

Cross-scale Institutional Fragmentation and Panarchic Collapse: From Extractive Traps to Nested Environmental Stewardship

Carlos Méndez-Vallejo¹

carlos.menvalle@gmail.com

Instituto Venezolano de Investigaciones Científicas

Meimalin Moreno-Villalobos¹

Instituto Venezolano de Investigaciones Científicas

Dinora Sánchez²

Instituto Venezolano de Investigaciones Científicas

María Isabel Arteaga²

Instituto Venezolano de Investigaciones Científicas

Miguel Ángel Contreras³

Instituto Venezolano de Investigaciones Científicas

Case Report

Keywords: cross-scale interactions, environmental governability, Ostrom, Panarchy, polycentric governance, social-ecological systems, sanctions, Venezuela

Posted Date: August 12th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10164997/v1>

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Additional Declarations: No competing interests reported.

Abstract

Background

Sustainability science faces an urgent challenge in understanding how governance failures contribute to systemic degradation of social-ecological systems (SES). This case study addresses the critical intersection of cross-scale institutional fragmentation and the risk of panarchic collapse in resource-dependent states. Methods: By synthesizing Panarchy theory with Ostrom's multi-level institutional analysis, we apply structured process tracing to examine Venezuela's oil-dependent SES between 2014 and 2021. Three mechanisms—veto-player density, exit-cost asymmetry, and functional redundancy—were operationalized to assess resilience under externally imposed institutional shocks. Results: When institutional mandates operated in isolated silos, they created rigidity traps that decoupled management actions from nested ecological feedback loops. Cross-scale fragmentation did not merely reduce production; it transformed a brittle extractive architecture into one incapable of sustaining technical maintenance, environmental monitoring, and emissions control. Energy intensity tripled and venting reached 85% of associated gas, indicating infrastructural failure rather than activity contraction. Conclusions: Extractive systems require genuine veto capacity below the executive level, positive interdependence with external partners, and redundant institutional pathways to prevent external pressure from propagating into ecological damage. These insights contribute a transferable diagnostic framework for institutional design in resource-dependent systems facing coercive shocks, directly supporting SDG 13 (Climate Action), SDG 16 (Peace, Justice and Strong Institutions), and SDG 12 (Responsible Consumption and Production).

1. Introduction

Human activity now drives planetary change to such an extent that the Anthropocene has been recognized as a new geological epoch [1, 2]. Yet the institutional arrangements used to govern social-ecological systems (SES) still rely heavily on territorial sovereignty, centralized control, and sectoral fragmentation. These approaches often fail to address the cross-scale dynamics of contemporary environmental risk, creating a core governability problem where shocks in one part of the system propagate rapidly across scales to generate social and ecological damage [3, 4]. For policymakers, this mismatch is not merely an academic concern: it means that economic pressure instruments, such as unilateral coercive measures, can trigger environmental degradation when applied to brittle, centralised resource systems.

Elinor Ostrom's work demonstrated that common-pool resources can be governed sustainably when institutions are nested, participatory and matched to ecological and social scales [5, 6]. However, these design principles were developed primarily through studies of local and regional commons. What remains much less understood from a governance perspective is how they apply to large-scale, resource-dependent SES embedded in global markets and exposed to externally imposed fragmentation. In such settings, resilience depends not only on local cooperation but also on the continuity of financial,

technical and administrative linkages across multiple levels [7, 8]. When those linkages are deliberately severed—for example, through financial unilateral coercive measures, asset freezes or exclusion from payment systems—institutional resilience can collapse in ways that existing commons theory has not yet fully theorised, with direct consequences for environmental policy.

This article therefore asks a specific, focused question: how does a centralised, oil-dependent social-ecological system respond when its cross-scale institutional linkages are deliberately severed? Our central hypothesis is that such a system becomes vulnerable to a distinct form of policy-driven failure—cross-scale institutional fragmentation—which transforms an already brittle extractive architecture into one incapable of sustaining technical maintenance, environmental monitoring and greenhouse gas emissions control. To explain this process, we propose three causal mechanisms that condition general resilience in vertically integrated, resource-dependent systems: (1) veto-player density, which distributes blocking power across scales and prevents unilateral disruption; (2) exit-cost asymmetry, which determines whether fragmentation is more costly for the actor imposing it or for the target; and (3) functional redundancy, which preserves alternative institutional pathways for finance, logistics and monitoring when primary channels fail. We expect that systems in which these three mechanisms are weak or absent will exhibit emissions intensification under external fragmentation.

To investigate these mechanisms, we draw on Panarchy theory, which conceptualises resilience as depending critically on cross-scale interactions, termed "Revolt" (upward influence of fast, small-scale processes) and "Remember" (downward support from slow, large-scale structures), between different levels of an SES [9]. From a policy standpoint, Panarchy implies that governance architectures must maintain both upward feedback (local actors able to signal distress and innovate) and downward support (national and global institutions providing resources and stability). When either direction is severed, the system loses its capacity to absorb shocks without regime shift [9].

