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RESEARCH ARTICLE

Governing the Paradox: Regenerative Coordination in Nigeria's Energy Transition

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Abstract

This study developed and tested a system-level account of sustainability coordination in Africa's extractives-to-energy transition, addressing the absence of a validated construct that captures how multi-actor coordination shapes regenerative outcomes when legacy extractive assets simultaneously constrain and enable decarbonisation. We introduced the Resource Regeneration Coordination Index (RRCI) and the Multi-Actor Resource Regeneration Systems Framework (MARSF), theorising coordination strength as an emergent ecosystem property comprising inter-firm regenerative alignment, socio-environmental embedding, and cross-sectoral resilience integration. Using 42 semi-structured interviews across three Nigerian transition corridors to generate and refine measures, we then surveyed 372 ecosystem participants spanning operators, renewable developers, EPC firms, financiers, regulators, grid actors, and community-facing leaders. Confirmatory factor analysis supports reliability and convergent and discriminant validity for RRCI's sub-dimensions, and a two-stage higher-order composite model yields consistent measurement performance. Structural estimation indicates that regenerative alignment predicts environmental regseneration, socio-environmental embedding predicts community resilience, and resilience integration predicts ecosystem legitimacy, with substantial explained variance across outcomes. Cross-validation assessment indicates out-of-sample utility, and multigroup comparisons across three ecosystem archetypes reveal context-contingent path strengths. Conceptually, we formalised a regenerative coordination paradox: extractive infrastructures become transition platforms only when alignment, embedding, and resilience routines cohere. In practice, RRCI provides an auditable diagnostic for targeting guarantees, contractual covenants, remediation oversight, and disclosure alignment at the weakest coordination links in transition governance.

Keywords Coordination · Energy Transition · Extractives · Circular Repurposing · Ecosystems · Systems Thinking · Measurement · PLS-SEM · Nigeria · Sustainability Outcomes

1. Introduction

The global transition from high-carbon extractive systems to low-carbon energy infrastructures has intensified scholarly and policy attention to the organisational conditions under which sustainability can be achieved beyond the boundaries of the focal firm (Williams et al., 2017; Adner, 2017; Grewatsch et al., 2023; De Angelis and Ianulardo, 2024; Weaver et al., 2025). Extractive industries remain materially indispensable to this transition because oil, gas, and mining continue to underpin economic activity and supply the minerals and legacy infrastructure on which renewable technologies depend (Sovacool et al., 2022; Liu et al., 2023; Berthet et al., 2024). This duality creates a governance problem that is not adequately captured by firm-centred sustainability models, because transition outcomes increasingly depend on whether multiple actors can align investment, infrastructure, remediation, and legitimacy across a shared system rather than within isolated

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organisational units (Adner, 2017; Grewatsch et al., 2023; De Angelis and Ianulardo, 2024). In Nigeria, this problem is especially acute. As Africa's largest oil producer and a resource-dependent emerging economy confronting decarbonisation pressures, Nigeria exemplifies the tension between continued hydrocarbon dependence, growing climate vulnerability, and the strategic importance of transition-related resources and infrastructures (Obi, 2021; Osabuohien et al., 2022; Okafor et al., 2023; Strambo et al., 2024). The central issue, therefore, is not only how to decarbonise extractive activity, but how to coordinate firms, regulators, financiers, grid actors, and communities in ways that generate environmental regeneration, community resilience, and ecosystem legitimacy.

Existing sustainability research provides important but incomplete foundations for addressing this problem. Systems-thinking scholarship has shown that sustainability challenges are characterised by interdependence, feedback effects, and cross-level causality, thereby shifting analysis away from linear and firm-bounded accounts of value creation and harm (Williams et al., 2017; Kump and Fikar, 2021; Wan Rosely and Voulvoulis, 2022; Grewatsch et al., 2023; Weaver et al., 2025). Circular economy research has likewise demonstrated that regenerative transitions depend on reconfigured material and energy flows rather than simple efficiency gains, with recent work arguing for a stronger theoretical linkage between circular principles and sustainability management (Lu et al., 2022; De Angelis and Ianulardo, 2024). Stakeholder, institutional, and ecosystem perspectives have further extended understanding of legitimacy, compliance, interdependence, and value co-creation across organisational fields and supply networks (Brammer and Walker, 2011; Ansari et al., 2013; Adner, 2017; Jacobides et al., 2018; Veldman et al., 2023). Yet this literature has largely developed around manufacturing, public procurement, consumer-facing supply chains, or relatively stable governance environments, and therefore offers only partial traction for sectors in which extractive assets simultaneously obstruct and enable the low-carbon transition.

The specific research gap is that the literature still lacks a theoretically specified and empirically validated construct to capture the strength of ecosystem-level coordination in extractives-to-renewables transitions, particularly in resource-dependent emerging economies where formal regulation, informal governance, infrastructure legacies, and community contestation coexist. Systems thinking identifies interdependence but has seldom translated it into measurable coordination constructs (Williams et al., 2017; Weaver et al., 2025). Circular economy scholarship foregrounds regeneration and repurposing, yet it tends to privilege material loops over the political, contractual, and relational mechanisms that make cross-sector coordination workable (Lu et al., 2022; De Angelis and Ianulardo, 2024). Stakeholder and institutional approaches explain legitimacy pressures and governance expectations, but they do not fully capture the regenerative coordination paradox in which extractive sectors damage present socio-ecological conditions while also supplying the assets, revenues, and infrastructures that may support renewable futures (Ansari et al., 2013; Sovacool et al., 2022; Liu et al., 2023). As a result, prior research does not yet explain with sufficient precision why some transition ecosystems remain locked into unsustainable trajectories while others begin to convert extractive legacies into regenerative platforms.

To address this gap, this study develops and tests two interlinked contributions. First, we introduce the Resource Regeneration Coordination Index (RRCI), a multidimensional construct designed to measure ecosystem-level coordination strength across extractives-to-renewables transitions. The RRCI captures three dimensions that emerged as theoretically and empirically salient in the Nigerian context: inter-firm regenerative alignment, socio-environmental embedding, and cross-sectoral resilience integration. Second, we propose the Multi-Actor Resource Regeneration Systems Framework (MARSF), which explains how these coordination dimensions translate into sustainability outcomes by linking coordination strength to environmental regeneration, community resilience, and ecosystem legitimacy. In contrast to prior work that mainly catalogues interdependencies, this study specifies coordination as the operative mechanism through which paradoxical transition sectors may shift from carbon lock-in to regenerative transition. This responds directly to calls for mechanism-centred theory development and for stronger articulation of what new constructs add beyond relabelling existing ideas (Lange and Pfarrer, 2017; Sandberg and Alvesson, 2021).

Nigeria offers an analytically suitable setting for this investigation because it condenses several tensions that make ecosystem coordination both difficult and consequential. The country remains deeply tied to oil and gas revenues even as global decarbonisation pressures intensify, while transition debates increasingly intersect with mining expansion, energy insecurity, environmental remediation, and subnational contestation over development benefits (Obi, 2021; Osabuohien et al., 2022; Okafor et al., 2023; Strambo et al., 2024). Nigeria is therefore not treated here as a peripheral case but as a demanding empirical setting in which the contradictions of transition governance are unusually visible. Extractive infrastructures such as pipelines,

terminals, and associated logistics can become stranded liabilities, but under some coordination conditions, they may also be repurposed into renewable transition assets (Obi, 2021; De Angelis and Ianulardo, 2024). At the same time, community outcomes depend not merely on the presence of projects but on whether coordination arrangements embed participation, remediation, and benefit-sharing into the transition architecture itself (Brammer and Walker, 2011; Osabuohien et al., 2022; Veldman et al., 2023). This contextualisation matters because it shows why an ecosystem lens is not an abstract preference in this study, but a requirement imposed by the empirical structure of the transition problem.

Methodologically, the study employs a mixed-methods design to advance both construct development and empirical validation. We first used qualitative evidence from multiple ecosystem actors to refine the dimensions and mechanisms of regenerative coordination and then validated the RRCI quantitatively as a higher-order construct associated with sustainability outcomes. This design is intended not simply to describe transition complexity but to generate a measurable framework for testing whether coordination strength varies systematically across transition settings and whether this variation explains outcome differences. By doing so, the study addresses concerns about oversimplified innovation claims by stating the objective more directly: our aim is to explain and measure how ecosystem-level coordination shapes regenerative transition outcomes in extractives-to-renewables systems within a resource-dependent emerging economy.

This study, therefore, makes three contributions. First, it introduces the RRCI as, to our knowledge, the first empirically validated measure of regenerative coordination strength in extractives-to-renewables ecosystems. Second, it advances MARSF as a mechanism-based framework that brings systems thinking, ecosystem theory, and sustainability governance into a single explanation of how coordination produces environmental, social, and legitimacy outcomes. Third, it repositions Nigeria and comparable emerging economies as sites of theoretical production rather than merely as empirical applications, showing that the governance contradictions of resource-dependent transition contexts can generate concepts with broader relevance to sustainability and supply chain scholarship.

2. Literature Review and Theoretical Background

2.1. Systems Thinking as a Foundation for Ecosystem Sustainability Analysis

Systems thinking has become a significant lens in sustainability scholarship because it shifts analysis from isolated firm actions to interdependent configurations of actors, institutions, and flows (Williams et al., 2017; Grewatsch et al., 2023; Weaver et al., 2025). It is particularly relevant to sustainability management because environmental and social harms are rarely produced or governed within a single organisational boundary. Instead, they emerge through feedback effects, cross-level dependencies, and path-dependent infrastructures that cut across supply chains, sectors, and regulatory domains (Williams et al., 2017; Wan Rosely and Voulvoulis, 2022; Grewatsch et al., 2023). For this reason, systems thinking is not merely a descriptive vocabulary in the present study; it is the starting point for theorising why sustainability outcomes in extractives-to-renewables transitions must be understood at the ecosystem level rather than at the focal firm level.

Yet the value of systems thinking has not been matched by equivalent progress in construct development. Existing studies have shown that systemic approaches can illuminate governance failures, resilience challenges, and unintended consequences in energy, water, and food systems, but they rarely specify measurable dimensions through which coordination strength can be evaluated empirically (Kump and Fikar, 2021; Laimon et al., 2022; Wan Rosely and Voulvoulis, 2022; Weaver et al., 2025). This is a material limitation for the present study because the empirical problem is not simply whether actors are interdependent, but whether their interdependence is organised in ways that support regeneration rather than reproduce degradation. In extractives-to-renewables transitions, oil and gas infrastructures may lock economies into carbon-intensive trajectories, yet under different coordination arrangements, the same assets may be repurposed to support renewable deployment and system resilience (Obi, 2021; Liu et al., 2023). Systems thinking, therefore, identifies interdependence but does not, by itself, explain which coordination mechanisms convert it into regenerative outcomes. This limitation points to the need for a more explicit mechanism-based and empirically operationalisable framework.

