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Navigating Sustainability: Revealing the Hidden Forces in Social–Ecological Systems

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Abstract: During the 1992 Rio Conference, the sustainable development agenda envisioned a transformative change for the management of natural resources, where the well-being of human society would be enhanced through the sustainable use of natural capital. Several decades on, relentless economic growth persists at the expense of natural capital, as demonstrated by biodiversity decline, climate change and other environmental challenges. Why is this happening and what can be done about it? We present three agent-based models that explore the social, economic and governance factors driving (un)sustainability in complex social–ecological systems. Our modelling results reinforce the idea that the current economic system fails to safeguard the natural capital upon which it relies, leading to the prevailing decoupling between the economic and natural systems. In attempting to find solutions for such disjunction, our research shows that social–ecological systems are complex, dynamic and non-linear. Interestingly, results also reveal that there are common factors to most social–ecological systems that have the potential to improve or diminish sustainability: the role of financial entities and monetary debt; economic speculation; technological development and efficiency; long-term views, tipping point management and government interventions; and top-down and bottom-up conservation forces. These factors can play a dual role, as they can either undermine or enhance sustainability depending on their specific context and particular conditions. Therefore, the current economic system may not be inherently unsustainable, but rather specific economic mechanisms, decision-making processes and the complex links between economic and natural systems could be at the root of the problem. We argue that short- and medium-term sustainability can be achieved by implementing mechanisms that shift capitalist forces to support environmental conservation. Long-term sustainability, in contrast, requires a more profound paradigm shift: the full integration and accounting of externalities and natural capital into the economy.

Keywords: sustainability; social–ecological system; natural capital; ecosystem services; biodiversity; agent-based model

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1. Introduction

Sustainability constitutes the paramount challenge for humanity in the Anthropocene era [1]. Extensive literature exists on environmental challenges confronting humanity, including climate change and biodiversity loss, although the practical solutions are less evident [2].

One of the key challenges to developing and deploying these solutions is the fact that our economic system is not institutionally embedded within the wider, more important environmental system [3]. The current dominant economic paradigm continues to embrace the growth-oriented strategy pioneered by the Bank of England in the 1700s [4]. In this system, the economy is not restricted or built upon the biophysical constraints of the environment. Whilst this system may have served us well for 400 years, the environmental degradation and damage highlights the need for a different approach to securing human health and well-being [5].

Global sustainability is only possible with transformative changes that address the actual drivers of the root economic, social and technological causes of nature's deterioration [6]. Unless economic development is unequivocally decoupled from environmental degradation, natural systems face the risk of collapse, thereby jeopardising the accessibility of essential natural resources and benefits, along with compromising human well-being [7,8]. Ensuring the preservation of nature necessitates the immediate restructuring of conventional global economies and operational frameworks.

Various pathways have been suggested to promote a more sustainable economy, such as steady-state and degrowth approaches [9,10], green growth [11,12] and circular economy [13,14], among others. However, none of these pathways has proven to be successful in transforming our economic system [1]. One of the issues is that most existing approaches are based on the largely monodisciplinary science of the 1950s, 60s and 70s, which were not designed to address the current complex environmental problems [15–18]. In the mid-20th century, sustainability issues were primarily perceived as local, reversible and direct; today, our understanding acknowledges that impacts are dynamic, interconnected and occur across broad geographical and economic scales [19]. Thus, while past scientific approaches were rooted in monodisciplinary concepts that overlooked the complexity of systems [20–23], current academics acknowledge that sustainability cannot be ascribed to a solitary cause; instead, it arises from a combination of diverse, non-linear, cross-scale and dynamic factors [24,25]. Examples of systems and concepts with the latter characteristics include financial markets and ecosystem resilience, among many others.

With the aim of addressing system complexity, scholars started to treat social, economic and ecological systems within a single coupled system [26–29]. This system is comprised of both human and natural elements, collectively defined as a social–ecological system (SES), which is characterized by being complex, dynamic, adaptive, interactive and multi-scalar [30,31]. This shift in the mindset of researchers emphasized that humans should be seen as a part of, and not apart from, nature [24,32]. In response, diverse frameworks have been developed to structure research into SESs [28–30,32–36].

Given the various timescales of ecological change and intricate characteristics of socio-economic dimensions [37], systemic, holistic, integrative and interdisciplinary approaches and frameworks are needed to better understand SESs. In this regard, SES science has a significant potential to benefit through computer modelling approaches that allow for a better understanding of system complexity, such as agent-based modelling (ABM). ABM facilitates the exploration of the interactions among autonomous and heterogenous agents through the property of emergence, by evolving relationships among the elements that characterize systems and their diverse equilibria [38]. This modelling approach integrates heterogeneity, feedback loops and multi-scalar interactions [39] and has been widely used in ecology—known as individual-based modelling (IBM) [40,41]—and economics through agent-based computational economics (ACE) [42,43]. ABMs prove advantageous in examining dynamics within complex SESs and offer insights regarding the sustainable management of natural resources [44–48].

In this research we present three ABMs, one conceptual and two that are based on case-studies. The three ABMs have been developed under the same SES framework, which allows to explore the socio-economic and governance factors driving (un)sustainable development in SESs. The three ABMs have been published as scientific articles [46,49,50].

This article summarizes the main modelling outcomes and provides new SES insights on the following question: what drives (un)sustainable development in SESs?

2. Materials and Methods

The methodology is divided into four sections (Sections 2.1–2.4). First, the conceptual framework of the research is presented, where the SES integrated in the three ABMs is analysed and described. Second, the context of the research is detailed, together with a description of the study areas. Third, the overall ABM approach is addressed. Finally, the specific ABMs are characterized and described to highlight detailed aspects of the SESs being investigated.

2.1. Modelling Framework

We built an integrated framework as a basis for the three ABMs. The framework itself is inspired by two widely recognized SES frameworks: the social ecological systems framework (SESF) [28,29,51] and the ecosystem services framework (ESF) [7,52–54].

Our integrated framework (Figure 1) includes a natural and socio-economic system, where the flow of ecosystem services (ESS) occurs bidirectionally, including feedback and nonlinearities. ESS and biodiversity—particularly biodiversity understood as the biotic element of natural capital—act as links between the socio-economic and natural systems. Additionally, economic–financial and protection–conservation forces refer, respectively, to market and economic powers (e.g., land privatization and acquisition and bank credit lending to companies involving deforestation) and environmental governance powers (e.g., land restoration and protection policies) that drive land use change (LUC) and other anthropic processes, thus affecting natural capital and its biodiversity. Consequently, these changes affect the land's capacity to provide different ESS, as well as the socio-economic setting of the system, referring to the beneficiaries of ESS along with the financial resources of users.

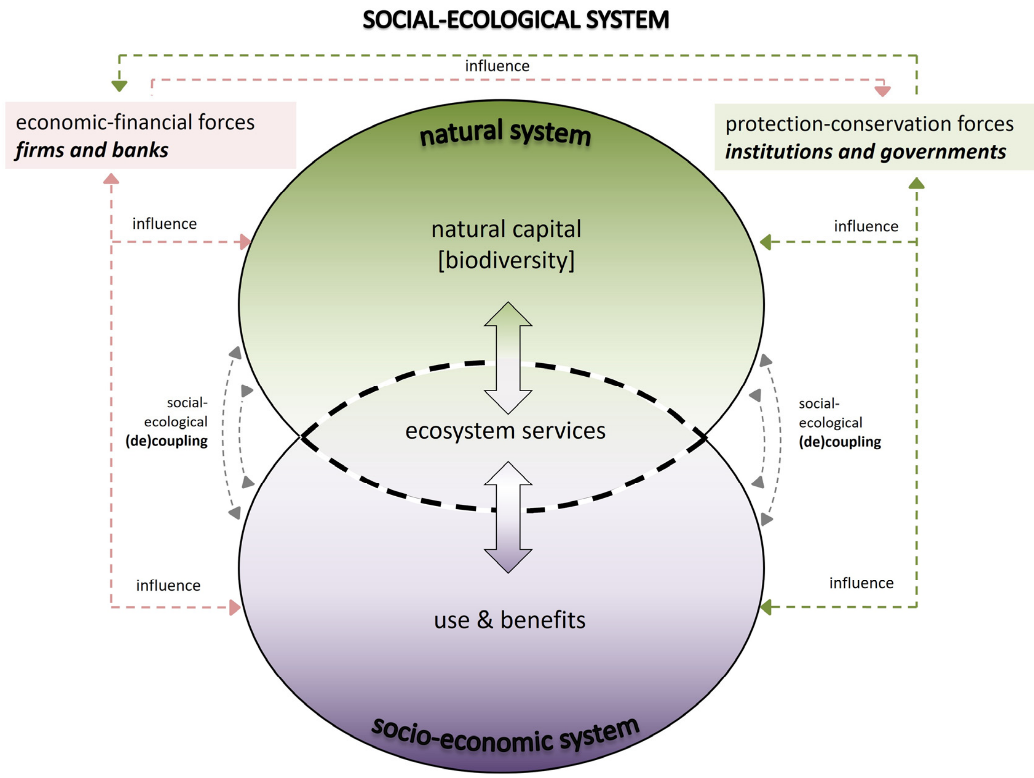

Figure 1. Integrated conceptual framework to explore (un)sustainability in social–ecological systems. The framework consists of coupled natural and socio-economic systems, where economic and

