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Enhancing Climate Policy Integration Through Synergistic Land Use Strategies

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Abstract

The land use sector holds significant potential for achieving both mitigation and adaptation goals in response to climate change. However, the complexity inherent in managing landscapes for multiple objectives, coupled with the lack of robust tools to assess outcomes, often results in this potential being underutilized in practice. To address this knowledge gap, this paper examines climate policy integration—the combined implementation of mitigation and adaptation measures—in the context of ecological thresholds. Using a hypothetical yet plausible economic-ecological system, the study analyzes the synergistic effects of various isolated and integrated policy configurations through a dynamic optimization framework and simulation tools. The research focuses on how different approaches to policy integration can enhance or hinder the achievement of climate goals, particularly when ecological thresholds are at play. The results reveal that, irrespective of specific circumstances, such as whether or not a regime shift is observed, the most effective policy configuration is one that adheres to the principles of synergy. Specifically, the study finds that a cross-sectoral approach, which involves coordinated efforts between agriculture and forestry, yields the most favorable outcomes. This suggests that harmonization among the different elements within the land use sector is crucial for maximizing policy effectiveness. The findings indicate that to achieve effective climate policy integration, it is essential to view the land use sector as a cohesive entity—such as a landscape—rather than as isolated components like agriculture and forestry. This perspective facilitates a more holistic approach to land management, leading to better alignment of mitigation and adaptation strategies and ultimately more successful outcomes in addressing climate change. The paper underscores the importance of cross-sectoral coordination and the integration of multiple land use objectives to enhance the efficacy of climate policies. This approach not only optimizes resource use but also strengthens the resilience of landscapes to ecological and climatic changes.

Keywords: Climate Policy, Land Use, Mitigation and Adaptation, Ecological Thresholds

JEL Codes: Q54, Q15, Q57

1. INTRODUCTION

In response to the growing threat of climate change, two primary strategies are employed: mitigation and adaptation. Mitigation refers to actions aimed at reducing the concentration of greenhouse gases in the atmosphere, thus addressing the root causes of climate change (IPCC, 2001). This includes efforts such as reducing carbon emissions, increasing energy efficiency, and transitioning to renewable energy sources (Locatelli et al., 2011). By mitigating these causes, the overall impact of climate change can be limited. On the other hand, adaptation involves adjusting social or natural systems to respond to both current and anticipated climate change impacts (IPCC, 2001). Adaptation strategies focus on managing the consequences of climate change, such as rising sea levels, extreme weather events, and shifts in ecosystems. These strategies could involve redesigning infrastructure to withstand extreme weather, developing drought-resistant crops, or enhancing coastal protection (Locatelli et al., 2011). Both mitigation and adaptation are regarded as equally crucial approaches, as some degree of climate change is now considered inevitable. Despite efforts to reduce emissions, certain changes to the climate are already underway and will continue to impact the planet for the foreseeable future. Therefore, while mitigation addresses the causes of climate change, adaptation focuses on dealing with its consequences, and a balanced approach incorporating both strategies is essential for effectively combating climate change (Tol, 2005).

Moreover, due to the interrelationship between mitigation and adaptation strategies, integrating both approaches could yield significant social and environmental benefits, such as achieving a greater reduction in greenhouse gases at a lower cost (Kane and Shogren, 2000). One area with high potential for such integration is the land use sector, where both strategies can be combined effectively to address climate change (Duguma et al., 2014; IPCC, 2014). Despite this potential, the practical implementation of such integration remains limited (Duguma et al., 2014; Locatelli et al., 2011). This is partly due to the complexity of managing landscapes with multiple objectives and the lack of adequate tools to assess the outcomes (IPCC, 2014; Locatelli et al., 2015). To help address this gap in knowledge, this paper examines a critical factor that could play a major role in shaping the integration of climate policy: the presence of ecological thresholds. Ecological thresholds are points at which small changes in environmental conditions can lead to significant shifts in ecosystem function, and recognizing these