2.2. Circular Economy and Cross-Sector Resource Regeneration

The circular economy has become a major strand of sustainability scholarship because it directs attention to material recovery, asset repurposing, waste reduction, and regenerative value creation across production systems (Kump and Fikar, 2021; Lu et al., 2022; De Angelis and Ianulardo, 2024). In supply chain research, circular principles have been linked to dynamic capabilities, digital integration, and more sustainable resource use, particularly in manufacturing and industrial operations (Lu et al., 2022). More recent work argues that circular economy thinking should also serve as a basis for sustainability management theory by linking systems reasoning to regenerative organising (De Angelis and Ianulardo, 2024). This shift is especially relevant to extractives-to-renewables transitions, where the reuse of infrastructure, by-products, technical interfaces, and logistics networks may determine whether extractive legacies become stranded liabilities or transition assets.

However, the circular economy literature remains underdeveloped in precisely those sectors where this question is most pressing. Much of the established work centres on manufacturing, consumer goods, and alternative food systems, while extractive sectors are often treated as environmentally problematic outliers rather than as constitutive parts of low-carbon transition systems (Kump and Fikar, 2021; Lu et al., 2022). That treatment is theoretically limiting because extractive sectors simultaneously cause environmental damage and supply the minerals, infrastructure, and fiscal resources needed for renewable energy expansion (Sovacool et al., 2022; Liu et al., 2023; Adenle et al., 2023). A circular economy perspective that focuses only on material loops, therefore, remains incomplete in this setting. What is additionally required is an account of how actors coordinate repurposing, share risks, align incentives, and secure legitimacy across sectors. Without that extension, circular economy reasoning risks overstating the technical plausibility of regeneration while understating the governance conditions required for it to be actionable.

2.3. From Stakeholder and Institutional Explanations to Ecosystem Coordination

Stakeholder theory has long provided a basis for analysing how firms secure legitimacy, respond to social pressures, and manage relationships with affected constituencies (Brammer and Walker, 2011; Hoejmose and Adrien-Kirby, 2012). Institutional theory has likewise shown how rules, norms, and legitimacy pressures shape sustainability practices, including disclosure and due diligence (Ansari et al., 2013; Veldman et al., 2023). These perspectives remain valuable because sustainability transitions are never purely technical. They are also political and social processes in which acceptance, accountability, and rule alignment matter. Nevertheless, both perspectives have limits in the present context. Stakeholder theory tends to privilege dyadic firm-stakeholder relations, while institutional theory often assumes relatively stable formal governance conditions. Neither, on its own, sufficiently captures the distributed, cross-sector, and infrastructure-bound coordination dynamics through which extractive and renewable actors jointly shape transition outcomes in an emerging economy such as Nigeria (Hilson and Maconachie, 2020; Osabuohien et al., 2022; Veldman et al., 2023).

Related firm-centred perspectives face a similar constraint. The resource-based view and dynamic capabilities literature explain how firms deploy and reconfigure resources to maintain performance under changing conditions, including sustainability pressures (Lu et al., 2022). These perspectives are analytically useful, but their explanatory centre remains the focal firm rather than the ecosystem. They therefore say little about how coordination is distributed across multiple actors who do not share ownership, authority, or objectives. By contrast, ecosystem theory is better positioned to address interdependence because it foregrounds complementarities, co-creation, and structural alignment across a network of actors (Adner, 2017; Jacobides et al., 2018). Yet even ecosystem theory stops short of providing a validated construct for measuring coordination strength in paradoxical sectors, and it has not adequately theorised the conditions under which extractive systems move from degenerative to regenerative roles (Table 1). This creates a substantial theoretical opening for the present study.

Table 1. Comparative Mapping of Theories Relevant to Extractives-to-Renewables Transitions

Theory	Applications in SCM/Operations	Strengths	Limitations in the Extractives-to-Renewables Context	Gap for Emerging Economies (e.g., Nigeria)
Stakeholder Theory	Explains firm-stakeholder relationships, legitimacy, CSR, and procurement inclusion (Brammer and Walker, 2011; Hoejmose and Adrien-Kirby, 2012).	Highlights accountability, inclusion, and legitimacy.	Dyadic emphasis underplays ecosystem-level coordination across sectors and infrastructures.	Does not sufficiently capture how multiple actors jointly shape regenerative outcomes under institutional heterogeneity.
Institutional Theory	Examines the rules, norms, and legitimacy pressures that shape sustainability reporting and practices (Ansari et al., 2013; Veldman et al., 2023).	Explains compliance, convergence, and legitimacy pressures.	Often assumes stronger formal institutions than are present in contested transition settings.	Insufficiently accounts for informal governance, community authority, and mixed regulatory capacity in emerging economies.
RBV	Analyses firm resources and sources of competitive advantage in sustainable supply chains.	Shows how resource endowments influence sustainability performance.	Firm-centred and weak on inter-organisational coordination.	Cannot explain how regenerative assets are jointly mobilised across organisational boundaries.
Dynamic Capabilities	Explains organisational adaptation and reconfiguration for sustainability transitions (Lu et al., 2022).	Highlights learning, adaptation, and reconfiguration.	Focuses on firm agility rather than ecosystem coordination.	Does not show how coordination across firms, regulators, financiers, and communities builds system resilience.
Ecosystem Theory	Emphasises interdependence, complementarities, and value co-creation across actor networks (Adner, 2017; Jacobides et al., 2018).	Best captures systemic interdependence and complementarities.	Lacks validated coordination measures and under-theorises paradoxical extractive transitions.	Requires operationalisation to explain how coordination strength shapes regenerative outcomes in emerging economies.

2.4. Research Gap and Theoretical Positioning of RRCI and MARSF

Comparative governance developments sharpen this gap rather than resolve it. In the European Union, the CSRD and CSDDD extend sustainability accountability beyond the focal firm by requiring attention to multi-tier impacts and due diligence processes (Veldman et al., 2023). In the United States, critical minerals policy has heightened strategic concerns about supply security and industrial resilience in low-carbon value chains (Nassar et al., 2022). These developments indicate that sustainability governance is moving toward broader coordination logics. However, they do not provide a transferable explanation of how coordination operates in resource-dependent emerging economies where regulatory capacity is uneven, informal governance remains influential, and community legitimacy is often constitutive rather than supplementary. Nigeria exemplifies this challenge because formal regulation, market volatility, infrastructure dependence, and local contestation jointly shape possibilities for transition (Hilson and Maconachie, 2020; Obi, 2021; Osabuohien et al., 2022; Okafor et al., 2023).

The literature, therefore, converges on a two-part gap. First, there is a measurement gap: existing scholarship lacks a validated instrument to capture the strength of ecosystem-level coordination across extractives-to-renewables transitions. Second, there is a conceptual gap: existing theories do not adequately explain the regenerative coordination paradox, namely the condition in which extractive sectors simultaneously undermine socio-ecological conditions and furnish the assets required for renewable transition. Systems thinking identifies interdependence but does not operationalise coordination strength (Williams et al., 2017; Weaver et al., 2025). Circular economy scholarship foregrounds regeneration but remains weak on multi-actor governance and political coordination (Lu et al., 2022; De Angelis and Ianulardo, 2024). Stakeholder and institutional theories explain legitimacy and compliance but remain insufficient for explaining how distributed actors align infrastructures, incentives, remediation, and resilience in contested transition settings (Ansari et al., 2013; Veldman et al., 2023). Ecosystem theory offers the closest starting point, but without a measurable construct and a specified paradox mechanism, it remains analytically incomplete for the present study (Adner, 2017; Jacobides et al., 2018).

To address these limitations, this study introduces the Resource Regeneration Coordination Index (RRCI) as a new multidimensional measure of ecosystem-level coordination strength and advances the Multi-Actor Resource Regeneration Systems Framework (MARSF) as the theoretical account explaining how such coordination translates into sustainability outcomes. The argument is that regenerative transition in extractives-to-renewables systems depends not merely on technological substitution or stakeholder accommodation, but on the quality of coordination across inter-firm alignment, socio-environmental embedding, and cross-sectoral resilience integration. In this respect, the study does more than relabel existing insights. It integrates disparate strands of systems thinking, circular economy, stakeholder governance, and ecosystem theory into a mechanism-based framework that is both conceptually specified and empirically testable. By situating this framework in Nigeria, the study also shows why emerging economies are not marginal to sustainability theory but central to understanding how transition governance operates under institutional plurality and infrastructural path dependence.

The conceptual development that follows, therefore, translates this research gap into a formal theoretical model. It specifies the dimensions of the RRCI, clarifies the logic of MARSF, and shows how regenerative coordination can be theorised as the mechanism linking extractive-renewable ecosystems to environmental regeneration, community resilience, and ecosystem legitimacy.

3. Conceptual Development

Coordination across extractive and renewable ecosystems requires a framework that captures not only interdependence but also the quality of alignment, embedding, and resilience-building through which interdependence becomes regenerative rather than degenerative (Ansari et al., 2013; Adner, 2017; Williams et al., 2017; De Angelis and Ianulardo, 2024). Existing perspectives, including institutional theory, systems thinking, and ecosystem theory, identify cross-actor dependencies but do not provide a sufficiently specified construct for measuring coordination strength in paradoxical transition sectors where extractive assets can either lock in carbon-intensive pathways or support low-carbon transition (Ansari et al., 2013; Adner, 2017; Williams et al., 2017; Liu et al., 2023). To address this limitation, we conceptualise coordination not as a background condition, but as the focal mechanism through which extractive-renewable ecosystems generate divergent sustainability outcomes. On this basis, we introduce the Resource Regeneration Coordination Index (RRCI) as a multidimensional ecosystem-level construct comprising three first-order dimensions: inter-firm regenerative alignment, socio-environmental embedding, and cross-sectoral resilience integration. These dimensions are specified to capture how actors jointly mobilise capital, infrastructures, social legitimacy, and governance routines in Nigeria's extractives-to-renewables transition, and, by extension, in comparable emerging economies (Table 2).

This dimensionalisation extends prior work in three respects. First, stakeholder approaches illuminate legitimacy and inclusion but remain centred on firm-stakeholder relations rather than on ecosystem-wide coordination across heterogeneous actors (Brammer and Walker, 2011; Hoejmose and Adrien-Kirby, 2012). Second, resource-based and dynamic capability accounts explain adaptation and reconfiguration at the firm level, yet do not show how regenerative assets are assembled across organisational boundaries (Lu et al., 2022). Third, ecosystem perspectives capture complementarities and structural interdependence, but they have not yielded a validated measure of coordination strength in transition settings marked by institutional plurality, infrastructural path dependence, and contested legitimacy (Adner, 2017; Jacobides et al., 2018; Veldman et al., 2023). RRCI, therefore, does more than rename existing constructs. It specifies a distinct ecosystem property: the extent to which extractive and renewable actors coordinate to convert stranded assets, contested communities, and fragmented governance into regenerative transition capacity.