We combine this lens with Ostrom's SES framework and a structured process-tracing methodology [10, 11] to analyse a critical case: Venezuela between 2014 and 2021. This case allows us to observe the interaction between a pre-existing centralised extractive architecture and a series of sharp, externally imposed institutional shocks, specifically, unilateral coercive measures that severed financial and logistical linkages. Since oil extraction is often treated as a state-controlled activity, the revenues it generates, the public goods they finance, and the regional and global atmospheric sinks affected by its emissions exhibit the two defining traits of a common-pool resource: high subtractability and difficult exclusion [5]. In a rentier state such as Venezuela, the entire social-ecological system is fiscally and institutionally tethered to a shared, depletable resource flow; when that flow is disrupted, the costs are distributed across households, communities, and ecosystems that cannot be excluded from the consequences. Thus, the Venezuelan petroleum system lends itself to being analysed as a commons, following the design principles Ostrom outlined for sustaining shared resources in complex, multi-scale settings. If a national oil sector is recognised as a common-pool resource rather than merely a state asset, then governance reforms should prioritise nested decision-making, cross-scale transparency and redundant institutional pathways, not simply state ownership or its absence. The Venezuelan case offers

a negative demonstration: when these institutional safeguards are absent, external pressure does not remain at the level of finance or governance but propagates through technical decay into measurable environmental damage, including rising flaring, venting and methane emissions.

The remainder of this paper proceeds as follows. Section 2 reviews the relevant literature on Panarchy theory, Ostrom's design principles, and the three proposed mechanisms. Section 3 describes our research design, case selection, data sources, and analytical methods. Section 4 presents and discusses our findings, reconstructing the causal chain from institutional fragmentation to infrastructure decay and emissions intensification. Section 5 offers concluding remarks and derives policy implications for the governance of resource-dependent systems facing external coercive pressure.

2. Literature Review

2.1 Panarchy and Cross-Scale Institutional Fragmentation

Social-ecological systems do not exist in a single plane. They are vertically interlaced: local resource extraction feeds into national governance, which in turn is embedded in global markets [7, 8]. Panarchy theory conceptualises these vertical linkages as "Revolt" and "Remember" interactions among the adaptive cycle [9]. In a healthy SES, "Revolt" allows small, fast processes—community organisations, regional authorities—to innovate and influence larger scales. "Remember" allows large, slow processes—national institutions, global markets—to provide stability and resources downward. Cross-scale institutional fragmentation occurs when an external shock, such as the imposition of unilateral coercive measures, strategically severs these connections. When both Revolt and Remember are disabled, the system undergoes cascading decoupling.

2.2 Three Mechanisms of Nested Environmental Stewardship

Extending Ostrom's Design Principles (DP) to multiscale settings, we identify three mechanisms that underwrite both general and specified resilience [5, 12, 13].

(1) Veto-player density (linked to Ostrom's DP 3 and DP 7, Collective Choice and Rights Recognition). This mechanism refers to the distribution of blocking power across scales. When local communities, regional authorities, national agencies, and international bodies each hold genuine veto rights, unilateral disruption becomes much harder [14, 15].

(2) Exit-cost asymmetry (linked to DP 4 and DP 6, Monitoring and Conflict Resolution). Here the question is whether disconnection is more costly for the actor threatening fragmentation or for the target. When interdependence is asymmetric in the target's favour, fragmentation is discouraged because the potential fragmenter stands to lose more [16]. Positive exit-cost asymmetry occurs when the actor imposing fragmentation faces higher costs than the target; negative asymmetry occurs when the target bears the higher cost.

(3) Functional redundancy (linked to DP 8, Nested Enterprises). Functional redundancy consists of alternative institutional pathways—parallel trade routes, alternative currencies, independent monitoring agencies—that can sustain connectivity if the primary channels collapse [17, 18].

Table 1 maps these mechanisms onto Ostrom's design principles, resilience attributes, and their roles in the Panarchy dynamic. We operationalise these mechanisms using the criteria shown in Table 2 (Methodology). We expect that systems with weak veto density, negative exit-cost asymmetry, and low functional redundancy will exhibit emissions intensification under external fragmentation.

