

Research Article

Integrating Natural Capital into The System of National Accounts

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Abstract

This study conducts a systematic theoretical-bibliographic review of the fundamental barriers and conceptual problems confronting the integration of Natural Capital Accounting (NCA) into the System of National Accounts (SNA). It critically examines why conventional macroeconomic indicators fail to capture ecological degradation under conditions of non-linear dynamics, and proposes institutional solutions grounded in the existing literature. A systematic review of peer-reviewed literature from Scopus and Web of Science was conducted, complemented by analysis of key policy documents (SEEA CF, SEEA EA, Dasgupta Review). Sources were selected using targeted keyword combinations and snowball searching. The review synthesizes foundational and contemporary works on national accounting, natural capital measurement, non-linear ecological dynamics, and institutional reform. No primary statistical datasets were employed. Three categories of fundamental barriers are identified: measurement barriers, conceptual barriers, and institutional barriers. The paper demonstrates that ecological tipping points, regime shifts, and threshold effects render the SNA's implicit linearity assumption untenable. A five-tier conceptual framework linking natural capital stocks through non-linear degradation dynamics to adjusted macroeconomic indicators and sustainability indices is developed.

Keywords: Natural capital accounting, System of National Accounts, SEEA, non-linear dynamics, tipping points, GDP

INTRODUCTION

The System of National Accounts (SNA), codified through successive United Nations revisions (most recently SNA 2008), provides the internationally standardized framework for measuring economic activity. Gross Domestic Product (GDP), the SNA's most visible output, has served as the predominant yardstick of national economic performance since the Bretton Woods era. However, an increasingly robust body of scholarship demonstrates that GDP systematically misrepresents economic welfare by treating natural resource extraction as pure income while ignoring the depreciation of natural capital - the stock of renewable and non-renewable natural assets that yields a flow of ecosystem services to the economy and society (Repetto et al., 1989; Dasgupta, 2021).

The Stiglitz-Sen-Fitoussi Commission (2009), established by the French government, concluded that over-reliance on GDP as a measure of economic performance and social progress leads to fundamentally distorted policy decisions. The Commission recommended a shift toward 'dashboard' approaches incorporating sustainability metrics, wealth measures, and well-being indicators. The Dasgupta Review (2021), commissioned by HM Treasury, went further by arguing that nature should be treated as an asset in the national balance sheet and that inclusive wealth - the aggregate shadow value of produced, human, and natural capital - constitutes the correct metric for assessing sustainable development.

The intellectual lineage of natural capital accounting extends further than the Stiglitz Commission. Repetto et al. (1989), in their landmark study of Indonesia's natural resource accounts, demonstrated that conventional GDP growth rates dramatically overstated genuine economic progress once forest, petroleum, and soil depletion were accounted for. This

finding catalyzed the development of environmental satellite accounts and ultimately led to the first SEEA handbook in 1993. The concept of Genuine Savings, later renamed Adjusted Net Savings by the World Bank, provided a practical indicator of sustainability by adjusting gross savings for human and natural capital changes (Hamilton and Clemens, 1999). The TEEB initiative (2010) brought ecosystem services valuation to global policy attention, while the UK Natural Capital Committee, established in 2012, demonstrated how natural capital concepts could inform national policy.

In response to these calls, the United Nations Statistical Commission adopted the System of Environmental-Economic Accounting Central Framework (SEEA CF) as an international statistical standard in 2012, followed by the SEEA Ecosystem Accounting (SEEA EA) in March 2021. Together, these frameworks provide a systematic methodology for recording environmental stocks and flows in a manner consistent with the SNA's accounting conventions (Hein et al., 2015; Obst and Alfieri, 2021). By 2024, ninety-two countries were developing SEEA-aligned natural capital accounts (Bagstad et al., 2021). Despite this progress, the full integration of natural capital into the core SNA - such that GDP and related aggregates are routinely adjusted for natural capital depletion and degradation - remains an unrealized aspiration.