Table 2. RRCI Dimensions and Sub-Dimensions

Dimension	Sub-dimensions	Description
Inter-firm regenerative alignment	(i) Joint regenerative investment; (ii) extractive infrastructure repurposing; (iii) knowledge and technology interoperability	The extent to which extractive and renewable firms align capital allocation, asset conversion, and technical knowledge to support transition-enabling resource regeneration.
Socio-environmental embedding	(i) Community co-decision; (ii) covenant-backed benefit sharing; (iii) remediation and ecological monitoring	The extent to which coordination is embedded in local participation, distributive inclusion, and verifiable ecological repair, thereby linking transition projects to social acceptance and restoration.
Cross-sectoral resilience integration	(i) Shared infrastructure utilisation; (ii) pooled financial risk management; (iii) policy and disclosure alignment across levels	The extent to which coordination creates long-horizon continuity through shared infrastructures, risk absorption mechanisms, and alignment with local, national, and transnational governance expectations.

The analytical value of these dimensions lies in their joint rather than isolated operation. Inter-firm regenerative alignment captures whether actors commit resources, assets, and technical standards in ways that make repurposing feasible rather than rhetorical (Adner, 2017; Lu et al., 2022; De Angelis and Ianulardo, 2024). Socio-environmental embedding captures whether coordination is anchored in forms of participation, distribution, and remediation that secure local acceptance and reduce the social fragility of transition projects (Brammer and Walker, 2011; Hilson and Maconachie, 2020; Osabuohien et al., 2022). Cross-sectoral resilience integration captures whether coordination extends beyond project execution to the creation of financial, infrastructural, and governance arrangements that preserve system continuity under uncertainty (Williams et al., 2017; Nassar et al., 2022; Veldman et al., 2023). These dimensions define regenerative coordination as an ecosystem property rather than an aggregation of bilateral relationships or isolated firm capabilities.

To explain how coordination strength translates into outcomes, we propose the Multi-Actor Resource Regeneration Systems Framework (MARSF). MARSF positions coordination as the causal mechanism linking extractives-to-renewables ecosystems to three outcome domains: environmental regeneration, community resilience, and ecosystem legitimacy. This framing builds on ecosystem theory's concern with complementarities and structure, while correcting its relative silence on measurement and paradox in extractive transition settings (Adner, 2017; Jacobides et al., 2018). The framework is grounded in what we term the regenerative coordination paradox: extractive systems degrade present socio-ecological conditions, yet the same systems may furnish the infrastructures, revenues, and strategic materials required for renewable transition. The outcome depends not on extractive presence alone, but on whether coordination routines transform extractive legacies into regenerative capacities.

The first outcome domain is community resilience. Community resilience is not treated here as a passive by-product of investment, but as an outcome of coordination arrangements that institutionalise participation, distribute benefits, and reduce exposure to transition-induced exclusion or conflict (Brammer and Walker, 2011; Hilson and Maconachie, 2020; Osabuohien et al., 2022). Where actors coordinate through community co-decision, enforceable benefit-sharing, and remediation commitments, transition projects are more likely to generate adaptive capacity and socio-economic upgrading rather than new forms of vulnerability. This makes socio-environmental embedding theoretically central because it links transition governance to the social conditions under which change can endure.

The second outcome domain is environmental regeneration. Environmental regeneration refers to measurable improvement in ecological conditions through remediation, asset repurposing, waste reduction, and transition-oriented reuse of legacy infrastructures (Williams et al., 2017; Sovacool et al., 2022; De Angelis and Ianulardo, 2024). It is unlikely to arise from isolated firm initiatives because extractive-renewable transitions often depend on cross-firm investment alignment, technical interoperability, and coordinated decisions about infrastructure reuse. For this reason, inter-firm regenerative alignment is theorised as the dimension most directly linked to environmental regeneration, as it captures whether actors jointly mobilise assets and capabilities that go beyond symbolic transition commitments.

The third outcome domain is ecosystem legitimacy. Ecosystem legitimacy refers to the extent to which coordinated transition activity is regarded as appropriate, credible, and governable across local communities, state institutions, financiers, and transnational disclosure regimes (Ansari et al., 2013; Adner, 2017; Veldman et al., 2023). In the present context, legitimacy is not reducible to compliance alone. It also depends on whether

infrastructures are governable, risks are manageable, and disclosures are aligned across scales. Cross-sectoral resilience integration is therefore theorised as the principal route to ecosystem legitimacy because it links local implementation to wider expectations of continuity, due diligence, and accountability.

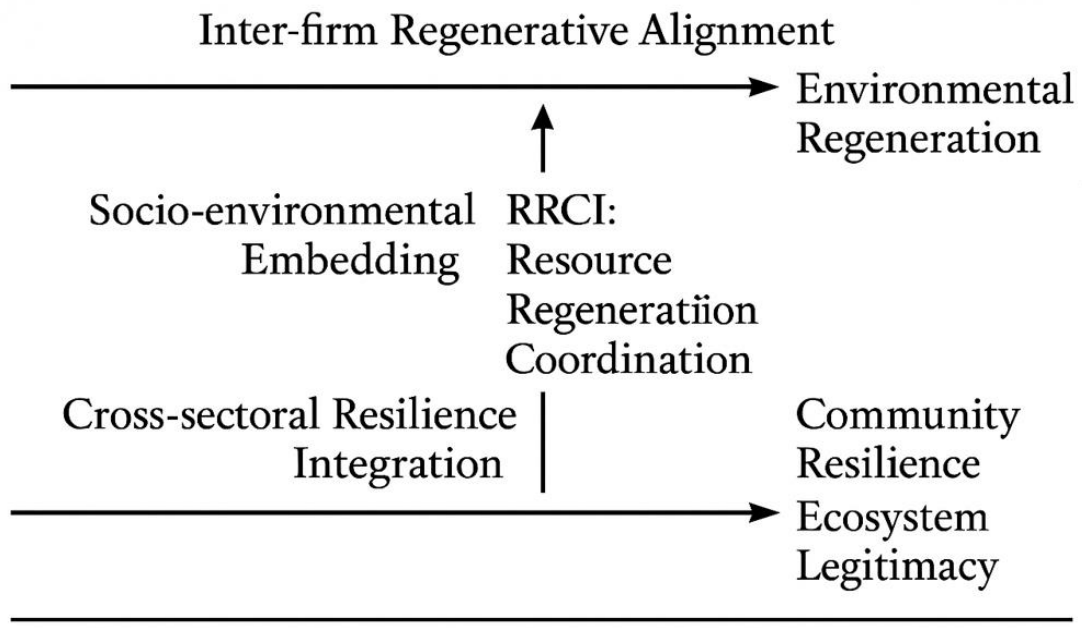

Figure 1. Conceptual logic of MARSF

Figure 1 shows that MARSF is not a generic ecosystem model. It specifies a directional mechanism in which distinct dimensions of coordination are linked to differentiated outcome domains while remaining part of a shared higher-order coordination construct. This design strengthens the theoretical architecture of the study in two ways. First, it avoids conflating all coordination practices into a single undifferentiated process. Second, it clarifies what the field gains conceptually: a measurable account of how coordination quality, rather than actor presence alone, explains whether extractive-renewable ecosystems move toward regeneration, resilience, and legitimacy.

Our framework also extends prior theory more explicitly than the original formulation. Stakeholder theory can explain why benefit-sharing matters, but it cannot explain how benefit-sharing becomes transition-effective when coupled with repurposed infrastructures, pooled guarantees, and disclosure alignment (Brammer and Walker, 2011; Hoejmose and Adrien-Kirby, 2012). Institutional theory can explain external pressures for due diligence and reporting, but it says less about how those pressures are translated into operational continuity under conditions of fragmented governance (Ansari et al., 2013; Veldman et al., 2023). Dynamic capabilities can explain resource reconfiguration, but they do not specify how multiple actors without shared authority coordinate such reconfiguration across a transition ecosystem (Lu et al., 2022). Ecosystem theory captures interdependence, but it has not yet specified how interdependence becomes regenerative in sectors marked by the extractive paradox (Adner, 2017; Jacobides et al., 2018; Liu et al., 2023). RRCI and MARSF address these deficiencies by integrating legitimacy, resource mobilisation, infrastructure conversion, and resilience governance into a single mechanism-based model.

Embedding the framework in Nigeria reinforces its broader theoretical value. Nigeria's extractive-renewable transition is shaped by hydrocarbon dependence, subnational contestation, ecological degradation, infrastructure lock-in, and increasing exposure to external governance expectations (Obi, 2021; Osabuohien et al., 2022; Okafor et al., 2023; Veldman et al., 2023). These features make Nigeria analytically demanding rather than exceptional. They expose coordination problems that are often muted in settings with stronger institutional consolidation. The relevance of RRCI and MARSF, therefore, extends beyond Africa. EU due diligence frameworks and U.S. critical minerals strategies both imply broader coordination needs, yet they do not theorise the extractive paradox as required here (Nassar et al., 2022; Veldman et al., 2023). By positioning Nigeria as an emerging economy where transition governance is visibly contested and infrastructurally path-dependent, the framework gains comparative relevance for other jurisdictions facing similar coordination pressures under different institutional configurations.

Building on this logic, we propose three refined hypotheses.

- H1: Higher levels of inter-firm regenerative alignment will be positively associated with environmental regeneration because coordinated investment, infrastructure repurposing, and technical interoperability increase the likelihood that extractive assets are converted into ecologically restorative transition resources.
- H2: Higher levels of socio-environmental embedding will be positively associated with community resilience because community co-decision, covenant-backed benefit sharing, and remediation commitments strengthen local adaptive capacity and reduce the social fragility of transition projects.
- H3: Higher levels of cross-sectoral resilience integration will be positively associated with ecosystem legitimacy because shared infrastructure, pooled risk management, and multi-level policy and disclosure alignment improve the continuity, credibility, and governability of transition ecosystems.

These hypotheses preserve the directional logic of the original model but tighten the causal rationale by linking each coordination dimension to the outcome domain it is theoretically best positioned to affect. The next section explains how this conceptual model is operationalised through construct refinement, measurement validation, and hypothesis testing within the study's mixed-methods research design.

4. Methodology

4.1. Research design

We employed a sequential mixed-method design that combined qualitative construct development with quantitative validation and theory testing, consistent with established guidance on mixed-method inquiry in management research (Eisenhardt and Graebner, 2007; Venkatesh et al., 2013; Gioia et al., 2013; MacKenzie et al., 2011). This design was appropriate because the study sought both to develop a new ecosystem-level construct, the Resource Regeneration Coordination Index (RRCI), and to test the outcome pathways specified in the Multi-Actor Resource Regeneration Systems Framework (MARSF). The qualitative phase was used to identify and refine the coordination mechanisms underlying the construct, while the quantitative phase was used to assess measurement properties and estimate the structural relations among the focal constructs (Reinartz et al., 2009; Becker et al., 2012; Sarstedt et al., 2019).