conservation forces affect natural capital and its biodiversity. This gives rise to trade-offs and synergies in ESS, which hold implications for the beneficiaries. The oval with dash-shaped points at its centre symbolizes the process of the (de)coupling of socio-economic and natural systems.

The framework operates in a bi-directional manner, meaning that decisions made by ES users have reciprocal impacts on biodiversity and the natural system's capacity to provide diverse ESS. Likewise, both economic–financial and protection–conservation forces exert direct influence on each other—as indicated by the dashed arrows at the top of Figure 1—and are also influenced by the state of the SES itself—as illustrated by the bi-directional arrows coming into both forces from the bottom. Both the protection–conservation and economic–financial forces symbolize internal and external (to SESs) forces affecting SES sustainability. Finally, the dash-shaped overlap at the core of the SES represents the existing disjunction between socio-economic and natural systems, and the degree of (de)coupling between the two systems is illustrated by the grey dashed arrows on either side of the dashed oval.

2.2. Context and Study Years

Our research employs both conceptual and empirical methodologies, where two models serve as case studies—one in Indonesia and another in the Wet Tropics of Queensland, Australia (Figure 2). Tropical regions serve as examples of SESs, characterized by intricate and dynamic interactions between people and nature [30,55]. Furthermore, tropical SESs present a suitable context for exploring those factors that enhance SES (un) sustainability due to a key existing trade-off for achieving global sustainability: food production–climate change mitigation–biodiversity conservation [56]. First, tropical SESs are essential areas for providing sustenance for the expanding human population [57]. The escalating demand for food requires a projected 50% increase in food production by 2050 to address the growing needs, eradicate hunger, achieve food security and enhance nutritional standards [58–60]. Second, there is a need to diminish emissions stemming from deforestation and land degradation as means to mitigate global warming [58]. Tropical SESs assume a pivotal role as a crucial arena necessitating immediate measures to address climate change [59]. Third, tropical SESs play a crucial role in the preservation of terrestrial ecosystems and the prevention of biodiversity loss [59].

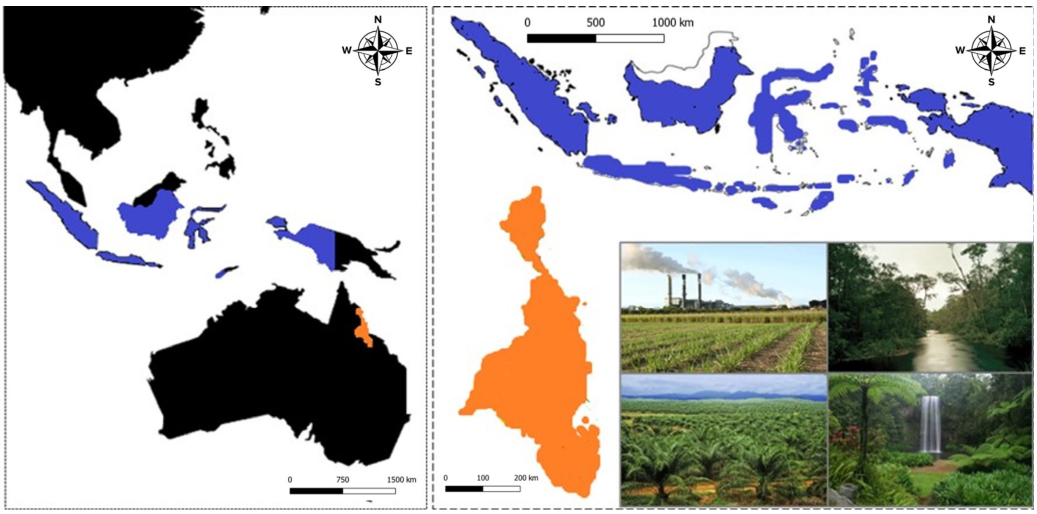

Figure 2. Modelled social–ecological systems. Map of Southeast Asia (**left**), where the two case studies of this research are located: Indonesia (blue) and the Wet Tropics of Queensland in Australia (orange). The map on the right zooms in on both case studies, with two scale bars (one per case-study). The photos (**right**) show palm oil plantations and protected areas from both case studies.

The above-noted trade-offs are present in both Indonesia and the Wet Tropics of Queensland [56,61,62]. However, the socio-economic and governance contexts of these regions are almost opposing. In Indonesia, the forces driving deforestation outweigh those supporting forest protection—a scenario prevalent in numerous tropical regions within developing countries [63]. Conversely, the scenario differs in the Wet Tropics of Queensland, where protected areas expanded by approximately 20% from 1999 until 2015, encompassing nearly 80% of the total protected land area [64,65]. Queensland and Australia dedicate a greater number of financial resources to conservation initiatives in comparison to Indonesia. However, the ability of developing countries to prioritize environmental objectives is hindered by the unfulfilled basic living necessities [66]. In fact, halting environmental pressures in developing countries may undermine the growth and competitiveness of an economy highly dependent upon natural resources [66].

In short, the almost opposing socio-economic and governance contexts in Indonesia and the Wet Tropics, while having the same trade-offs among climate change, biodiversity conservation and food production, provide an interesting research opportunity to examine what socio-economic and governance elements contribute to (un) sustainability in complex SESs.

2.3. Agent-Based Modelling

ABM can be used to study how interactions among agents give rise to emergent properties, unveiling patterns that define system dynamics [67]. More specifically, ABM simulates interconnected autonomous and heterogeneous agents. These agents engage in interactions with one another and the environment, whereby decisions and actions mutually influence each other and the environment [68]. The benefits of using ABM to simulate SESs can be summarized by the following four statements [69]: (i) ABM captures emergent phenomena; (ii) agents exhibit heterogeneity, enabling the simulation of complex and nonlinear behaviour along with the incorporation of limitations in agent rationality; (iii) ABM furnishes a dynamic natural description of a system rather than focusing solely on final output results; and (iv) ABM facilitates the inclusion of social networks and physical spatial interactions, a capability challenging to achieve with other modelling approaches.

The capability of ABM to model complex SESs from the bottom-up, relying on interactions among heterogeneous actors, is crucial for representing our SESs. Furthermore, ABM enables outcomes at a specific point in time to influence future events, a fundamental feature for modelling future scenarios and a key aspect of our research. Finally, very few modelling methods provide the opportunity to create spatially explicit and hybrid models that integrate two or more modelling techniques.

2.4. Models' Description

Our three models—one conceptual and two case-study-based—were developed using NetLogo 5.1.0 version [70]. The models integrate the conceptual framework (Figure 1) and, as such, share certain modelling processes and characteristics. With the aim of describing the basic and shared framework and modelling elements between the three models, Figure 3 shows the model interoperability. This figure analyses those framework characteristics (top row, in bold) and modelling elements and processes (second row from top) that are present in each of the three models (left column). The filled circle in Figure 3 shows that the corresponding framework or model element is explicitly modelled in the ABM, while the empty circle shows that it has been modelled implicitly. In other words, explicitly modelled elements are those with specific variables, agents, input data and/or processes in the model that represent them. Implicitly modelled elements are distinct from those that are not being modelled at all, yet they can be inferred from the status of other model parts.