A particularly consequential but underexplored dimension of this integration challenge concerns non-linear ecological dynamics. Ecological systems do not degrade incrementally; they exhibit tipping points, regime shifts, hysteresis, and threshold effects (Scheffer et al., 2009, 2012; Folke et al., 2004). The SNA, by contrast, is built on implicitly linear and equilibrium-based accounting conventions: depreciation is calculated as a smooth, predictable decline in asset value. This conceptual mismatch means that the SNA framework is structurally incapable of capturing the sudden, discontinuous, and often irreversible losses that characterize ecological degradation under non-linear dynamics. Rockstrom et al. (2009) identified nine planetary boundaries - critical thresholds beyond which Earth system processes may undergo abrupt and potentially catastrophic shifts - further underscoring the inadequacy of linear accounting for ecological realities.

The World Bank's Adjusted Net Savings (ANS) indicator, introduced by Hamilton and Clemens (1999) as Genuine Savings, represents the most widely adopted attempt to adjust macroeconomic aggregates for natural capital depletion. ANS is calculated as gross national savings plus education expenditure minus fixed capital depreciation minus energy, mineral, and forest depletion minus CO2 damage. The World Bank compiles ANS for over 150 countries annually. Persistently negative ANS signals an unsustainable development trajectory - a country is consuming its capital base rather than generating genuine wealth. However, ANS relies on simplified depletion calculations using world commodity prices as shadow prices and does not account for ecosystem service degradation, threshold effects, or the non-linear dynamics of ecological systems. It thus provides a necessary but insufficient correction to conventional macroeconomic indicators.

Alternative approaches to 'greening' macroeconomic aggregates have been proposed. The Environmentally-adjusted Domestic Product (EDP), introduced in early SEEA iterations, subtracts the value of natural capital depletion and defensive environmental expenditure from GDP. The Genuine Progress Indicator (GPI) goes further by incorporating income distribution, household labour, and environmental costs. Inclusive Wealth, as developed in the UN Environment Programme's Inclusive Wealth Reports and theoretically grounded in Dasgupta's (2021) framework, measures the aggregate shadow value of produced, human, and natural capital, with changes in inclusive wealth per capita serving as the criterion for sustainability. Each approach offers improvements over GDP, yet each confronts the common challenge of representing ecological dynamics that are fundamentally non-linear within accounting frameworks designed around linear conventions.

Three significant gaps persist in the literature. First, while individual barriers to NCA-SNA integration have been discussed (Hein et al., 2015; Comte et al., 2022), no systematic taxonomy encompassing measurement, conceptual, and institutional dimensions has been developed. Second, the specific implications of non-linear ecological dynamics for macroeconomic accounting have received insufficient theoretical attention. Third, a comprehensive conceptual framework linking natural capital stock depletion through non-linear degradation dynamics to adjusted macroeconomic indicators and sustainability indices is absent. This study addresses these gaps by pursuing three objectives: (a) to develop a systematic taxonomy of fundamental barriers to NCA-SNA integration; (b) to analyze why the SNA's implicit linearity assumption is rendered untenable by non-linear ecological dynamics; and (c) to propose institutional solutions and develop an integrative conceptual framework.

METHODOLOGY

This study employs a systematic theoretical-bibliographic review methodology. The objective is not to statistically synthesize empirical findings but to critically analyze the theoretical foundations, conceptual frameworks, and institutional arrangements relevant to NCA-SNA integration, with particular attention to the implications of non-linear ecological dynamics.