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thresholds is essential for effectively designing policies that blend both mitigation and adaptation. By understanding and accounting for these thresholds, more effective and sustainable strategies for land use and climate policy integration can be developed, potentially unlocking the benefits of combining mitigation and adaptation in practice. Ecological systems that are characterized by the presence of thresholds or tipping points (as discussed by de Zeeuw and Li, 2016) respond minimally to external stresses within a certain range. This limited response is due to the existence of multiple stable states within the system. However, once a threshold is crossed, even a minor change in the external stress can lead to a sudden and dramatic shift, known as a regime shift. This shift fundamentally alters the system's structure, often resulting in a significant change in the quantity or quality of the ecosystem services that the system provides. A key consequence of such a regime shift is that simply reducing the stress to the level it was at before the collapse will not restore the ecosystem to its previous state. The system's internal dynamics require that the stress be reduced even further—potentially to another threshold level—before the original state can be regained (Scheffer et al., 2001). This irreversible or hard-to-reverse nature of regime shifts emphasizes the importance of proactively managing ecological systems to prevent crossing thresholds that could lead to undesirable and persistent changes. Understanding these dynamics is crucial for developing effective climate policies that take into account the delicate balance within ecological systems and the potential for abrupt and lasting changes. The ability of some ecological systems to alternate between different regimes is known as hysteresis. In such cases, even if external stresses are reduced, the system may not easily revert to its original state without significant additional effort. In some instances, restoration may be either impossible or extremely costly, making the regime shift effectively irreversible (Scheffer et al., 2001).

Numerous ecosystems have demonstrated this behavior. For example, shallow lakes can abruptly shift from a clear water state to a murky, eutrophic condition, and once this change occurs, reversing it can be extremely difficult (Scheffer et al., 2001). In terrestrial ecosystems, similar regime shifts have been observed, such as the conversion of forests into savannas, particularly in tropical regions (Leonel Da Silveira Lobo Sternberg, 2001), and the disruption of regional climates following deforestation, as recorded in various studies (Zheng and Eltahir, 1998). Additionally, research indicates that forest functions may not fully recover after land abandonment, even over long periods, further highlighting the challenges of restoring ecosystems once a regime shift has occurred (Locatelli et al., 2017). These examples emphasize the importance of preventing regime shifts through proactive management and policy interventions. Once these tipping points are crossed, the costs and difficulties of reversing the changes can be substantial, making prevention and early intervention critical for maintaining ecosystem health and resilience. In fact, growing evidence suggests that ecological thresholds are not exceptions but rather the norm in many ecosystems. Human activities are exacerbating this trend, as regime shifts become more frequent due to anthropogenic disturbances that undermine ecosystems' resilience (Folke et al., 2004). These disturbances, such as deforestation, overexploitation of resources, and pollution, push ecosystems closer to critical tipping points, beyond which recovery is difficult or impossible.

From an economic perspective, the presence of ecological thresholds in terrestrial ecosystems poses significant challenges for the optimal use of land resources. In the case of tropical deforestation, there is a conflict between environmental goals and the social and economic needs of local communities. For instance, the conservation of forestland is essential for preventing further climate change and maintaining the resilience of ecosystems. However, the livelihoods of rural communities in these areas are often tied to land use practices that involve environmental degradation, such as deforestation and forest degradation, to meet agricultural or economic needs (Pramova et al., 2012). The crux of the issue lies in the fact that the long-term consequences of environmental degradation are frequently overlooked in land use decisions. Immediate economic benefits often take precedence, while the long-term costs of environmental harm, such as loss of ecosystem services and reduced resilience, are neglected (Barbier et al., 2010). This tension between short-term economic gains and long-term sustainability complicates efforts to balance development with environmental conservation, highlighting the need for more integrated land use policies that account for both ecological thresholds and human welfare.

Excessive deforestation can push ecosystems past ecological thresholds, leading to regime shifts and the eventual collapse of productivity in the affected areas. In such situations, policy interventions aimed at balancing environmental goals with social and economic needs have the potential to deliver substantial benefits for both human welfare and the environment. Effective interventions can help prevent unsustainable land use practices that lead to long-term ecological and economic damage. In the present analysis, the performance of specific policy interventions was evaluated through the concept of synergy. This approach seeks to optimize landscape functions by integrating both mitigation and adaptation measures, rather than focusing on these goals in isolation (Duguma et al., 2014). Synergy, as interpreted in this study, involves achieving the highest sustainable output with the least amount of environmental degradation. Essentially, it looks for solutions that maximize both productivity and environmental resilience. The primary objective of this analysis was to identify policy configurations that can trigger these synergies. By comparing the performance of isolated policy interventions against integrated approaches, and both against an unregulated scenario, the study aimed to determine which policy strategies are most effective at simultaneously addressing environmental sustainability and social needs. The results highlight the importance of coordinated policy efforts that incorporate both mitigation and adaptation strategies to optimize outcomes for both ecosystems and human communities.