	SES		**economic-development forces**			**protection-conservation forces (government)**				
	ecological system	socio-economic system	banks	firms	speculators	protected area policies	land restoration policies	technology & innovation policies	land clearing policies	speculation policies
ABM 1 (conceptual)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
ABM 2 (Indonesia)	✓	✓	✓	✓	✗	✓	✓	✓	✓	✗
ABM 3 (Wet Tropics)	✓	✓	✗	✗	✗	✓	✓	✗	✓	✗

	land-use change processes			**ecosystem services & biodiversity**					**use & benefits**
	protection	restoration	land clearing	carbon sequestration	carbon emissions	food production	biodiversity	others	households
ABM 1 (conceptual)	✓	✓	✓	✗	✗	✗	✗	✓	✓
ABM 2 (Indonesia)	✓	✓	✓	✗	✓	✓	✓	✗	✓
ABM 3 (Wet Tropics)	✓	✓	✓	✓	✗	✓	✓	✗	✓

Figure 3. Model interoperability. Both tables show the utilization of the primary conceptual framework (top row, in bold) and modelling (second row) elements in each model (left column). Green markers refer to explicitly modelled elements, red crosses show those implicit elements.

The primary entities in all three models are agents, which represent firms, banks, speculators, governments and households (consumers), as well as the environment, composed of a grid of land covers (i.e., *patches*). Although agents are heterogeneous and, therefore, follow their own decision-making processes in each model, we set a common ground for all ABMs by modelling two types of agents: *economic agents* and *conservation agents*. Economic agents, consistent across all models, are responsible for driving resource extraction, production and consumption processes. Specifically, economic agents encompass firms engaged in the extraction and sale of resources; *households* are involved in purchasing and consuming these resources; *banks* provide funding for resource extraction through credit; and *speculators* borrow credit from banks to purchase derivatives and engage in speculation regarding the future price of produced goods (i.e., assets).

Economic agents exhibit a focus on generating profits, directly or indirectly facilitating persistent economic growth by expanding agriculture, irrespective of potential environmental consequences. Consequently, economic agents are self-interested entities and individuals striving to maximize utility as consumers, and profit as producers within a competitive market setting. Our economic agents incorporate elements of individual irrationality, subjectivity and more complex decision-making procedures, aligning with recent critiques of the idea of *Homo economicus* [71,72]. These critiques argue that portraying market actors as completely rational and self-serving individuals is overly simplistic and lacks depth.

The other pertinent agent type in our ABMs represents conservation forces—termed *conservation agents*. In this context, government agents embody policies focused on enhancing environmental benefits, such as land protection and degraded land restoration. The objective of government agents is to counterbalance the adverse effects on the environment caused by economic agents. The inclusion of two opposing types of agents (*economic* and *conservation agents*) establishes a conducive context for exploring how power (im) balances between economic growth and environmental sustainability impact the (un)sustainability of SES.

A detailed description of the ABMs can be found both in the following three articles, each corresponding to one of the three ABMs: Gonzalez-Redin et al. (2018) [46]; and Gonzalez-Redin et al., 2019 [49,50].

3. Results

In this section, we present the results from the three ABMs which simulate the dynamics of different complex SES, each integrating a particular debt-based economic system driven by economic growth. Economic growth is opposed by environmental forces, thereby enabling us to analyse which socio-economic and governance factors drive SES (un)sustainability.

3.1. ABM 1 (SES: Conceptual): Re-Coupling Economic Growth and Natural Resource Availability

Table 1 describes the two scenarios modelled under ABM 1: non-debt (full reserve) and debt-based (fractional reserve) economic systems. In the fractional reserve system, governmental intervention was introduced via conservation policies, taking into account two distinct critical biomass stock thresholds: 25% and 50%. These threshold values represent the upper limit of natural resource stock, expressed as a percentage, that must be retained within the system for government intervention to take place (Gonzalez-Redin et al. (2018) [46] for the justification on the selection of these values). Figure 4 shows the results obtained from ABM 1.

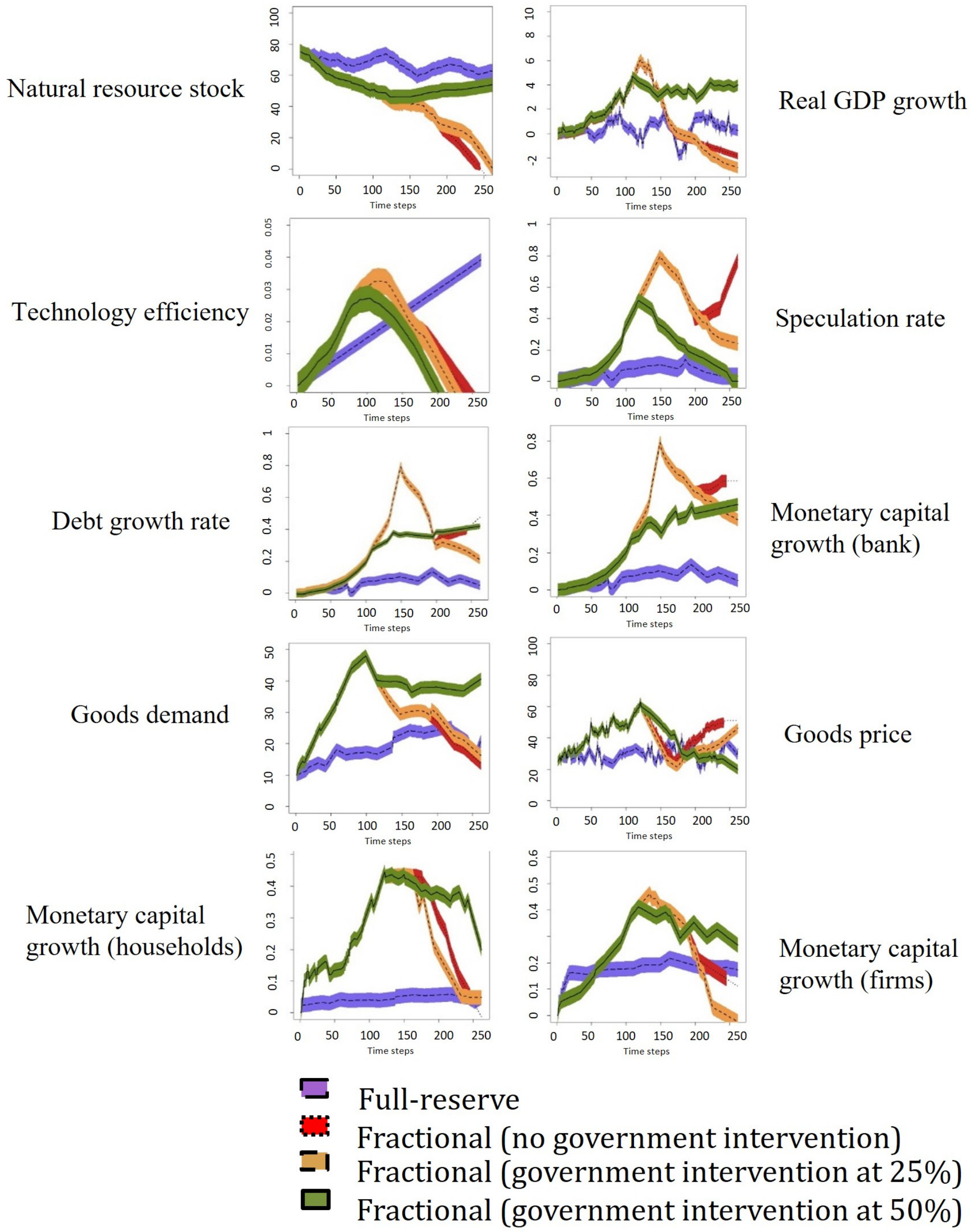

Figure 4. Simulation results for different indicators regarding ABM 1. Results are divided in full-reserve (in purple) and fractional reserve system—without government intervention (in red) and with government intervention when the total natural resource stock is at 25% (in yellow) and 50% (in green). The mean values are depicted by the black lines within each coloured band (i.e., dotted, solid and dashed), while the coloured bands indicate the standard error bars encompassing all the runs calculated for each indicator in each scenario. The unit of measurement of 'Goods demand' and 'Goods price' are non-dimensional, while the other graphs show rates or percentages.