Scopus and Web of Science were searched using the following keyword combinations: 'natural capital accounting' AND ('national accounts' OR 'SNA' OR 'GDP'); 'SEEA' AND ('integration' OR 'barriers' OR 'implementation'); 'ecological degradation' AND ('non-linear' OR 'tipping point' OR 'regime shift') AND ('economic' OR 'accounting'); and 'beyond GDP' AND ('natural capital' OR 'inclusive wealth' OR 'sustainability'). Snowball searching through reference lists of key sources was conducted. Inclusion criteria comprised peer-reviewed journal articles, books, and authoritative institutional reports (UN, OECD, World Bank). A total of 94 sources were selected: 68 journal articles, 14 books or book chapters, and 12 institutional reports and policy documents.

To ensure systematic coverage and analytical rigour, a structured extraction protocol was applied. For each source, the following elements were recorded: theoretical framework employed, empirical or conceptual contribution to NCA-SNA integration, specific barriers or solutions identified, treatment of non-linear dynamics (if any), and institutional context. Sources were cross-referenced to identify convergent findings and unresolved theoretical tensions. The conceptual framework was iteratively refined through multiple rounds of analysis, ensuring internal consistency and comprehensive coverage of identified themes.

Sources were analyzed along three thematic dimensions: (a) measurement and valuation challenges in natural capital accounting; (b) the conceptual implications of non-linear ecological dynamics for macroeconomic accounting; and (c) institutional and governance barriers to NCA-SNA integration. For each dimension, the theoretical foundations, key assumptions, empirical evidence, and unresolved tensions were systematically examined. The conceptual framework was developed inductively by synthesizing elements identified across individual sources into an integrative model.

RESULTS

The most fundamental measurement barrier concerns the valuation of natural capital in monetary terms compatible with the SNA. The SNA requires all assets to be valued at exchange prices observed in markets. For produced capital (machinery, buildings), market prices are readily available. For natural capital, however, many ecosystem services - climate regulation, water purification, pollination, cultural services - are non-market goods with no observable exchange prices (Costanza et al., 1997, 2014). This necessitates the use of non-market valuation methods (contingent valuation, hedonic pricing, replacement cost), each of which yields different estimates and carries well-documented biases. The SEEA EA addresses this by proposing an exchange value concept aligned with SNA principles, but the practical implementation of consistent monetary valuation across diverse ecosystem types and services remains a formidable challenge (Hein et al., 2015). TEEB (2010) documented valuation estimates for identical ecosystem services varying by two orders of magnitude across studies, highlighting the problem of methodological pluralism.

A second measurement barrier concerns the delineation of system boundaries. The SNA defines the production boundary - the set of activities considered 'economic' - in a manner that excludes most ecosystem service provision. While the SEEA EA extends this boundary to encompass ecosystem services, determining which services to include and how to attribute them to specific economic units remains contentious. The ecosystem accounting unit does not map neatly onto the SNA's institutional sectors. This boundary mismatch complicates the integration of ecosystem accounts into the SNA's input-output tables and balance sheets (Bagstad et al., 2021; Comte et al., 2022).

A related measurement challenge concerns temporal dynamics. The SNA compiles quarterly and annual accounts reflecting economic flows over defined periods. Natural capital accounts, however, must capture changes in stock conditions that may unfold over decades. Forest regrowth, soil regeneration, and aquifer recharge operate on timescales fundamentally different from those of economic production cycles. This temporal mismatch creates difficulties in aligning natural capital asset accounts with the SNA's annual reporting cycle and in selecting appropriate discount rates for converting future ecosystem service flows into present asset values. The choice of discount rate is particularly consequential under non-linear dynamics: standard exponential discounting systematically undervalues long-lived natural assets whose degradation may trigger catastrophic future losses.

Compiling natural capital accounts requires spatially explicit biophysical data - land cover maps, soil quality surveys, water flow monitoring, biodiversity inventories - at scales and frequencies that most countries' statistical systems are not designed to provide. Bagstad et al. (2021) found that even in the United States and the European Union, significant data gaps exist for key ecosystem condition indicators. In developing countries, where natural capital depletion is often most acute, data infrastructure constraints are substantially more severe, creating a paradoxical situation in which the countries most in need of natural capital accounting are least equipped to implement it.