The empirical setting is Nigeria's extractives-to-renewables transition, with emphasis on oil and gas asset repurposing and mining activities linked to grid-scale solar and hydrogen value chains, where coordinated action across firms, financiers, regulators, grid actors, and communities is central (Adner, 2017; Jacobides et al., 2018; Obi, 2021). We defined the ecosystem as the unit of analysis and conceptualised it as an interdependent configuration of actors jointly engaged in a transition pathway through linked assets, contractual arrangements, regulatory interfaces, and community-facing obligations (Adner, 2017; Jacobides et al., 2018). Operationally, ecosystem boundaries were drawn around actor constellations connected by a common transition problem, shared infrastructures or resource interfaces, and a recognisable governance architecture spanning commercial, regulatory, and community domains. This boundary rule aligns with the study's focus on coordination routines rather than on any single organisation.

The qualitative setting comprised three Nigerian transition corridors: the Niger Delta, the Middle Belt mining hub, and the national grid-to-independent power producer interface. These corridors were selected to maximise institutional and governance variation rather than to rely solely on geographical spread. The Niger Delta captures hydrocarbon dependence, remediation pressures, and community contestation; the Middle Belt captures mining-linked transition dynamics and local institutional heterogeneity; and the national grid-to-IPP interface captures coordination problems associated with energy infrastructure integration and cross-level regulatory alignment. The three corridors provide variation in asset profiles, governance forms, conflict exposure, and transition logics, thereby strengthening construct development under contrasting institutional conditions.

Because the model theorises ecosystem-level constructs from individual respondents, aggregation was treated as an empirical rather than automatic step (James et al., 1984; Bliese, 2000). Aggregation adequacy was assessed through within-ecosystem agreement and intraclass correlation diagnostics prior to ecosystem-level estimation, alongside ANOVA-based tests of between-group variance. This procedure ensured that the

transition from individual observations to ecosystem-level inference remained consistent with the study's theoretical architecture.

4.2. Qualitative phase: sampling, data collection, and saturation

The qualitative phase consisted of 42 semi-structured interviews conducted across the three corridors and sequenced in four waves of 12, 10, 10, and 10 interviews, respectively, to permit iterative refinement of the interview protocol and progressive assessment of construct boundaries (Eisenhardt and Graebner, 2007; Gioia et al., 2013; Gehman et al., 2018). Participants were drawn from oil and gas operators, transition-minerals mining actors, renewable IPPs, EPC firms, financiers, regulators, grid or distribution actors, and community leaders, reflecting the ecosystem logic of the study rather than a firm-centred sampling frame. Sampling was purposive, with maximum variation in orientation, and focused on governance forms such as joint ventures, PPPs, cooperative arrangements, and project-finance structures, because the study sought variation in coordination routines rather than statistical representativeness.

Interview prompts focused on coordination mechanisms, including joint planning, benefit sharing, data exchange, repurposing logistics, remediation commitments, infrastructure interfaces, and community consent. Interviews were audio-recorded, transcribed verbatim, and triangulated with 68 supporting documents, including ESIAs, MoUs, remediation reports, regulatory filings, and corporate materials, to strengthen interpretive reliability and contextual grounding (Bansal and Corley, 2012; Gioia et al., 2013; Gehman et al., 2018). Coding followed the Gioia methodology and produced 29 first-order codes, 11 second-order themes, and 3 aggregate dimensions, aligned with inter-firm regenerative alignment, socio-environmental embedding, and cross-sectoral resilience integration. Two researchers coded independently and resolved disagreements through adjudication, yielding a second-order Cohen's κ of .82, indicating strong intercoder consistency (LeBreton and Senter, 2008; Gehman et al., 2018). Member checks were conducted with 14 participants to verify interpretive fit and refine sectoral terminology before the quantitative stage.

Thematic saturation was assessed at the level of second-order mechanisms. No new second-order mechanisms emerged after Wave 3, and Wave 4 confirmed thematic stability. This sequencing supports the adequacy of the qualitative sample for construct development and strengthens the traceability between interview evidence and later item generation (Gioia et al., 2013; Gehman et al., 2018).

4.3. Item generation and refinement

The qualitative phase served as the basis for item development for the RRCI. Stabilised second-order themes were translated into an initial item pool covering the three RRCI dimensions and their sub-dimensions, consistent with accepted procedures for construct specification and content validation (Jarvis et al., 2003; MacKenzie et al., 2011). Expert judges drawn from the interviewee pool and from independent scholarly reviewers assessed item representativeness and wording clarity, while cognitive interviews with five to seven managers were used to identify ambiguities in interpretation before pilot administration. This sequence, from coded mechanism to expert review to cognitive pretesting, linked the inductive emergence of constructs to formal scale-development procedures.

Item refinement was guided jointly by conceptual fit and empirical performance. Items were revised, merged, or removed when they did not adequately represent the intended domain, generated comprehension problems during cognitive interviewing, or showed weak performance in pilot-stage factor-analytic diagnostics. This approach ensured that the retained items were both theoretically grounded and empirically defensible.

4.4. Quantitative phase: survey design, sample, and screening

The quantitative phase surveyed 372 ecosystem participants embedded in Nigerian extractives-to-renewables systems, spanning operators, renewable developers, EPC firms, financiers, regulators, grid actors, and community-facing managers. Recruitment combined professional associations, cluster registries, and partnership networks, with personalised invitations and follow-ups designed to mitigate nonresponse bias (Kumar et al., 1993; Armstrong and Overton, 1977). This respondent profile was appropriate to the unit of analysis because ecosystem coordination is observed through actors occupying different structural positions

within the transition system. Early-late response comparisons indicated no statistically significant differences on the focal constructs, suggesting limited nonresponse bias under the extrapolation logic commonly used in survey research (Armstrong and Overton, 1977; Rogelberg and Stanton, 2007).

The questionnaire incorporated procedural remedies against common method bias through temporal separation of predictor and outcome blocks, psychological separation in instructions, varied response formats, and a theoretically unrelated marker variable, followed by statistical assessment through marker-variable and latent-method-factor checks (Podsakoff et al., 2003; Lindell and Whitney, 2001; MacKenzie et al., 2011). Missingness was low, below 2% per item, and was handled through full-information maximum likelihood in the covariance-based stage and screened-listwise treatment in the PLS stage, where appropriate (Enders, 2010; Newman, 2014). Skewness, kurtosis, and Mardia diagnostics did not indicate problematic departures from distributional assumptions for the covariance-based stage, while the later PLS stage was less distribution-sensitive by design (Finney and DiStefano, 2013; Reinartz et al., 2009). These screening procedures strengthened the quantitative phase by combining diagnostic discipline with estimator fit (Table 3).

Table 3. Core methodological facts

Element	Specification
Research design	Sequential mixed-method design
Qualitative sample	42 interviews across 4 waves (12, 10, 10, 10)
Transition corridors	Niger Delta; Middle Belt mining hub; national grid to IPP interface
Documentary triangulation	68 documents
Coding structure	29 first-order codes; 11 second-order themes; 3 aggregate dimensions
Intercoder reliability	Cohen's $\kappa = .82$
Member checks	14 participants
Quantitative sample	N = 372
Measurement strategy	Reflective CFA plus higher-order composite PLS-SEM
Predictive checks	PLSpredict, MICOM, MGA, Gaussian copula sensitivity analysis

4.5. Measurement strategy and model specification

The measurement stage followed a two-step logic. First, a reflective CFA model was estimated for the nine RRCI sub-dimensions and the three outcome constructs, consistent with scale-development protocols that separate measurement confirmation from subsequent structural testing (Jarvis et al., 2003; MacKenzie et al., 2011). Model fit was strong: $\chi^2/df = 2.11$; CFI = .961; TLI = .952; RMSEA = .055; SRMR = .041. Standardised loadings exceeded .70 for retained items, composite reliability ranged from .84 to .93, and AVE ranged from .57 to .72, while HTMT values were below .85 with bootstrapped confidence intervals excluding 1.00, supporting convergent and discriminant validity (Fornell and Larcker, 1981; Henseler et al., 2015; Hair et al., 2017; Voorhees et al., 2016). A latent method factor explained less than 2 per cent additional variance, and the marker-variable adjustment was non-significant, suggesting that common method bias was unlikely to account for the substantive findings.

Second, the higher-order RRCI construct was modelled as a two-stage composite in PLS-SEM, using the three lower-order dimensions as components. This mixed reflective-composite specification is theoretically coherent because the lower-order items were treated as manifestations of narrower latent constructs, whereas the higher-order RRCI was theorised as an emergent coordination configuration formed by conceptually distinct but complementary dimensions (Becker et al., 2012; Dijkstra and Henseler, 2015; Sarstedt et al., 2019). Inter-firm regenerative alignment, socio-environmental embedding, and cross-sectoral resilience integration were therefore not treated as interchangeable manifestations of a single latent trait but as constituent dimensions whose combination defines the strength of ecosystem-level coordination.

The manuscript also compared the retained higher-order model with alternative formulations that relied only on separate dimensions. Those alternative models yielded weaker explanatory and predictive performance, supporting the retained specification of RRCI as a higher-order composite rather than a loose bundle of independent coordination variables.

4.6. Aggregation and structural estimation

After measurement validation, structural relations were estimated using PLS-SEM to prioritise explanatory power and out-of-sample prediction, in line with the study's causal-predictive objective (Reinartz et al., 2009; Shmueli and Koppius, 2011; Shmueli et al., 2019). The model linked the three lower-order coordination dimensions to environmental regeneration, community resilience, and ecosystem legitimacy, while including control variables for firm size, ownership, segment, respondent function, region, exposure to EU due diligence, and conflict risk. Bootstrapping with 10,000 resamples yielded significant positive paths for all focal hypotheses: IRA → ERE, $\beta = .46$, $t = 9.21$, $p < .001$; SEE → CRO, $\beta = .58$, $t = 12.44$, $p < .001$; CRI → EL, $\beta = .52$, $t = 10.87$, $p < .001$, with $R^2 = .48$, .55, and .51, respectively. Effect sizes and Q^2 statistics were also positive, indicating substantive explanatory and predictive relevance.

Predictive assessment through PLSpredict indicated better out-of-sample performance than linear benchmarks for all three outcomes, while MICOM procedures supported partial measurement invariance across the three ecosystem archetypes prior to multigroup analysis (Henseler et al., 2016; Shmueli et al., 2019). MGA showed stronger path coefficients for different mechanisms across repurposing-led, mining-to-renewables, and IPP-grid configurations, consistent with the qualitative sequencing logic. Endogeneity was probed using Gaussian copula diagnostics and a CB-SEM comparison, both of which suggested that the main results were not artefacts of specification choice or omitted-variable bias (Park and Gupta, 2012; Hult et al., 2018). This combination of explanatory, predictive, invariance, and endogeneity checks strengthens the model's inferential credibility by demonstrating that it was evaluated from multiple analytical angles (Table 4).