Table 1. Description of the two scenarios modelled under ABM 1.

SCENARIO	DESCRIPTION
Fractional reserve banking	The most common form of banking practised by commercial banks worldwide. It involves accepting deposits from customers and making loans to borrowers while holding in reserve an amount only equal to a fraction of the bank's deposit liabilities.
Full reserve banking	Also known as 100% reserve banking. Banks are required to keep the full amount of depositors' funds in cash, ready for immediate withdrawal on demand.

3.1.1. Debt-Based Fractional Reserve System (No Government Intervention)

In the context of debt-based (fractional) economic systems without government intervention (see red curves), firms can meet their daily expenses, pay wages and invest in technological advancements because of the ample availability of natural resources and bank credits. Profits accumulate for both firms and banks through the sales of goods and the borrowing (and lending) of credits. Households also experience the positive outcome of rising wages implemented by firms. This cycle sustains ongoing economic growth fuelled by loans that contribute to the continuous improvement of labour productivity. At this juncture, the rising of debt and the inclination to borrow more in response to profit increments, do not exhibit an apparent impact on the economy. From an environmental standpoint, the escalating extraction of resources influences natural resource stocks, leading to decreasing values as the simulation progresses.

Concurrently, the upward trend in speculation indicates that some monetary capital fuelling economic growth is entering the system with speculative objectives, rather than purely production-oriented goals. This is attributable to speculator agents, who borrow credits to garner future profits by trading assets in a rising market. As the borrowing of credits by speculator agents aligns with increasing prices and GDP, this process initiates heightened price inflation and, consequently, additional speculation. This reinforcing cycle exacerbates the growing debt burden that contributes no productive value to the system.

Once indicators of speculation, economic growth and the debt burden reach their peak, households find themselves unable to afford the consumption of goods. Consequently, the demand for goods diminishes, leading to a decrease in the firms' monetary capital and a subsequent reduction in labour because firms are unable to remunerate employees. The reduction in household purchasing power contributes to a deflationary trend, rendering firms incapable of funding investments in technological development to enhance production efficiency. Moreover, decreases in price reduce speculation, as the quantity of speculators in the system is directly linked to inflationary trends. Consequently, most speculators face bankruptcy, reinforcing further price deflation. As most speculators are unable to repay debt credits to the bank, the outstanding debt becomes an obligation of the bank. This reduction in available capital for extending credit lending triggers a chain reaction effect that impacts both firms and households.

Viewed through an environmental lens, the decrease in resource extraction processes is advantageous for the stocks of natural resources. Subsequently, the decline in prices stimulates an increase in goods demand from households, leading to a duration of system equilibrium. Yet, as this upturn is insufficient to boost the monetary capital of businesses and GDP values persist in declining, albeit at a slower pace compared to conditions characterized by high speculation. The economy experiences a modest recovery, and the subsequent increases in price once more draw in speculative agents to amplify debt levels and raise prices further, albeit at a reduced rate compared to the initial stages of the simulation. Due to the nearly complete depletion of natural resources resulting from excessive extraction, both firms' incomes and production of goods are adversely impacted. Consequently, the firms' ability to settle borrowed credits with the bank diminishes. This altered scenario adversely impacts banks, firms, speculator agents and households. Ultimately, a collapse in natural resources takes place, leading to the breakdown of the system and concluding the simulation.

3.1.2. Non-Debt-Based Full Reserve System

Figure 4 illustrates the outcomes derived from a *full reserve system* (indicated by purple curves), wherein the bank is obliged to keep 100% of households' deposits accessible for withdrawal. Even though the bank allocates a small percentage of capital for lending credits, generated from the contrast between credit interest (profits) and deposit interest (losses), this allocation remains relatively low.

In this situation, a majority of environmental and economic metrics exhibit a degree of stability over time compared to fractional reserve systems. However, this stability is achieved at lower values for metrics like 'Natural resources stock', 'Real GDP growth', 'Debt growth rate', 'Speculation rate' and 'Monetary capital growth (firms, households and bank)', among others. Essentially, the limited allocation of credits (debt) by the bank for both production-oriented (via firms) and speculative (via speculators) objectives results in a system characterized by low income and profits, coupled with minimal environmental impacts. Consequently, the model outcomes do not reveal occurrences of economic or environmental collapses during the simulation period, as the risks associated with natural resource depletion, heightened speculation, debt or inflation rates (which could elevate the likelihood of economic collapses) remain low.

3.1.3. Government Intervention in Fractional Reserve Systems

The model incorporates the implementation of *government policies* under a *fractional-reserve system*, specifically focusing on conservation governance as a mechanism to compensate the adverse environmental effects resulting from economic activities. The policies aim to improve the sustainability of natural resources when the overall stock within the system drops below specific thresholds, specifically 25% and 50% of the initial stock. In Figure 4, it is evident that conservation policies, initiated only after the 'Natural resources stock' drops below 25% of its initial capacity, fail to prevent system collapse (indicated by the yellow short dash curves). Notably, the limited number of natural resources remaining at this stage, coupled with high rates of technological development and resource extraction activities, presents an unsolvable challenge for the government to prevent a system collapse. Interestingly, GDP, despite government intervention, experiences a more rapid decline over time compared to fractional-reserve systems without government interference. Conversely, conservation policies, implemented prior to the complete depletion of the total natural resource stock in the system failing below 50% (illustrated by the green solid curves), effectively promote stability in natural resources over time, with no occurrences of system collapses noted throughout the simulation period.

3.2. ABM 2 (SES: Indonesia): The How, Instead of the What, to Achieve Sustainability

Table 2 describes the four scenarios modelled under ABM 2, while Figure 5 shows the modelling results of ABM 2. This model, which uses Indonesia as a SES case-study, shows the results concerning two ESS: crude palm oil (CPO) production and CO_2 emissions—in addition to biodiversity. The other economic, social and environmental indicators are included in the corresponding published article—Gonzalez-Redin et al. (2019) [49].

3.2.1. Business as Usual (BAU)

In Figure 5, the initial row illustrates outcomes from the BAU scenario. This setting shows the highest values for CPO production and CO_2 emissions, accompanied by a detrimental trend in biodiversity outcomes. This negative trend arises from the inadequacy of protection measures in Indonesia to counteract the economic forces driving land clearing for CPO production. Typically, palm oil companies necessitate a continuous influx of bank credits to expand their plantations, often into areas with high rich biodiversity (such as undisturbed upland forests,) and substantial carbon stocks (such as swamp forests).

Table 2. Description of the four scenarios modelled under ABM 2.

SCENARIO	DESCRIPTION
Business As Usual (BAU)	The expansion of oil palm plantations in Indonesia is driven by a growing global demand for vegetable oils. This expansion increases credit borrowing from overseas banks to finance CPO production. While being financially advantageous for both banks and palm oil companies, this process contributes to biodiversity loss and global warming. The focus of the Indonesian government is primarily on job creation and poverty reduction through the expansion of oil palm plantations. This emphasis is reinforced by insufficient environmental governance and a shortage of funding from international organizations for conservation efforts.
Reduce Biodiversity Loss (RBL)	With the rise in international conservation funding, biodiversity experiences positive outcomes through the expansion of the protected area network and the restoration of moderately degraded forests in Indonesia. Additionally, biodiversity loss is mitigated as companies leverage credits and public funding to address the additional expenses associated with establishing new plantations in degraded lands and enhancing production efficiency in existing plantations.
Reduce Carbon Emissions (RCE)	International funding is directed towards the Indonesian government with the aim of optimizing above-ground biomass accumulation and minimizing carbon emissions. The restoration of highly degraded forests is prioritized due to their significant potential for carbon sequestration. While the protected area network undergoes expansion, investments are comparatively lower compared to a scenario where area protection is prioritized, as area protection has a more direct impact on biodiversity conservation. Additionally, carbon sequestration is boosted as companies utilize credits and public funding to establish plantations in degraded lands with low carbon stocks and enhance productivity in existing cultivations.
Sustainable Futures (SF)	Supported by international organizations and developed nations, the government strives to establish mutually beneficial outcomes for both climate change mitigation and biodiversity conservation. The restoration of degraded land is undertaken in areas with varying degrees of degradation, benefiting biodiversity and carbon preservation. Additionally, companies utilize credits and public funding to improve production to enhance production efficiency in existing cultivations and initiate plantations in degraded lands.

