keynesian structural models. It is not built on explicit microfoundations, relies on deterministic rather than stochastic dynamics, and abstracts from forward-looking expectations. As a result, it cannot capture the role of uncertainty, belief formation, or heterogeneous agent behavior in shaping macroeconomic-

[10] The Sraffian tradition, grounded in the work of Piero Sraffa (1960), emphasizes the classical surplus approach to value and distribution, focusing on the physical input-output relations in production and rejecting neoclassical capital theory. It provides a framework for analyzing income distribution and growth without relying on marginalist assumptions, making it particularly relevant for ecological analyses concerned with biophysical constraints. The Minskyan tradition, developed by Hyman Minsky (1986), centers on the endogenous nature of financial instability in capitalist economies. It highlights how cycles of debt accumulation, speculative finance, and liquidity preferences can generate systemic crises, particularly in the absence of strong financial regulation. Together, these traditions inform ecological macroeconomic models that integrate material limits and financial fragility into macroeconomic dynamics. Dafermos et al. (2017) synthesizes these traditions by using Sraffian logic to represent the biophysical structure of the economy and the distribution of surplus, and by applying Minskyan dynamics to model financial fragility, debt accumulation, and macro-financial instability—while showing how these interact with ecological constraints (e.g., climate damages reduce profitability and financial stability).

environmental outcomes. These features, while consistent with the post-Keynesian critique of representative-agent, rational-expectations models, limit the capacity of the framework to engage with mainstream macroeconomics or to be empirically disciplined through econometric estimation. Addressing these gaps —by introducing stochastic processes, incorporating expectations, and developing empirically tractable tools—remains a crucial step for advancing ecological macroeconomics beyond its current boundaries. SEM could be a powerful tool to fulfill this purpose.

SEM offers a compelling complement to stock-flow models. By providing an empirically grounded framework that can capture latent structures, stochastic relationships, and system-wide interdependencies, SEM helps operationalize the causal complexity at the heart of ecological macroeconomic theory while remaining consistent with macroeconomic principles.

First, on the causal structure and feedback loops. At its core, SEM is designed to handle systems in which causal influence is not unidirectional, but instead runs through feedback loops, mediation effects, and simultaneous interactions (see Section 4.2). This structure mirrors the ecological macroeconomic vision of the economy as an open system embedded in a larger biosphere, with reciprocal interactions across domains (see Section 4.1).

Second, on the stock-flow and latent-fund compatibility. One of the central innovations of ecological macroeconomic models is the explicit representation of stocks and flows in closed accounting frameworks. Stock-flow models, such as those proposed by Dafermos et al. (2017), Bovari et al. (2018), and Berg et al. (2015), provide consistency between real and financial flows while allowing for environmental dynamics. SEM, while originating in social sciences, is methodologically compatible with this logic. In fact, latent variables in SEM can be understood as conceptual analogues to ecological "funds" or stocks, whose effects manifest indirectly through observable flows or proxies. Taking the example presented in Figure 1, a latent construct such as "ecosystem health" can influence observed flows like "agricultural yields". These flows, in turn, may mediate effects on other macroeconomic outcomes such as food prices, capital investment, or trade balances. Importantly, SEM can represent these dynamics in a recursive or non-recursive structure, depending on whether the feedback between variables is contemporaneous or time-lagged.

Third, on the integration of non-market and latent dimensions. Perhaps the most difficult modeling challenge in ecological macroeconomics is the incorporation of non-market environmental variables (such as biodiversity, ecosystem resilience, or climate stability) into core economic dynamics. These variables often lack direct price signals and cannot be observed directly, but are critical to understanding long-term economic sustainability. SEM addresses this issue by allowing such variables to be modeled as latent constructs, defined by observable indicators but not directly measurable themselves. This is not merely a technical feature: it provides a conceptual pathway for integrating ecological realism into macroeconomic analysis. By allowing researchers to estimate the empirical influence of non-market ecological factors on macroeconomic outcomes, SEM can help embed ecological constraints into the heart of economic analysis, rather than treating them as exogenous shocks or boundary conditions. This ability is particularly important in extending the insights of Rockström et al. (2009b)'s planetary boundaries and Dasgupta (2021)'s nature-augmented production function, where natural capital is modeled not only as a direct input but also as a stock whose depletion or regeneration alters productive capacity over time. SEM provides the statistical architecture to estimate such relationships empirically, without requiring full observability of all system components.

Bringing SEM into the framework of ecological macroeconomics suggests a vision for empirical-ecological macroeconomics, that is an approach that seeks to ground complex, systems-based models in observed data, even when such data are incomplete, noisy, or indirect. Rather than relying exclusively on calibration or synthetic scenarios, SEM enables the estimation of structural relationships in macroeconomic models that account for ecological feedbacks, measurement uncertainty, and systemic complexity.

Moreover, SEM offers a flexible platform for model validation, allowing ecological macroeconomists to test whether the hypothesized causal relationships in their models are supported by empirical data. This can aid in refining theoretical assumptions, improving model realism, and enhancing the policy relevance of ecological macroeconomic research.