Table 4. Measurement architecture

Design choice	Rationale
Reflective CFA for lower-order sub-dimensions	Items are treated as manifestations of narrower coordination and outcome constructs
Higher-order composite RRCI in PLS-SEM	RRCI is theorised as an emergent ecosystem property formed by three distinct coordination dimensions
CB-SEM followed by PLS-SEM	Confirmation first, prediction and hierarchical modelling second
Alternative-specification comparison	Supports the higher-order composite formulation of RRCI

4.7. Ethical considerations and reproducibility

Because the study involved interviews and survey responses from human participants, the research process incorporated consent, confidentiality, and de-identification principles appropriate to human-participant inquiry. Participant-facing procedures were aligned with accepted norms for voluntary participation, confidentiality, and the careful handling of organisationally sensitive information. The qualitative stage further reduced disclosure risk by combining role-based reporting with anonymised quotations and by maintaining an audit trail that separated analytical documentation from personally identifying material.

The study also adopted a relatively high standard of reproducibility (Table 5). It reports a preregistered quantitative analysis plan, an audit trail for the qualitative stage, de-identified material-sharing subject to confidentiality constraints, and a traceable path from first-order codes to second-order themes and then to construct formation (Gehman et al., 2018; Aguinis and Solarino, 2019). These features make the methodology more than a procedural description. They establish a documentable research architecture through which the development of RRCI can be followed from empirical observation to validated measurement.

Table 5. Reproducibility and transparency features

Feature	Implementation
Qualitative traceability	Gioia's data structure linking first-order terms, second-order themes, and aggregate dimensions
Coding transparency	Independent coding, adjudication, $\kappa = .82$, maintained audit trail
Member validation	14 participant checks
Quantitative transparency	Preregistered analysis plan and reported screening, validity, and prediction diagnostics
Data sharing	De-identified materials shared are subject to confidentiality constraints

5. Qualitative Analysis

5.1. Dataset and thematic saturation

We conducted 42 semi-structured interviews across three Nigerian transition corridors, namely the Niger Delta, the Middle Belt mining hub, and the national grid to independent power producer interface, in order to capture ecosystem-level coordination routines linking extractives and renewables under contrasting governance and infrastructure conditions (Eisenhardt and Graebner, 2007; Adner, 2017; Jacobides et al., 2018). Participants included oil and gas operators, transition-minerals miners, renewable IPPs, EPC firms, financiers, regulators, grid or distribution actors, and community leaders, which ensured that the analysis reflected the distributed structure of the ecosystem rather than the perspective of a single actor class (Adner, 2017; Jacobides et al., 2018). The three corridors were selected not simply for sectoral spread, but because they captured meaningful variation in hydrocarbon dependence, mining-linked transition activity, infrastructure integration, conflict exposure, and the relative salience of formal and informal governance. This design allowed the study to identify coordination mechanisms that recur across settings while also observing how they vary under different institutional pressures (Ketokivi and Choi, 2014; Gehman et al., 2018).

Sampling followed a maximum-variation purposive logic across governance forms, including joint ventures, PPPs, cluster cooperatives, and project-finance SPVs, because the objective was to surface the organisational routines through which regenerative coordination is accomplished rather than to estimate population parameters (Eisenhardt and Graebner, 2007; Ketokivi and Choi, 2014). Interviews were conducted in four waves of 12, 10, 10, and 10 participants, enabling iterative refinement of prompts and progressive assessment of the emergence of mechanisms (Gioia et al., 2013; Gehman et al., 2018). Interviews averaged 74 minutes, were audio-recorded and transcribed verbatim, and were triangulated with 68 supporting documents, including ESIAs, MoUs, remediation reports, regulatory filings, and related project materials, thereby strengthening interpretive reliability through convergence across talk, text, and documented practice (Bansal and Corley, 2012; Ketokivi and Choi, 2014; Gehman et al., 2018).

Thematic saturation was assessed at the level of second-order mechanisms rather than raw descriptive statements. No new second-order mechanisms emerged after Wave 3, and Wave 4 confirmed thematic stability rather than producing additional aggregate dimensions. This is important because the study's aim was to stabilise mechanism-level categories that could later underpin item generation for the RRCI, not merely to accumulate additional quotations (Gioia et al., 2013; Gehman et al., 2018). The saturation logic, therefore, supports the adequacy of the qualitative sample for construct development and reinforces **the credibility of the subsequent transition from qualitative evidence to measurement design.**

5.2. Coding protocol and qualitative data structure

We used the Gioia methodology to build a transparent data structure linking first-order informant terms to second-order themes and then to aggregate dimensions, thereby connecting raw field material to the conceptual architecture of RRCI and MARSF (Gioia et al., 2013; Bansal and Corley, 2012). Two researchers independently open-coded the transcripts, met weekly to refine the codebook, and maintained an audit trail consisting of versioned memos, adjudication logs, and stability checks, which supported both traceability and reproducibility (Gehman et al., 2018; Aguinis and Solarino, 2019). After two coding rounds, intercoder agreement at the second-order level reached Cohen's $\kappa = .82$, indicating strong coding consistency, while residual discrepancies were resolved through adjudication in line with established guidance on agreement and interrater reliability (James et al., 1984; LeBreton and Senter, 2008).

The final data structure (Table 6) comprised 29 first-order codes, 11 second-order themes, and 3 aggregate dimensions, corresponding to Inter-firm Regenerative Alignment (IRA), Socio-environmental Embedding (SEE), and Cross-sectoral Resilience Integration (CRI). This structure is analytically significant because it shows that the proposed dimensions were not imposed deductively on the data. Rather, they emerged through repeated clustering of mechanism-level evidence across multiple actor groups and corridor settings. In this sense, the qualitative analysis did not merely illustrate the framework. It generated the mechanism map from which the framework could be specified and later tested.

Table 6. Qualitative data structure

Layer	Content	N	Illustrative exemplars
First-order codes	Informant-centred terms describing coordination practices	29	"joint SPV for solar"; "convert idle pipeline"; "co-designed grievance"; "pooled guarantee"; "grid intertie sharing"
Second-order themes	Mechanism-level categories derived from cross-case coding	11	JV co-investment; stranded-asset repurposing; standards harmonisation; community co-decision; covenant-backed benefit sharing; third-party remediation audits; shared emergency procedures; pooled risk instruments; multi-level disclosure alignment
Aggregate dimensions	Higher-order coordination dimensions	3	IRA; SEE; CRI

5.3. Integrated coordination logic and mechanism elaboration

5.3.1. Inter-firm Regenerative Alignment (IRA) IRA emerged as the first aggregate dimension and captures the degree to which extractive and renewable actors align capital, assets, and technical standards in ways that make transition projects feasible rather than aspirational (Adner, 2017; Williams et al., 2017). Across all three corridors, co-investment vehicles such as joint SPVs and cost-sharing agreements repeatedly appeared as the initial mechanism that reduced financing barriers for asset-heavy renewable projects by spreading risk and aligning project time horizons across otherwise heterogeneous actors (Adner, 2017; Jacobides et al., 2018). One EPC manager stated: *"Our gas-export JV shifted 15% of capex into a shared SPV for a 90-MW solar farm at the terminal; without the JV's balance sheet, the IPP would not have cleared financing."* This quotation is not used merely illustratively. It indicates that capital alignment served as a precondition for subsequent transition activity, particularly when renewable sponsors alone could not absorb early-stage project risk.

A second IRA mechanism concerned the repurposing of extractive infrastructure through codified technical and legal arrangements, including conversion studies, tariff agreements, and liability-sharing clauses. These arrangements turned potentially stranded assets into transition enablers and reduced lead times for project execution, consistent with systems-oriented views that path dependence can be redirected rather than simply abandoned (Williams et al., 2017; Weaver et al., 2025). A joint-venture director explained this logic directly: *"The only way to justify converting the disused pipeline was a shared tariff with the hydrogen off-taker; that required a pooled SPV and credit support from both sides."* What is analytically important here is that repurposing was not a purely technical issue. It depended on contractual alignment and shared financial commitment, which supports treating repurposing as a coordination mechanism rather than a stand-alone engineering decision.

A third IRA mechanism involved knowledge and technology interoperability. Joint engineering teams, open interface standards, and shared data rooms reduced redesign risk and enabled multiple sponsors to interconnect on compatible terms, which mirrors research showing that capability recombination and standardisation are central to multi-actor execution under uncertainty (Gioia et al., 2013; Lu et al., 2022). An IPP executive put this succinctly: *"We opened our inverter specs and proposed a common intertie standard so the converted oil terminal can host both solar and storage without custom retrofits."* The qualitative evidence suggests that IRA is constituted by a linked sequence of capital alignment, repurposing discipline, and technical interoperability. These mechanisms jointly convert idle extractive assets into transition platforms and therefore explain why IRA is theoretically proximate to environmental regeneration.

5.3.2. Socio-environmental Embedding (SEE) If IRA made projects feasible, SEE made them governable. SEE captures the extent to which coordination is embedded in participation, benefit distribution, and ecological accountability rather than confined to commercial alignment among project sponsors (Bansal and Corley, 2012; Grewatsch et al., 2023). A recurrent mechanism across the cases was the move from consultation to co-decision, whereby community representatives participated in design forums rather than being engaged only after major technical choices had already been made. One community leader stated: *"Our representatives sit in the design forum, not just at 'public hearing day'; when flood-risk maps were shared, we shifted the solar pad by 400 meters and avoided a seasonal swamp."* This example is analytically important

because it shows that local knowledge entered the project as a design input, thereby converting participation from symbolic legitimacy work into a functional coordination routine.

A second SEE mechanism involved covenant-backed benefit sharing. Interviewees repeatedly described how local jobs, SME participation, and revenue-sharing arrangements gained credibility when embedded as enforceable covenants in permits, financing conditions, or milestone-based disbursement structures. A DFI officer explained the mechanism as follows: *"Benefit-sharing is now a covenant, miss the SME target and disbursement pauses; it changed how EPCs source locally."* This evidence indicates that distributive inclusion became consequential when attached to enforceable financial and regulatory instruments. The implication is that, in this setting, benefit sharing cannot be adequately understood as discretionary CSR. It functioned as a governance routine that shaped procurement behaviour and local acceptance.

A third SEE mechanism concerned remediation with independent monitoring. Funded remediation plans, third-party audits, and tracking of ecological indicators converted legacy liabilities into measurable environmental obligations rather than rhetorical commitments (Gehman et al., 2018; Williams et al., 2017). Across the cases, SEE therefore operated as a distributional and ecological discipline on IRA. Where co-investment and repurposing advanced without co-decision and enforceable covenants, protest, delay, and mistrust were recurrent. Where they advanced together, the process flowed more smoothly, and implementation was more stable. The qualitative evidence thus supports interpreting SEE as the mechanism by which transition projects become socially and ecologically tenable, thereby explaining its conceptual linkage to community resilience.

