CODEX PLANETARIUS

Ecosystem Condition in Agricultural Performance Standards: Insights from Digital Nature Credit System Design

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About *Codex Planetarius*

Codex Planetarius is a proposed system of minimum environmental performance standards for producing globally traded food. It is modeled on the *Codex Alimentarius*, a set of minimum mandatory health and safety standards for globally traded food. The goal of *Codex Planetarius* is to measure and manage the key environmental impacts of food production, acknowledging that while some resources may be renewable, they may be consumed at a faster rate than the planet can renew them.

The global production of food has had the largest impact of any human activity on the planet. Continuing increases in population and per capita income, accompanied by dietary shifts, are putting even more pressure on the planet and its ability to regenerate renewable resources. We need to reduce food production's key impacts.

The impacts of food production are not spread evenly among producers. Data across commodities suggest that the bottom 10-20% of producers account for 60-80% of the impacts associated globally with producing any commodity, even though they produce only 5-10% of the product. We need to focus on the bottom.

Once approved, *Codex Planetarius* will provide governments and trade authorities with a baseline for environmental performance in the global trade of food and soft commodities. It won't replace what governments already do. Rather, it will help build consensus about key impacts, how to measure them, and what minimum acceptable performance should be for global trade. We need a common escalator of continuous improvement.

These papers are part of a multiyear proof of concept to answer questions and explore issues, launch an informed discussion, and help create a pathway to assess the overall viability of *Codex Planetarius*. We believe *Codex Planetarius* would improve food production and reduce its environmental impact on the planet.

For more information, visit www.codexplanetarius.org

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Introduction

The *Codex Alimentarius* Commission international food standards were established with a dual mandate: to protect public health and ensure fair practices in food trade. They have become critical reference points for national food agencies and exert substantial influence on the structure and operation of global food systems (Lawrence et al., 2024). However, *Codex Alimentarius* standards must operate within a free-market paradigm characterized by the increasing dominance of financial and corporate logics. In the context of food production, processes of financialization and corporatization have created and extended industrialized agricultural systems optimized for shareholder value, capital accumulation, and GDP growth (Sievert et al., 2025).

These industrial systems are characterized by large-scale monocultures that supply commodity ingredients for ultra-processed foods (UPFs), animal-source foods (ASFs), export-oriented fruit and vegetables, and a wide range of other bulk commodities. While *Codex Alimentarius* is primarily concerned with setting standards at the level of farm production rather than downstream processing or manufacturing, the structural dynamics of these supply chains shape how land is managed. They reflect a shift from traditional, resource-constrained agricultural systems to yield-led production, enabled by fossil-carbon inputs, mechanization, and technological intensification, especially across expanding production zones in the global South (Fuglie, 2024).

These forms of agriculture have played a major role in meeting rising global demand for calories, yet they have done so in a way that is fundamentally extractive, relying on non-renewable inputs and uniform cropping systems. As a result, they have replaced natural ecosystems and locally adapted agro-ecological systems with simplified monocultures that drive ecosystem degradation, soil and water depletion, chemical and plastic pollution, and greenhouse gas emissions. They also perpetuate social injustice through exploitative labor practices and diminish human wellbeing by eroding the cultural and psychological benefits of biodiverse, healthy landscapes (IPES-Food, 2022).

The *Codex Planetarius (Codex)* initiative has emerged in response to these challenges and aims to embed environmental sustainability and equity within the governance of global food trade. It reflects a recognition that, while *Codex Alimentarius* standards have contributed to progress on certain Sustainable Development Goals (SDGs), the rise of industrialized agriculture helps explain why many others, particularly those related to biodiversity (SDG 15), climate action (SDG 13), and decent work (SDG 8), remain off track (Wycjhuy's et al., 2024). *Codex Planetarius* proposes a shift towards a holistic food-standards framework that addresses the full spectrum of ecological and social dimensions necessary for a just food systems transformation (Clay, 2016). This approach seeks to ensure a safe operating space for humanity (Rockström et al.'s 2009) and build climate resilience (Clay, 2016).

This paper conceptualizes *Codex Planetarius* as an innovation in food system governance, designed to align global trade standards with planetary health. It adopts an ecosystem perspective, framing land systems as emergent outcomes of intertwined human and non-human processes. The argument draws on applied insights gained by the author during his tenure as Head of Innovation at CreditNature Ltd, where he led the design of a novel nature-crediting mechanism. Nature credits are intangible assets underpinned by systems of standards, codes, quantification methods, data feeds, and audit protocols. A similarly interlinked architecture will likely be required to operationalize *Codex Planetarius* standards

The paper is structured in four sections. Section 1 examines standards as governance tools, highlighting their evolution, their role in coordinating systems of production, and their growing use to address environmental externalities. This establishes the broader context within which *Codex* standards operate and sets the stage for moving biodiversity standardization and measurement beyond traditional approaches. Section 2 adopts a systems ecology perspective to introduce a new generation of ecosystem condition metrics and outlines the conceptualization of the CreditNature NARIA framework, which applies these to quantify changes in ecosystem integrity. Section 3 provides the core contribution of the paper: practical insights from early applications and pilots of NARIA metrics, highlighting challenges, trade-offs, costs, and solutions for implementing an ecosystem condition index at scale. These insights are directly relevant to advancing biodiversity measurement and standardization, and to informing the development of a minimum agricultural performance standard under *Codex*. Section 4 summarizes key insights for *Codex Planetarius*.

1 Standards and Environmental Governance

Standards are fundamental instruments for the coordination and governance of society. They enable shared expectations, facilitate trade, and underpin efforts to manage collective risks. For instance, the *Codex Alimentarius*, established in 1963 by the FAO and WHO, arose in response to a proliferation of conflicting food safety rules that hindered global trade and jeopardized consumers (FAO & WHO, 2006). By harmonizing standards for food production and safety, *Codex Alimentarius* enabled the integration of global agri-food markets while protecting public health.

Beneath each standard lies a conceptual framing: a vision of what a standard is, what it seeks to govern, and how it will do so. This includes not only procedural rules but also assumptions about what constitutes good performance, which qualities are measurable, and which outcomes matter. In environmental governance, such assumptions shape how ecological systems are made visible, legible, and governable.

1.1 A Brief History of Environmental Standards

The 1980s saw conservationists engaging more pragmatically with development and markets. The Brundtland Report (Our Common Future, 1987) institutionalized the concept of sustainable development, catalyzing voluntary market mechanisms for environmental governance. A significant development was the Forest Stewardship Council (FSC) 1993 that aimed to shift timber markets towards sustainability through a system of voluntary forest certification standards that would reward improved practices.

The Roundtable on Sustainable Palm Oil (RSPO), launched in 2004, extended this approach into agricultural tropical forest landscapes designated for rapid oil palm expansion. RSPO introduced some of the first land system standards. These went beyond product certification (e.g., palm oil itself) to require land managers to adopt practices such as: Protecting High Conservation Value Forests (HCVF), Maintaining forest buffer zones along rivers and on steep slopes, and limiting conversion of peatlands. The HCVF concept required landscape-level planning to identify and manage sites of high biodiversity, ecosystem, and cultural value, and has since been embedded in other commodity standards such as the Roundtable on Responsible Soy and Bonsucro (Senior et. al., 2014).

However, as Clay (2016) notes, while voluntary standards such as FSC and RSPO have achieved significant market penetration in some sectors, they have struggled to shift the practices of the bottom quartile of producers who are disproportionally responsible for environmental harm.

In parallel, conservation finance developed carbon markets based on tradable carbon credits as a mechanism to reduce emissions from deforesting and degradation (REDD+, Corbera & Schroeder, 2011). These credits are intangible utility (reporting) assets created by standards and codes for the quantification and reporting of units of environmental change relative to a baseline (ie. tonnes of CO_2 sequestered or avoided). Similar logics are now being applied to create markets for biodiversity offset and nature recovery credits (WEF 2024).

1.2 Standards as Technological Zones

Standards structure systems of codes, metrics, and assurance that organize production processes and enable governance across diverse landscapes and supply chains. Barry (2006) conceptualizes such systems as "technological zones," namely areas where differences between technical practices, procedures, and forms are reduced through the establishment of common standards. In environmental governance, these zones make the qualities of production systems visible, comparable, and governable. Drawing on this concept, a *Codex Planetarius* standard might be considered as anchoring a technological zone with four components.

1. **Social and Governance Dimension (Standards and Codes).** Standards articulate broad principles and define key attributes to be conserved or enhanced, while codes provide procedural frameworks and contextual guidance for translating these principles into local practice (Mallet, 2024). Together, they establish a shared reference system for actors involved in land system governance.

2. **Production Dimension (Land Management Practices).** This dimension classifies and specifies land management practices in a standardized format that enables the translation of abstract standards into actionable on-the-ground activities. It provides the operational logic for how land use must be managed to deliver the outcomes envisioned by the standards (Jepson et al., 2024).

3. **Technological Dimension (Metrics and Assurance Systems).** To ensure credibility and accountability, this dimension introduces the measurable indicators, data collection tools, and validation procedures required to assess whether land management practices and/or production outcomes comply with the intended standards. It operationalizes the link between prescribed practices and evidenced performance (Richter, 2025).

4. **Adoption and Scalability Dimension (Feasibility and Transparency).** This dimension reflects the degree to which the zone framework can be feasibly implemented and trusted at scale. The clarity, cost-effectiveness, and transparency of its metrics and codes shape the likelihood of uptake by practitioners, institutions, and regulators, thereby influencing system-wide traction (Moberg, 2025).

This framing positions standards as the foundational structure within a broader technical zone of implementation, linking principles, practices, metrics, and assurance into a coherent system. It supports a systematic and scalable approach to developing environmental performance standards for agriculture, particularly in the context of land systems.

1.3 Product vs. Land System Standards

Codex Alimentarius (CA) is a collection of product-level performance standards. This reflects its core concern with human health, its trade-based origins, respect for national sovereignty over land-use policy, and the practicalities of aligning standards with global supply chains (FAO & WHO, 2006). *Codex Alimentarius* defines thresholds for contaminants, additives, hygiene, and labelling in traded food commodities, ensuring consistency and safety without prescribing how food is produced.

Codex Planetarius (CP), modelled on *Codex Alimentarius*, has adopted a similar logic. In their research papers, Boyd (2024) and Moberg (2024) propose quantifiable performance metrics, such as a feed conversion ratio (FCR) for aquaculture and a maximum CO_2 intensity per unit of product, as potential components of minimum product standards. These metrics are intended to support practice-neutral frameworks, allowing producers flexibility in how they meet defined thresholds. By linking compliance to the attributes of the commodity itself, rather than specific production conditions, such metrics also aim to align with international trade norms.

However, product-level standards have important limitations. They often fail to account for the dynamic complexity of land systems or the cumulative ecological impacts of production at the landscape scale. These include pressures such as habitat fragmentation, water stress, and biodiversity loss, which cannot easily be disaggregated into individual units of product (Neufeldt et al., 2013). In addition, indirect effects of supply chains, such as leakage (where unsustainable practices are displaced to non-certified areas) or spillovers (e.g., local water depletion impacting neighboring ecosystems), further erode the integrity of product-based performance systems. These limitations point to the need for land system or landscape-level approaches. For *Codex*, the critical design challenge is to connect such approaches to supply sheds and aggregation points (such as mills), since these represent the level at which ecological performance can be linked to trade flows and regulatory instruments.

Perhaps in recognition of these challenges, several CP research papers, including those on biodiversity (Redford, 2025), mycorrhizal fungi (Moberg, 2025), and water use (Richter, 2025), begin to propose outcome metrics that imply substantial changes in farming practice. The biodiversity paper, for instance, highlights the importance of retaining native vegetation and maintaining ecological corridors as necessary conditions for sustaining biodiversity at scale. The fungi paper points to indicators of soil microbial communities that are often supported by management practices such as reduced tillage and cover cropping. Likewise, the water paper recommends extraction caps and collective governance mechanisms that, if adopted, would require significant shifts in practice. Together, these examples reinforce the argument for land-system approaches as a complement or alternative to product-level standards, while remaining within *Codex*'s commitment to performance-based measures.

Such an approach would better capture the relationship between agricultural land management practices and their environmental outcomes, providing a more coherent basis for structuring performance standards that reflect how ecosystems respond to human intervention. The following sections illustrate what this means in practice, showing how land system metrics can be developed and tested at scale.