Consequently, over time, there is a notable rise in both the quantity of credits borrowed and CPO production. Simultaneously, the opportunity cost associated with refraining from converting land into palm oil plantations continues to diminish. This trend reinforces biodiversity loss and increased CO_2 emissions, further intensified by the reduction in the government budget allocated for conservation purposes.

3.2.2. Reducing Biodiversity Loss (RBL) and Carbon Emissions (RCE)

The results depicted in the second and third rows of Figure 5 represent the outcomes obtained for RBL and RCE scenarios, respectively. RBL and RCE scenarios exhibit similar trends for most indicators, aligning with the SF scenario (see below), which minimizes land requirements by intensifying CPO production. However, CPO production reflects more adverse outcomes than those observed under BAU, primarily due to the relatively weaker economic forces driving land clearing for oil palm production compared to the conservation forces. Within the RBL scenario, the strict enforcement of forest protection contributes to the establishment of new protected areas, land restoration and the implementation of policies that force firms to reduce the establishment of new plantations in areas with high biodiversity. Consequently, there is an increase in biodiversity. A similar pattern is noted for CO_2 emissions, with more sustainable outcomes achieved under scenarios featuring high conservation governance values (i.e., GB values). The key difference between RBL and RCE scenarios concerning biodiversity and CO_2 emissions is related to the type of forests restored. In RCE scenarios, moderately degraded forests are less favoured for restoration, whereas under RBL, highly degraded forests are less favoured. This leads to higher biodiversity values in RBL scenarios and lower CO_2 emissions in RCE scenarios, as shown in Table 1.

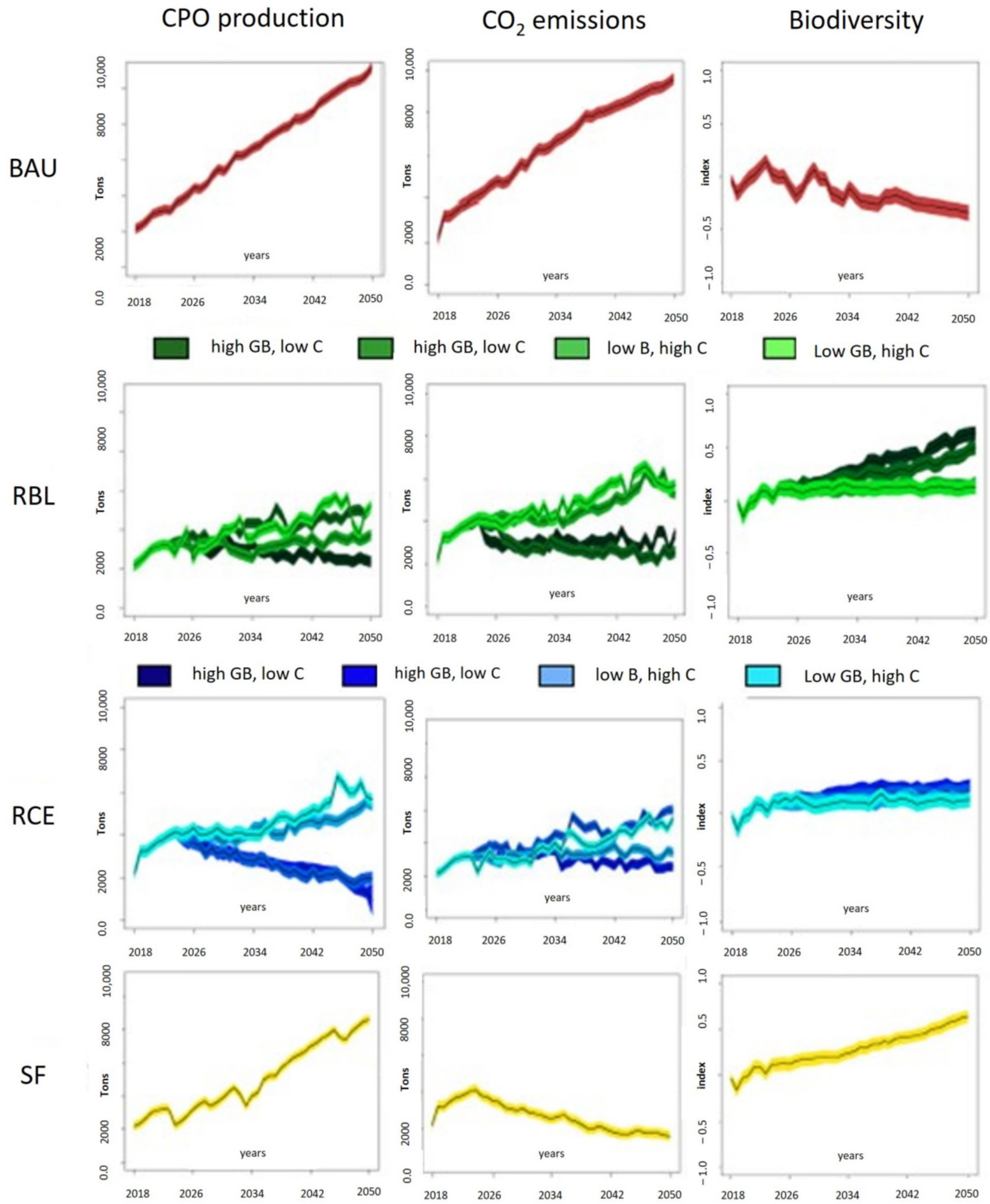

Figure 5. Simulation results for different indicators regarding ABM 2. The indicators encompass crude palm oil (CPO) production (measured in metric tons), CO_2 emissions (metric tons) and biodiversity (indexed). The RBL and RCE scenarios are segmented into four distinct sub-scenarios: dark green (or blue) coloured curves represent scenarios characterized by robust conservation forces (high GB) and weak economic forces (low C).

3.2.3. Sustainable Futures (SF)

The fourth row in Figure 5 illustrates the outcomes derived from the SF scenario. This is the only scenario demonstrating the synergies between CPO production, CO_2 emissions and biodiversity, along with relatively positive results for the rest of the indicators (refer to the published article for detailed information). Notably, this is achieved within the same credit-based economic system modelled under the BAU scenario, where there is a continual rise in the number of credits borrowed by firms. The positive outcomes in the SF scenario can be attributed to a combination of the following factors: (i) the utilization of technology by companies to enhance production efficiency in existing cultivations, leading to a substantial reduction in land requirements for CPO production; (ii) the exclusive establishment of new plantations in degraded lands, thereby avoiding expansion into areas with high biodiversity and carbon stocks; (iii) the increase in the extent of degraded land restored; and (iv) the augmentation in both the number and size of protected areas.

3.3. ABM 3 (SES: Wet Tropics): Evidencing a Sustainable Business-As-Usual Scenario

Table 3 describes the three scenarios modelled under ABM 3, while Figure 6 shows the modelling results of ABM 3. Like ABM 2, only the results concerning the two ESS—i.e., sugarcane production and carbon sequestration—and biodiversity are presented here, while other indicators are included in the corresponding published article—Gonzalez-Redin et al. (2019) [50].

Table 3. Description of the four scenarios modelled under ABM 3.