Table 1
Cross-scale mechanisms, Ostrom Design Principles, and resilience attributes

Mechanism	Ostrom DP Link	Resilience Attribute	SES Function	Panarchic Role
Veto-player density	DP 3 (Collective Choice) + DP 7 (Rights Recognition)	Modularity + Diversity	Prevents top-down cascades of failure; distributes authority	Enables Revolt (upward influence of small/fast scales)
Exit-cost asymmetry	DP 6 (Conflict Resolution) + DP 4 (Monitoring)	Tightness of feedbacks + Resistance	Incentivizes cooperation by raising the cost of decoupling	Strengthens Remember (obligation to maintain cross-scale flows)
Functional redundancy	DP 8 (Nested Enterprises)	Response diversity + Redundancy	Provides insurance against institutional chokepoints	Maintains connectivity when primary Revolt/Remember channels fail

2.3 The Extractive Trap as an Anti-Panarchic Configuration

Ostrom long warned that centralisation is a governance failure [5]. We call the extreme expression of this failure the extractive trap, a configuration in which centralised resource control eliminates lower-scale veto players and functional redundancy, leaving a system with high specified resilience (it can survive familiar price cycles) but practically no general resilience. In Panarchic terms, the adaptive cycle becomes locked into a brittle "conservation" phase. When a novel disturbance arrives, the system cannot pass through release and reorganisation, and catastrophic collapse follows [9].

3. Methodology

3.1 Research Design

We conducted a qualitative single-case study of Venezuela's oil-dependent SES to explain how cross-scale institutional fragmentation contributed to the collapse of the petroleum sector and to subsequent environmental impacts, especially greenhouse gas emissions from the energy sector [11, 19]. The study used a structured process-tracing design to reconstruct the Venezuelan causal pathway and assess

whether the evidence supported the sequence linking external coercive measures, institutional decoupling, infrastructure deterioration, and biophysical degradation [10, 11].

3.2 Analytical Framework

The analysis combined Panarchy theory, Ostrom's Social-Ecological Systems framework, and resilience thinking. Panarchy theory was used to interpret the loss of cross-scale feedbacks and the weakening of upward influence and downward support across institutional levels [9]. Ostrom's framework provided a diagnostic structure for identifying governance, resource, and outcome variables relevant to the Venezuelan petroleum system [5, 12, 13]. Resilience thinking was used to distinguish between specified resilience to familiar shocks and general resilience to novel disruptions [20, 21, 22].

3.3 Case Boundaries

The unit of analysis was Venezuela's oil-dependent social-ecological system (SES). The analysis focused on the Venezuelan oil industry, the state-owned company Petróleos de Venezuela, S.A. (PDVSA), the central fiscal and financial system of Venezuela, and the institutional interfaces linking oil extraction to global markets [5, 19]. The temporal window covered 2014 to 2021, spanning the pre-shock restructuring period, the escalation of unilateral coercive measures between 2017 and 2019, and the subsequent period of production decline and environmental deterioration [10, 23]. This period captures both the institutional weakening that preceded the unilateral coercive measures shock and the emissions consequences that followed.

3.4 Data Sources

Documentary sources included United States executive orders, designations by the U.S. Department of the Treasury's Office of Foreign Assets Control (OFAC), reports on the seizure of CITGO Petroleum Corporation (CITGO), and materials documenting Venezuela's exclusion from the Society for Worldwide Interbank Financial Telecommunication (SWIFT) network and related financial constraints [23, 24]. Sectoral production and macroeconomic trends were drawn from reports by the Organization of the Petroleum Exporting Countries (OPEC) and the World Bank. Venezuela's national inventory informed emissions and flaring trends, the World Bank's Global Gas Flaring Tracker data, and recent atmospheric studies on Venezuelan methane emissions [25, 26, 27, 28]. Additional background on institutional and economic conditions was drawn from [29, 30, 31, 32].

3.5 Process Tracing

We reconstructed the causal chain using process tracing. The key hypothesis was that institutional fragmentation reduced the capacity to import technology, maintain infrastructure, and sustain environmental monitoring, thereby increasing flaring, venting, and methane emissions [11, 33]. Each link in the chain was evaluated using temporal ordering, mechanistic plausibility, and corroboration across independent sources [10, 11]. Competing explanations, including price collapse and long-term governance decay, were assessed against the timing and specificity of the observed changes.

3.6 Mechanism Coding

We coded the Venezuelan case using three mechanism categories derived from the theoretical framework: veto-player density, exit-cost asymmetry, and functional redundancy [14, 15, 16, 17, 18]. Veto-player density was assessed by identifying whether subnational, sectoral, or organizational actors possessed meaningful blocking power over resource governance. Exit-cost asymmetry was evaluated by examining how the costs of fragmentation were distributed between external actors and Venezuela. Functional redundancy was assessed by determining whether alternative financial, logistical, and monitoring pathways remained available after the shock. Each mechanism was coded qualitatively as weak, moderate, or strong, based on documentary evidence and process-tracing consistency (Table 2).

Table 2
Mechanism coding criteria

Mechanism	Weak	Moderate	Strong
Veto-player density	No subnational actor can block any decision	Some actors can delay but not block	Multiple actors at different scales have independent veto power
Exit-cost asymmetry	Fragmenter faces zero or negative cost	Fragmenter faces moderate cost	Fragmenter faces prohibitive cost
Functional redundancy	No alternative pathways	One partial alternative	Multiple fully independent pathways

3.7 Emissions Analysis

To connect institutional change to environmental outcomes, we analyzed emissions inventory data for the Venezuelan energy sector and compared trends in total emissions, emissions intensity, and fugitive emissions across the study period [28, 27]. We focused on indicators sensitive to infrastructure failure, including flaring, venting, methane leakage, and energy intensity [25, 26]. This allowed us to evaluate whether the post-shock changes were consistent with capture-system deterioration rather than with a simple decline in activity alone.