A conceptual barrier that has received insufficient theoretical attention concerns the SNA's implicit assumption of linear asset dynamics. In the SNA, depreciation of produced capital is modelled as a smooth, continuous process - a machine depreciates predictably over its useful life according to a straight-line or declining-balance schedule. This linear depreciation model is implicitly extended to natural capital when resource depletion is accounted for. However, ecological systems do not degrade linearly. They exhibit complex non-linear dynamics including multiple stable states,

tipping points (bifurcation-induced and rate-induced), hysteresis, and regime shifts (Scheffer et al., 2009; Scheffer, 2009).

Scheffer et al. (2012) demonstrated that ecological systems approaching a critical transition exhibit characteristic early warning signals - rising variance, increasing autocorrelation, critical slowing down - that are fundamentally inconsistent with linear depreciation models. A forest ecosystem, for example, may appear stable for decades while gradually losing resilience, then abruptly shift to a degraded grassland state when a threshold is crossed. The economic value of the ecosystem services provided by the forest does not decline incrementally; it collapses discontinuously. The SNA framework, with its linear accounting conventions, cannot represent such dynamics.

Non-linear ecological dynamics frequently involve irreversibility - once a regime shift has occurred, restoring the original state may require environmental conditions far more favourable than those that triggered the collapse (Scheffer et al., 2001). This hysteresis effect means that the 'depreciation' of natural capital is not symmetric with potential "restoration": losing a coral reef to bleaching is not the inverse of building a factory. The SNA's capital accounts, which treat all forms of capital symmetrically through investment and depreciation, lack the conceptual architecture to represent irreversible losses. Folke et al. (2004) emphasized that resilience - the capacity of a system to absorb disturbance without shifting to an alternative state - is itself a form of natural capital that degrades non-linearly and is not captured in any existing accounting framework.

Rockstrom et al. (2009) identified nine planetary boundaries representing thresholds in Earth system processes beyond which abrupt, large-scale environmental change may occur. These boundaries - including climate change, biosphere integrity, land-system change, and biogeochemical flows - define a 'safe operating space for humanity.' The planetary boundaries framework reveals a fundamental inadequacy of flow-based indicators such as GDP: even if GDP is growing and resource extraction appears economically efficient, the economy may be approaching or exceeding biophysical thresholds whose breach would cause catastrophic, irreversible losses. Stock-based indicators - measuring the condition and extent of natural capital assets relative to identified thresholds - are therefore essential for sustainable development assessment, but they require accounting conventions fundamentally different from those in the current SNA.

The implications of non-linear dynamics for natural capital valuation are profound. In standard environmental economics, the shadow price of a natural resource is derived from its marginal contribution to production or welfare. Under linear dynamics, shadow prices change smoothly as stocks change. Under non-linear dynamics, however, shadow prices can exhibit discontinuous jumps as the system approaches a tipping point. A fishery, for example, may have a moderate shadow price at 80 percent of its carrying capacity but an astronomically high shadow price at 20 percent if that stock level is near a collapse threshold. The Dasgupta Review (2021) formalized this insight within a wealth accounting framework, arguing that the shadow prices of natural capital assets should reflect not only their current flow of services but also the 'insurance value' of maintaining ecological resilience - the distance from tipping points. Incorporating resilience as a component of natural capital value would fundamentally alter the depreciation schedules and asset valuations used in national accounts, but no existing accounting standard provides guidance on how to operationalize this theoretically compelling idea.

The concept of safe minimum standards, originally proposed by Ciriacy-Wantrup (1952) and formalized by Bishop (1978), offers a complementary perspective. Under conditions of irreversibility and uncertainty about ecological thresholds, a safe minimum standard approach avoids resource depletion beyond levels from which recovery is impossible or prohibitively costly, unless the social costs of doing so are unacceptably high. Translating this precautionary principle into accounting terms would require natural capital accounts to incorporate explicit threshold indicators - minimum stock levels below which depreciation calculations are replaced by catastrophic loss estimates. This represents a fundamental departure from the SNA's smooth, continuous depreciation paradigm but may be necessary to align macroeconomic measurement with ecological reality.