SCENARIO	DESCRIPTION
Business As Usual (BAU): "World Heritage"	In the Wet Tropics NRM region, both the number and extent of protected areas continue to increase, aligning with the imperative to fulfil conservation targets as a World Heritage-listed site. The overall size of semi-natural areas experiences a slight increase, following trends observed in the period from 1999 to 2015. Meanwhile, production, primarily centred around sugarcane, maintains stability over time. This stability is attributed to other regions in Queensland, such as the Mackay and Whitsunday regions, assuming a greater focus on meeting national production demands.
Land Sparing (LSP): "World Heritage and Queensland's 'food bowl' region"	In the Wet Tropics NRM Region, the ongoing commitment to achieving conservation goals is evidenced by the continuous raise in both the number and the area of protected areas. Simultaneously, there is an accompanying increase in the allocation of land for agricultural purposes, with a focus on sugarcane production. This agricultural expansion is facilitated and supported by initiatives from the Queensland and Australian governments. The overarching objective is for the Wet Tropics NRM Region to strengthen and augment its role in the Australian 'food bowl' initiative.
Land Sharing (LSH): "Multifunctional landscapes"	Under the guidance of the Queensland and Australian Governments, there is a strategic shift toward more multifunctional discourses and governance frameworks in the Wet Tropics NRM Region. This transition prioritizes wildlife-friendly farming practices, albeit at the cost of reduced sugarcane yields. Consequently, the trends observed in the Wet Tropics NRM Region diverge from those in the LSP scenario. Here, both protected areas and sugarcane lands experience a reduction, making room for the expansion of semi-natural areas, with a particular emphasis on production forestry. This reflects a deliberate effort to balance conservation objectives with sustainable land use practices.

3.3.1. Estimated Spatial Impacts

The model, detailed by Gonzalez-Redin et al. (2019) [50], produces spatially explicit results. The resulting maps show the spatial distribution of land uses, and their temporal variations, over time for each of the scenarios modelled. The full article provides a detailed explanation of the reasons and drivers behind the specific LUC in each scenario. Likewise, the LUC trends for each scenario can also be found in this article.

3.3.2. Estimated Impacts

Figure 6 displays the graphical outcomes derived from the SES sustainability indicators for the three modelled scenarios: BAU, LSH and LSP (see Table 2).

In the comparison between the BAU, LSH and LSP scenarios, BAU exhibits favourable trends in both biodiversity and carbon sequestration. This is achieved by maintaining a consistent level of sugarcane production. In contrast, the LSH scenario displays slightly positive trends in biodiversity and carbon sequestration, accompanied by a decrease in sugarcane production. As for the LSP scenario, sugarcane production rises, while biodiversity remains stable and carbon sequestration undergoes a slight decrease.

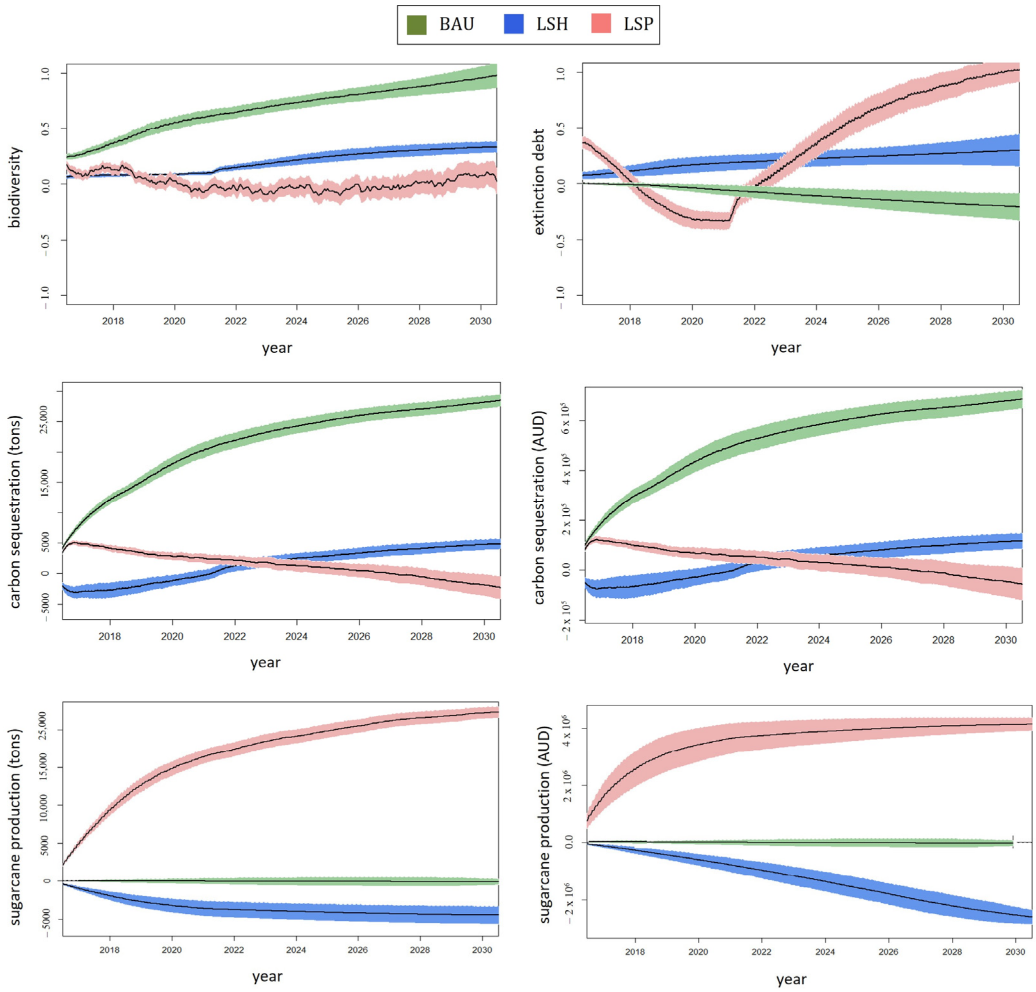

Figure 6. Simulation results from ABM 3. Results are shown as the temporal variation (in net gains & losses) of biodiversity, carbon sequestration and sugarcane production for each scenario modelled: BAU (green), LSP (red) and LSH (blue). Both sugarcane and carbon sequestration are shown in tons and Australian Dollars (AUD). The colour bands represent the standard error bands regarding all the runs computed for each indicator under every scenario. The black-coloured lines show the mean values.

4. Discussion

4.1. It Is Not the What, but the How

The SESs modelled show that the current economic system, driven by a debt-based growth paradigm, is not environmentally sustainable. These results align with previous studies arguing that our economic system is not capable of providing solutions to the current environmental challenges [73]. However, our models show that, through various structural changes, sustainable pathways can be achieved, even under the current economic structure. Therefore, the '*how*' is shown to be more relevant than the '*what*'—understanding the '*what*' as our economic system itself and the '*how*' as the need to re-adapt and re-adjust system characteristics and mechanisms to enhance sustainable development.

4.2. What Factors Drive (Un)Sustainability in Social–Ecological Systems?

The SESs modelled reveal their susceptibility towards various factors affecting (un)sustainability. An analysis of these mechanisms is included below.

4.2.1. Monetary Debt and Financial Entities: Avoiding the Blindness of the Market Economy

The ABM 1 (conceptual model) showed that the current debt-driven SES creates a context where continual economic growth becomes a necessity. Under this scenario, an ever-faster growth rate, fuelled by increasing debt stocks, necessitated the utilization of resources and the release of pollutants. Interestingly, Model 1 showed that the economy did not collapse due to the debt burden, or the inherent debt-based nature of the economic system. Instead, the collapse was attributed to the inappropriate utilization of debt by firms and speculators. This suggests that the system does not inherently impose a growth imperative. In other words, the debt-based economic system may not be, by definition, environmentally unsustainable. Instead, the natural resource arises unsustainability from the speculative and profit-seeking actions of agents rather than an inherent flaw in the economic system itself.

Similarly, ABM 2 (Indonesian case-study) showed an increase in CO_2 emissions and biodiversity loss due to the inappropriate use of bank credits by oil palm companies. Here, again, the problem is not the "*what*"—i.e., the (type of) SES—, but the "*how*"—i.e., the role of entities and their use of credits. More specifically, ABM 2 showed that allocating bank credits for purposes other than fuelling deforestation could help in halting biodiversity loss and carbon emissions, while still meeting CPO production demand targets. In this regard, enhancing the production efficiency of current palm oil cultivations and planting oil palm trees on degraded land [74] could assist in meeting the global CPO demand without triggering the release of excessive CO_2 and exacerbating biodiversity loss.