Finally, the SEM framework can be extended to multi-group comparisons (e.g., across countries or regions), time-series cross-sectional analysis, or dynamic SEM, enabling the study of ecological-economic interactions under different institutional, geographic, and temporal contexts. Such extensions could prove vital in evaluating the differential impacts of ecological degradation or policy interventions across economies at varying stages of development.

In sum, SEM is not merely a complementary estimation technique but a structural ally to ecological macroeconomic modeling. In particular, its compatibility with SFF and SFC reasoning, its ability to estimate latent and non-market variables, and its formal representation of feedback and mediation effects align it closely with models. Where SFC models offer a theoretically rigorous map of the economy-ecology nexus, SEM offers the empirical compass to navigate it. By combining the strengths of both, researchers can begin to construct models that are not only ecologically realistic and macroeconomically consistent, but also empirically validated, which is an essential step toward informing the policies needed to manage the planetary economy in the Anthropocene.

5 Conclusion

This thesis has addressed a critical omission in mainstream macroeconomic modeling: the exclusion of nature as a foundational input in the production process. Drawing on the conceptual framework proposed by Dasgupta (2021), it has explored the theoretical and empirical challenges of incorporating natural capital, specifically ecosystem regulating and maintenance services, into production function estimation. By adapting the Ackerberg, Caves, and Frazer (2015) method, I have proposed a tentative econometric extension capable of identifying nature's role as a latent but essential contributor to firm-level productivity. While this framework remains largely conceptual due to severe data limitations, it marks a first step toward operationalizing ecological macroeconomics in measurable terms.

The tentative empirical application, using aggregate European agricultural data, illustrates the potential of this approach to challenge existing productivity measures that overstate the contribution of produced capital by omitting ecological foundations. However, as emphasized throughout, the absence of microdata capturing firm-level interactions with natural systems significantly hinders empirical validation. This points to a broader institutional gap: the prevailing economic metrics and reporting standards systematically overlook the biosphere, treating its services as either infinite or external, contrary to the mounting ecological evidence.

Recognizing these limitations, the thesis also investigates Structural Equation Modeling (SEM) as an alternative empirical strategy. SEM's ability to incorporate latent variables and model feedback loops positions it as a powerful, yet underutilized, tool for ecological macroeconomic analysis. In doing so, this work contributes not only to methodological innovation but also to the conceptual realignment of economics with planetary boundaries. Ultimately, the integration of natural capital into core economic modeling remains both a technical and epistemological challenge, one that this thesis begins to confront and that future research, including my forthcoming PhD, aims to deepen and expand.

6 Appendix

6.1 Adding Provisioning Services in the Extended ACF Estimation Process

Nature-based intermediate inputs, or "provisioning services" from the biosphere, are needed in the production process, R_{it}, can be considered, just like labor, as a variable with potential dynamic implications chosen at period $t-b$ (with $0 \leq b \leq 1$). The reason for R_{it} to have potential dynamic implications while M_{it} remains chosen conditional on the information available at the period t - that is statically - lies in two main arguments: (i) the asymmetrical reaction times between R_{it} and M_{it} and biological constraints of R_{it}, and (ii) the decoupling of purchasing and usage decisions.

To expand on (i), industrial inputs are generally available on short notice, via well-developed markets, with relatively stable prices and controlled logistics. They can be adjusted almost instantaneously, according to anticipated productivity for the current period. On the other hand, natural inputs such as seeds, organic inputs or volumes of water required for irrigation, are often subject to decision, maturation or regeneration delays. Their mobilization therefore relies on decisions made potentially and likely before t, incorporating anticipations of future productivity ω_{it} and climatic or environmental shocks. This justifies a dynamic modeling of R_{it}.

Focusing now on (ii), in many sectors, natural inputs are produced or ordered upstream (e.g. seeding, hay stockpiling, breeding stock), while industrial inputs are purchased on the fly on the market, often depending on observed production conditions (e.g. fine-tuning of fuel or spare parts). Put otherwise, the company chooses R_{it} in anticipation of productivity ω_{it}, just like labor, while M_{it} remains a contemporary choice variable.

In such case, the addition of R in the estimation framework would be similar to the addition of S suggested in section 3 (Equations 15 to 17), but instead of extending the "fixed" variable timing assumption, we extend the "free" variable modeling assumption.

6.2 On the Regeneration and Degradation of the Maintaining and Regulating Services

Regeneration. Natural regeneration corresponds to nature's biophysical capacity to renew its stock by itself. A simple and commonly used form for $g(.)$, as defined in section 3, is logistic regeneration, capturing ecological limits is

$$g(s_{it}) = \rho s_{it} \left(1 - \frac{s_{it}}{\bar{s}}\right) \tag{18}$$

where ρ is the intrinsic regeneration parameter, and $\bar{s}$ is the carrying capacity —maximum attainable natural capital in the region. This specification captures that regeneration is fast when S is moderate, but slows down as S gets close to collapse ($S \to 0$) or saturation ($S \to \infty$).