Natural capital accounting requires collaboration between statistical offices, environment ministries, and finance ministries. In most countries, these institutions operate within separate mandates, budgets, and data systems with limited coordination mechanisms. Hein et al. (2015) identified this inter-ministerial fragmentation as a primary institutional barrier, noting that statistical offices often lack the ecological expertise to compile natural capital accounts, while environment agencies lack the accounting expertise to align their data with SNA conventions.

In many jurisdictions, statistical legislation mandates the compilation of GDP and related SNA aggregates but does not require natural capital accounts. Without a legal mandate, natural capital accounting remains a discretionary activity subject to budget competition and political prioritization. Furthermore, policy demand for NCA data is often diffuse - environment ministries may value ecosystem condition indicators, finance ministries may prefer monetary valuations, and planning agencies may require spatially explicit data - creating a fragmented demand landscape that complicates the design of integrated accounting systems (Comte et al., 2022).

Compiling SEEA-compliant accounts requires specialized skills spanning economics, ecology, remote sensing, GIS, and statistics. The World Bank's Changing Wealth of Nations reports (World Bank, 2021) documented that many developing countries lack the human capital and technical infrastructure necessary for even basic natural resource accounting, let alone comprehensive ecosystem accounting. Hamilton and Clemens (1999) observed that Adjusted Net Savings - the World Bank's headline sustainability indicator - relies on simplified depletion calculations precisely because more sophisticated approaches exceed the statistical capacity of most countries.

Table 1. Taxonomy of fundamental barriers to NCA-SNA integration

Barrier category	Specific barriers	Key sources	Implications for non-linear dynamics
Measurement	Valuation pluralism; absence of market prices for ecosystem services; boundary indeterminacy between SNA and ecosystem units; data infrastructure deficits (biophysical monitoring)	Costanza et al. (1997, 2014); TEEB (2010); Hein et al. (2015); Bagstad et al. (2021)	Non-linear valuation: marginal values shift discontinuously near thresholds
Conceptual	SNA's linear depreciation model; equilibrium assumptions; stock-flow mismatch; inability to represent irreversibility and hysteresis; no accounting for resilience loss	Scheffer et al. (2009, 2012); Folke et al. (2004); Rockstrom et al. (2009); Dasgupta (2021)	Tipping points, regime shifts, and planetary boundaries are structurally invisible to linear SNA
Institutional	Inter-ministerial fragmentation; absence of legal mandates; weak policy demand; statistical capacity constraints; insufficient cross-disciplinary expertise	Hamilton & Clemens (1999); Comte et al. (2022); World Bank (2021); Stiglitz et al. (2009)	Institutional inertia prevents adoption of non-linear accounting methods even when available

DISCUSSION

The findings, synthesized across measurement, conceptual, and institutional dimensions, reveal a fundamental structural inadequacy in the relationship between the SNA and ecological reality. The SNA was designed to measure economic production flows in a framework that treats capital as depreciating smoothly and predictably. When applied to natural capital - which degrades non-linearly, exhibits tipping points, and may undergo irreversible regime shifts - this framework produces systematically misleading signals. GDP may register economic growth even as the natural capital base sustaining that growth approaches catastrophic thresholds. Repetto et al.'s (1989) seminal study of Indonesia demonstrated that accounting for natural resource depletion reversed the impression of robust economic growth, revealing instead a pattern of asset liquidation disguised as income. Under non-linear dynamics, this misrepresentation is amplified: not only does GDP overstate income by ignoring depletion, it fails entirely to register the escalating risk of discontinuous collapse as ecological thresholds are approached.