4. Results and Discussion

4.1 Institutional Fragmentation and the Loss of Revolt

The central role of oil in the global economy transformed human relationships across space and time, fostering and accelerating the use of fossil fuels in global industrial activity [34]. Venezuela's vast oil reserves consolidated a socio-technical infrastructure anchored in dependence on international oil revenues, making oil revenues the primary source of funding for the rentier state. The Venezuelan oil economy was organized around a highly centralized extractive architecture in which PDVSA controlled extraction, processing, and marketing, while the central government absorbed the bulk of the foreign exchange. This institutional disconnect between oil activity and the financial management of revenue strengthened the vertical and centralizing nature of the state and, at the same time, increased vulnerabilities to unilateral coercive measures. The socio-technical arrangements between the economy,

oil, and technology that had served as the foundation for Venezuela's rentier institutions made a systemic response to the unilateral measures impossible, leading to economic, environmental, and social imbalances. Thus, regional and community institutions remained fiscally dependent and politically subordinate [29, 30]. This configuration weakened lower-scale autonomy, eliminated meaningful veto players outside the executive branch, and eroded the institutional memory needed to absorb external shocks [31, 5]. In Panarchic terms, the system had already lost much of its "Revolt" capacity before the financial unilateral coercive measures intensified.

4.2 Unilateral Measures and Decoupling

The institutional shock intensified between 2017 and 2019 through Executive Order 13808, Executive Order 13850, the CITGO seizure, and Venezuela's exclusion from SWIFT. Each of which severed a different part of the chain connecting extraction to fiscal conversion and international finance [23, 24]. These actions sharply reduced the state's capacity to import technology, obtain spare parts, finance maintenance, and sustain operational continuity in the petroleum sector [32, 24]. The result was not simply lower output, but a broader institutional decoupling affecting technical capacity and environmental oversight. The state's top-down and centralizing nature, combined with institutional fragmentation, created vulnerabilities to unilateral measures, exacerbating a preexisting institutional disconnect. The widespread belief in separating technology, nature, and politics disrupted historical socio-technical arrangements, leading to increased environmental degradation and social violence in the region [34].

4.3 Causal Chain from Fragmentation to Ecological Unsustainability

The institutional shock cascaded into ecological damage through a clear sequence. Fragmentation blocked dollar clearing and international financing, making it difficult to import technology or perform maintenance. Without spare parts, monitoring equipment, or upgrade capacity, PDVSA became locked into obsolete technology. Gas-capture systems decayed, and the heavy crude of the Venezuelan oil industry could no longer process associated gas effectively. Flaring and venting increased sharply, reaching about 85% of associated gas, and Venezuela registered one of the highest methane-emission factors per barrel globally [25, 26, 27].

4.4 Emissions Trends and Energy Efficiency

The emissions inventory confirms that total emissions declined from 502,600 Gg CO₂eq yr⁻¹ in 2014 to a minimum of 168,559 Gg. However, this decline masked a deterioration in system efficiency and environmental performance [28]. Energy intensity tripled relative to 2012 levels by the 2019–2021 period, and venting accounted for 85% of fugitive emissions, indicating a failure of capture infrastructure rather than a simple contraction of activity [28]. These patterns are consistent with a system in which production collapse did not produce environmental relief but instead generated a more carbon and methane-intensive mode of extraction. The breakdown of the socio-technical arrangements that had organized the institutional infrastructure dismantled the mechanisms for socio-environmental control

and oversight and, at the same time, led to the displacement of populations into informal work (mining, logging, and slash-and-burn farming). Figure 1 illustrates the decoupling of extraction efficiency under cross-scale fragmentation from 1999 to 2021.

4.5 Ruling Out Alternative Explanations

Two plausible alternative accounts might be advanced to explain Venezuela's oil-sector collapse: the 2014–2016 oil-price drop and the cumulative effect of decades of underinvestment and mismanagement. Both explanations capture part of the background conditions, but neither accounts for the timing, magnitude, and specific biophysical signature of the observed changes. International oil prices partially recovered from 2017 onward. A price-driven story would predict some levelling off or recovery alongside the price rebound, which did not occur. Yet, Venezuela's production fell most steeply, and flaring intensity rose most sharply, after the 2017–2019 financial unilateral coercive measures were imposed, particularly after the SWIFT exclusion and the CITGO seizure eliminated the remaining channels for technology imports [24, 32].