1.3.1 Benefits of a Land System Approach

In his review of voluntary standards, Mallet (2024) argues for a more holistic view that integrates ecological processes and socio-technical systems at the landscape scale. This reflects Neufeldt et al.'s (2013) call for innovation in the development of integrated indicators and the view that sustainability via minimum environmental standards can only be achieved by addressing the socio-ecological dynamics of land systems.

A land system approach would focus on the state of the production landscape, setting thresholds for key ecosystem characteristics. This approach offers several benefits:

- A broader governance scope that engages not only producers but also investors, technology providers, and other actors shaping agricultural practices (Mallet, 2024).
- Feasibility and efficiency through the use of ecological system indicators rather than multiple product attributes, thereby simplifying monitoring and verification (Richter, 2025).
- Comparability across geographies supporting globally applicable benchmarks while allowing for local variation in production methods.
- Collateral benefits for ecosystems and society through the restoration of ecological functions such as pollination, water regulation, and carbon sequestration that provide public goods beyond the production system.
- Contextual flexibility by allowing governments and local producers to select portfolios of practices suited to their socio-ecological contexts while ensuring compliance with minimum environmental standards.
- Alignment with the Global Biodiversity Framework (GBF) by directly supporting its restoration targets, which call for landscape-scale interventions to recover biodiversity and ecosystem integrity (CBD, 2022).

By conceptualizing *Codex Planetarius* standards in relation to the state of agricultural land systems, there is potential to design implementation zones that integrate governance frameworks (standards and codes), affordable ecosystem and biodiversity metrics, and the technological infrastructures required for monitoring and assurance. A practical challenge is to determine the most appropriate unit of application, whether individual farms, clusters, supply sheds and other aggregation points, political jurisdictions, or alternative geographical units, so that standards are both operational and linkable to trade. This issue will be explored further in section 3.

2 Designing Metrics for Agricultural Performance Standards

Metrics are the operational backbone of standards. They define how principles and thresholds are measured, making qualities of production systems visible, comparable, and governable across diverse landscapes and supply chains. In environmental governance, the choice and design of metrics profoundly influence the type of standards that emerge and their capacity to deliver ecological outcomes.

It is useful to distinguish three broad categories of metrics, each reflecting distinct ecological reference frames and policy applications. First, physical attribute metrics quantify tangible environmental variables such as carbon stocks or water levels. These underpin carbon markets and several of the proposed *Codex Planetarius* product-level indicators. Second, species and habitat metrics assess the composition and condition of biodiversity. They track the presence and health of specific taxa and habitats and are widely used in conservation planning and offsetting schemes, Third, is a newer class of natural process metrics.

These integrity-oriented metrics evaluate the capacity of ecological systems to function, self-organize, and recover. They support land system governance through the lens of ecosystem condition and functional resilience. They are also designed to operate across multiple scales, from large farms to landscapes, as exemplified by CreditNature's NARIA framework (Jepson et al. 2024), which underpins Scotland's Ecosystem Restoration Code. These natural process metrics form the analytical focus of this paper.

2.1 From Biodiversity Metrics to Ecosystem Condition: A Brief History

2.1.1 Biodiversity Policy and the Challenge of Measurement

During the 1990s, biodiversity emerged as the dominant policy framework for governing the relationship between society, markets, and nature. Its origins can be traced to rising awareness in the 1970s of an impending sixth mass extinction and the associated biodiversity crisis, driven by environmental modification and human population growth (Myers, 1979; Ehrlich & Ehrlich, 1981). The concept of biodiversity reframed species, ecosystems, and genetic material as resources that could be systematically inventoried, managed, and utilized to deliver sustainable development benefits (Hailla & Kouki, 1994). Its ability to bridge the utilitarian imperatives of international policy with the ethical concerns of conservation movements contributed to its widespread adoption in global environmental governance, including its codification in the 1992 Convention on Biological Diversity (Glowka et al., 1994).

In the 1990s and 2000s, new metrics were developed to support advocacy and global biodiversity reporting. These included adaptations of site-based ecological indicators, such as species richness and habitat extent—for tracking regional and global trends. Examples include the Living Planet Index, Red List Index, and Biodiversity Intactness Index (BII) (Scholes & Biggs, 2005). While these metrics support the pressure–state–response model used in environmental reporting, they are difficult to apply at site or supply-area resolution and lack the spatial specificity needed for operational standards or market-based mechanisms.

However, from a measurement perspective, biodiversity has proven challenging to operationalize. Vastly different phenomena are captured depending on the unit and object of measurement, and it is difficult to disentangle scales and criteria when assessing biodiversity across genes, species, and ecosystems (Magurran, 2021). A generation on, there is still no international agreement on how to define, measure, and report biodiversity. The diversity of available metrics often creates confusion, and many remain costly or impractical to implement at scale.

2.1.2 Essential Biodiversity Variables and the Ecosystem Services Turn

In the 2010s, the concept of Essential Biodiversity Variables (EBVs) emerged through the work of GEO BON and the CBD. EBVs aimed to bridge local field data and global indicators by identifying a minimal set of variables, such as species populations, ecosystem structure, and community composition, that could support multi-scale monitoring. This framework was designed to improve alignment with targets such as the Aichi Biodiversity Targets and later the Kunming-Montreal Global Biodiversity Framework.

In parallel, The Economics of Ecosystems and Biodiversity (TEEB) initiative reframed biodiversity as a form of natural capital underpinning the delivery of ecosystem services (Sukhdev et al., 2010). It promoted economic valuation as a way to integrate nature into decision-making. This framing has influenced national accounting systems, corporate sustainability strategies, and mechanisms such as payments for ecosystem services (PES) (Guerry et al., 2015).

However, the relationship between biodiversity and ecosystem services is complex and context dependent. TEEB's framing implied a direct link between them, but evidence suggests that biodiversity–function relationships are often non-linear, and ecosystem services can persist in simplified or degraded systems (Cardinale et al., 2012; Balvanera et al., 2006). As with biodiversity metrics, ecosystem service quantification also faces methodological challenges, particularly for regulating and cultural services, where valuation methods are often uncertain and culturally biased (Costanza et al., 2017).

2.1.3 From Biodiversity to Ecosystem Condition

In response to these challenges, the United Nations Statistics Division led the development of the System of Environmental-Economic Accounting – Ecosystem Accounting (SEEA EA), published in 2021 (United Nations, 2021). Developed over two decades of collaboration among statisticians, ecologists, economists, and policymakers, the SEEA EA provides a globally agreed scientific and statistical framework for defining, measuring, and tracking the ecological condition of ecosystems.

SEEA EA represents a significant conceptual shift. Rather than using biodiversity or ecosystem services as the primary units of analysis, it centers on ecosystem condition, defined as "the overall quality of an ecosystem as measured by its abiotic and biotic characteristics." This framing treats condition as a foundational system state from which both biodiversity and services emerge. It offers a bridge between Goal A of the Kunming-Montreal Global Biodiversity Framework (restoring and conserving ecosystem integrity) and Goal B (sustainable use and equitable sharing of biodiversity benefits) (CBD, 2022).

2.1.4 Condition-Based Metrics for Markets and Standards

Since 2020, the prospect of nature markets has driven the emergence of new biodiversity and ecosystem metrics designed to quantify ecological uplift not just for monitoring, but as tradable units. These include CreditNature's Ecosystem Condition Index (ECI) and the Wallacea Trust's biodiversity credit methodology. These approaches mark a shift from observational and advocacy metrics to market-grade accounting tools built for standardization, verification, and scalability. They combine structural, functional, and landscape-scale indicators to support crediting and reporting schemes.

At the same time, advances in ecosystem science have deepened understanding of biodiversity as an emergent property of ecological systems, arising from dynamic interactions among organisms, and between biotic and abiotic processes (Levin, 1998; Cadotte et al., 2011). This view underpins recent policy emphasis on ecosystem recovery as a means to secure both biodiversity and ecosystem services.

Yet the links between biodiversity and function remain highly context-dependent and non-linear (Hector & Bagchi, R., 2007; Cardinale et al., 2012; Tscharntke et al., 2012,) and this limits the suitability of species-based indicators for regulatory or market use. In contrast, ecosystem condition metrics, grounded in systems thinking and structured for spatial and functional comparability, offer the prospect of a more robust basis for performance standards in ecosystem recovery and agriculture, where regulatory enforceability and outcome-orientation are essential. This logic underpins the SEEA EA framework and its operationalization in the NARIA framework (Jepson, et. al., 2024).

2.2 NARIA Framework and Ecosystem Condition Index

Frameworks such as NARIA were originally developed to enable investment in ecosystem recovery through nature credit mechanisms and debt instruments linked to improvements in ecological condition. Their relevance, however, extends beyond nature finance. NARIA offers a structured, systems-based approach to representing and quantifying ecological change in ways that are credible, scalable, and suitable for both regulatory and market applications.

Crucially, such frameworks function as an infrastructural interface: a mediating layer that connects the complex, context-specific realities of socio-ecological systems with the abstraction, standardization, and verification requirements of environmental crediting and performance-based governance. In this role, they provide both a conceptual and operational bridge between ecological complexity and the institutional architecture required to deliver robust environmental standards for agriculture.

This shift toward quantification-based governance is evident in the broader evolution of standards. Certification schemes such as the Forest Stewardship Council (FSC) construct zones of 'qualification' by assessing whether a production system meets predefined thresholds, resulting in pass/fail judgments. By contrast, nature finance mechanisms, and increasingly *Codex*-style product standards, rely on quantification. Metrics enable performance to be measured, valued, and translated into reporting or crediting instruments. In this context, they establish 'zones of quantification', bridging the dynamic realities of ecosystems with the structured requirements of institutional governance. This orientation underpins the case for ecosystem condition metrics as the basis for future minimum agricultural standards.

2.2.1 Conceptual Architecture of the NARIA Framework

The NARIA framework conceptualizes land as a governed asset: a form of real estate that humans engineer to varying degrees to generate value for themselves and wider society. This lens emphasizes that land management is a form of ecosystem engineering. It directly influences ecological integrity, which in turn determines the quality and quantity of ecosystem services and co-benefits valued by economies and communities.

NARIA translates this conceptualization into a three-component analytical architecture (Fig. 1, next page). At its core is an assessment of ecosystem integrity, expressed through an Ecosystem Condition Index (ECI). Interacting with this is an Ecological Land Management Rating (ELMR), which evaluates the quality of land management practices. A third strand comprises ecosystem service metrics, which can be reported individually or aggregated, providing a link between ecological condition and the services that underpin human well-being. Together, these analytics provide complementary and non-redundant perspectives on the relationship between land management, ecosystem integrity, and service provision.