The challenge at hand lies in the reluctance of debt-dependent palm oil companies to utilize credit facilities for financing less profitable and financially riskier 'innovative' CPO production methods. Examples of such processes include high-yielding oil palm genome projects or information systems offering real-time insights of palm oil plantations. Additionally, financial institutions are hesitant to extend credits to companies unless the borrowed funds are utilized to support processes or activities guaranteeing immediate profits, thereby providing financial security for banks. Moreover, 'innovative' palm oil companies implementing sustainable strategies would face challenges in international markets as traditional palm oil producers from other countries could potentially undercut them unless a premium is offered for their products. As a result, current traditional oil palm cultivation takes place mainly in biologically rich areas since it provides security for banks and higher short-term profits for firms.

Our models showed that SES can lead to the total breakdown of both natural and economics systems due to debt burdens. Nonetheless, the findings indicate that debt-driven fractional reserve economic systems do not inherently enforce a growth imperative. In other words, the debt-based system is not inherently, by definition, unsustainable. Instead, it is the behaviour of entities and agents, along with their environmental decisions and relationships, that tends to contribute to the escalation of natural resource unsustainability. Thus, there is a need to shift the current speculation- and profit-based debt use to a production- and efficiency-based one.

4.2.2. Technological Development: Two Sides of the Same Coin

Our models showed that technological development is another primary factor influencing SES (un)sustainability. Yet, SES collapses are not specifically driven by the net peak values reached by technology efficiency (i.e., high technological efficiency rates), but rather by the *pace* (i.e., growth rate) at which technological development occurs. For instance, Model 1 shows how technology efficiency, under full reserve systems—i.e., systems with low investments in technological development—reaches a higher long-term net value compared to fractional reserve systems—i.e., systems with no government intervention. However, the speed of reaching this value is higher in the latter. We argue that a gradual, yet constant, rise in technological development, with a focus on production efficiency rather than speculation, could help create win-win scenarios for GDP and natural resource availability.

Overall, there is a social tendency to believe in technology as an article of faith or based on statistically flawed extrapolations of historical trends, despite the lack of support for this proposition [75]. Economists traditionally rely on technology and innovation as drivers of ever-increasing efficiency and economic growth, irrespective of the inherent uncertainty and unpredictable nature associated with technological advancements [76]. Advancements in technology indeed follow a discontinuous process in which most significant innovations occur by "fits and starts" [77]. The discontinuous nature of technology has the risk of affecting the entire economic system and can lead to far-reaching changes in different social factors [78], as well as socio-economic collapse [79]. Moreover, the Jevons Paradox establishes that increases in efficiency of resource use are usually outpaced by the rate at which consumption of those resources increases [80].

Conversely, it is important to note that technological development, applied to different fields, has positive implications for SES sustainability. For instance, those implementations of technological development that prioritize enhancing waste management practices (e.g., reduce, reuse, recycle) contribute positively to environmental well-being, among numerous other potential benefits. Hence, it is crucial to clearly define and examine the specific use of technology when arguing or stating whether technological development enhances or diminishes SES sustainability.

4.2.3. Speculation and Price Volatility: The Need to Recouple Economic and Natural Systems

The economic and natural systems are currently decoupled: not only in terms of GDP and environmental impacts—which is a yet-to-achieve key goal for global sustainability—but regarding the idea that the economy needs to act upon, and within, the state and condition of the environment.

Our models reveal that speculation, due to its impact on price volatility, plays a significant role in intensifying the decoupling process between economic and natural systems. Concerns among international policymakers and non-governmental entities have risen due to apprehension that the involvement of speculators in the system may manipulate commodity prices through the creation of excessive price volatility [81,82]. The fractional-reserve banking scenario in our ABM 1 creates unpredictable, artificial and challenging to predict speculative markets. This volatility arose because monetary debt was predominantly utilized by speculators to maximize their own profits rather than being employed by the private sector to boost productivity and, consequently, contribute to the well-being of society (e.g., by improving technological efficiency). As a result, prices and demand processes were rather influenced by economic (i.e., the grade of speculation in the system) instead of environmental factors (i.e., resource availability). Thus, those periods in our models when speculation followed positive increasing trends showed weak coupling values between the economy (represented by the GDP) and the environment (represented by natural resource stocks), while those periods where artificial speculative markets were absent showed strong coupling between the economy and the environment.

These results support our previously described argument that debt is not the main cause of SES unsustainability, but rather the use that firms and speculators make of it is. Our results also align with Keen (2009) [83], who asserted that funding in the existing debt-based economic system predominantly follows speculative rather than production-oriented goals. We argue that changes in commodity prices should be correlated with supply demand dynamics and the accessibility of natural resources, rather than speculative processes and markets, thus helping to move towards decoupling GDP and the use and availability of natural resources.

4.2.4. Government Timely Interventions: The Importance of Tipping Points and Supporting Long-Term Views

As previously mentioned, the economy does not inherently have to experience growth or instability because of the burden of debt facilitated by the monetary system. However, the common outcome tends to be influenced by the inappropriate utilization of credit by firms [84]. In our models, this was addressed by implementing government policies focused on enhancing natural resource conservation and more sustainable practices being taken on by firms.

In this regard, late government intervention in our models is incapable of either enhancing a decrease in the resource extraction rates of companies' or increasing resource replenishment rates. The gradual implementation of conservation policies by the government in our BAU scenarios is insufficient to offset the adverse impacts exerted on resources by the accelerated rates of technological development. Hence, a mismatch occurs between the government's ability to enforce conservation policies and the promotion of economic growth driven by companies.

This is connected to the complexity of detecting tipping points and predicting environmental changes within complex coupled SES [85]. Complex systems exhibit multiple scales, non-linearity and interactive dynamics that often defy predictability [24,86]. Institutions face the formidable task of foreseeing the complexity of SES dynamics across diverse temporal and spatial scales to avert collapse, as exemplified in common pool resources like marine fisheries [87] and freshwater systems [88].

The discrepancy between the government's implementation of conservation policies and economic growth under our BAU scenarios could be addressed through timely governmental interventions. Such interventions could mitigate market failures by implementing policies focusing on the enduring stability and resilience of SESs in environmental matters. For example, our case study in Indonesia (Model 2) illustrates that market intervention through various policies could address the aversion to risk among Indonesian smallholders, as currently manifested by their reluctance to utilize credit facilities for establishing new plantations in degraded lands [89]. Consequently, encouraging a more sustainable use of bank credits by farmers could be facilitated through the implementation of more affordable financing mechanisms, such as interest-free loans, by secure financial entities including micro-finance institutions [89].

A balance is likely needed between government interventions and the market. The problem here is that, as shown by our models, seeking long-term objectives in the current economic paradigm is discouraged by a system oriented toward short-term gains. There is a need to provide the economic system with enhanced opportunities to allocate resources toward achieving long-term environmental goals. Using climate change as an example, Nordhaus (2007) [90] argues that limited and gradual government interventions in the economy are necessary, where optimal regulation should reduce long-run growth by only a modest amount. Stern's (2007) [91] view is less optimistic; it calls for more extensive and immediate interventions and argues that these interventions need to be in place permanently even though they may entail significant economic cost. The more radical answers, such as those coming from degrowth economics [92–94], argue that, fundamentally, all growth must cease to ensure the preservation of the planet.

Our findings align with a middle-ground perspective: responsible, incremental and gradual interventions are necessary, avoiding marginal measures but also recognizing the importance of strong actions to prevent the economic collapse.

4.2.5. Overcoming Government Powerlessness and Unwillingness to Protect the Environment: The Need to Combine Bottom-Up and Top-Down Conservation Forces

Our models showed that there is a need to enhance and integrate both top-down and bottom-up conservation forces to engender SES sustainability. This challenging context is currently being achieved in the Wet Tropics of Queensland (see Model 3 results). Hence, in the forested landscape of the Wet Tropics, the BAU scenario is contributing to the provision of food, conservation of biodiversity and sequestration of atmospheric carbon.

These outcomes stem from the dominance of robust conservation forces in contrast to economic forces promoting land clearing. Back in the 1970s, bottom-up forces started to rise on account of an increasingly growing public awareness about the importance of wilderness areas in this region [95]. Scientists, conservation groups and the society overall started to mobilise and take actions against the economic forces promoting land clearing for agriculture. Over time, this grassroots movement succeeded in influencing top-down conservation processes [95], leading to significant milestones such as the inclusion of the Wet Tropics rainforests on the World Heritage Register in December 1988 and the establishment of the Wet Tropics Management Authority. As a result, a solid and multilayer policy network—a top-down conservation force—focused on the protection of rainforest biodiversity was created [65].