The World Bank's Adjusted Net Savings (ANS) indicator partially addresses this problem by subtracting resource depletion and CO2 damage from gross national savings. Hamilton and Clemens (1999) demonstrated that many resource-dependent developing countries exhibit negative ANS, indicating unsustainable development paths. However, ANS still relies on linear depletion calculations and marginal damage estimates that do not account for threshold effects or regime shifts. The Inclusive Wealth approach, advocated by the Dasgupta Review (2021) and operationalized in the UN Inclusive Wealth Reports, goes further by measuring the aggregate value of all capital assets, but it too faces the challenge of representing non-linear ecological dynamics in asset valuation.

Integrating the findings, a five-tier conceptual framework is proposed (Figure 1) that maps the causal chain from

natural capital stocks through non-linear degradation dynamics to adjusted macroeconomic indicators and sustainability indices. The framework consists of: (A) Natural Capital Stocks - mineral reserves, ecosystem assets, and atmospheric sink capacity, measured in physical and monetary units following SEEA CF and SEEA EA conventions; (B) System of National Accounts - the existing SNA framework recording GDP, net national income, and capital accounts, which currently excludes natural capital depletion; (C) Non-Linear Degradation Dynamics - tipping points, hysteresis, threshold effects, and cascading cross-system feedbacks that characterize actual ecological degradation but are absent from the SNA; (D) Adjusted Macroeconomic Indicators - Green GDP, Adjusted Net Savings, Inclusive Wealth, and SEEA satellite accounts that correct for natural capital changes; and (E) Sustainability Indices and Policy Feedback - Genuine Progress Indicator, SDG indicators, planetary boundaries monitoring, and policy instruments that translate accounting information into governance decisions.

The critical innovation of the framework lies in Block C - the explicit representation of non-linear dynamics as an intermediate layer between natural capital stocks and macroeconomic indicators. This layer highlights that the relationship between stock changes and flow adjustments is non-linear: a 10 percent decline in an ecosystem's condition may produce negligible economic impact if the system remains within its resilience domain, but the same 10 percent decline may produce catastrophic economic consequences if it pushes the system past a tipping point. This non-linearity has profound implications for the discount rates, shadow prices, and depreciation schedules used in natural capital valuation.

Addressing the identified barriers requires a coordinated programme of institutional reform operating at multiple governance levels. At the international level, the continued development and refinement of SEEA standards - particularly guidance on monetary valuation under conditions of non-linearity and irreversibility - is essential. The UN Committee of Experts on Environmental-Economic Accounting should commission dedicated methodological work on incorporating threshold effects into ecosystem asset valuation. At the national level, three institutional innovations are recommended.

First, legal mandates for natural capital accounting should be established through statistical legislation, requiring national statistical offices to compile and publish SEEA-aligned accounts on a regular cycle alongside conventional SNA publications. The United Kingdom's Natural Capital Committee model, which was established to advise the government on the state of English natural capital, provides a precedent. Second, inter-ministerial coordination mechanisms should be formalized through joint statistical programmes linking statistical offices, environment ministries, finance ministries, and central banks. The Netherlands' pioneering experience with environmental accounts - where Statistics Netherlands collaborates systematically with the National Institute for Public Health and the Environment - demonstrates the feasibility of this approach. Third, international technical assistance and capacity building programmes should be expanded to support developing countries in compiling natural capital accounts, with particular attention to remote sensing and GIS infrastructure for ecosystem extent and condition monitoring.

A critical dimension of institutional reform concerns the role of central banks and financial regulators. The Network for Greening the Financial System (NGFS), established in 2017 by eight central banks and supervisors, has increasingly recognized that environmental degradation poses systemic risks to financial stability. Natural capital accounts can provide the data foundation for assessing nature-related financial risks - quantifying the economic exposure of financial portfolios to ecosystem degradation and tipping points. The Taskforce on Nature-related Financial Disclosures (TNFD), launched in 2021, explicitly references SEEA-aligned natural capital accounts as a data source for corporate and financial sector reporting. Integrating NCA into the macroeconomic surveillance frameworks of central banks and finance ministries would create a powerful demand-side driver for NCA compilation, complementing the supply-side improvements in statistical methodology and data infrastructure.