This paper is organized as follows: The next section outlines the structure of the model used in the analysis. In the third section, the analytical solution is presented, focusing on examining the impact of environmental policy on land allocation. The fourth section provides the simulation results from a parameterized version of the model, offering insights into its practical applications. The final section presents concluding remarks and summarizes key findings. Additionally, an appendix is included, detailing the methods used to measure resilience and the specific computational procedures employed to conduct the model simulations.

2. METHODOLOGY

The model analyzed in this study consists of two interdependent systems: the economic system and the ecological system, both of which are linked through land allocation. The ecological system is influenced by the state of forestland, which is assumed to contribute to environmental regeneration, while the economic system is affected by agricultural land, which tends to degrade the environment. However, the negative impact of agricultural land use can be mitigated through the adoption of environmentally friendly practices. In line with recent research (Reed et al., 2017), the model further assumes that economic output is a function of both the state of the environment (ecological system) and the amount of land dedicated to agriculture (economic system). This reflects the interconnected nature of land use decisions, where the health of the ecosystem directly influences agricultural productivity, and vice versa. In the subsequent sections, each of these systems—the ecological and economic—are described in greater detail, highlighting their interactions and the role land allocation plays in balancing economic and environmental objectives. The economic system in the model features a representative competitive firm that uses cleared land for production. The firm's objective is to maximize the discounted value of its profits by making decisions regarding the investment rate and the level of adaptation. Investment in this context refers to the conversion of forestland into productive agricultural land, encompassing both the cost of acquiring land and the cost of clearing it for agricultural use. Additionally, the firm's adaptation efforts involve the adoption of ecologically friendly practices, such as soil conservation techniques, agroforestry, and silvopastoral systems, which aim to mitigate the environmental impact of agricultural activities. The formulation of the economic system largely follows the adjustment cost model (Barro and Sala-i-Martin, 2004), but it extends this framework by incorporating the costs associated with implementing adaptation measures within the agricultural sector. These measures are essential for balancing productivity with sustainability, allowing the firm to continue operating without causing significant environmental degradation.

On the other hand, the ecological system governs the state of the environment, which is determined by its internal dynamics and its interaction with the economic system. A key feature of the ecological system is the presence of thresholds or tipping points, which enable distinct dynamic regimes. These thresholds imply that the system may remain stable over a range of conditions but could undergo rapid, potentially irreversible changes when certain limits are crossed. The interaction between land use (economic decisions) and these environmental dynamics is crucial for understanding how land allocation choices affect both agricultural productivity and ecosystem resilience. The first two terms on the right-hand side of the previous equation illustrate the interaction between the economic system and the ecological system. The first term represents an ecological factor that benefits from the presence of forests. Forestland, by maintaining ecological balance, contributes to the overall health of the environment. For example, forests play a crucial role in regulating local climate, supporting biodiversity, and maintaining ecosystem services such as water retention and carbon sequestration. The second term reflects an adaptation measure, aimed at mitigating the negative effects of agriculture on the environment. This term represents practices or interventions that reduce the environmental footprint of agricultural activities, such as soil conservation, reforestation, or sustainable farming techniques. The goal of this adaptation is to allow agricultural production to proceed while minimizing its degradation of natural systems.