Long-term governance erosion undoubtedly produced the centralised, brittle architecture we describe, but the emissions record shows a non-linear threshold change, not merely the continuation of a gradual trend. Before 2017, Venezuela's flaring intensity was already high but relatively stable; after the unilateral measures, both the volume of flared gas per barrel and the share of venting in fugitive emissions jumped to extreme levels [26, 27]. This disjuncture is consistent with what our institutional-fragmentation mechanism predicts: a system that loses access to foreign equipment and chemicals cannot maintain gas-capture infrastructure, so flaring and venting accelerate even as production falls. A simple production collapse or a long-run decay path would not uniquely produce the sharp divergence between falling output and rising emissions intensity that appeared in 2018–2021. We therefore conclude that, while prior institutional weakness was a necessary condition, the unilateral coercive financial measures of 2017–2019 were the proximate trigger that turned a fragile system into one characterized by ecological degradation.

4.6 Mechanism Failure and Regime Shift

The three resilience mechanisms were even more weakened after the shock. Figure 2 maps this configuration of broken "Remember" connections and weak "Revolt" capacity within Venezuela's oil-dependent SES. Veto-player density was effectively absent, exit-cost asymmetry was sharply negative, and functional redundancy was lacking [14, 16, 17]. Once the global "Remember" connection was severed, oil production fell by roughly 75%, GDP contracted by about 65%, health systems deteriorated, and environmental monitoring largely ceased [32, 35]. Rather than reconfiguring through release and reorganization, the system crossed a threshold into a degraded regime marked by humanitarian emergency and unmanaged ecological damage.

4.7 Social and Ecological Costs

Because local veto players had already been eliminated, the costs of fragmentation were externalized onto marginalized communities and ecosystems [36, 37]. The consequences included mass emigration, severe food insecurity, and uncontrolled methane releases, all of which illustrate how institutional architecture can shape the distribution of environmental harm. In this sense, the Venezuelan case shows that unilateral coercive measures operated not only as an economic shock but also as a mechanism that amplified social and ecological vulnerability [38].

4.8 Interpreting the Venezuelan Case

This study shows how a highly centralized oil-dependent social-ecological system can become vulnerable to cross-scale institutional fragmentation when lower-scale autonomy, redundancy, and veto capacity have already been eroded. In Venezuela, the collapse was not simply the result of unilateral coercive measures as an external shock, but of the way these measures acted on a pre-fragmented institutional architecture that had already weakened the system's ability to absorb disruption [29, 30, 31]. In Panarchy terms, the oil system had already lost much of its "Revolt" capacity, and when the "Remember" connection to global finance and technology was severed, the system had little remaining adaptive capacity to buffer the shock [9]. This interpretation is consistent with Ostrom's view that resilience depends on nested institutions, cross-scale feedbacks, and the availability of multiple centres of decision making [5, 12, 13].

4.9 Institutional Architecture and Collapse

The Venezuelan case suggests that unilateral coercive measures become environmentally consequential when they intersect with an institutional architecture that is already overly centralized and brittle. The combination of executive concentration, weak regional autonomy, and the dismantling of internal checks within PDVSA meant that the system had few mechanisms to preserve continuity once external finance, spare parts, and technological inputs were restricted [31, 24]. This aligns with the broader literature on resource dependence and institutional fragility, which shows that centralized extractive systems are especially prone to cascading failure when external conditions shift [29, 30, 39, 38]. Our contribution is to specify the causal pathway: fragmentation did not remain at the level of governance, but propagated through technical decay into emissions growth and environmental damage [28, 27].

4.10 From Production Loss to Emissions Intensification

A key result of this study is that declining oil production did not automatically produce lower environmental pressure. Instead, the loss of maintenance capacity, monitoring equipment, and upgrading pathways increased flaring, venting, and methane leakage, especially in the Venezuelan oil industry [25, 26, 27]. The emissions inventory shows that total emissions fell, but energy intensity rose sharply and venting came to dominate fugitive emissions, indicating infrastructural failure rather than cleaner production [28]. This pattern is important because it shows that environmental degradation can intensify even as economic output collapses, a point that has been highlighted in political ecology but less often demonstrated through detailed process tracing of energy-system breakdown [40, 41, 42].

4.11 General and Specified Resilience

The Venezuelan case also helps clarify the distinction between specified and general resilience. The system had demonstrated a limited ability to absorb familiar oil-price shocks, which suggests some specified resilience, but it lacked the institutional diversity and redundancy needed to respond to a novel compound shock involving unilateral coercive measures, financial isolation, and technical decay [21, 22]. In other words, the architecture could survive routine volatility but not a deliberate disruption of cross-scale linkages. This supports Panarchy theory's central insight that resilience depends on the maintenance of both upward and downward feedbacks across scales, not only on local persistence [9]. It also reinforces Ostrom's argument that nested enterprises are not an optional governance feature, but a structural condition for durable collective action in complex systems [5, 12].

4.12 Alternative Analytical Frameworks

We briefly compare our nested-stewardship framework with four influential traditions: rentier-state theory, resource-curse literature, dependency and world-systems theory, and political ecology.