5.3.3. Cross-sectoral Resilience Integration (CRI) CRI emerged as the third aggregate dimension and captures the extent to which actors create long-horizon continuity through shared infrastructures, pooled financial protections, and alignment across governance levels (Williams et al., 2017; Weaver et al., 2025). In contrast to IRA, which concerns making projects feasible, and SEE, which concerns making them acceptable, CRI concerns making them durable. A recurrent mechanism here was the utilisation of shared infrastructure, especially common interties, joint shutdown procedures, and coordinated operating rules across repurposed and newly built assets. A grid operator explained this point directly: *"We scripted one emergency-shutdown protocol for both the repurposed terminal and the new IPP; drills cut restart times by half."* This indicates that resilience was not treated as a residual property of better infrastructure. It was produced through joint routines that turned multi-sponsor assets into a single operating system.

A second CRI mechanism involved pooled reserves, guarantees, and other risk-sharing clauses designed to stabilise cash flows under volatility. A project-finance banker stated: *"A pooled reserve and partial risk guarantee pulled in two hesitant sponsors; absent pooling, the PPA would not have closed."* This illustrates that pooled risk management acted as a coordination device that widened participation and preserved continuity under uncertainty, rather than simply as a financial add-on. In settings marked by asset-stranding concerns and governance heterogeneity, such arrangements reduced the fragility of transition investment.

The third CRI mechanism was the alignment of policy and disclosure across local, national, and transnational levels. Interviewees repeatedly linked local permits and community approvals to national plans and export-facing disclosure requirements, especially where projects were exposed to EU-linked buyer expectations or lender due diligence standards (Adner, 2017; Grewatsch et al., 2023). This linkage matters because it shows that legitimacy at the ecosystem level depended not only on local acceptance but also on whether the coordinated system could present itself as governable and reportable to external audiences. CRI therefore protects the gains produced by IRA and SEE over time by linking operational continuity to risk absorption and governance coherence.

5.4. Archetypes and negative cases

Cross-case synthesis revealed three ecosystem archetypes that combined IRA, SEE, and CRI in distinct sequences: Repurposing-led ecosystems (IRA-RI → CRI-IC/FR → SEE), Mining-to-Renewables hubs (SEE-BS/ER → IRA-JI/KT → CRI-PA), and IPP-grid integrators (CRI-PA/IC → IRA-KT/JI → SEE-CI). These archetypes indicate that the same aggregate dimensions matter across settings, but that they do not enter in identical temporal order (Adner, 2017; Jacobides et al., 2018). In a repurposing-led case, the sequence began with tariffed asset conversion backed by a pooled SPV, followed by shared interties and pooled reserves, and

only then a formalised community pact once grid access had been secured. This sequence produced the fastest commissioning times but also showed that rapid technical and financial alignment can generate later legitimacy strain if SEE is deferred.

In a mining-linked case, by contrast, seated co-decision and auditable remediation preceded later co-investment in shared processing and PV supply. Here, SEE functioned as the gateway mechanism because access and trust had to be stabilised before capital alignment could proceed. This sequence reduced stoppages but lengthened early-stage negotiation. In grid-integrator settings, policy alignment and standardised interties were negotiated first, thereby enabling joint engineering and co-financing, with SEE introduced subsequently through procurement covenants. These differences show that regenerative coordination is not a fixed linear process. It is configurational, and its operative sequence depends on which constraint is most binding in a given ecosystem.

Negative cases sharpened the boundaries of the framework. A pipeline conversion failed where liability-sharing was omitted from the MOU and community channels remained advisory rather than co-designed, indicating that IRA-RI without SEE-CI or SEE-ER is brittle even when engineering feasibility exists (Bansal and Corley, 2012; Gioia et al., 2013). In a mining cluster, guarantees were available, but local procurement targets were not anchored in permits, and pooled finance did not alter sourcing behaviour. This negative case shows that CRI-FR requires CRI-PA to translate financial protection into implementation discipline. These boundary conditions strengthen the argument that the three dimensions are complementary rather than substitutable.

5.5. From mechanisms to measures

We triangulated interview evidence with ESIA excerpts, remediation audits, MoUs, and procurement dashboards to verify the presence of each routine before translating them into sub-dimensions of the RRCI, consistent with guidance on qualitative credibility, transparency, and theory-method fit (Bansal and Corley, 2012; Pratt, 2009; Gehman et al., 2018). Member checks with 14 participants sharpened survey wording and aligned item phrasing with sector usage, including terms such as “pooled reserve” and “co-decision forum,” thereby improving content validity before the quantitative stage (Gioia et al., 2013; Gehman et al., 2018). We also maintained a disclosure-ready audit trail comprising protocol versions, codebook lineage, adjudication logs, and quote provenance, in line with contemporary expectations for qualitative transparency (Aguinis and Solarino, 2019).

The resulting construct-mechanism-item map is analytically coherent. IRA is evidenced by co-investment routines, repurposing milestones, and knowledge-sharing or interoperability practices, which together support environmental regeneration through asset reuse and aligned technical execution (Adner, 2017; Williams et al., 2017). SEE is evidenced by co-decision, covenant-backed benefit sharing, and third-party remediation, which support community resilience through predictable inclusion and grievance reduction (Bansal and Corley, 2012; Grewatsch et al., 2023). CRI is evidenced by shared interties and emergency routines, pooled financial protections, and multi-level policy or disclosure alignment, which support ecosystem legitimacy by delivering continuity and externally credible governance (Williams et al., 2017; Weaver et al., 2025). This traceability is important because it shows that the later quantitative specification of RRCI did not begin with abstract dimensions and then search for empirical support. Rather, the dimensions were induced from mechanism-level evidence and only then formalised for measurement.

Informants also linked these routines to export-facing due diligence and lender covenants. They observed that meeting EU-style multi-tier expectations simplified offtake negotiations, while local legitimacy still depended on seated representation and auditable remediation. This combination indicates that ecosystem coordination in Nigeria was shaped simultaneously by local acceptance and by transnational governance demands. Respondents further highlighted asset-stranding risk as a trigger for co-investment and risk pooling, which reinforces the point that IRA-RI and CRI-FR are not optional embellishments but stabilising mechanisms in resource-dependent transition settings (Okafor et al., 2023; Ketokivi and Choi, 2014).

6. Quantitative Analysis

6.1. Data screening

We analysed a cross-sectional survey of 372 ecosystem participants in Nigeria, including operators, renewable developers, EPC firms, financiers, regulators, grid actors, and community-facing managers, which is consistent with an ecosystem-as-structure view of interdependent coordination (Adner, 2017; Jacobides et al., 2018). Early- and late-responder comparisons across the focal constructs of inter-firm regenerative alignment (IRA), socio-environmental embedding (SEE), cross-sectoral resilience integration (CRI), environmental regeneration (ERE), community resilience (CRO), and ecosystem legitimacy (EL) revealed no statistically significant differences, indicating limited nonresponse bias under the extrapolation approach (Armstrong and Overton, 1977; Rogelberg and Stanton, 2007). The instrument incorporated procedural remedies against common method variance through temporal and psychological separation, varied scale formats, and the inclusion of a theoretically unrelated marker block, in line with established survey-design guidance (Podsakoff et al., 2003; MacKenzie et al., 2011). We also estimated an unmeasured latent method factor at the confirmatory stage to assess residual common method effects, which is an appropriate diagnostic for cross-sectional designs (Lindell and Whitney, 2001; Podsakoff et al., 2003).

Item distributions exhibited acceptable skewness and kurtosis, and Mardia's coefficients did not indicate problematic multivariate non-normality for the covariance-based stage, while the later PLS-SEM stage was less distribution-sensitive by design (Finney and DiStefano, 2013; Reinartz et al., 2009). Missingness was low, below 2 per cent per item, and was handled through full-information maximum likelihood in the CFA stage and screened-listwise treatment in the PLS stage, where appropriate (Enders, 2010; Newman, 2014). These diagnostics suggest that the data were suitable for a dual-estimator strategy in which CFA was used to confirm lower-order measurement properties, and PLS-SEM was used to estimate the higher-order composite and assess predictive performance.

6.2. Measurement model: confirmatory analysis, validity, and higher-order specification

We first estimated a reflective CFA model for the nine RRCI sub-dimensions grouped under the three lower-order dimensions of IRA, SEE, and CRI, together with the three outcome constructs ERE, CRO, and EL, following scale-development guidance that separates measurement confirmation from subsequent structural estimation (Jarvis et al., 2003; MacKenzie et al., 2011). This step was necessary because the lower-order sub-dimensions were conceptualised as common-factor constructs whose indicators should co-vary as manifestations of narrower latent domains. The CFA indicated good overall fit: $\chi^2/df = 2.11$; CFI = .961; TLI = .952; RMSEA = .055, 90% CI [.049, .061]; SRMR = .041, which is consistent with accepted benchmarks for covariance-based SEM when interpreted with attention to model complexity and sample characteristics (Hu and Bentler, 1999; Kline, 2016). Standardised factor loadings exceeded .70 for all retained items and were significant at $p < .001$, while item-retention decisions followed both conceptual and statistical criteria to preserve domain coverage (MacKenzie et al., 2011; Worthington and Whittaker, 2006).

Composite reliability ranged from .84 to .93, and AVE ranged from .57 to .72, supporting convergent validity across constructs (Fornell and Larcker, 1981; Hair et al., 2017, Table 7). Discriminant validity was supported by HTMT ratios below .85 for all construct pairs, with bootstrapped 95 per cent confidence intervals not including 1.00, which is the prevailing criterion for discriminant validity in both variance-based and hybrid measurement settings (Henseler et al., 2015; Voorhees et al., 2016). The latent method factor explained less than 2% additional variance and did not materially alter substantive loadings, while the marker-variable partial correlation was non-significant. These results indicate that the lower-order measurement structure is empirically stable and that the observed relations are unlikely to be artefacts of method bias.

Table 7. Descriptive statistics and measurement properties

Construct	Mean	SD	1	2	3	4	5	6	7	8	9	10	11	12	AVE	CR	α
1. IRA_JI	4.98	1.03	—												.61	.88	.86
2. IRA_RI	4.76	1.07	.54	—											.60	.87	.85
3. IRA_KT	5.12	0.96	.51	.49	—										.64	.89	.87
4. SEE_CI	4.71	1.10	.37	.34	.39	—									.57	.84	.82
5. SEE_BS	4.65	1.12	.35	.33	.36	.58	—								.59	.86	.84
6. SEE_ER	4.52	1.14	.31	.35	.32	.49	.55	—							.62	.88	.86
7. CRI_IC	4.94	1.01	.46	.43	.48	.36	.34	.31	—						.63	.89	.87
8. CRI_FR	4.69	1.08	.42	.44	.41	.30	.29	.33	.56	—					.60	.87	.85
9. CRI_PA	4.88	1.05	.44	.39	.45	.36	.34	.32	.53	.50	—				.62	.88	.86
10. ERE	4.83	1.02	.55	.52	.57	.33	.29	.36	.49	.40	.44	—			.66	.90	.88
11. CRO	4.77	1.05	.36	.31	.35	.57	.60	.53	.34	.31	.33	.41	—		.64	.89	.87
12. EL	4.95	0.98	.40	.39	.44	.35	.33	.34	.55	.51	.58	.46	.42	—	.65	.90	.88

Notes: N = 372. Correlations are Pearson coefficients. All $r \geq .29$ are significant at $p < .001$. HTMT values for all construct pairs were below .85.