This top-down–bottom-up initiative can be considered a remarkable example of polycentric governance, i.e., a governance system in which multiple governing bodies interact to make and enforce rules within a specific policy arena or location, to achieve collective action in the face of disturbance change [96]. The Wet Tropics case shows the importance of developing a multilayer set of rules, efficiently coordinated by different centres of authority [96], that allows the protection of nature in the face of land clearing forces.

As a result, currently almost 80% of the Wet Tropics is protected [97], mainly rainforest, helping to protect biodiversity and enhance the supply of multiple ES, such as climate regulation, air quality regulation and cyclone protection [98]. The Wet Tropics' case of combining both bottom-up and top-down conservation forces is unique due to various local and regional conditions and characteristics (see next section). Poorer, developing countries have weak environmental governance schemes, which means that they need external financial support to strengthen their conservation governance. Governments from developed countries need to provide help to developing countries through different incentive mechanisms [99]. In this regard, international schemes, related to payment for ecosystem services (PES) [100], have been providing incentives to developing nations for preserving and improving forests through initiatives like REDD programs [61]. As an illustration, Indonesia entered into a US $1 billion agreement with Norway through the REDD framework in 2010 with the goal of curbing deforestation [101]. So far, the agreement has not made much difference to the rate of deforestation, due to corruption, bad practices and stronger economic forces compared to the conservation forces [101,102]. Yet, supporting these types of international agreements and schemes is key to overcoming the political challenges associated with implementing policies that indirectly diminish the influence of powerful financial entities resistant to paradigm shifts. Governments from poorer countries often find themselves compelled to consider the influence of industries and other interest groups [103]. This is due to the significant reliance of national economies on a handful of corporations or monopolies.

In conclusion, there is a need to shift market-driven, capitalist forces to align with environmental conservation. This necessitates robust bottom-up and top-down conservation efforts. The crucial question lies in whether national and international governments are willing to bear the financial and societal costs associated with industries rooted in the current development model. Alternatively, they must consider a comparatively smaller trade-off involving agricultural land in exchange for enhancing sustainability of SES.

4.2.6. Careful with Extrapolations: Considering Specific Factors and Conditions to Each Social-Ecological System

Besides the rather generalist factors addressed so far, there exist particular factors specific to each SES that need to be considered separately. This is, for instance, the case for the Wet Tropics of Queensland (ABM 3). The existing BAU context in the forested SES of the Wet Tropics region is contributing to the reconciliation of biodiversity conservation, climate change mitigation and sugarcane production. We use this case study to highlight the importance of analysing and considering specific local and regional factors in SES studies.

The forest in the Wet Tropics shows an unusual example of a tropical SES where both economic growth and environmental conservation are achieved under the current economic system. While numerous tropical areas in developing countries find it challenging to achieve this win-win scenario, the forested area of the Wet Tropics possesses specific local and regional characteristics that facilitate it: (**1**) *Economic*—temperate forests produce twenty times more timber than tropical forests, being the main provider of industrial wood worldwide [104,105]. Additionally, the ban on logging due to the World Heritage protection in 1988 reduced the use of tropical wood for timber production [106], making the production of timber in forests in the Wet Tropics an uncompetitive economic use [107] compared to other sectors, such as tourism [108]. Furthermore, Australia, as a developed country, attracts and has more access to funding for conservation programmes than any other developing country with tropical rainforests, the latter prioritizing other poverty and social challenges [109]. (**2**) *Governance*—different public governance indicators, including corruption and poor governance, show better results for Australia in comparison to other South Asian countries [110]. In fact, countries with negative values for some indicators, such as corruption control and quality public services, tend to support or experience an increase in the availability of agricultural land through deforestation [109]. (**3**) *Legal*—the Australian Constitution states that the federal government has the authority to override the different territories in topics directly related to international treaties, including the World Heritage Convention. Thus, the Australian Government can halt environmentally unsustainable activities, such as logging in the Wet Tropics forests. (**4**) *Social–political*—additionally, conservation of tropical forests was strengthened by politicians seeking their own political benefit [111]. Timber harvesting in north Queensland had ceased since the inscription of the region on the World Heritage List in 1988 [112]; thus, the national government took advantage of the previously described bottom-up conservation mobilisation to make forest conservation a vote-winner nationally [111]. As a result, support for conservation by politicians was a key factor to enhance SES sustainability in the Wet Tropics. (**5**) *Environmental–scientific*—the importance of the Wet Tropics World Heritage Site from a scientific and environmental perspective facilitates the justification and the reception of both political and financial support for conservation. (**6**) *Geographical*—from a land-use, landscape and protected area management perspective, Australia has no spatial conflicts with neighbouring countries. Therefore, the Queensland Government can administer the Wet Tropics without having to contend with potential cross-national or international conflicts.

In conclusion, the positive results obtained for the Wet Tropics case study (ABM 3) are worthwhile exploring further. This represents a notable accomplishment in the context of a tropical region, especially when considering that the majority of other tropical areas exhibit more pronounced economic and land-clearing pressures compared to conservation. This imbalance tends to exacerbate challenges such as biodiversity loss, habitat destruction, climate change and other environmental concerns. However, the context present in the Wet Tropics forested landscape should not be compared, nor extrapolated, to other SESs or tropical areas worldwide. For example, the political, cultural, environmental and socio-economic context in Indonesia, as shown by our ABM 2, is completely the opposite, thus the Wet Tropics scenario cannot be implemented in Indonesia. In fact, specific factors to the Indonesian SES could be preventing it from achieving sustainability. First, Indonesia holds the position of being the foremost global exporter of palm oil [113], where the contribution of the national economy is essential [114]. Second, the production of CPO has led to economic advancements in rural areas by creating employment opportunities for local residents [115]. Third, the prevailing debt-based structure of the palm oil industry enjoys backing from both financial institutions and the industry itself. This collaborative framework establishes a mutually beneficial economic environment, where banks derive advantages from loan interest, and the industry sees continued revenue growth owing to the increasing demand for CPO. As a result, the current debt-based palm oil industry is supported by both banks and the industry itself. Last, but by no means least, weak conservation governance in Indonesia fails to offset the stronger land-clearing processes, thus placing BAU economic forces in a privileged position at the expense of conservation forces [63].

5. Conclusions

Our three agent-based models, under the framework and contexts modelled, showed evidence of a disconnection between the economic and conservation components fundamental to the sustainable development paradigm. The economy does not hold internal mechanisms to safeguard the natural capital essential for its functioning, leading to the prevailing decoupling between the economic and natural systems. In attempting to find solutions for such disjunction, our research reinforces the idea that social-ecological systems are complex, dynamic and non-linear. Therefore, within each geographic context and among the stakeholders engaged, there is a necessity to explore their own pathway towards sustainability. Yet, our results also showed that there are common social, economic and governance factors to most social–ecological systems that are pivotal determinants of sustainability or unsustainability. Namely: the role of financial entities and the specific utilization of monetary debt; technological development and efficiency; market and economic speculation; detecting tipping points and timely government interventions; long-term priorities and views over short-term gains; and the need to integrate and consider both top-down and bottom-up conservation forces. Our research shows that most of these factors have a dual role, since they can both diminish or enhance sustainability in social–ecological systems in their own contexts and particular conditions. We argue that social–ecological systems, and the embedded economic systems, may not be inherently unsustainable: it is the institutions and (polycentric) governance systems and agents' decision-making, including their relationship with the environment, that drives unsustainability. We demonstrate the feasibility of adopting a short-term strategy for sustainable development that significantly mitigates the trade-offs between economic advancement and environmental conservation. This will require efforts from different societal and economic agents through the development, and acceptance, of mechanisms that can help to shift away from the current capitalist forces towards strengthening environmental conservation. This should be the first step toward transforming our economic production system into one that integrates and comprehensively considers externalities and the value of natural capital. In doing so, we should ensure that the human society is intricately connected within the wider, and more crucial, natural system.

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