Degradation. Degradation refers to the decline in the quantity or quality of ecosystem functions due to direct or indirect human activity. It's a process, often gradual but sometimes abrupt, that reduces the capacity of natural capital S. In mathematical terms, degradation is a negative flow that reduces the stock of natural capital over time. There is not a unique way to write d_{it}. Yet, as an example and to give further intuition, I suggest using an intensity-adjusted non-linear specification. Under this form, I reflect that as S_{it} declines, degradation per unit of emissions E_{it} gets worse (e.g., threshold effects, tipping points). Other specifications could be used and will be discussed in the Appendix.

$$d_{it} = \delta \frac{{E_{it}}^2}{S_{it}} \tag{19}$$

where E_{it} is the pollution generated by firm i's production process at date t.

Restoration and maintenance investment. Regarding firm's investment in in restoration and maintenance of natural capital, I assume that $h(.)$ is a non-decreasing function. This behavior is economically and ecologically justified for several straightforward reasons. First, in the absence of perverse effects such as maladaptation or ecological mismanagement, more investment in maintenance or restoration should not reduce the natural capital stock. Moreover, even if the returns are small, a higher level of well-directed effort is expected to lead to at least no worse —and typically better—outcomes. Second, restoration actions typically involve physical or biological processes (e.g., reforestation, erosion control, wetland recovery) that accumulate over time. These actions increase the availability of ecological functions, and unless mismanaged, their marginal effect should be non-negative. Third, a non-decreasing $h(.)$ is consistent with ecological regeneration dynamics. In most ecological models, the human-enhanced component of recovery (here, $h(.)$) is treated as complementary to natural regeneration $g(s_{it})$. If $h(.)$ were decreasing, this complementarity would break down, leading to unintuitive or unstable dynamics. For simplicity purposes, one could be tempted to define $h(.)$ as affine, and even in its simplest form as:

$$h(\alpha_{it} i_{it}) = \alpha_{it} i_{it}$$

Yet, this linear form assumes constant marginal returns to investment in restoration and ignores threshold effects, ecological resilience, and diminishing returns. This specification may therefore not be adequate to depict reality. Indeed, natural capital restoration processes often exhibit nonlinearities, threshold effects, and diminishing returns. For example, initial restoration efforts may have little visible effect if the ecosystem is severely degraded or fragmented, as critical ecological functions (e.g., biodiversity, soil structure, hydrological cycles) may have already collapsed. Conversely, beyond certain ecological thresholds, small investments can trigger synergistic recovery through self-reinforcing natural regeneration processes. Additionally, restoration outcomes depend on complex ecological interactions and may involve long time lags, meaning that investment today may only yield benefits over extended horizons—or not at all if thresholds are crossed. These characteristics imply that the marginal effectiveness of restoration investment is likely to be state-dependent, possibly requiring concave or sigmoidal functional forms rather than linear specifications. I could suggest that:

$$h(\alpha_{it} i_{it}) = \psi \left(\frac{(\alpha_{it} i_{it})^\gamma}{1 + \exp(\lambda(\alpha_{it} i_{it} - \bar{i}))} \right) \tag{20}$$

where $\gamma \in (0, 1)$ is the curvature parameter of the marginal return profile ; $\bar{i}$, the minimum critical investment level to trigger restoration (threshold) ; λ, the steepness of the response curve $\psi \equiv \psi(S_{it}) = \frac{\theta}{1+\kappa S_{it}}$, the state-dependency effectiveness of investment. Equation (20) allows for low efficiency at low investment levels, accelerating response beyond a minimum, and diminishing returns after a certain point. The concavity borne by $\psi(\alpha_{it} i_{it})^{\gamma}$ captures the idea that additional units of investment become less effective and that deeper restoration requires exponentially more resources. The activation threshold modeled by the logistic response $\frac{\psi}{1+\exp(\lambda(\alpha_{it} i_{it} - \bar{i}))}$ reflects that ecosystems may not respond at all to sub-threshold restoration efforts, but respond rapidly above the threshold. The state-dependency effectiveness reflected by the definition of $\psi \equiv \psi(S_{it}) = \frac{\theta}{1+\kappa S_{it}}$ translates that restoration becomes harder as S increases. The possibility of an inverted state-dependent function reflects the reality that some ecosystems only begin to respond to restoration efforts once a minimal ecological structure or critical functional threshold has been reestablished.

6.3 Extended-ACF Estimation with Paid and Unpaid Labor

Estimation Model	**Without S**			**With S**			
	K	**Paid L**	**Unpaid**	**K**	**S**	**Paid L**	**Unpaid L**
Estimate	0.037	0.14	0.196	0.144	0.319	0.271	0.571
Std. Error	(0.208)	(0.959)	(1.671)	(0.367)	(0.367)	(2.566)	(2.4)
N	42			42			
Bootstrap repetitions	5			5			
1st Stage Parameters	NA	NA	NA	NA	NA	NA	NA
Optimizer	optim			optim			
Elapsed Time	0.01 mins			0.01 mins			

Table 3: Production Function Estimation Summary - With Paid and Unpaid Labor Distinction

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