Figure 1: NARIA conceptualisation of natural assets and Ecosystem Condition Index architecture (from Jepson et al, 2024)
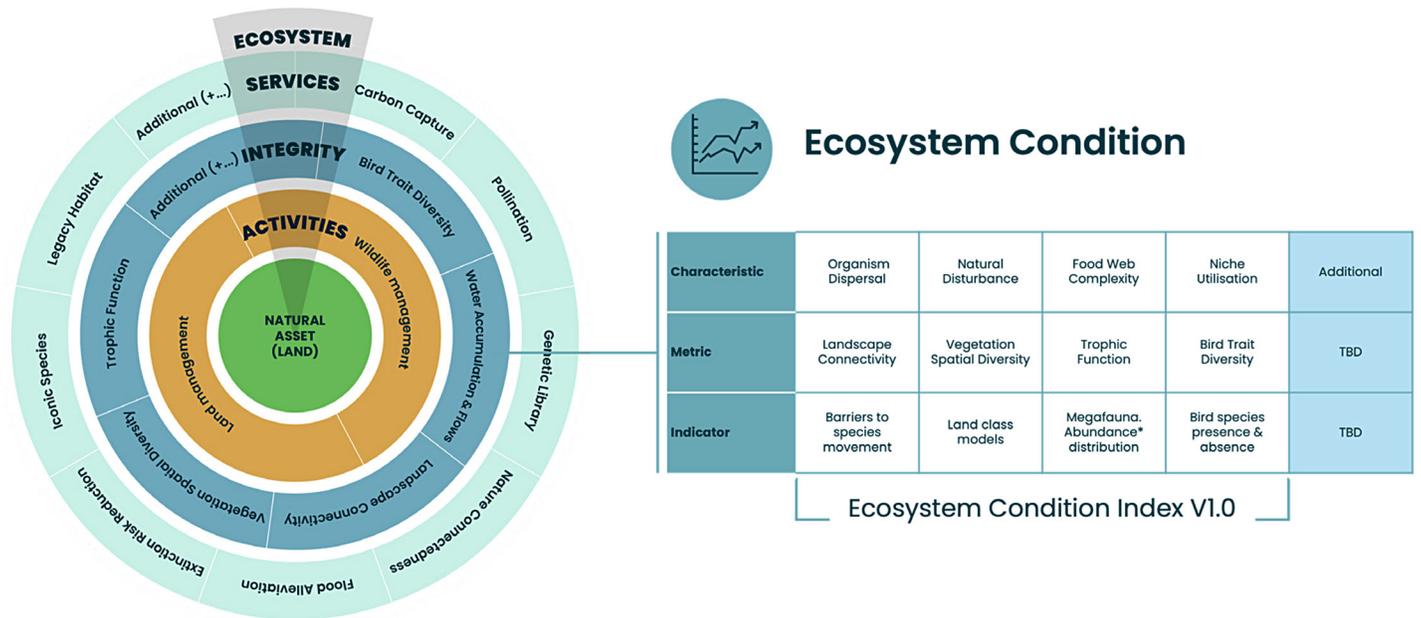
The core analytic measures the condition of ecosystem integrity. Its architecture reflects and extends the UN System of Environmental-Economic Accounting for Ecosystem Accounting (SEEA-EA) three-tier framework for condition accounting, further elaborated by Czucz et al. (2021). The three tiers represent a structured process for metric development. The first step is to identify the most important ecosystem characteristics, ensuring that selected metrics capture essential dimensions of ecosystem integrity. The second step involves selecting indicators that meaningfully represent these characteristics. The third step assesses the data availability and scientific robustness of the measurement approaches for each indicator. In practice, insights from one tier often prompt revisions in another, for example, data limitations may lead to the selection of alternative indicators, or the specification of ecosystem characteristics may evolve through indicator testing. This structured, iterative process enables the development of condition metrics that are both scientifically credible and operationally feasible.

2.2.2 Natural Processes as Key Ecosystem Characteristics

The NARIA-ECI specifies natural processes as key ecosystem characteristics. These processes are increasingly recognized in science and policy as foundational to ecosystem resilience and functionality. Harnessing them to address environmental and societal challenges is central to nature-based solutions (NBS) frameworks (Cohen-Shacham et al., 2016) and aligns with the SEEA-EA definition of ecosystem characteristics, which cites natural processes as integral to ecosystem condition and function (United Nations, 2021). Building on these concepts, the NARIA-ECI adopts a process-oriented approach to quantifying ecosystem integrity (Jepson et al., 2024).

In systems ecology, natural processes are conceived as flows and exchanges of energy, materials, and organisms. These processes interact to sustain broader ecosystem functions, which in turn underpin structure, dynamics, and resilience (Odum, 1983; Jørgensen et al., 2007). Natural processes encompass a wide range of interactions, such as primary production, nutrient cycling, pollination, and predator–prey dynamics.

The NARIA-ECI design process identifies functional natural processes (FNPs), defined as packages of basic processes that interact to create emergent properties operating at large spatial and temporal scales. FNPs sustain and structure ecosystems, supporting their capacity to evolve, adapt, and recover (de Groot et al., 2010). The NARIA-ECI incorporates three FNPs identified by Perino et al. (2019) as key levers for ecosystem restoration and sustainable land management: stochastic disturbance (e.g., fire, flooding), dispersal (of genes, species, and propagules), and trophic cascades. Historically, these processes shaped the evolution of modern ecosystems during the Pleistocene (Svenning et al., 2016; Jepson & Blythe, 2020, Inostroza et. al., 2020).

By framing natural processes in this way, the NARIA-ECI can be extended beyond rewilding and conservation contexts to agricultural systems. Here, maintaining, restoring, or mimicking key functional natural processes (e.g., water retention, pollination, decomposition) can help sustain minimum levels of ecosystem integrity This, in turn, supports agricultural system resilience, enhances biodiversity conservation at landscape and regional scales, and underpins human well-being and environmental habitability (Foley et al., 2005).

A Simplified Scheme of Ecosystem Components and Dynamics

Ecosystems are dynamic systems where energy, materials, and organisms interact across scales to sustain structure and function.

- **Processes** describe the fundamental flows and transformations (e.g., photosynthesis, decomposition)

- **Functions** emerge from the integration of processes and maintain system performance (e.g., nutrient cycling, hydrological regulation)

- **Actants** (such as functional species) play key roles in driving and modulating processes and functions

- **Emergent properties** (e.g., biodiversity, resilience) arise from these dynamic interactions and underpin ecosystem integrity

- **Ecosystem services** are the benefits humans derive from the functioning and integrity of ecosystems

Feedback loops link processes, functions, actants, and emergent properties creating adaptive and sometimes non-linear system behaviors.

Ecosystem Integrity vs. Ecosystem Condition

Ecosystem integrity refers to the overall health, functionality, and resilience of an ecosystem – its capacity to maintain its characteristic composition, structure, and processes over time, and to adapt to environmental changes.

Ecosystem condition, by contrast, describes the current state of an ecosystem, assessed through specified biological, physical, and chemical attributes. In ecosystem accounting, we quantify and track ecosystem condition to evaluate the state of – and changes in – ecosystem integrity over time.

Measured improvements in ecosystem condition can underpin financial instruments such as nature credits and investment KPIs. Similarly, threshold scores on an ecosystem condition index could provide a robust basis for establishing minimum agricultural production standards.

2.2.3 Principles for Ecosystem Condition Metrics Design

Building on the index architecture described above, the development, piloting, and accreditation of the NARIA Ecosystem Condition Index (ECI) revealed a set of foundational principles for indicator design. These principles provide the normative and technical scaffolding for constructing ecosystem condition metrics that are scientifically robust, ecologically meaningful, and operationally feasible.

The principles, listed in Table 1, serve to guide and assure the development of metrics that meet international environmental accounting standards. In NARIA, they enabled the creation of "finance-grade" metrics suitable for asset valuation, credit issuance, and condition-based key performance indicators. However, they offer a transferable foundation for designing robust, scalable metrics capable of supporting the implementation of future *Codex Planetarius* environmental performance standards, where global comparability and regulatory credibility will be essential.

Table 1. Standard-related nature metric design principles (adapted and extended from Czucz et al , 2021)

Principle	Descriptor	Principle	Descriptor
Scientifically rigorous	Based on sound ecological science and indicator methods	**Governable**	Subject to oversight and governance to maintain integrity
Holistic	Capture ecological complexity and emergent system properties	**Auditable and Transparent**	Derivation and data sources are fully traceable and verifiable
Quantifiable	Provide auditable, consistent, and relevant quantities	**Timely**	Delivered in line with market and decision-making cycles
Scalable	Can be applied consistently from site to landscape to jurisdiction scales	**Timely**	Delivered in line with market and decision-making cycles
Comparable	Enable meaningful comparisons across geographies and contexts	**Aggregative**	Can combine with other domains for co-benefit analysis
Future-proofed	Able to evolve with advances in science and technology	**Integrative**	Data integrates meaningfully with other datasets for rigor
Affordable & Cost-effective	Deliver value relative to cost and support broad participation	**Usable & Communicable**	Outputs are meaningful, clear, and decision-maker friendly

2.2.4 The Importance of Ontologies

A critical but often overlooked aspect of metric design is the integration of ontologies: formal structures that define how different ecological entities and processes are related. Raw environmental data, whether from field surveys, remote sensing, or automated sensors, are often "meaning-neutral," describing physical or biological properties without inherent ecological interpretation. Ontologies are the hidden logic of credible metrics. They provide the conceptual scaffolding that translates such data into ecologically meaningful attributes, ensuring that indicators capture the ecosystem characteristic of interest rather than isolated measurements.

For example, CreditNature's trophic function metric includes an ontology that links the traits and behaviors of large herbivore species to their ecological role in maintaining trophic cascades. This structured representation allows data on animal groups to be interpreted consistently as evidence of a broader functional natural process.

By embedding ontologies in this way, ecosystem condition metrics move beyond technically valid but narrow measurements toward indicators that are scientifically robust, policy-relevant, and consistent with the UN SEEA-EA framework. For *Codex*, ontologies ensure that condition metrics are interpretable across different production systems and geographies, providing the comparability and transparency needed for minimum agricultural standards.

2.2.5 The Need for Normalization

To meet the principles of quantification and comparability (Table 1), ecosystem condition metrics must be transformed from their original units into a common normative scale (typically 0 to 100) anchored to reference data. A widely used approach is to define the maximum value (100) using a reference site deemed to be in a "natural" or undisturbed state. However, such natural baselines are invariably cultural constructs, often tied to historically contingent dates such as the pre-industrial landscape of ~1850 in Europe or the period prior to the arrival of Christopher Columbus in the Americas in 1492. It is now widely recognized that significant ecological simplification and degradation had already occurred by these dates. As a result, basing normalization on such reference conditions risks entrenching a legacy of ecological loss, a phenomenon known as the shifting baseline syndrome (Soga & Gaston, 2018).

To address this limitation, the NARIA framework developed an attainable maximum approach in which the upper bound of the metric is defined in ways that reflect ecological limits and recovery potential rather than historically contingent states. This method supports a rewilding-aligned perspective that emphasizes ecosystem self-organization and recovery under changing climatic and environmental conditions. Options for setting attainable maxima are described in Jepson et al. (2024).

For *Codex*, normalization methods of this kind are essential to ensure that condition metrics provide credible, comparable signals across different agricultural systems and geographies, while avoiding the entrenchment of degraded baselines.

2.2.6 Aggregation into Composite Indices

The normalization process enables structured aggregation of metrics into composite indices (or sub-indices). The NARIA-ECI adopts a composite 'jigsaw' of metrics approach, in which metrics representing ecosystem characteristics are selected and designed to interact, providing a holistic, multi-characteristic measurement of ecosystem condition. This contrasts with the 'basket of metrics' approach used in many biodiversity metrics, where separate metrics, often species- or attribute-based indicators, are aggregated as complementary representations of change rather than as an integrated measure of system state.

The 'jigsaw' of metric approach could be particularly beneficial in meeting *Codex Planetarius* goals of demonstrating continuous improvement against established baselines and monitoring cumulative impacts to understand overall carrying capacity and planetary boundaries (Clay, 2016). For example, countries could set a minimum threshold score (e.g., 25/100) for each commodity and/or land system, with producers' progress towards or beyond this threshold evaluated over time. Each point on the scale represents a constant unit of ecological change within an ecosystem type, although the ecological meaning of a "five-point improvement" may differ between ecosystems.

Expressing diverse ecological attributes on a shared 0–100 scale also facilitates benchmarking, target-setting, and communication across sectors. By placing complex ecological data into a common reference frame, composite indices enable farmers, policymakers, and investors to evaluate land management strategies against shared sustainability criteria. This provides *Codex* with a transparent and practical means of linking agricultural performance to global ecological goals.

2.3 Industrial Agroecosystems as the Focus for *Codex Planetarius* Standards

The preceding sections have foregrounded the foundational role of functional natural processes in generating biodiverse and resilient land systems that support a range of ecosystem services. Agricultural systems are widely considered the single largest driver of planetary boundary transgressions (Rockström et al., 2023). If the goal of *Codex Planetarius* is to steer humanity back into a safe operating space and restore planetary health through agricultural standards, then the structure and financing of food production systems must be brought into focus.

Agro-industrial landscapes represent the most ecologically impactful and economically significant zone of production within the global food system. These systems are engineered for high yield and financial return, and are characterized by ecological simplification, intensive external inputs, and technological substitution for natural processes (Clapp & Isakson, 2018; Weiss et al., 2023). In temperate regions, they have largely displaced traditional small-scale or mixed farming systems, while in tropical regions they have replaced extensive areas of natural, often mega-diverse ecosystems (Foley et al., 2005). Their expansion, nearly threefold since 1960, has been enabled by a global infrastructure of agro-input transnational corporations (TNCs), commodity traders, institutional investors, and public subsidies.

Given their scale, environmental impact, and role in international markets, agro-industrial systems will likely be a primary target for *Codex Planetarius* environmental performance standards. This section offers a conceptual framing of such systems from a systems ecology perspective, highlighting their structural simplifications and key ecological characteristics. It lays the groundwork for Part II of the paper, which assesses the feasibility of adapting the NARIA ecosystem condition approach to agro-industrial contexts—including challenges related to data, metrics, and assurance.