An illustrative example of such interactions is water balance, where deforestation can have dramatic regional impacts. For instance, documented cases reveal that deforestation may significantly disrupt regional weather patterns, such as causing a collapse of the monsoon system (Zheng and Eltahir, 1998), lead to the degradation or collapse of specific ecosystems like cloud forests (Scheffer et al., 2001), or trigger a regime shift in the environment, such as a transition from forestland to savanna (Leonel Da Silveira Lobo Sternberg, 2001). These examples emphasize the interconnectedness of ecological and economic systems and the need for adaptation strategies that mitigate the impacts of land use on the environment. These cases share a common feature: changes in forest cover disrupt the water cycle, which can have severe environmental consequences. As a result, ecologically-friendly agricultural practices that maintain trees within cropland, such as agroforestry or silvopastoral systems, are effective in reducing the ecological impact of deforestation (Harvey et al., 2014). These practices integrate trees into farming systems, helping to stabilize water cycles, improve soil health, and provide additional ecosystem services, thereby mitigating some of the negative effects associated with deforestation. In the model analyzed, it is demonstrated that the unregulated scenario is a special case of the broader solution where no policy intervention occurs. In this unregulated state, land use decisions are made without consideration for environmental impact, typically leading to a larger share of land being allocated to agriculture at the expense of forestland. Policy interventions, by contrast, generally lead to a reduction in the amount of land devoted to agriculture, as they seek to balance agricultural productivity with environmental conservation. Consequently, environmental gains—such as reduced deforestation and improved ecosystem resilience—are easily anticipated as a result of these interventions.

The effect of such policies on agricultural output, however, is more context-dependent. For example, in situations where the unregulated scenario leads to a regime shift—such as a transition from forestland to savanna—the introduction of policy interventions can help prevent environmental collapse, but the impact on economic output will vary based on the severity of the environmental degradation and the ability of the system to recover. In cases where a regime shift is avoided, agricultural output may remain stable or decline slightly, depending on the extent of the land-use restrictions and the efficacy of adaptation measures.

3. DISCUSSION

To derive a general solution for the model presented in the previous section, a dynamic optimization framework was applied from the perspective of a policy maker. The policy maker has access to both adaptation and mitigation instruments, particularly in the forestry subsector, and these instruments can be implemented through price mechanisms (such as taxes) or direct regulations (such as quotas). Additionally, the policy maker can incentivize the adoption of ecologically friendly practices in agriculture, which are considered as adaptation measures in this subsector. The adaptation measure in forestry is designed to internalize the environmental impacts of land-use changes. This means that the effects of altering forestland on the broader ecological system are explicitly accounted for in the policy maker's decision-making process. More specifically, equation (2), which likely represents the dynamic relationship between land use and environmental quality, is treated as a dynamic constraint that influences the overall optimization strategy. This ensures that land use decisions are made with full consideration of their long-term environmental impacts. The mitigation instrument in the model follows a conservation-based approach, where forestland conservation directly contributes to social welfare. It is assumed that the policy maker is aware of how changes in forestland affect social welfare and can quantify the importance of forest conservation relative to other societal needs. In this model, forestland is a component of the social utility function, meaning that society derives utility not only from economic productivity but also from the environmental benefits of preserving forests. The policy maker's role is to balance these competing interests, using forest conservation as a tool for enhancing long-term social welfare. It is important to note that this approach differs from international conservation schemes like REDD+ (Reduction of Emissions from Deforestation and Forest Degradation), which focus on reducing deforestation relative to a historical or baseline level. In contrast, the model presented here involves a more direct integration of forestland into the social utility function and dynamic decision-making framework, reflecting a more holistic approach to balancing environmental sustainability and economic productivity. Instead of merely avoiding deforestation, the model emphasizes the long-term benefits of forest conservation and the active role of policy makers in optimizing both adaptation and mitigation strategies within the context of sustainable land use.

The process by which ecologically friendly practices are implemented in agriculture is not explicitly modeled in this framework. Instead, it is assumed that once a policy is enacted, farmers make rational decisions about adaptation levels based on economic considerations (as described by equation (1)). A plausible scenario for this assumption is one where farmers were either previously unaware of these practices or unable to fully assess their benefits before the policy intervention. Thus, after policy implementation, farmers are incentivized to choose adaptation measures that align with their economic interests, integrating environmental considerations into their decision-making process. The numerical solution for the model was implemented using the R programming language (R Core Team, 2016), leveraging the deSolve package (Soetaert et al., 2010) for solving differential equations and the rootSolve package (Soetaert and Herman, 2008) for root-finding algorithms. The results were visualized using the ggplot2 package (Wickham, 2016), which facilitated clear and comprehensive graphical representations of the outcomes. A consistent finding across various policy schemes is that, in general, land allocated to agriculture decreases when compared to the unregulated economy. However, this reduction is achieved through different mechanisms, depending on the type of policy. For instance, a mitigation policy reduces agricultural land by increasing the opportunity cost of forestland, as it incorporates the utility loss from deforestation. The higher opportunity cost discourages the conversion of forestland to agricultural use.