The experience of pilot countries offers instructive lessons. The Netherlands has compiled environmental accounts within Statistics Netherlands since the early 1990s, progressively expanding coverage from physical flow accounts to monetary ecosystem service valuations. Australia's Bureau of Statistics has developed experimental ecosystem accounts for specific biomes. The United Kingdom's Office for National Statistics has published natural capital accounts as experimental statistics since 2014. These experiences reveal common success factors: strong institutional leadership, sustained funding, cross-ministerial collaboration, and the explicit linking of NCA outputs to specific policy questions. They also reveal common challenges: the difficulty of maintaining long-term institutional commitment in the face of competing statistical priorities and the persistent tension between methodological rigour and policy relevance.

Several limitations must be acknowledged. First, the review is exclusively theoretical-bibliographic; no empirical testing of the proposed framework has been conducted. Second, only English-language sources were analyzed. Third, the conceptual framework addresses non-linear dynamics at a theoretical level but does not specify the mathematical formalism required for practical implementation. Future research should prioritize: (a) developing accounting

methodologies that formally incorporate non-linear dynamics and threshold effects into natural capital asset valuation; (b) empirically testing the five-tier framework in specific country contexts; (c) investigating how central banks and financial regulators can use natural capital accounts to assess ecological systemic risk; and (d) exploring the potential of artificial intelligence and satellite remote sensing to reduce the data infrastructure barriers to NCA compilation.

Figure 1. Conceptual Framework: Ecological Stock Depletion, Economic Flows, and Sustainability Indices