2.3.1 Systems Ecology Characterization of Industrial Agricultural Systems

Industrial agroecosystems dominate global food production. Characterized by large-scale monocultures and high external inputs, they have enabled major gains in calorie supply but at the cost of significant ecosystem degradation, resource depletion, and greenhouse gas emissions (Fuglie, 2024; IPES-Food, 2022). From a systems ecology perspective, such systems are best understood as non-ecological land systems. Unlike natural or traditional agroecosystems, which are structured by solar energy flows and natural feedback processes, industrial systems substitute these with fossil-fuel-derived energy, chemical inputs, and mechanized infrastructure. They are simplified, high-entropy ecosystems that require constant external inputs because internal feedbacks have been disrupted.

Many of these non-ecological land systems now extend over continental scales and their integration into global supply chains make them central to *Codex*, since any system of minimum environmental standards must apply credibly to these production models. At the same time, standards must be designed for global applicability, including smallholder and rural systems where production

contexts are very different. Ecosystem condition metrics provide a common basis for bridging these contexts. By focusing on underlying ecological processes rather than specific practices or commodities, they allow environmental performance to be assessed in a way that is both comparable across geographies and adaptable to local realities.

2.3.2 Specification of *Codex Planetarius* Impact Areas as Natural Processes

To test the feasibility of applying a functional natural processes approach, a preliminary mapping of *Codex Planetarius* impact areas onto representative natural processes was conducted. This specification was guided by five criteria: (i) ecological validity, (ii) relevance to agricultural management practices, (iii) potential to act as proxies for ecosystem integrity, (iv) feasibility of quantification, and (v) coverage of multiple process types to support a holistic "jigsaw metrics" approach.

The outcome of this mapping is presented in Table 2 and should be viewed as an illustrative feasibility exercise rather than a prescriptive list. It is important to note that the natural process of dispersal (i.e. the movement of organisms through space and time), along with two production-oriented processes, pollination and pest regulation (Kleijn et al., 2019), are only implicitly represented in this rapid exercise rather than explicitly specified.

Were *Codex Planetarius* to formally adopt this approach, a structured process of expert elicitation and validation would be required to agree on a scientifically robust suite of natural processes. This would likely include subsets tailored to reflect i)the functional natural processes of reference ecosystems in a given ecoregion, ii) the minimum ecological functionality appropriate to different types of industrialized agri-systems, and iii) the pragmatic reality that agro-ecosystems will always be novel systems. In this context, some stakeholders may emphasize inclusion of FNPs directly linked to ecosystem services that provide tangible benefits to agricultural production.

In parallel, the Food System Countdown to 2030 Initiative (FSCI) has developed a complementary framework of food system indicators, including six environment-related domains (Schneider et al., 2023). Their emphasis is on monitoring anthropogenic input–output stressors, whereas the approach proposed here focuses on the internal dynamics of natural processes and ecosystem condition. The two perspectives align in domains such as biosphere integrity and water and carbon cycling, but diverge in others. Future integration of these approaches could strengthen minimum agricultural standards by linking reductions in external stressors with the restoration of core ecosystem functionality.

Table 2. Illustrative translation of CP impact areas into Functional Natural Process equivalents

CP impact area	Functional natural process	Why this process?	How agricultural practices impact this process
Biodiversity loss	Trophic cascades	Regulates species composition and interactions; large functional species maintain food web complexity	Simplification of food webs (e.g., predator removal, monocultures) disrupts cascades
Habitat conversion/ loss	Plant community diversification	Vegetation succession and heterogeneity create structurally rich habitats supporting primary/secondary consumers	Monocultures and tillage simplify plant communities
Soil Health	Soil transformations and flows	Biotic and abiotic processes (decomposition, nutrient cycling) sustain soil fertility and structure	Plowing and chemical inputs disrupt soil biota
Water take quantity	Water retention and infiltration	Ecosystem capacity to capture, store, and infiltrate water, reducing runoff and supporting hydrological balance	Compaction and drainage reduce infiltration
Water effluent quality	Water filtering and detoxification	Wetlands and soils trap and neutralize pollutants through physical, chemical, and microbial processes	Excessive fertilizers/pesticides overwhelm filters
GHG emissions	Carbon fixation and biotic respiration	Ecosystem processes sequester carbon (photosynthesis) and regulate respiration-related CO_2 release	Tillage and peat drainage increase emissions
Agrochemical toxicity	Detoxification processes	Organismal pathways for metabolizing toxins; disrupted when agricultural inputs overwhelm natural systems	Herbicides and pesticides overload detoxification

2.3.3 A Typology-Based Tool for Applying an Ecological 'Floor' in Industrial Systems

Establishing a minimum threshold for ecosystem condition is a central challenge in applying a natural-process approach to agricultural performance standards. Within the NARIA framework, this challenge is addressed by linking an Ecological Management Rating (EMR) with the Ecosystem Condition Index (ECI) to bridge land management structures and ecological outcomes.

At the core of the EMR is a land asset typology derived from a structured classification of value-generating practices (VGPs): bundled land management activities designed to maximize either economic or ecological value from a given land asset. Each landholding (asset) is characterized by the specific combination of VGPs it implements (Jepson et al., 2017). The ecological implications of these practices are evaluated against functional natural processes (FNPs) represented in the ECI. The results are expressed as an A–G ecological land management rating, analogous to energy-efficiency labels used in consumer products.

While the EMR reflects management intent and structural potential, the ECI independently quantifies ecosystem condition based on observed data. Together, the two measures create a feedback loop: management choices influence ecological condition, and observed changes in condition inform the refinement of ecological "floors," or minimum thresholds required for credit issuance. This structure supports continual improvement, allowing both practices and performance expectations to evolve over time.

In the context of *Codex Planetarius*, the EMR–ECI framework provides a means of setting stratified expectations for environmental performance. Thresholds can be tailored to specific land systems and raised incrementally over time, analogous to benchmarking approaches in corporate sustainability. This offers a performance-based pathway, not a prescriptive practice standard, and enables *Codex* to advance minimum standards while allowing for contextual flexibility.

Industrial agricultural systems, by design, are highly standardized. Their efficiency depends on the consistent application of predefined VGPs, enabling vertical integration, automation, and coordinated input sourcing. This structural regularity allows for the compilation of standardized VGP typologies for major production systems. These typologies offer a practical entry point for applying EMR logic within *Codex Planetarius* standards, enabling credible ecological floors to be set, tracked, and verified across complex but repeatable land system architectures.

3 Implementation Feasibility: Navigating the Three Horizons

The previous section set out the conceptual rationale for using ecosystem condition as the basis for minimum agricultural standards. This section shifts from concept to practice. Drawing on our piloting of NARIA metrics, it explores the practical realities of biodiversity monitoring as they exist today, the challenges of moving toward scalable solutions, and the system infrastructure that is already visible on the horizon.

This section applies the Three Horizons model (Sharpe et al., 2016), a foresight framework that distinguishes between current systems, transitional innovations, and emerging futures, as a way of structuring these insights. Horizon 1 represents current practice: consultancy-style surveys, specialist taxon monitoring, fragmented datasets, and escalating costs. This logic remains entrenched across much of the sector. Horizon 2 is the transition zone where pilots, pioneer applications and innovations attempt to break from Horizon 1. Here, IoT sensors, metric adaptation, and new data protocols are being tested, but costs, institutional resistance, and technical gaps make progress uneven. Horizon 3 is the solution space: an emerging system infrastructure based on modular sensors with edge AI, integrated data-provider platforms, and public–private assurance systems.

The contours of Horizon 3 were visible 5-10 years ago, and a MVP (minimum viable product) is nearing completion in Scotland. This offers a blueprint for a digital infrastructure to enable scalable, cost efficient, and auditable minimum environmental standards for agriculture. In addition, it provides the 'upward' data source parameters to refine and develop ecosystem metrics and to model the cost of monitoring and assuring standard compliance.

Our early applications and pilots, and the following case study accounts, are located in Horizon 2, the transitional pathway between Horizon 1 and 3. They show how Horizon 1 practice continually pulls the field back into costly and piecemeal modes and foreground the vital importance of an authoritative sponsoring agency with the willingness to resist this. Working in Horizon 2 has brought into

focus the limitations of Horizon 1, while also demonstrating the kinds of trade-offs, adaptations, and institutional conditions that will be needed to enable a transition to Horizon 3. These lessons are distilled under two case studies and a series of headings, beginning with the cost and scalability constraints that define feasibility, before examining data capture and ownership, technical trade-offs, and institutional contexts. In practice the topics of each heading intertwine, but they help chart a pathway from fragmented current practice toward the simple yet robust compliance numbers *Codex* will require. The section concludes with a tentative design for an 'aggressively simple' single metric of ecosystem condition based on the near-ready Horizon 3 technology system outlined below.

3.1 Horizon 3: The Emerging Data Infrastructure Future

Horizon 3 is best understood as a layered end-to-end infrastructure for biodiversity monitoring and ecosystem accounting. At its core is the metric-calculation and assurance platform, through which a standard or code is operationalized. This layer is supported by data-provider platforms and services that supply ecological information at different scales. Together, they create a system that can deliver agricultural standards at scale, cost-effectively, and with strong safeguards for data privacy.

Metric-Calculation and Assurance Platform. The CreditNature Platform, developed under the Scottish Government's CivTech innovation procurement and subsequently procured as a service, exemplifies this layer. It operationalizes the requirements of a standard (i.e., the draft Scottish Ecosystem Recovery Code) by providing i) user interfaces for landowners, data providers, investors, and regulators, ii) standardized protocols for uploading land management and field data, and iii) APIs that connect directly to Earth Observation and bioacoustic data providers. It calculates metrics such as the Ecosystem Condition Index (ECI) and Ecological Land Management Rating (ELMR), converts these into ecosystem accounting units, and issues digital credits and performance indicators on a distributed ledger. At the same time, it functions as an assurance platform, embedding digital trust chains that verify every step of data ingestion, processing, and credit issuance, with both automated and human oversight. It enables aggregation across landholdings, automatic compliance audits, and transparent 'touch of a button' engagement for auditors, regulators, and markets.

Bioacoustic Data-Provider Platform. Soprano, being developed by Edinburgh University and funded through the UK Natural Environment Research Council's Innovation in Environmental Monitoring program, represents the next frontier of data-provider platforms. It combines modular acoustic sensors, edge AI, and robotic deployment with a local mesh radio network that links devices across a site and connects them to the internet via uplink gateways. The platform manages classifiers on the devices, coordinates deployment and updating, and ensures data is processed and transferred in standardized formats. By automating bioacoustic and other field-level monitoring, Soprano addresses the cost and capacity constraints of human surveyors, providing a scalable source of fine-grained ecological signals.

Earth Observation (EO) Service Providers. EO providers, such as Planet and other specialist firms, already offer authoritative datasets on land cover, vegetation dynamics, soil condition, and hydrological change. These services form an established backbone of spatial data that can be integrated directly into ecosystem condition metrics via the assurance platform.

Both the CreditNature and Soprano platforms are designed with data quality, security and privacy as core features. Raw data remains with landholders, while processed and verified outputs are stored for audit and transparency. The platforms themselves are validated against the standards they enable, the metrics are independently accredited under UN-SEEA compliant procedures, and the coding is accredited against relevant digital standards.

Together, these infrastructures characterize Horizon 3 as a near fully operational system in which EO service providers supply broad-scale spatial data, bioacoustic and sensor networks add fine-grained ecological signals, and the Metric calculation & assurance integrates these inputs into trusted accounting units and digital credits. This layered architecture represents a credible pathway for delivering future agricultural standards at global scale, with the efficiency, affordability, audibility, and legitimacy that *Codex* will require.

3.2 Pilot Case Studies: Illustrating the Horizon 2 Transition Pathway

The following case studies illustrate the practicalities of applying an Ecosystem Condition Index in two very different contexts. They are simultaneously pioneering applications and pilots of the NARIA framework that illustrate insights into the feasibility, trade-offs, costs, and institutional requirements of moving beyond consultancy-based monitoring towards digital infrastructure. Each case shows how context drives metric refinement and shapes approaches to data capture, while also highlighting how principles of ecosystem accounting can be applied under contrasting conditions. Taken together, they demonstrate how early applications can build momentum along the Horizon 2 pathway.