Rentier-state theory [43, 29] holds that states funded by resource rents rather than broad-based taxation become unaccountable and fragile. Venezuela's experience confirms this diagnosis. While a full comparative analysis is beyond the scope of this paper, the framework we advance implies that countries with greater veto-player density and higher functional redundancy, a description that may apply to Iran, where parliamentary and factional checks partially constrained executive action during unilateral coercive measures [44], should exhibit lower emissions-intensity rebounds under similar external pressure. Future work could test this hypothesis by comparing Venezuela and Iran's flaring intensity and methane emission factors before, during, and after unilateral coercive measures. Our framework suggests a missing variable: the distribution of veto players. Rentier states that have preserved pluralistic veto points (e.g., parliamentary oversight, regional counter-weights) can buffer external shocks; those that have concentrated all authority at the apex cannot.

Resource-curse literature [39, 45] attributes poor developmental outcomes to Dutch disease, price volatility, and the erosion of governance. From this perspective, Venezuela is an extreme case of the curse. Yet the resource-curse lens struggles to differentiate Venezuela from Norway or from Iran unless it is supplemented with a theory of institutional design, precisely what our three mechanisms (veto-player density, exit-cost asymmetry, functional redundancy) provide.

Dependency and world-systems theory [46, 47] argues that peripheral economies are structurally vulnerable because of their subordinate position in global capitalism. Our case does not refute this; it does, however, show that domestic institutional architecture significantly modulates that vulnerability. The divergent trajectories of two peripheral, resource-dependent states under similar external pressure—Venezuela and Iran—suggest that dependency frameworks need an account of internal institutional variation. Our mechanisms supply that account.

Political ecology [40, 41, 42] has powerfully documented how power asymmetries marginalise communities and environmental values. Our analysis aligns with this tradition, showing that the

elimination of local vetoes allowed costs to be externalised onto the most vulnerable. Political ecology has long proposed mechanisms of cost externalisation; our distinct contribution is to formalise three mechanisms that are measurable, comparable across cases, and explicitly linked to Panarchy and Ostrom's design principles, without losing the justice dimension.

In short, each of these traditions captures an important piece of the puzzle, but none alone can explain why identical external pressure produced collapse in one case and mere stress in another. The nested-stewardship framework integrates their insights by specifying how resource dependence, power asymmetries, and institutional design interact to shape social-ecological outcomes under coercive shocks.

4.13 Justice and Burden Shifting

The Venezuelan case further indicates that institutional fragmentation is inseparable from distributive injustice. Because veto points had been concentrated at the top of the system, the costs of breakdown were shifted downward onto households, workers, and ecosystems, with severe humanitarian and environmental consequences [36, 37]. This is consistent with political ecology's long-standing emphasis on power asymmetries, but the present analysis adds a more explicit mechanism-based account of how those asymmetries become biophysical outcomes [40, 41, 42]. In that sense, the case shows that environmental harm is not only a by-product of weak governance; it is also a consequence of governance structures that allocate vulnerability unevenly across scales and social groups.

4.14 Implications for SES Research

For social-ecological systems research, the Venezuelan case has two implications. First, single-case process tracing can identify the sequence through which institutional breakdown becomes environmental degradation, especially when the case is theoretically rich and the causal chain is observable across multiple domains [10, 11]. Second, Ostrom's SES framework remains highly useful, but it benefits from being combined with Panarchy when the object of analysis is not a local commons but a vertically integrated extractive system exposed to external pressure [5, 12, 13]. The case therefore extends SES analysis into the domain of unilateral coercive measure-affected resource systems, where governance failure, technical obsolescence, and emissions growth can be traced as linked outcomes.

5. Conclusions

This study shows that Venezuela's petroleum system was not made fragile by unilateral coercive measures alone, but by the interaction between unilateral coercive measures and a pre-existing institutional architecture that had concentrated authority, weakened lower-scale autonomy, and eroded redundancy [29, 30, 31]. In Panarchic terms, the system had already lost much of its ability to generate upward influence and sustain downward support, so the shock of financial isolation quickly propagated into technical decay and environmental harm [9, 5]. The result was a collapse in oil-system functionality accompanied by rising flaring, venting, and methane emissions, even as total production declined [28, 27].

For policy, the implication is direct: extractive systems need genuine veto capacity below the executive level, positive interdependence with external partners, and redundant financial, technical, and monitoring pathways if they are to avoid turning external pressure into ecological damage [17, 16, 18]. Venezuela illustrates what happens when those safeguards are absent. These findings are directly relevant to SDG 13 (Climate Action), SDG 16 (Peace, Justice and Strong Institutions), and SDG 12 (Responsible Consumption and Production), offering a transferable diagnostic framework for institutional design in resource-dependent systems facing coercive shocks.

Declarations

Competing Interests

The authors declare no competing interests.

Ethics, Consent to Participate, and Consent to Publish declarations:

Not applicable.