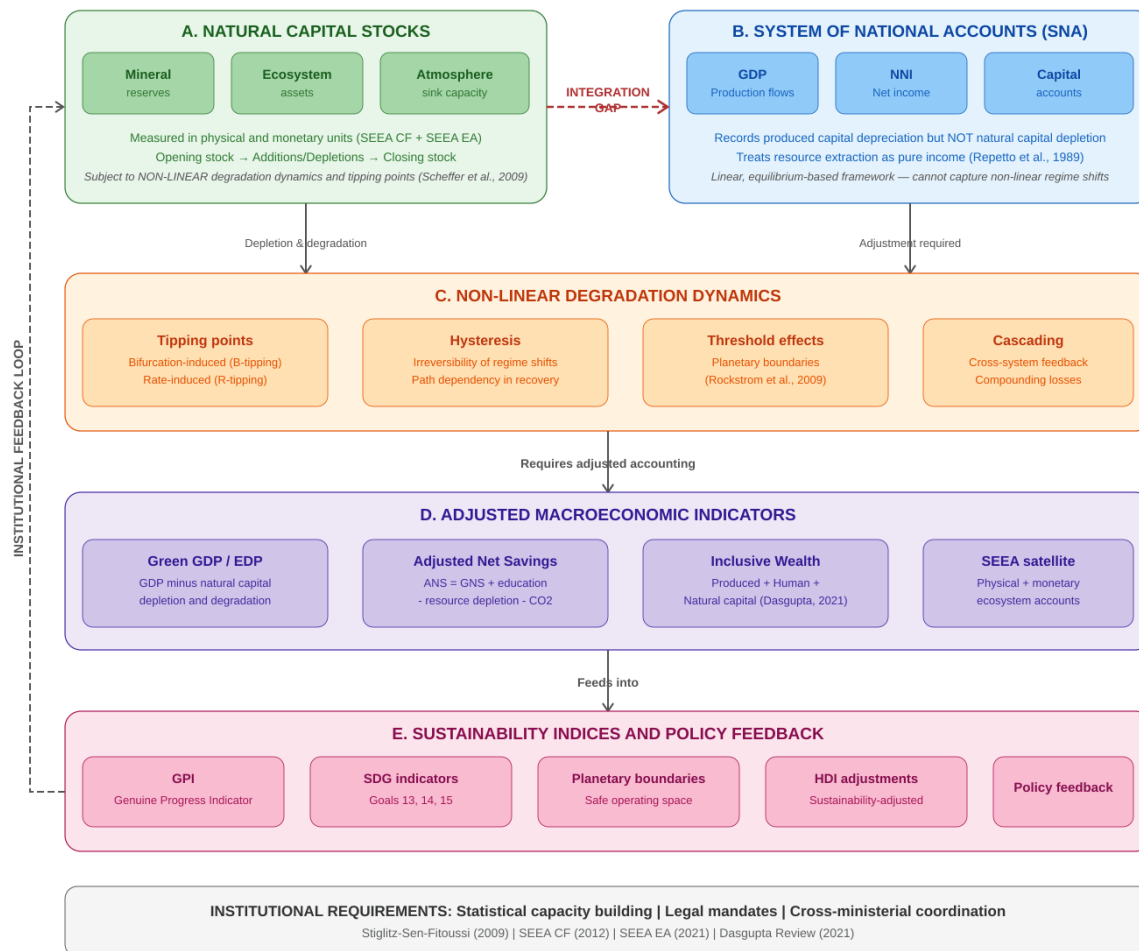


Figure 1. Conceptual framework: ecological stock depletion, non-linear dynamics, economic flows, and sustainability indices

CONCLUSION

This study has systematically reviewed the fundamental barriers confronting the integration of Natural Capital Accounting into the System of National Accounts, with particular attention to the implications of non-linear ecological dynamics for macroeconomic measurement. The principal findings may be summarized as follows.

First, three categories of barriers - measurement, conceptual, and institutional - collectively explain why, despite three decades of SEEA development, natural capital remains effectively absent from the core SNA and its headline aggregates. Second, the non-linear dynamics of ecological degradation - tipping points, regime shifts, hysteresis, and planetary boundary thresholds - render the SNA's implicit linear depreciation model fundamentally inadequate for natural capital. GDP and related flow indicators can register economic growth while the natural capital base approaches catastrophic thresholds, producing systematically misleading policy signals.

Third, the five-tier conceptual framework developed in this study - linking natural capital stocks through non-linear degradation dynamics to adjusted macroeconomic indicators and sustainability indices - provides an integrative theoretical architecture that makes the non-linearity problem visible within the accounting framework and identifies the specific points at which institutional intervention is required.

From a theoretical standpoint, the non-linearity problem identified in this study suggests that the next generation of accounting standards must incorporate concepts from complex systems science - resilience, adaptive capacity, critical transitions, and safe operating space - that are foreign to the equilibrium-based conventions of the current SNA. This does not require abandoning the SNA framework but rather extending it through satellite accounts, supplementary tables, and adjusted aggregates that make ecological non-linearity visible to policymakers. The SEEA EA, adopted in

2021, represents a significant step in this direction, but its current formulation does not explicitly address tipping points, threshold effects, or hysteresis in asset valuation. Closing this gap represents perhaps the most important methodological frontier in natural capital accounting.

The study contributes to the literature by providing the first systematic taxonomy of NCA-SNA integration barriers that explicitly encompasses the non-linear dynamics dimension, and by developing a conceptual framework that links ecological theory to macroeconomic accounting reform. For policymakers, the central message is that reforming national accounts to include natural capital is not merely a technical statistical exercise but a fundamental institutional transformation requiring legal mandates, inter-ministerial coordination, capacity building, and - crucially - accounting methodologies capable of representing the non-linear, discontinuous, and often irreversible dynamics that characterize actual ecological degradation.

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