Although CFA was appropriate for evaluating the lower-order reflective sub-dimensions, the higher-order RRCI was not conceptualised as a latent common factor reflected identically by IRA, SEE, and CRI. Rather, RRCI was theorised as an emergent ecosystem property formed by three distinct yet complementary coordination dimensions. For this reason, we modelled RRCI as a two-stage higher-order composite in PLS-SEM, which is well suited to hierarchical component models and prediction-oriented evaluation where the higher-order construct is composite rather than reflective (Becker et al., 2012; Dijkstra and Henseler, 2015; Sarstedt et al., 2019). In the first stage, the nine sub-dimensions were estimated reflectively and latent scores were saved for the three lower-order dimensions. In the second stage, these lower-order scores were used to form the higher-order composite. This design tightened the study's estimator logic: CFA was used to confirm lower-order common factors, whereas PLS-SEM was used for the higher-order composite and for predictive assessment of the structural model.

To align composite estimates with common-factor interpretations, we used consistent PLS and examined reliability, HTMT, and weights or loadings with bootstrapped inference, following current guidance for hybrid higher-order models built from reflective lower-order constructs (Dijkstra and Henseler, 2015; Henseler et al., 2016). The higher-order specification was not merely technically convenient. It followed directly from the theoretical claim that inter-firm alignment, socio-environmental embedding, and resilience integration are not interchangeable expressions of a single latent trait, but rather constituent dimensions whose combination defines coordination strength at the ecosystem level (Table 8).

Table 8. Measurement summary

Construct	Items retained	Loading range	CR	AVE	HTMT (max)
IRA_JI	4	.73–.88	.88	.61	.78
IRA_RI	4	.72–.86	.87	.60	.76
IRA_KT	4	.75–.89	.89	.64	.79
SEE_CI	4	.71–.84	.84	.57	.82
SEE_BS	4	.72–.86	.86	.59	.80
SEE_ER	4	.74–.88	.88	.62	.79
CRI_IC	4	.76–.88	.89	.63	.77

Notes: All loadings are significant at $p < .001$. HTMT values below .85 indicate satisfactory discriminant validity (Henseler et al., 2015; Hair et al., 2017).

Table 8 (cont.). Measurement summary

Construct	Items retained	Loading range	CR	AVE	HTMT (max)
CRI_FR	4	.72–.85	.87	.60	.75
CRI_PA	4	.74–.87	.88	.62	.78
ERE	4	.77–.89	.90	.66	.70
CRO	4	.75–.88	.89	.64	.74
EL	4	.76–.90	.90	.65	.73

Notes: All loadings are significant at $p < .001$. HTMT values below .85 indicate satisfactory discriminant validity (Henseler et al., 2015; Hair et al., 2017).

6.3. Structural model tests

We estimated the MARSF structural model in PLS-SEM with direct paths from IRA → ERE (H1), SEE → CRO (H2), and CRI → EL (H3), while allowing the three coordination dimensions to covary, consistent with the mechanism-based structure developed conceptually and qualitatively (Sandberg and Alvesson, 2021; De Angelis and Ianulardo, 2024). Control variables included firm size, ownership, segment, respondent function, region, exposure to EU due diligence requests, and conflict risk, which are plausible contextual influences in sustainability operations settings (Lu et al., 2022; Veldman et al., 2023). Bootstrapping with 10,000 resamples yielded significant positive effects for all three focal paths: IRA → ERE, $\beta = .46$, $t = 9.21$, $p < .001$; SEE → CRO, $\beta = .58$, $t = 12.44$, $p < .001$; CRI → EL, $\beta = .52$, $t = 10.87$, $p < .001$. Endogenous explained variance was substantial, with $R^2 = .48$ for ERE, .55 for CRO, and .51 for EL (Reinartz et al., 2009; Hair et al., 2017). Effect sizes were $f^2 = .35$, .47, and .39, respectively, while Stone-Geisser's Q^2 values of .32, .37, and .34 indicated predictive relevance for all endogenous constructs (Chin, 1998; Shmueli et al., 2019).

These results (Table 9) show that the three lower-order coordination dimensions are not merely correlated with desirable outcomes in a diffuse manner. Each dimension exhibits its strongest empirical association with the theoretically matched outcome domain specified in the conceptual model. This correspondence strengthens the internal coherence of MARSF and supports the view that the higher-order RRCI is underpinned by differentiated rather than redundant mechanisms.

Table 9. Structural paths

Path	β	t	p	f^2	Q^2	R^2 (endogenous)
IRA → ERE (H1)	.46	9.21	< .001	.35	.32	.48
SEE → CRO (H2)	.58	12.44	< .001	.47	.37	.55
CRI → EL (H3)	.52	10.87	< .001	.39	.34	.51
Controls → outcomes	mixed	—	ns–.05	—	—	—

Notes: 10,000 bootstrap resamples. Bias-corrected confidence intervals excluded zero for all focal paths. Controls included size, ownership, segment, function, region, EU due diligence exposure, and conflict risk.

We then assessed case-level predictive performance using PLSpredict with 10-fold cross-validation and one-step-ahead holdouts, which supplements explanatory fit with out-of-sample evidence (Shmueli and Koppius, 2011; Shmueli et al., 2019). For all three outcomes, PLS RMSE values were lower than linear benchmark RMSE values for the majority of indicators, specifically ERE: 4/4; CRO: 4/4; EL: 4/4, and MAE improvements exceeded 5 per cent on average (Shmueli et al., 2019; Sarstedt et al., 2019). This is an important result because it indicates that the RRCI-based representation of coordination strength has practical forecasting value and is not limited to retrospective variance explanation. In other words, the construct performs not only as a theoretically meaningful representation of coordination but also as a predictive tool with potential managerial and policy relevance.

Next, we examined the measurement invariance of composites using MICOM across the three qualitative archetypes of Repurposing-led ecosystems, Mining-to-Renewables hubs, and IPP-grid integrators, which is

required before comparing group-specific path relations (Henseler et al., 2016; Cheah et al., 2018). Configural conditions were satisfied through identical indicators and equivalent data treatment, and permutation tests indicated compositional invariance and equality of means and variances sufficient for partial measurement invariance (Henseler et al., 2016; Sarstedt et al., 2019). MGA then showed that IRA → ERE was stronger in Repurposing-led ecosystems (Δβ = .14, p_perm = .018), SEE → CRO was stronger in Mining-to-Renewables hubs (Δβ = .12, p_perm = .026), and CRI → EL was stronger in IPP-grid integrators (Δβ = .11, p_perm = .031) (Ringle et al., 2015; Ketokivi and Choi, 2014).

The multigroup contrasts (Table 10) are theoretically consequential because they indicate that the same coordination dimensions matter across ecosystem types, but not with equal intensity. Mechanisms appear most powerful where they are functionally first in the sequencing logic identified in the qualitative analysis. This pattern gives empirical support to the claim that regenerative coordination is configurational rather than uniform across transition contexts.

Table 10. MICOM and multigroup contrasts

Test	Repurposing-led vs Mining-to-Renewables	Repurposing-led vs IPP-Grid	Mining-to-Renewables vs IPP-Grid	Decision
Compositional invariance (all composites)	yes	yes	yes	Invariance supported
Equal means/variances (α = .05)	yes	yes	yes	Partial invariance
Δβ: IRA → ERE	+.14*	+.11†	+.03	Stronger in Repurposing-led
Δβ: SEE → CRO	−.12*	−.05	+.07	Stronger in Mining-to-Renewables
Δβ: CRI → EL	−.03	−.11*	−.08†	Stronger in IPP-Grid Integrators

Notes: Group sizes were approximately 120–130 each. *p_perm < .05. †p_perm < .10. MICOM stages 1–3 supported partial invariance.

Because non-experimental structural models remain vulnerable to omitted-variable bias, we estimated Gaussian copula corrections for each focal relationship and found no significant copula terms, suggesting limited endogeneity after accounting for these risks (Park and Gupta, 2012; Hult et al., 2018). As an additional specification check, we estimated a CB-SEM structural model using the same latent architecture and obtained comparable standardised path coefficients, indicating estimator consistency rather than dependence on a single modelling family (Reinartz et al., 2009; Kline, 2016). Models omitting the higher-order RRCI and relying solely on lower-order dimensions showed weaker explanatory and predictive performance, further supporting the conceptual and empirical value of the composite representation (Becker et al., 2012; Sarstedt et al., 2019).

The quantitative analysis provides three forms of support for the proposed model. First, the lower-order measurement structure is empirically sound. Second, the higher-order composite formulation of RRCI is theoretically and statistically defensible. Third, the structural paths, predictive tests, invariance checks, and endogeneity diagnostics collectively indicate that regenerative coordination is not an artefactual summary label, but a measurable ecosystem property associated with environmental regeneration, community resilience, and ecosystem legitimacy. The stronger legitimacy effects associated with policy and disclosure alignment also suggest that CRI_PA functions as an especially consequential coordination lever in export-oriented ecosystems exposed to multi-tier governance demands, which is consistent with contemporary work on due diligence and transnational accountability (Veldman et al., 2023; De Angelis and Ianulardo, 2024).

7. Discussion

This study advances sustainability and operations scholarship by showing that regenerative coordination is not merely a descriptive label for collaboration, but a measurable ecosystem property that conditions whether extractive legacies become transition liabilities or transition platforms (Adner, 2017; Williams et al., 2017; De

Angelis and Ianulardo, 2024). By validating the Resource Regeneration Coordination Index (RRCI) as a higher-order composite comprising inter-firm regenerative alignment, socio-environmental embedding, and cross-sectoral resilience integration, the study moves beyond firm-centred capability accounts and provides an empirically tractable way to capture system-level coordination strength (Jacobides et al., 2018; Lu et al., 2022; Weaver et al., 2025). The central contribution, therefore, lies not only in identifying relevant coordination mechanisms but in demonstrating that these mechanisms can be specified as an ecosystem construct with differentiated and predictable consequences for environmental regeneration, community resilience, and ecosystem legitimacy.