Similarly, an adaptation policy increases the cost of agricultural land by factoring in the environmental degradation associated with its use. This policy also adjusts for the marginal product of agricultural land, reflecting the current state of the environment. As a result, land-use decisions are corrected to account for the true environmental costs, incentivizing a reduction in agricultural expansion and promoting more sustainable practices. Through these channels, both mitigation and adaptation policies aim to balance agricultural productivity with environmental conservation, reducing the negative impacts of land use on the ecosystem. The reduction in the share of agricultural land due to policy implementation naturally contributes to the achievement of environmental goals, such as improved ecosystem resilience and reduced degradation. However, for these policies to be considered truly synergistic, they must also avoid or minimize negative effects on economic output. The impact of the analyzed policy configurations on output is, however, somewhat ambiguous. On one hand, a reduction in agricultural land is expected to decrease output due to the smaller area available for cultivation. On the other hand, increasing forestland improves the state of the environment, which can have an indirect positive effect on output by enhancing ecosystem services, such as water regulation, soil fertility, and biodiversity, all of which benefit long-term agricultural productivity.

The net effect of these policies depends on additional factors, such as whether the unregulated scenario leads to a regime shift in the ecosystem, and whether the policies implemented can prevent or mitigate such an outcome. A regime shift, such as the transformation from forest to savanna, can severely reduce the long-term productivity of the land, so policies that avert such shifts could have a positive influence on overall output despite the immediate reduction in agricultural land. One of the challenges in modeling these dynamics, particularly in the ecological system, is the uncertainty surrounding specific processes, such as those associated with Shallow Lake Dynamics—a term used to describe systems with abrupt regime shifts and complex internal feedbacks. The threshold locations where regime shifts occur are difficult to predict and highly uncertain, making it challenging to pinpoint when and how such shifts might happen. Nevertheless, an effort has been made to establish a plausible specification for the parameters.

The internal dynamics of the system (as outlined in equation (3)) were quantified based on research by Folke et al. (2004) and Heijdra & Heijnen (2013). In land ecosystems, forest cover has been observed to play a critical role in determining the dynamics of the ecosystem and the likelihood of regime shifts (Cochrane, 2001; Leonel, 2001). Evidence suggests that significant disruptions, potentially signaling regime shifts, occur when forest cover losses exceed 90% of the original area. Based on this, the parameter εf was selected to define the threshold of the upper branch at approximately 10% of the initial forest cover (Zheng and Eltahir, 1998). The parameters used to define the mitigation policy in the model were selected to replicate forest cover values observed during the post-transition phase of forest ecosystems. This approach is based on the understanding that recent efforts to combat deforestation have primarily been driven by mitigation policies. In particular, the reported forest cover values for this phase of the forest transition process—a stage where forest loss begins to slow or reverse—are approximately 25% of the total land area allocated to forest cover (Hosonuma et al., 2012). This reflects a point where mitigation policies, such as reforestation and forest conservation efforts, begin to stabilize or restore forested areas. The introduction of adaptation measures in the agricultural subsector was aimed at analyzing their effects on the overall model dynamics and their broader implications for sustainable land use. The parameters for adaptation were chosen to ensure that a positive optimal choice for adaptation in the agricultural subsector could be observed in the model's outcomes. Without this, the adaptation scenario would merely replicate the outcomes of the base mitigation scenario (as described in equations (9) and (14)). These adaptation parameters were carefully selected to reflect realistic conditions. In addition to adhering to standard economic assumptions—such as marginally decreasing benefits—they acknowledge the limitations of adaptation measures in agriculture. While practices such as agroforestry or sustainable land management can help mitigate some of the negative impacts of deforestation, they cannot fully substitute the ecological functions provided by intact forest ecosystems. Thus, although adaptation in agriculture can reduce environmental degradation, it is not a complete replacement for forest conservation. The balance between mitigation in forestry and adaptation in agriculture is critical for ensuring sustainable land use while maintaining economic productivity. This nuanced approach highlights the importance of integrating both strategies to address deforestation and land degradation while acknowledging the unique roles of forests in maintaining ecosystem stability and resilience.