3.2.1 Pentland Hills, Scotland Case Study

Overview

The Pentland Hills, southwest of Edinburgh, are a patchwork of upland pastures, moorland, and forestry traditionally managed for sheep, cattle, and grouse. Declining farm margins and changing public values have triggered land-use transitions, particularly expansion of softwood plantations, that risk diminishing ecological condition and visual amenity. In response, five farmers (managing c. 3,000 ha) formed a company and secured £100,000 of public innovation funding to pilot the Scottish Ecosystem Recovery Code. They are applying the NARIA Ecosystem Condition Index (ECI) to baseline and monitor ecosystem health, while testing whether credits from biodiversity, carbon, and recreational access could provide new revenue streams.

This was the first full test of the NARIA-ECI in an active agricultural landscape and the first time all four metrics were applied at farm-cluster scale. It offered a proving ground for evaluating data collection feasibility, metric interpretation, and transitions from consultancy-based to platform-based monitoring.

Metrics Applied

1. **Landscape Connectivity (LC).** This metric evaluates how easily animals can move across a landscape, based on structural barriers. Farmers already map fences and land parcels for subsidy systems, so data could be annotated with barrier types and permeability conditions. However, the original LC metric, based on "effective mesh size", was designed for rewilding contexts and proved misaligned with livestock systems where fencing is essential. A key insight was the need for a version of LC based on land-cover permeability rather than fencing density. While this approach is more compatible with Earth Observation, it requires scoring habitat types for species movement.

2. **Vegetation Spatial Diversity (VSD).** This metric captures the spatial complexity and diversity of vegetation, rewarding mosaic patterns that support ecological function. In the UK, habitat data is organized using a four-level classification system, but EO platforms cannot reliably distinguish between the finer levels (L3 vs. L4) without ground-truthing. The pilot considered co-developing an automated VSD product with a satellite analytics firm but ultimately commissioned a consultant habitat map to ensure alignment with national standards. This provided robust baseline data but missed an opportunity to build scalable EO workflows specific to the VSD metric.

3. **Trophic Function (TF).** This metric estimates the ecological effects of large herbivore guilds (e.g., deer, cattle, ponies). In the Pentlands, livestock data were readily available from farmers. However, estimating wild deer numbers, especially solitary species like roe deer, is challenging. Local academic advice favored precise counts using vantage point surveys but this reflected a wildlife management tradition focused on establish cull quotas. After clarifying the metric was intended to capture changes rather than numbers a useful future refinement to the TF ontology emerged that could reduce the need for burdensome animal population assessments.

4. **Bird Trait Diversity (BTD).** BTD tracks seasonal variation in bird functional traits, based on confirmed presence and absence. In the Pentlands, this metric was deployed alongside Soprano passive acoustic sensors, enabling a side-by-side trial of human and AI survey methods.

Bird survey tenders came in at ~£80,000, driven by compliance-oriented pricing. Instead, the project is piloting a citizen science approach using route-mapped surveys and a birder competence self-verification tool. Birder recruitment revealed many hobby birders lacked the time or fitness for upland surveys, and land owners were wary about publicity or regulatory exposure. Nonetheless a breakthrough came with the realization that sequential-list bird survey method was also being trialed for acoustic analysis, opening up new hybrid survey models in which verified birders help calibrate and validate bioacoustic outputs.

Partnership and Process Dynamics

- The pilot highlighted the importance of farmer trust, especially in relation to access, data sharing, and fears of "being told what to do."

- Engagement with local academics was productive but required clearer communication of metric purposes to avoid misapplied survey logic.

- Public procurement frameworks constrained options for agile innovation, particularly around co-developing scalable EO solutions.

Key Takeaways for *Codex*

1. Metric design needs a degree of flexibility. In working landscapes, metric data needs must be responsive to land-use realities and survey practicalities.

2. Human-AI hybrid monitoring shows promise. Combining acoustic sensors with verified birders may offer a credible, cost-effective pathway for scaling biodiversity metrics.

3. EO-based monitoring requires co-development. Buying consultant habitat maps provides compliance but not scalability. *Codex* systems will need to enable partnerships with EO providers to create metric-specific, reusable products.

4. Trust and framing matter. Farmers and local actors must see the metrics as tools for empowerment, not surveillance.

3.2.2 Kilimanjaro Ecosystem Restoration Initiative (KERI) Case Study

Overview
The southern slopes of Mount Kilimanjaro in Tanzania form a diverse and climate-sensitive landscape of savannah, montane forest, and mixed farming systems. These mosaics, long stewarded by Chagga communities through agroforestry are now increasingly vulnerable to the interlinked pressures of expanding agriculture, declining rainfall, soil erosion, and degradation of native vegetation. In response, a long-term collaborative effort, the Kilimanjaro Ecosystem Restoration Initiative (KERI) was launched to restore ecological function and strengthen the resilience of local livelihoods and water systems.

KERI brings together indigenous Chagga landholders, Tanzanian research institutions, national agencies such as the Tanzania Forest Service, local project developers, and international partners. The coalition is focused on enhancing tree cover, soil stability, and hydrological function across the region. To support scalable, measurable, and investable ecological restoration, the Initiative is piloting the NARIA Ecosystem Condition Index (ECI) as a unifying framework for assessing baseline ecosystem condition and tracking the effectiveness of interventions over time.

Unlike the Pentlands case, which focused on data collection trade-offs and metric calibration in a UK context, Kilimanjaro illustrates how process innovation, especially around local legitimacy, ontological translation, and governance alignment is central to embedding ecological metrics in socio-ecologically complex landscapes.

Metrics Applied
The core NARIA Ecosystem Condition Index (ECI) architecture of four Functional Natural Processes (FNPs) and metrics developed for European ecoregions translated well to a tropical African setting. Its core logic (functional ecosystem thinking, simplicity, and modularity) were quickly grasped by KERI partner agencies.

A South African ecology consultancy and restoration contractor, who had previously worked with a neighboring Sugar-Cane plantation, worked effectively with CreditNature analysts to adapt metrics.

Key adaptations included:

- **Typology localization:** Habitat types and land systems were classified using local terminology and vegetation forms.
- **Species-level adjustments:** Indicator species were replaced or expanded based on local ecological knowledge, with bird and mammal indicators sourced from locally relevant checklists.
- **Data method substitution:** Where Earth Observation or acoustic data were unavailable or prohibitively expensive, structured observation and participatory monitoring were introduced.
- **Platform constraints:** Some survey intervals and seasonal windows were adjusted due to different climatic and ecological rhythms compared to temperate regions.

Despite these changes, the core metric design (based on functional traits and process benchmarks) remained intact, affirming its scientific robustness across biogeographies.

Translating the Framework: Local Legitimacy and Ontological Fit
A key insight from the Kilimanjaro case is that data quality and cost is closely linked to process legitimacy. Ensuring that ecological metrics were understood, adapted and implemented by local stakeholders is underpinning long-term success.

- African consultants and LERI academic partners played a pivotal role in adapting metric components while preserving fidelity to the framework's original intent.
- Chagga farmers and youth were engaged in sensor deployment, data collection, and field interpretation, providing valuable ecological insights and building community capacity.
- Co-development of ontologies, such as functional trait categories, habitat typologies, and species roles, ensured that the metrics spoke to local realities rather than imposing external classifications.
- Job creation through tasks like battery swapping for acoustic sensors, trail-camera maintenance, and community fieldwork incentivized participation and knowledge-sharing.

This participatory approach countered any perception that the ECI was a colonial or technocratic instrument. Instead, it became a co-owned tool that added structure and scientific depth to existing community-led conservation ambitions.

Partnership Lessons

The enabling role of institutional sponsors is another important feature of the Kilimanjaro case:

- Initial funding and legitimacy were provided by Dalberg, a respected consultancy with community-driven impact credentials.
- Government alignment, including from the Tanzania Forest Service (TFS), was essential to securing permissions and building long-term pathways for integration into national policy and practice.
- Private-sector actors like neighboring sugar-cane company and Corporation Foundation funders brought practical help and innovation finance to the pilot.

These partnerships created the conditions for a Horizon 2 transition, where local adaptation, institutional legitimacy, and field testing converge to move from proof-of-concept to early uptake. Importantly, the process fostered alignment between global standards and local implementation.

***Codex*-Relevant Takeaways**

From the perspective of the *Codex Planetarius* environmental performance standard, the Kilimanjaro case offers four key insights:

1. Standard metric architectures must be globally coherent but locally adaptable. The ECI's FNP structure allowed standardized logic to be expressed through locally adapted ontologies, exemplifying how *Codex*-aligned frameworks can operate across diverse biomes without collapsing into noise or rigidity.

2. Legitimacy derives from embedded processes, not just technical accuracy. *Codex* should consider institutional and cultural alignment as part of what constitutes "minimum environmental performance", especially in community-led or Global South contexts.

3. Hybridized data strategies are essential. Where EO or sensor coverage is limited, community-held data, structured observations, and mixed-method approaches may be necessary to meet standard requirements in a valid and inclusive way.

4. Scaling depends on coalition-building. Adoption of performance standards in complex, climate-sensitive regions will depend as much on process leadership and institutional bridges as on methodological coherence.

3.3 Horizon 2: Practical Insights and Emerging Lessons

Over the past three years, CreditNature has applied its ecosystem condition metric across 15 sites in the UK and Africa. These pioneering applications have contributed directly to the detailed design of Horizon 3 infrastructure, while also exposing the trade-offs, forms of resistance, and enabling conditions that shape what is feasible in practice.

These early applications generated applied insights that inform the technical and institutional architecture of future metric-calculation and assurance platforms. In addition they highlight the constraints and frictions that keep biodiversity monitoring tied to Horizon 1 logics. These include costly surveys, fragmented datasets, and entrenched norms. In doing so, they make visible some of the transitional challenges that *Codex Planetarius* will need to address if Horizon 3 infrastructures are to succeed.

We summarize these lessons under the following headings, with examples to illustrate how they play out in real-world settings and how many are intertwined:

3.3.1 Costs and Scalability

Affordability in the context of nature-led land management, metric implementation, and auditing constitutes a central determinant of nature credit market development, and is likely to prove equally critical for the wider uptake of *Codex* environmental standards. The early NARIA applications revealed that affordability is rarely determined by absolute expenditure; rather, it is evaluated in terms of proportionality and cost–benefit alignment. Specifically, costs are judged according to whether they represent a reasonable fraction of project development outlays required to secure a license to operate, an acceptable deduction from anticipated returns on investment, or a commensurate expenditure relative to the reputational, compliance, and strategic advantages gained through demonstrating sustainability and nature-positive performance, including the avoidance of regulatory penalties.

Traditional biodiversity surveys have typically been undertaken as part of capital expenditure linked to licenses to develop or operate (for example, a mine or solar installation), where their cost forms only a minor proportion of overall project budgets. Carbon credit markets extended this model by introducing a hybrid cost structure: an upfront, capital-style expenditure to establish

baselines and project plans, followed by recurring operational costs associated with land management, periodic monitoring, and third-party verification. In some jurisdictions, such as Scotland, the initial capital component has been partly supported through government grants. The tolerance of these recurring costs is generally assessed relative to anticipated credit revenues, with monitoring and verification expenditures expected to remain within a modest fraction of annualized returns.

The approach developed by CreditNature for nature markets builds upon this carbon-market structure while introducing enhanced transparency and flexibility in cost allocation. Early engagement with landholders highlighted that a change to land management regimes constitutes a major long-term commitment, and this requires assurance that financing from nature credit production would be sustained across the full project vesting period (commonly 10 years). To address this, CreditNature has pioneered mechanisms to modularize principal cost categories such as baseline assessment, land management interventions, monitoring, and verification, and to link disbursements to agreed performance indicators. This distributes expenditure across the crediting period, provides assurance to both landholders and investors, and strengthens governance. For *Codex* purposes, a similar mechanism could be envisaged: for example, a certificate of compliance covering a 10-year period, underpinned by a fully costed and scheduled program of land management, monitoring, and assurance.

Another learning point from this applied work is the value of creating standardized units of cost for land management and monitoring on a per-hectare basis. Contracting of agricultural and conservation work is now commonplace and can be priced using agricultural cost guides. Structuring ecosystem recovery plans into "value-generating practices" (VGPs): packages of activities that maintain, restore, or create land-based natural assets, offers a pathway for building a price book to support consistent costing models. Developing such a typology and price book is a Horizon 2 pathway activity that would allow rapid scaling with the aid of digital tools and standardized contracting practices.