The findings also sharpen the theoretical meaning of the regenerative coordination paradox. Prior work has acknowledged that extractive sectors can both obstruct and enable low-carbon transition, yet this duality has often remained at the level of contextual tension rather than explanatory mechanism (Williams et al., 2017; Sovacool et al., 2022; Liu et al., 2023). The present study shows that extractive assets do not become transition-enabling by virtue of repurposability alone. They do so only when capital alignment, socio-environmental embedding, and resilience integration cohere in a way that renders repurposing investable, governable, and durable. This is a more disciplined formulation than generic claims about collaboration because it identifies the organisational conditions under which paradoxical infrastructures shift from degenerative to regenerative roles (Adner, 2017; Jacobides et al., 2018; De Angelis and Ianulardo, 2024).

A further theoretical contribution concerns the matched outcome logic of the three dimensions. The empirical results indicate that inter-firm regenerative alignment is most strongly associated with environmental regeneration, socio-environmental embedding with community resilience, and cross-sectoral resilience integration with ecosystem legitimacy. This pattern matters because it suggests that coordination is not a single undifferentiated capability. It is internally structured, and its constituent dimensions exhibit domain-specific explanatory relevance. Consequently, the study refines systems thinking by moving from broad claims about interdependence to a more specific account of which forms of coordination matter for which forms of outcomes (Williams et al., 2017; Grewatsch et al., 2023; Weaver et al., 2025). The archetype further strengthens this point by showing that the same coordination dimensions matter across ecosystems, but with varying intensities depending on sequencing and structural position. Regenerative coordination is therefore not uniform across transition settings. It is configurational.

The Multi-Actor Resource Regeneration Systems Framework (MARSF) contributes to theory by integrating, but not collapsing into, adjacent perspectives. Within stakeholder theory, MARSF moves beyond dyadic legitimacy management by showing that participation and benefit-sharing matter most when tied to capital allocation, infrastructure conversion, and enforcement routines across a broader ecosystem (Brammer and Walker, 2011; Hoejmose and Adrien-Kirby, 2012; Grewatsch et al., 2023). This is not a minor extension. It shifts the analytical focus from whether firms engage stakeholders to how stakeholder inclusion is institutionalised within the execution architecture of transition projects. In this sense, social acceptance is treated not as a peripheral reputational asset, but as an operational condition of ecosystem performance.

Relative to circular economy scholarship, MARSF extends the idea of closing loops from intra-sectoral material recirculation to cross-sectoral repurposing of infrastructures, interfaces, and technical standards (Kump and Fikar, 2021; Lu et al., 2022; De Angelis and Ianulardo, 2024). The findings suggest that industrial symbiosis in extractives-to-renewables transitions is not achieved solely through material reuse. It requires coordination arrangements that make such reuse contractually credible, financially viable, and socially legitimate. This introduces a governance dimension into circularity that is often underdeveloped when the emphasis rests primarily on technical recovery or waste reduction.

Within institutional theory, the study shows that external rules and due diligence demands do not automatically produce legitimacy- or compliance-capable transition systems (Ansari et al., 2013; Veldman et al., 2023). Rather, policy and disclosure alignment exert their strongest effects when paired with pooled financial protections, shared emergency routines, and local embedding practices. Institutional pressure, in other words, is filtered through the quality of coordination. This is especially important in emerging economies such as Nigeria, where formal regulation coexists with informal governance and community-based authority. MARSF thus contributes a mechanism-based account of how formal expectations become operationally consequential under conditions of institutional plurality.

Relative to ecosystem theory, the main contribution is operationalisation. Ecosystem theory has convincingly shown that complementarities and structural alignment matter, but it has offered fewer tools for measuring coordination strength in empirically testable terms (Adner, 2017; Jacobides et al., 2018). RRCI addresses that limitation by translating ecosystem interdependence into a measurable coordination architecture.

This means that the present study does not simply borrow ecosystem language. It extends ecosystem theory toward the development of constructs and comparative testing, which is essential if the field is to move beyond evocative descriptions of interdependence.

The Nigerian case strengthens the broader relevance of the findings by revealing coordination problems in a setting where hydrocarbon dependence, infrastructure lock-in, local contestation, and transnational governance expectations converge sharply (Obi, 2021; Osabuohien et al., 2022; Okafor et al., 2023; Veldman et al., 2023). Nigeria is, therefore, not simply an empirical backdrop. It is a theoretically demanding setting that exposes the limits of firm-centred and institutionally thin transition accounts. The study's findings suggest that emerging economies should not be treated as lagging recipients of external sustainability models. They are sites where the coordination conditions of transition become unusually visible and analytically productive.

This implication matters for cross-context application. The matched logic between coordination dimensions and outcome domains suggests that the core architecture of regenerative coordination may travel, but that its sequence and intensity will vary across governance environments. The multigroup results indicate that path strengths differ across repurposing-led, mining-linked, and grid-integrator ecosystems, implying that a single coordination profile should not be prescribed universally. Accordingly, the contribution of RRCI is not that it offers a single score with universal meaning, but that it offers a structured profile through which actors can identify which coordination deficit is most constraining in a given transition system. This makes the framework adaptable without making it theoretically loose.

For ministries, regulators, and development financiers, the results imply that support for transition projects should be targeted at coordination bottlenecks rather than distributed as generic sustainability incentives (Veldman et al., 2023; Boute et al., 2025). Where inter-firm regenerative alignment is weak, guarantees for co-investment, asset conversion support, and interface standard harmonisation are likely to matter most. Where socio-environmental embedding is weak, covenant-backed benefit sharing, seated co-decision, and audited remediation should be prioritised. Where cross-sectoral resilience integration is weak, pooled reserves, common operating routines, and disclosure alignment are more likely to raise legitimacy and continuity. The value of RRCI in this regard is diagnostic. It identifies where intervention should occur first.

For firms, developers, EPC contractors, and financiers, the findings indicate that social acceptance is more effectively secured by embedding inclusion and remediation into contracts, milestones, and finance conditions than by relying on peripheral CSR activity (Grewatsch et al., 2023; Williams et al., 2017). Firms can use RRCI-informed dashboards to monitor whether co-investment, repurposing milestones, interoperability standards, co-decision procedures, and pooled risk instruments are present together. The absence of any one of these does not merely reduce symbolic coherence. It weakens transition execution and lengthens delivery timelines. This is particularly relevant to asset repurposing, where there may be a temptation to treat technical conversion as sufficient. The findings suggest otherwise.

For communities and civil-society intermediaries, the study indicates that seated representation in design forums, tied to independently monitored remediation and enforceable benefit-sharing, is the combination most likely to reduce stoppages and strengthen local upgrading (Grewatsch et al., 2023; Williams et al., 2017). This shifts communities from the position of peripheral consultees to that of ecosystem co-governors. RRCI offers a way to monitor whether participation is substantive, whether benefit-sharing is covenant-backed, and whether resilience routines encompass both repurposed and new assets within a single coordinated system.

Overall, the study recasts the sustainability transition from a problem of isolated firm adaptation to one of ecosystem coordination quality. The theoretical importance of this move lies in identifying an intermediate analytical level between macro transition discourse and micro-organisational practice. The empirical importance lies in producing a validated coordination construct rather than a loose metaphor. The practical importance is that it gives policymakers, financiers, firms, and communities a way to identify where transition systems are most fragile and where corrective action is most likely to matter. In that sense, RRCI and MARSF do not simply add another sustainability framework. They specify how coordination becomes regenerative, under what conditions, and with what consequences for outcomes that matter to both scholarship and practice.

8. Conclusion

This study introduces the Resource Regeneration Coordination Index (RRCI) and the Multi-Actor Resource Regeneration Systems Framework (MARSF) to measure and explain ecosystem coordination in extractives-

to-renewables transitions where legacy assets can simultaneously impede and support decarbonisation. By operationalising coordination through inter-firm regenerative alignment, socio-environmental embedding, and cross-sectoral resilience integration, the study provides a reproducible ecosystem-level metric that responds to longstanding calls for testable systems constructs in sustainability and operations research. Mixed-methods evidence shows that higher RRCI scores are associated with environmental regeneration, community resilience, and ecosystem legitimacy, thereby linking a system-level coordination construct to outcomes central to transition performance and accountability. Conceptually, the study advances the regenerative coordination paradox by showing that extractive infrastructures become transition platforms only when alignment, embedding, and resilience routines cohere. In this way, systems thinking is translated from a general account of interdependence into a mechanism-based explanation that can be specified, measured, and examined empirically across settings (Adner, 2017; Williams et al., 2017). MARSF further extends stakeholder, circular economy, and institutional perspectives by showing that legitimacy, circular repurposing, and due diligence compliance are not separate governance concerns, but outcomes of coordination quality within a wider ecosystem architecture. Practically, RRCI functions as a diagnostic tool through which ministries, financiers, operators, and communities can target guarantees, covenant-backed benefit sharing, remediation oversight, and interconnection standards at the weakest coordination points in a transition system.

Two boundaries qualify these conclusions. First, the findings arise from Nigerian ecosystems, where export-facing due diligence interacts with local co-decision and infrastructural path dependence in ways that make coordination especially visible and analytically tractable. Second, the archetype contrasts indicate that the same coordination mechanisms matter across settings but do so in different sequences, including repurposing-led, mining-to-renewables, and grid-integrator configurations. RRCI should therefore be interpreted not as a universal score with a fixed meaning, but as a coordination profile indicating where intervention is most needed in a given ecosystem. Transfer to other emerging-economy or Global North settings will likely require contextual recalibration of dimension salience, for example, where policy alignment is more institutionally consolidated or risk pooling is more central to project bankability.

Future research should examine how RRCI changes across project lifecycles, shocks, and governance transitions in order to determine whether coordination strength persists, consolidates, or decays over time. Comparative studies should apply RRCI and MARSF in other settings shaped by the EU CSRD/CSDDD and U.S. critical-minerals agendas to identify which policy instruments most effectively strengthen coordination and improve transition outcomes. To strengthen causal inference, future work may employ multi-method field designs that vary contractual clauses, co-investment guarantees, benefit-sharing triggers, joint emergency routines, or data-sharing standards and then trace their effects on regeneration, resilience, and legitimacy. Sectoral extension is also warranted in other paradoxical infrastructure systems, such as urban water and integrated resource networks, where legacy assets may likewise be repurposed under conditions of multi-actor governance. Finally, linking RRCI trajectories to digital standards, capability development, and institutional adaptation may reveal when coordination strength becomes durable enough to survive beyond a single project cycle, thereby offering more general design rules for transition ecosystems.

By specifying what regenerative coordination is, how it can be measured, and why it matters for environmental, social, and legitimacy outcomes, this article offers a mechanism-based account of transition ecosystems and an actionable framework for comparative research and policy design. Through RRCI and MARSF, the study moves the conversation beyond generic appeals to cooperation and toward auditable coordination routines that can be financed, governed, and evaluated across extractives-to-renewables pathways.

Data Availability The data that support the findings of this study are available on request.

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Declarations

Competing Interests The authors declare no competing interests.

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