Funding

This research received no specific grant from any funding agency, commercial entity, or external institution. The work was conducted using facilities and resources provided by the Venezuelan Institute for Scientific Research (IVIC).

Author Contribution

Conceptualization: Carlos Méndez-Vallejo, Meimalin Moreno-Villalobos, Methodology: Carlos Méndez-Vallejo, Meimalin Moreno-Villalobos. Investigation: Carlos Méndez-Vallejo, Meimalin Moreno-Villalobos, Dinora Sánchez, María Isabel Arteaga, Miguel Ángel Contreras. Writing – original draft: Carlos Méndez-Vallejo. Writing – review & editing: All authors. Funding acquisition: None. All authors have read and agreed to the published version of the manuscript.

Acknowledgement

We used Perplexity AI (powered by Grok 4.1, accessed via perplexity.ai in February 2026) solely to translate and rephrase sections of the original text into clear academic English. No modifications were made to the tool, and no proprietary data was added. All AI-generated outputs were thoroughly reviewed,

edited, and verified for accuracy and originality by the authors, who take full responsibility for the final content.

Data Availability

The data that support the findings of this study are openly available. Emissions inventory data for Venezuela are available in Méndez-Vallejo et al. [28]. Global gas flaring data are available from the World Bank Global Gas Flaring Tracker [25]. Methane emissions data are available in Scarpelli et al. [26] and Nathan et al. [27]. OFAC executive orders and designations are publicly available at <https://ofac.treasury.gov/>. OPEC production data are available at <https://www.opec.org/>. All other documentary sources are cited in the reference list.

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Figures

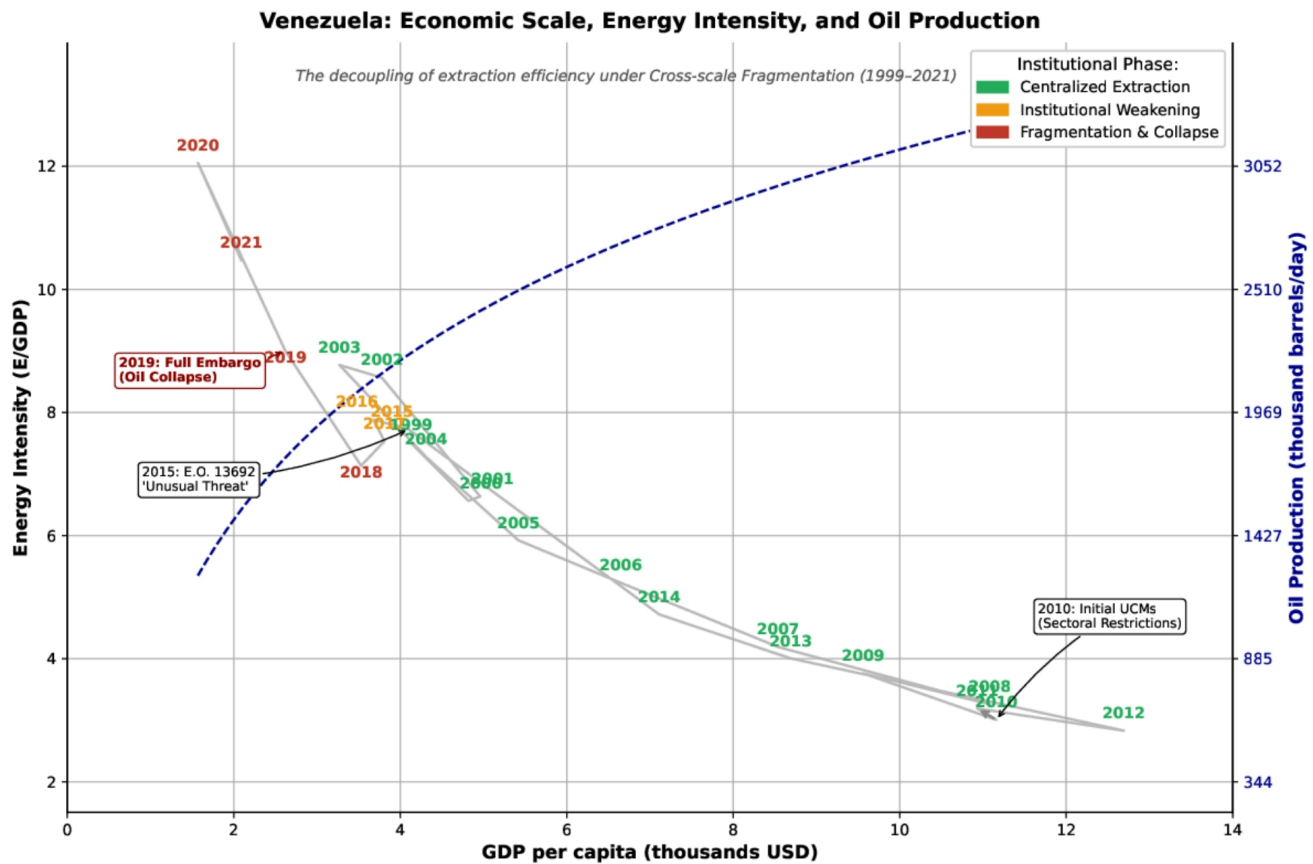


Figure 1

Economic scale, energy intensity and oil production in Venezuela (1999–2021). The decoupling of extraction efficiency under cross-scale fragmentation (1999–2021). Data sources: OPEC Annual Statistical Bulletin; World Bank Global Gas Flaring Tracker; Venezuelan national emissions inventory [28].