A further challenge concerns the cost of data capture, which remains variable and often high because there is not yet a standardized or efficient system for undertaking it (see Case Studies). This creates risks for future monitoring since costs are difficult to predict and budget with confidence. At present, activities are typically priced under two headings: data capture and platform analytics or service charges. In some cases, capture and processing are bundled together by a single provider (for example, Earth Observation services); in others, capture is undertaken by consultants while processing is carried out separately. Future system design should prioritize clearer modularization and standardization of these functions to improve predictability, efficiency, and affordability.

Section 3.4 outlines a concept for a simple agricultural metric derived from Earth observation and bioacoustic data streams. These are currently the most affordable, scalable, and auditable forms of data available. Earth observation is generally priced on a per-project basis with a per-hectare component. Once habitat segmentation models are trained, our case applications suggest that vegetation diversity metrics can be run for around $75,000-100,000 per million hectares, which demonstrates affordability at scale. Bioacoustic networks are also becoming increasingly cost-effective: a system of 100 sensors might require $50,000-75,000 upfront (at $500-750 per unit) and about $10,000 annually for processing and platform services. These figures are illustrative, but they suggest that within the next three to five years both EO and bioacoustics will be viable for large-scale monitoring, offering an accessible entry point for lower-income contexts alongside a pathway to more advanced digital infrastructures.

3.3.2 Data Capture

Capturing the data needed to calculate ecosystem condition indicators has proven one of the most complex and time-consuming aspects of implementing the NARIA ECI in practice. While the ECI benefits from accreditation under the Accounting-for-Nature method standard (AfN 2025), field deployment reveals that ensuring the accreditation standard for data quality, consistency, and comparability across space and time currently requires significant effort, particularly when scaling across different assessment areas and ecological contexts.

Each assessment area brings unique challenges: baseline data availability is variable, landholder expectations differ, seasonal constraints apply to species surveys, and human resource capacity can be uneven. Moreover, nature finance introduces new demands, requiring repeat surveys at intervals shorter than those typical in conservation (e.g. every 3 years or less rather than every 5–10), and a mechanism to offer early-stage feasibility assessments based on available data. As a result, delivering credible metrics necessitates a tiered approach to data quality standards, one that can accommodate provisional and formal assessments while maintaining integrity.

Pilots and early applications show that a hybrid model of human and machine sensing is the most viable path forward. While trained surveyors remain essential for ground-truthing, sensor deployment, and local ecological interpretation, the future of scalable environmental assurance lies in standardized, machine-aligned workflows, particularly in agricultural systems where regular repeatability, cost-efficiency, and digital integration will be key. The next phase of implementation must focus on building this capability, combining Earth observation, IoT, and structured data protocols with relational elements that engage landholders and local communities.

The following subsections that follow detail both the human and machine components of this evolving data architecture, including lessons from pilot and early deployments, key constraints, and pathways to scalable solutions.

Human Surveyors

Like most biodiversity metrics, the NARIA ECI metrics require data on large mammals, birds, and habitat types. Traditionally, such data have been collected by human surveyors using protocols developed for rare species monitoring or game management. While machine-based solutions are advancing rapidly, field experience from early applications and pilots indicates that human surveyors will remain necessary for at least the next five years, and likely beyond.

We found that landholders often expect their existing survey data to contribute to baseline assessments (e.g. Pentlands case study). In practice, these datasets are usually fragmented, only partially align with ECI protocols and standards, and are time-consuming to extract and adapt. In most cases, it proves more efficient to commission new surveys. However, this requires briefing professional ecologists on unfamiliar protocols, with varying degrees of receptivity. To address this, standardized protocols are being developed linked to structured platform interfaces, ensuring compliance with method requirements and data quality standards.

The availability of skilled surveyors is a major constraint. In the UK, demand for ornithologists, mammalogists, and botanists is already stretched by Environmental Impact Assessment (EIA) requirements for renewable energy and other green infrastructure projects. By contrast, in many African countries, demand pressure is lower and professional wildlife ecologists are often more multi-skilled, flexible, and willing to travel between sites. However, expertise gaps remain in newer and more pioneering approaches to data capture, in the application of emerging technologies, and in the integration of diverse data sources. In particular, there is limited experience in synthesizing local ecological knowledge (LEK), sensor outputs, and traditional ground surveys into standardized formats that can underpin single-index and unit calculations. This uneven geography of human survey capacity highlights both the opportunities and the challenges of scaling a survey-dependent monitoring model globally.

The implication for *Codex Planetarius* is clear: biodiversity and ecosystem condition metrics that rely heavily on human surveyors will face scalability limits due to human resource constraints. A transition toward machine-aligned data sources (Earth observation, bioacoustics, IoT) is therefore inevitable.

However, biodiversity surveyors also act as a point of human contact with landholders, often reinforcing their interest in nature recovery. Further, in our African applications, the importance of including local people in some way is important. This is because they add contextual insight, can alert metric providers to significant changes (e.g. arrival of new species) and help ensure the security of sensors. Scaling up through automation risks losing this relational value. The most realistic pathway is a hybrid future in which machines handle repeatable, large-scale monitoring tasks while human surveyors and/or local people provide calibration, ground-truthing, contextual ecological interpretation and deploy and maintain sensors.

Machine-Sensing

In the early implementation of ECI metrics, we explored a wide range of potential data capture technologies. Our aim was to identify options that could be integrated into standardized, scalable workflows compatible with *Codex*-aligned environmental performance standards. While several technologies showed scientific promise, we found that trade-offs between cost, area coverage, processing complexity, and integration readiness significantly shaped their operational feasibility.

We initially appraised eDNA and drone-mounted sensors, given their innovative potential and growing use in ecological studies. However, we found both to be unsuitable for widespread deployment in the current phase of development. In the case of eDNA, the sampling area is highly localized, with results shaped by environmental conditions and decay rates. The cost and complexity of laboratory processing, coupled with the lack of standardized methods for converting taxon unit detections into species identities and associated functional or trait-based metrics currently limits its value as a data input natural process-based metrics.

Drone-mounted sensors were also considered, particularly for vegetation photogrammetry and thermal mammal mapping. While the resolution and flexibility are attractive at the site scale, limitations around flight range, regulatory compliance, weather dependency, and the intensive processing required to convert raw imagery into metric-ready outputs led us to deprioritize them for the current phase. In small-scale applications or for targeted calibration, they may still have a role, but we do not see them as a near-term solution for systematic monitoring across large rewilding landscapes. However, in intensive agricultural systems, where drone-assisted management is becoming commonplace and existing flight operations could be adapted, drone-mounted sensors may offer a scalable solution, particularly if environmental metrics can be integrated into precision agriculture workflows.

Camera traps are widely used in mammal research and biodiversity assessments, but we found that the number of units required to capture reliable mammal data for our trophic function metric is prohibitively large. Achieving adequate spatial coverage and detection probability across diverse agricultural landscapes would demand extensive deployment, making this approach operationally and financially unfeasible at scale. While new panoramic models have improved detection range, this does not fully

overcome the fundamental constraint. As such, we have deprioritized camera traps as a core data source for the ECI, though they may retain value for calibration or targeted ecological verification.

In contrast, we found bioacoustic monitoring and Earth observation (EO) data to offer a stronger balance of readiness, relevance, and potential for standardization.

Passive Acoustic Monitoring (PAM) overcomes many of the limitations of other machine-based methods and is advancing rapidly. Bioacoustic sensors are relatively inexpensive, have broad detection ranges (typically 250 m or more), can be programmed for different recording intervals, and are supported by AI species classifiers such as BirdNET. Trial deployments in our pilots, as well as by others, are highly encouraging. It is relatively straightforward to design robust sampling frameworks that balance habitat representation and sensor density using free GIS tools, with deployment supported by navigation apps. This enables verifiable placement by land managers or ecologists with minimal training.

Current constraints include the need to change batteries and SD cards every two to three months, and some technical knowledge for configuration. AI classifiers still produce variable confidence levels across species, with false positives common for rare or cryptic taxa, necessitating expert review of suspect detections. This introduces additional labor and cost, though these issues are being rapidly addressed. As noted in Section 3.1 (Horizon 3), advances in statistical protocols and confidence-scoring algorithms are improving classifier reliability, while edge-AI deployments (e.g. through the Soprano project) allow real-time data processing and transmission, reducing storage and power demands.

An additional advantage is that bioacoustic surveys keep projects closely connected to cutting-edge ecological research. Emerging soundscape (Darras et al. 2025) and diel-cycle metrics (Bradfer-Lawrence et.al 2019) may provide more holistic indicators of ecosystem condition than taxon-level presence or absence, offering a pathway to scalable, functionally relevant monitoring.

Satellite EO provided valuable lessons on scalability and systems integration. We used free datasets such as Sentinel and Landsat, which offered reliable temporal coverage, low cost, and compatibility with cloud processing platforms. However, the spatial resolution, typically 10–30 m, limits detection of fine-grained vegetation patterns in some systems (e.g. Pentlands case study). In upland UK farms and smallholder African landscapes, early vegetation recovery was often invisible at this scale. However, in mechanized agroecosystems, such resolution may prove sufficient. The main challenge was not the data per se, but aligning EO-derived products with the ecosystem ontology used in the ECI. Most EO platforms return land cover or vegetation indices, not functional ecosystem process indicators. This required us to invest in developing custom classifications and calibration datasets. While this work was time-consuming, it has laid the foundation for developing robust EO data products aligned with our metrics.

We also found that partnerships with EO providers were easier to develop in African settings, where technical interest was high and baseline classification systems less entrenched. In the UK, more established classification protocols and institutional workflows made integration more difficult. This highlighted a broader systems issue: while EO infrastructure is globally available, its effective deployment in metric-aligned workflows requires governance coordination, investment in calibration, and iterative co-design with data providers.

The key learning from these early applications is that no single sensing technology can meet all requirements. Each comes with trade-offs between ecological representativeness, cost, automation potential, and integration complexity. We are now moving towards hybrid workflows that combine EO and bioacoustic sensing, supplemented by human verification where needed. These offer a path toward scalable, verifiable, and functionally relevant data capture at farm and landscape scales, with flexibility to adapt by region and production system type.

3.3.3 Data Management and Ownership

Our pilots revealed that farm businesses have little tradition of retaining or managing biodiversity data. Where such data exist, they are typically collected for a specific compliance purpose, such as agri-environment schemes, by external consultants, and remain stored in consultancy files or temporary project folders. CreditNature's early applications follow this pattern. However, it is clear that as nature credit markets expand, and as environmental performance standards are applied in agriculture, robust protocols for biodiversity data management will become essential.

Engagement with international biodiversity credit working groups has highlighted data ownership as a critical issue. Many Indigenous and local communities argue that biodiversity data are inseparable from land and identity, and therefore ownership should rest with landholders or communities. This view aligns with broader debates on data sovereignty and environmental governance.

A practical solution now being formulated distinguishes between raw data, processed data, and derived models. Ownership of raw data is assigned to the landholder, while processed data, transformed, interpreted, or aggregated for analysis are owned by the analytic enterprise or platform. This arrangement allows landholders to retain control over how their data are used beyond the immediate purpose of crediting or compliance, while enabling platforms to standardize and share processed outputs under agreed rules.

Such a distributed model avoids the costs and risks of large, centralized data repositories and creates clearer governance pathways. Standards can then specify rules for the transparency, accessibility, and permissible use of processed data, embedded within platform user agreements. This approach supports the emergence of a scalable, ethical, and trust-based system of biodiversity data governance – one that aligns with both agricultural transformation and evolving expectations around environmental data rights.

3.3.4 Technical and Measurement Trade-offs

Metrics and models are necessarily abstractions of reality that trade ecological complexity and the nuance of process for the discipline of quantification. Such trade-offs occur at every stage: from the selection of natural attributes that can be feasibly measured, to the categorization choices made in indicator development, and the selection of data sources. For example, the Ecosystem Condition Index (ECI) rests on a small set of functional ecosystem processes rather than the full breadth of biodiversity and ecological interactions. This choice allows comparability and scalability but inevitably simplifies the dynamics of individual taxa or localized interactions. Similarly, Earth observation metrics prioritize land cover segmentation at 10 × 10 m resolution, which keeps costs down but trades off the ability to capture finer-scale microhabitats or species-specific associations.

As a general rule, the more comprehensive a metric becomes, the less feasible it is to apply at scale; conversely, metrics designed for affordability and scalability risk excluding important ecological or cultural dimensions of ecosystem integrity. Establishing the optimal balance between these competing demands will be a central challenge for *Codex* environmental standards. In the context of nature credits this balance is largely determined by the market, and it is likely that commercial considerations will also shape outcomes in the *Codex* context.