4. CONCLUSIONS

In this paper, a coupled economic-ecological system characterized by the presence of ecological thresholds was analyzed to identify policies with synergistic properties. These synergies were defined as policies capable of delivering the highest possible sustainable output—output that does not decline over time—while minimizing environmental degradation. The results consistently demonstrate that, regardless of specific circumstances (such as whether or not a regime shift occurs), a cross-sectoral approach offers the most effective policy configuration in achieving these synergistic outcomes. In particular, the study highlights that policy coherence across the entire land use sector is crucial for realizing synergies. Rather than treating agriculture and forestry as separate, isolated components, effective policies must consider the land use sector as an integrated whole—what can be conceptualized as a landscape approach. This holistic approach ensures that interactions between sectors are accounted for, and that both mitigation and adaptation strategies are harmonized to optimize land use sustainably. The findings underscore that a cross-sectoral approach—one that integrates the agricultural and forestry subsectors—offers the best chance of achieving sustainable outcomes by balancing economic productivity with environmental preservation. This approach promotes policy integration that recognizes the interconnectedness of the land use system, paving the way for more effective and coherent strategies for sustainable development. The results of this study suggest that the implementation of forest conservation strategies, such as REDD+, should ideally be complemented by the adoption of coherent ecologically-friendly practices in agriculture to ensure resilient and productive landscapes. By integrating these strategies, the negative impacts of deforestation can be mitigated, while also promoting sustainable agricultural practices that reduce environmental degradation and enhance ecosystem services. However, translating these theoretical insights into specific, actionable measures requires a careful contextualization of regional realities. Each region presents unique environmental, social, and economic conditions that must be considered when designing and implementing policies to avoid or minimize trade-offs between conservation and agricultural productivity.

Further research is essential to develop tailored approaches that align with regional needs, ensuring that sustainable land management practices are effective on the ground. Thus, while the study points to the benefits of a cross-sectoral policy approach, the success of these policies depends on adapting them to local contexts, where specific conditions will determine the balance between forest conservation and agricultural productivity. It is important to note that the results of this study are based on two key assumptions: first, that ecological processes play a crucial role in sustaining the productivity of the agricultural system; and second, that the agricultural sector has the capacity to mitigate the negative impacts of land use changes on these key ecological processes. Both of these assumptions are supported by empirical evidence from existing research. For example, a systematic review of the contribution of ecosystem services to crop production found that the presence of forests nearby, as well as trees within cropland, has the potential to maintain or even enhance agricultural yields compared to monoculture systems. These findings highlight the essential role that ecological processes, such as pollination, nutrient cycling, and water regulation, play in sustaining agricultural productivity. Similarly, the identified mitigation and adaptation potential in agriculture—through practices like agroforestry and sustainable land management—suggests that the second assumption holds to a significant extent. These ecologically-friendly practices reduce the environmental impact of agriculture and help preserve the underlying ecological processes that support long-term productivity. Proper management of these practices can foster a more sustainable form of agriculture that aligns with both environmental and economic goals. The assumptions on which the study's results are based are supported by research findings, particularly regarding the positive influence of ecosystems on agriculture and the ability of sustainable agricultural practices to mitigate environmental impacts. This reinforces the notion that a synergistic approach combining forest conservation with ecologically-friendly agriculture has the potential to create resilient and productive landscapes. It is important to emphasize that this analysis was primarily focused on the sustainable production aspects of a coupled ecological-economic system. As a result, certain environmental services that may be highly relevant but are not directly linked to productivity were implicitly excluded from the analysis. One notable omission is biodiversity, which, despite not being directly addressed, plays a crucial role in ecosystem health and resilience.

According to various studies, biodiversity has one of the highest correlations with the provision of a wide range of other ecosystem services, such as pollination, water purification, and disease regulation. Its presence enhances the stability and functionality of ecosystems, which indirectly support long-term agricultural productivity and ecological resilience. By maintaining diverse species and habitats, ecosystems can better withstand disturbances and continue providing essential services. The exclusion of biodiversity from the model represents a potential limitation, as its role in sustaining ecological processes and supporting ecosystem resilience may have significant implications for both environmental and economic outcomes. Future research should consider incorporating biodiversity as a critical factor in the analysis to provide a more comprehensive understanding of the interconnectedness of ecosystem services and the sustainability of coupled ecological-economic systems.

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