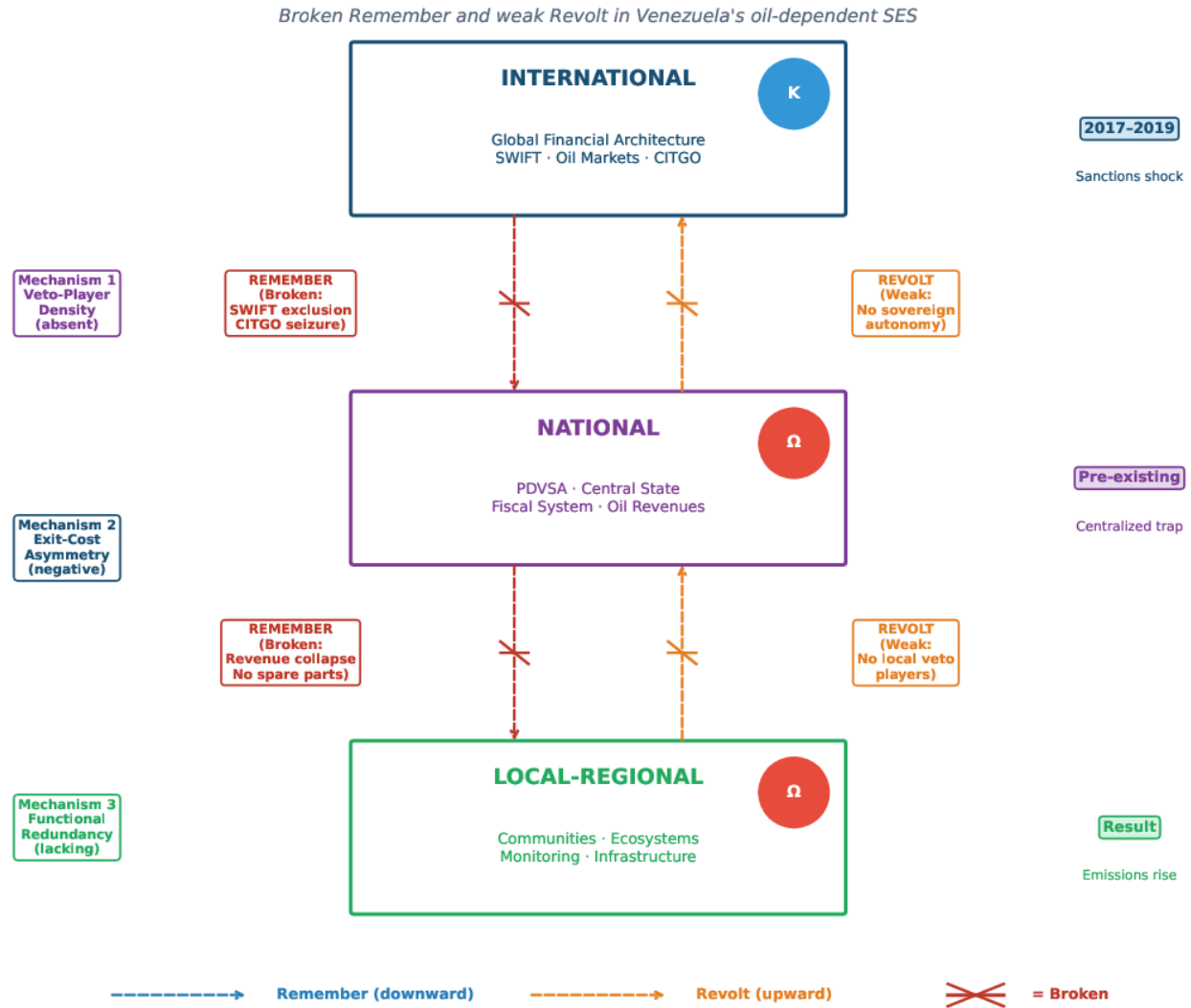


Figure 2

Venezuela's cross-scale institutional fragmentation. Broken Remember and weak Revolt in Venezuela's oil-dependent SES. Solid arrows indicate functional pathways; dashed arrows indicate severed or weakened pathways. The diagram conceptualizes the loss of upward feedback (Revolt) and downward support (Remember) following the 2017–2019 unilateral coercive measures.