The development of the NARIA Bird Trait Diversity (BTD) metric illustrates a pragmatic approach to balancing ecological realism with operational feasibility. Designed to represent the niche diversity and dynamics that underpin biotic complexity, the BTD metric uses variation in avian functional traits as an indicator. In its ideal form, the metric would incorporate both species presence–absence and relative abundance data to reflect trait dominance as well as diversity, thereby offering a fuller representation of niche occupation and ecological structure.

However, established methods for collecting reliable bird abundance data are slow, costly, and often impractical to implement at scale. A deliberate decision was therefore taken to introduce a minimum viable product (MVP) version of the metric based on presence–absence data only. This approach allowed for confident data collection, clear survey protocols, and practical data workflows, while still generating meaningful signals of change from degraded to recovering ecosystem condition states.

The MVP version was introduced alongside a clear plan to upgrade to a version 2.0 that integrates an abundance component (see Pentlands case study). Advances in low-cost, scalable bird survey methods (see Case Study 1) and bioacoustics have since delivered a viable pathway for this upgrade, affirming the initial design strategy. The experience highlights the value of early-stage trade-offs that enable scalability and practical uptake while laying a clear foundation for subsequent refinement. It also underlines the importance of strict protocols for metric versioning to ensure scientific integrity, transparency, and consistency in evolving performance standards.

3.3.5 Cultural and Institutional Context

Our direct experience of applying the NARIA framework has shown that cultural and institutional barriers can be as significant as technical ones in shaping what is possible along the Horizon 3 pathway. These influences are not abstract but were repeatedly encountered during pilots, often determining whether metrics could be applied efficiently or whether opportunities for innovation were lost. The key learning is that scaling nature credit markets, and by extension minimum agricultural standards, will require not just robust protocols but a deliberate program of sector engagement, education, and expectation management.

Language and Knowledge Systems

In practice, we found that the use of vague or contested terms such as biodiversity, ecosystem services, or even nature created barriers to collaboration. Different actors assumed a shared understanding when in fact they were often working with different definitions. For example, none of the partners we engaged with were familiar with the UN-SEEA glossary until we introduced it. This lack of reference to a common lexicon meant that time and energy were often consumed by basic clarification rather than by forward progress.

We also encountered a persistent silo problem: very few stakeholders had working knowledge across all four areas that NARIA integrates: standards, technology, biodiversity measurement, and land management practice. This left us constantly bridging domains on behalf of others, rather than co-designing on an effective footing. Without this 'boundary' knowledge, even technically expert partners struggled to engage productively with metric design and application.

Professional Authority and Institutional Logics
Working with academics and government officers was essential to adapt NARIA-ECI metrics to local contexts and show respect for established expertise. However, our experience was that these groups often approached our pilots through the lens of traditional ecology or entrenched biodiversity assessment cultures. Public procurement rules reinforced this: when our new metric and data solutions were presented, academics and officials tended to default to traditional consultancy style products, such as wildlife censuses and habitat maps, considered already proven and low risk to procure. In addition, the widespread reliance on simple pressure–state–response or risk logics among government officials was a persistent barrier to production engagement.

Trust, Legitimacy, and Representation
In our pilots, civil society organizations were often reluctant to engage. Some were focused on their own monitoring programs, agendas and collaborative networks, while others were suspicious of commercial nature enterprises, even when framed as "profit-for-nature." Many perceived themselves as the legitimate experts in nature assessment and saw little reason to collaborate with technology or market-facing actors.

Equally significant were the cultural divides and deep-rooted animosity between agriculturalists and environmentalists. All of our pilots involved landowners motivated to restore nature, but building the necessary trust required multiple face-to-face meetings to explain concepts, listen to concerns, and show how metrics could serve land management goals. In Scotland, these conversations were further complicated by the political pressure to demonstrate "community involvement." However, no-one could define who or what a "community" was in practice, leading to vague and sometimes tokenistic processes that generated procedural burden without delivering ecological value.

Colonial Sensitivities
In both our African and Scottish pilots, we encountered forms of initial resistance rooted in deeper histories of political identity and control over knowledge systems. When first presented to African biodiversity institutions, the NARIA framework and its metrics were viewed by some as reflecting European scientific authority and top-down governance, resonant with patterns of historic imposition. However, these perceptions softened when local consultants and scientists were involved in the adaptation of metric ontologies and data protocols to reflect local ecological and institutional realities. A similar dynamic played out in Scotland, where some stakeholders perceived our metric system, developed in England, as encroaching on Scottish scientific autonomy or replicating centralized governance models.

Market Perception Gaps
Another barrier we encountered came from the investor community. Many assumed that biodiversity or ecosystem credits could be structured to mirror carbon markets, with a single headline number acting as the unit of exchange. This expectation reflects a lack of systems thinking: carbon is a measurable physical element, whereas nature is a complex system. The NARIA approach requires multiple interdependent metrics to capture ecological integrity. We found that many financial actors lacked the 'band width' to engage with the complexity of ecosystem/biodiversity measurement and struggled to understand why nature credits cannot be reduced to a single scalar quantity like carbon.

Key Learnings for *Codex*
These experiences highlight two important lessons for the implementation of international environmental standards.

First, the successful introduction of standards or frameworks must be accompanied by carefully designed communication and co-development strategies. In both Scotland and Africa, initial resistance was shaped by perceptions of scientific and governance imposition, whether through legacies of colonialism or concerns about national autonomy. Emphasizing alignment with global frameworks such as the UN System of Environmental-Economic Accounting – Ecosystem Accounting (UN-SEEA-EA) helped to reframe our approach as grounded in international norms rather than external control. This framing opened space for dialogue and adaptation, encouraging local actors to see the metrics as tools for progress rather than threats to sovereignty. *Codex Planetarius* will need to anticipate and navigate similar sensitivities, particularly where standards originate from international bodies but must gain legitimacy in politically and culturally diverse national contexts.

Second, we found that institutional sponsorship is essential to confer legitimacy, credibility, and access to innovation finance. In Scotland, this role was played by the Government's Civil Technology Innovation Programme (CivTech), which runs challenge rounds inviting new solutions where public policy delivery has stalled. Winning teams enter an accelerator process, co-designing innovations with sponsor teams of civil servants and CivTech experts. For the NARIA pilots, this support proved critical. It enabled

access to landowners and the influential land agent profession, fostered policy alignment with government officials, and helped co-develop a "born-digital" ecosystem recovery code that was both technically robust and institutionally credible.

Just as important, the CivTech process built institutional understanding. Government officials gained hands-on exposure to the technical and governance dimensions of transitioning from consultancy-style biodiversity monitoring to digital, infrastructure-style assurance services. This shared learning now resides within government, supporting confident, informed decision-making around Horizon 2 transitions that balance public civil society, sectoral and market interests.

In Africa, our initial institutional sponsor was the international development agency Dalberg, who had been commissioned to develop a Biodiversity Investment Readiness Analytic (BIRA) for catalyzing external investment in African biodiversity. Early in this process, they surveyed available metric frameworks and identified NARIA as the most promising fit. This alignment gave the framework early legitimacy among progressive projects and funders, fostering a distributed form of credibility through association. As shown in Case Study 2, early applications helped raise awareness among influential corporate, foundation, and government actors, helping to seed a network of recognition and trust across the region.

3.4 Towards a Simple but Upgradeable Metric

The *Codex Planetarius* initiative is seeking a single biodiversity metric to set a threshold for environmental performance. To succeed, such a metric must be simple enough to gain early traction with industry and regulators, yet designed in a way that allows it to evolve toward greater scientific robustness as technology and knowledge advance.

Section 2 argued that it is unfeasible to design such a metric using taxonomic or habitat indicators, as their variety is too great to support a single, robust measure. To overcome this, it outlined a functional ecosystem process approach that measures the condition of a small set of key functional ecosystem processes (FEPs) and combines them in an Ecosystem Condition Index (ECI).

From a pragmatic perspective, however, this composite index is likely to be perceived as too complex and costly to gain early buy-in from industry and other food system actors. This sub-section therefore presents a tentative design for an initial ecosystem/biodiversity condition metric that could be used to set a minimum environmental threshold.

The design builds on the Horizon 3 digital infrastructure described in Section 3.1 and relies on Earth observation and bioacoustic data sources because they are scalable, affordable, consistent, and auditable. We are in a rapid phase of technological development that is driving advances in machine-based data capture, AI analysis, and ecosystem science. In this context, it is useful to think of quantitative agricultural standards in terms of software versioning: the metric outlined here could be considered "Version 1.0", while the NARIA ECI described in Section 2 represents a more advanced "Version 3.0". A digital infrastructure approach makes it possible to upgrade iteratively in line with advances in science, technology, and user needs.

3.4.1 Concept for an Ecosystem Condition Index – Agriculture (ECI-Ag)

The Brazilian Forest Code remains the only legally enacted environmental threshold for agriculture. It mandates that landholders retain a proportion of their property under native vegetation - 20% in most regions, up to 80% in the Amazon biome (Soares-Filho et al., 2014). Its strength lies in its clarity, enforceability, and scalability: the headline metric (% native vegetation) can be monitored consistently using Earth observation (EO), with well-established models trained to distinguish native from non-native vegetation types.

Other countries, such as Indonesia, have adopted similar policies, requiring native vegetation to be retained along waterways, on steep slopes, and in erosion-prone zones as part of watershed management. These approaches are underpinned by evidence that even basic retention of natural habitat contributes to key ecological processes: soil stabilization, water retention, microclimate buffering, and provision of structural habitat for biodiversity (Nahib, et al., 2024).

However, these single-indicator thresholds have well-known limitations. They offer no information on the quality, spatial configuration, or functional role of retained vegetation. Landscapes may meet the legal target while remaining functionally degraded: narrow fragments, monoculture edge effects, and isolated patches often support limited ecological integrity. Crucially, such metrics do not represent animal-mediated functions such as pollination, seed dispersal, or trophic regulation, processes that support long-term agricultural resilience and sustainability (Tilman et al., 2002; Brancalion et al., 2016).

ECI-Ag v1.0 : A Scalable, Upgradeable Improvement

Building on the policy examples outlined above, a concept for an Earth Observation–derived Ecosystem Condition Index for Agriculture (ECI-Ag) is outlined below. The purpose is to demonstrate that a low-cost, globally applicable, and scientifically credible performance metric can be developed using satellite EO data. It will require the creation of a model that supports the definition

and tracking of minimum environmental condition thresholds within *Codex*-aligned agricultural standards. Importantly, the ECI-Ag outlined is designed to be upgradeable: it provides a foundational structure that can be progressively refined through the incorporation of biophonic or other ecological indices as technologies and capacities evolve.

The initial version, ECI-Ag v1.0, rests on three core components. First, a simple land cover typology classifies landscapes using EO into broad categories of native and non-native vegetation. These include wetlands, grasslands, and woodlands on the native side, and croplands, pastures, and plantations on the agricultural side. Each land cover type is then assigned a position along an ecological degradation scale, ranging from remnant native and restored native vegetation to traditional agriculture, mechanized agriculture, and intensive, financialized agricultural systems. While simplified, this typology is intended to be practical for training EO models and capturing meaningful ecological differences relevant to agricultural systems.

Second, the model incorporates a set of spatial configuration rules. These are drawn from established ecological theory (such as principles of connectivity, fragmentation, and edge effects) as well as widely adopted policy standards like riparian buffer zones and slope protection requirements. Minimum thresholds are set for the proportion and distribution of native vegetation blocks, buffers along watercourses, vegetation cover on steep slopes, and the presence of refuge patches or fallows. These parameters are then integrated into a composite landscape integrity score, which can be further refined through a permeability model. This estimates the extent to which different land uses inhibit or facilitate the movement of focal species across the landscape, providing a proxy for ecological flow and functional connectivity.

Finally, the land use classification and landscape configuration scores are weighted and aggregated into a single Vegetation Spatial Integrity (VSI) metric. The VSI evaluates not only the extent, configuration, and heterogeneity of land cover types within the assessment area, but also the functional contribution of each. Land cover types are weighted according to their relative influence— positive or negative—on farm- or landscape-scale ecosystem condition. This approach ensures that intensive monocultures, mixed farming systems, natural habitats, and areas under active restoration are all reflected in proportion to their ecological function. The VSI score is normalized to a reference benchmark of 100, representing either a local or regional analogue of an intact, uncultivated ecosystem (e.g. native forest or grassland), or a pre-industrial agro-ecological system with high functional integrity. This index allows assessment areas to be evaluated against a defined minimum ecological condition threshold.

By integrating land cover composition, spatial configuration, and functional weighting, the VSI provides a proxy indicator for the state of key natural processes. These include animal-mediated seed dispersal, pollination, natural pest regulation, water infiltration, niche diversity, and the stabilization of soils and slopes. The model's structure also permits context-sensitive application: thresholds and reference values can be set at national or regional levels, allowing the ECI-Ag to reflect biogeographic variation and differences in agricultural systems without compromising comparability.

From an implementation perspective, ECI-Ag v1.0 has the potential to be introduced and governed in a scalable and cost-effective manner. Once the model core architecture, ontologies and scoring logic are standardized and made openly available, national agencies or commercial EO providers could generate provisional ECI-Ag scores across large agricultural areas, defined, for example, by supply aggregation points such as mills or grain silos, or by the reach of individual farms. A fixed time period could then be specified for each assessment area to submit a spatial plan demonstrating how it intends to meet or maintain the minimum threshold. Using a centralized digital platform, EO data could be updated and the model re-run at regular intervals to track progress toward compliance.

One challenge may lie in the early detection of restorative land management. In many cases, initial interventions may not be readily observable through EO models. To address this, a mechanism could be built into the platform that allows landholders to submit geo-tagged photographic evidence, triggering a review process that adjusts the classification and improves the model's training dataset over time. This hybrid approach would enable continuous improvement of model accuracy while building trust and lowering transaction costs.

Importantly, ECI-Ag offers not only an ecological performance standard but also a means of embedding ecological condition into agricultural policy and finance. Governments could link compliance to subsidies or procurement eligibility. Banks and investment platforms could offer preferential terms to producers operating above the threshold. Food brands could use ECI-Ag ratings to differentiate products in consumer markets. In short, a metric of this type could provide a transparent, auditable, and scientifically grounded entry point for embedding ecosystem integrity into agricultural systems globally.

Towards an ECI-Ag 2.0
The basic ECI-Ag framework described above offers a scalable, low-cost entry point for setting environmental condition thresholds in agricultural landscapes. However, as technology, capacity, and ambition grow, this structure could be enhanced through the addition of a second, complementary metric: offering a clear upgrade pathway for companies wishing to go beyond compliance, or for national regulators seeking to raise standards over time.

A logical next step would be to pair the Vegetation Spatial Integrity (VSI) score with a Biophonic Integrity Metric (BIM). Whereas VSI captures the structural and compositional integrity of land cover, BIM offers a window into the animal-mediated processes underpinning ecological function. Based on passive acoustic monitoring, the BIM could, for example assess the presence and activity of selected 'focal species' representing three categories: (i) functionally important species with disproportionate ecological effects; (ii) threatened or endangered species; and (iii) species of cultural significance. Focal species sets improve the performance of AI-based classifiers and ensure broad ecological relevance across seasons and taxa.

By combining spatially explicit EO data with bioacoustic indicators of faunal activity, ECI-Ag 2.0 would offer a dual-metric system. The VSI provides the structural baseline, while the BIM amplifies or adjusts this score to reflect the presence, absence, or degradation of fauna-driven processes such as pollination, seed dispersal, bioturbation, and trophic regulation. This hybrid structure preserves simplicity while offering richer ecological insight, thereby supporting both performance benchmarking and adaptive landscape management.

In summary, a simple, scalable ECI-Ag metric, underpinned by EO and structured to allow progressive upgrades, could offer a powerful tool for aligning agricultural practice with environmental performance. By linking this index to a centralized digital platform, national and regional authorities could track changes in ecosystem condition across production landscapes, generating consistent datasets to support reporting against Global Biodiversity Framework targets, SDGs, and climate–nature co-benefit strategies. It would also support the integration of nature-related data into agricultural supply chain disclosures, green finance instruments, and ESG frameworks.

3.4.2 Toward Digital Assurance Architecture for Ecological Standards

A central learning from our development of digital nature credit systems is the critical importance of assurance infrastructure. As with any standards system, the credibility of environmental performance metrics rests not only on their technical design, but on the reliability, transparency, and scalability of the mechanisms used to verify them. In nature credit markets, the assurance challenge is particularly acute: ecosystem condition must be assessed in situ, over time, and often across complex landholding structures.

Conventional environmental assurance models, which rely on document reviews and periodic site visits, are too slow, costly, and inconsistent to support scalable ecosystem accounting. In response, we developed a "born-digital" alternative: a semi-automated audit system anchored in digital trust chains, method certification, and machine-verifiable workflows. This system has proven both robust and cost-efficient in early applications, and we believe it holds significant potential for agricultural standards aligned with *Codex Planetarius.*

Key components of the system include:

- **Independent methods certification** aligned with UN-SEEA-EA, providing a formal process to accredit the scientific rigor and fitness-for-purpose of each metric and data sourcing protocol.

- **Workflow encoding with machine/human-in-the-loop logic**, where data ingestion, processing, and verification steps are modularized, hashed, and cryptographically chained to support auditability.

- **Digital platforms** that include user-facing interfaces for structured data submission, and internal APIs for interoperability across data sources, models, and decision rules.

- **Distributed ledger integration**, ensuring that verified metric outputs are tamper-proof, traceable, and accessible for crediting, compliance, or reporting purposes.

- **Land unit registration and typology**, which anchors metrics to clearly defined accounts (e.g. farms or landscapes), and links performance outcomes to land management practices through structured metadata and EO-verified self-reporting.

- **Governance protocols**, including rules for platform certification, metric versioning, auditor accreditation, and data transparency.

These elements enable a shift from consultancy-style verification to a digitally native assurance model, with clear roles, audit trails, and scalable logic. The approach has been piloted in both Global North and Global South contexts, and has proven adaptable to different regulatory, infrastructural, and cultural settings.

The *Codex Planetarius* framework presents an opportunity to embed these learnings into the design of environmental performance standards for agriculture. Realizing this potential will require cross-sector coordination and investment in digital infrastructure, alongside the development of new institutional capabilities – such as methods accreditation bodies, platform certification processes,

interoperable data standards, and oversight structures for audit and data access. The benefits of doing so are substantial: lower costs, greater transparency, broader participation, and more credible implementation of ecological standards. Models from digital nature credit systems already demonstrate a realistic pathway to scalable, cost-effective, and trustworthy assurance for metrics linked to farm- and landscape-level environmental outcomes.

4 Conclusions

This paper was commissioned to examine how biodiversity metrics, designed on the basis of systems ecology, can inform the development of minimum performance standards for agricultural systems within the *Codex Planetarius* proof-of-concept. The task was to assess the feasibility of applying such metrics in a way that is scientifically credible, practically implementable, and aligned with the UN System of Environmental-Economic Accounting.

More specifically, the objective was to draw on lessons learned from the design and application of CreditNature's NARIA framework, and in particular the Ecosystem Condition Index (ECI), to illustrate how next-generation metrics can provide finance-grade evidence of ecological condition and recovery. In doing so, the assignment has sought to connect the principles of ecosystem condition metric design with the practical requirements of performance standards, offering insights that can guide both the technical design of *Codex Planetarius* and its eventual uptake by market and regulatory actors.

An ecosystem condition approach offers a practical solution to the limitations of taxon- and habitat-based biodiversity metrics. Because taxonomic classifications and habitat typologies are often subjective and vary between biogeographies, their use reduces consistency and comparability and typically requires costly, expert-led surveys. In contrast, a systems ecology framework focuses on underlying ecological processes that are common across ecosystems, allowing for the development of metrics that are more transferable, affordable, and scalable.

Experience with nature credit design and implementation also highlights the importance of adopting a structured architecture for metric design guided by pragmatic design principles. Alignment with the three-tier framework of the UN System of Environmental-Economic Accounting ensures that indicators of ecosystem condition are organized in a way that supports policy and accounting needs at multiple scales. Within this, a critical design feature is the use of ontologies to clarify relationships between ecosystem processes, land management practices, and service outcomes. Ontologies not only improve transparency but also ensure that the distinction between raw data, processed data, models, and metrics is maintained—an essential step for creating standards that are auditable, reproducible, and trusted by regulators and markets alike.

The Three Horizons framework has been useful in guiding our approach to nature credit market building and could help clarify both the feasibility and the trajectory of agricultural performance standards. Horizon 1 reflects entrenched biodiversity monitoring practices: fragmented, consultancy-based surveys that are costly, inconsistent, and ill-suited for scaling. Horizon 2, where our pilots and early applications are located, demonstrates the opportunities and frictions of transition. Here, innovations in digital capture, hybrid human–machine workflows, and modularized cost structures show promise, yet remain vulnerable to institutional inertia and the pull of established logics. Horizon 3 is becoming increasingly visible as a destination system: an integrated digital infrastructure where ecological condition metrics can be applied at scale, affordably and with assurance.

Having this destination in sight offers major benefits for *Codex*. It allows near-term standards to be framed not as perfect endpoints but as pragmatic "version 1.0" metrics that are deliberately simple, auditable, and affordable, while designed for progressive upgrading. This approach could build confidence among producers, regulators, and investors that minimum standards are achievable today, while also charting a clear pathway toward greater rigor and ecological realism as technologies and institutions mature.

From our experience on the Horizon 2 pathway, several key takeaways stand out for *Codex*. First, metrics must be designed with architectures that ensure consistency across ecoregions, while also allowing adjustment to the ecological specificities of different contexts and the capacity for continual improvement (versioning) in response to lessons from application, advances in technology, and user needs. Second, assurance infrastructure is as important as the metrics themselves and incorporates digital trust chains, accreditation protocols, and clear data governance as prerequisites for credibility and uptake. Third, institutional sponsorship, legitimacy, and associated sector engagement and education are critical to overcoming entrenched resistance and securing buy-in across government, landholders, and markets. Fourth, a decisive shift from human-based surveys to machine-based ecosystem

sensing, with humans in the loop, is essential to overcome the limitations of cost, data assurance, and scalability inherent in traditional methods. . Finally, standards gain traction when framed not as surveillance or compliance burdens but as tools that empower land managers and communities to participate in the ecological transition.

Drawing on these lessons, we have outlined a tentative design for a basic single ecosystem condition metric that could serve as a pragmatic starting point for *Codex*. This prototype focuses on vegetation spatial integrity, a characteristic that can be consistently measured across biogeographies and directly linked to ecosystem processes such as habitat connectivity, resilience, and soil protection. The metric is quantifiable using low-cost satellite Earth observation data combined with accessible models, ensuring affordability and scalability from the outset. While deliberately simple, it is conceived as an upgradeable foundation: a version 1.0 standard that can be progressively extended with complementary metrics as technologies mature and user capacities expand.

More broadly, the approach outlined in this paper could help catalyzse the uptake of ecological technologies in rural areas, extending the digital economy, stimulating innovation in nature-based solutions, and supporting the emergence of a new class of rural service providers. Importantly, by combining a core standard with modular upgrade paths, the ECI-Ag model accommodates different country contexts and investment capacities, ensuring that global performance standards are not only ambitious, but fair and implementable at scale. Crucially, a metric and assurance platform of this kind would also enable minimum agricultural standards to align with national reporting obligations under the Kunming-Montreal Global Biodiversity Framework, particularly Target 2 on restoring at least 30% of degraded ecosystems and Target 3 on ensuring that 30% of land and sea areas are effectively conserved through protected areas and Other Effective Area-Based Conservation Measures (OECMs). In both cases, demonstrable improvement in ecosystem condition is the critical measure of success.

Livelihood and equity issues have not been directly addressed within the scope of this paper. However, the expectation is that environmental performance standards will stimulate demand for more ecologically sensitive land management, creating new livelihood opportunities in ecosystem stewardship and restoration. At the same time, the digital assurance infrastructure proposed here enhances transparency and accountability, helping to support greater equity and environmental justice.

In sum, the analysis demonstrates that metrics designed on the basis of systems ecology can provide a credible and implementable foundation for *Codex Planetarius* standards. Lessons from the NARIA framework show that it is possible to bridge ecological integrity, land management practice, and finance-grade reporting within a coherent metric architecture. Taken together, these insights suggest that a global standard built on ecosystem condition has the potential not only to safeguard environmental performance in food production but also to enable the innovation, legitimacy, and fairness required for successful adoption at scale.

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