PLANETARY CAATINGIZATION: THE BRAZILIAN SEMI-ARID AS A BLUEPRINT FOR ADAPTATION IN THE ANTHROPOCENE

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Abstract: The global expansion of drylands represents one of the most pressing challenges of the Anthropocene, challenging development models historically grounded in climatic stability and resource abundance. Within this context, the central problem concerns how systems adapted to scarcity can inform global adaptation strategies. This study aims to analyze how the biological, technological, and social model of the Brazilian Caatinga can serve as a paradigm for the emerging climatic "new normal." Methodologically, an integrative literature review was conducted using an interdisciplinary approach, drawing on international scientific databases and environmental data through a systematic

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selection and thematic analysis process. The results reveal a convergence of global climate toward semi-arid conditions, the high adaptive complexity of Caatinga biodiversity, and the effectiveness of social technologies based on coexistence with environmental variability. The discussion highlights the need to move beyond the paradigm of abundance and adopt resilience-centered frameworks, culminating in the proposal of the "Epistemology of the Thorn" as a novel interpretive model. It is concluded that the Caatinga constitutes an anticipatory system of future planetary conditions and should be recognized as a strategic reference for global adaptation policies and practices.

Keywords: Resilience. Drylands. Climate Adaptation. Social Technologies. Sustainability.

INTRODUCTION

The twenty-first century marks a profound civilizational inflection, defined by escalating climate instability and the erosion of ecological conditions that historically sustained modern development. Within the framework of the Anthropocene, the assumption of environmental stability no longer holds analytical or practical validity. Intensified extreme events, hydrological variability, and shifts in atmospheric circulation patterns suggest that the Earth system is transitioning toward a state characterized by persistent uncertainty and structural stress on social-ecological systems (Reyers et al., 2018).

Among the most consequential processes underlying this transition is the global expansion of drylands. Contemporary research demonstrates that aridity is no longer confined to traditionally semi-arid regions, but is progressively affecting temperate zones through altered precipitation regimes, rising temperatures, and feedback mechanisms between land and atmosphere (Huang et al., 2016; Yao et al., 2020; Zhang et al., 2025).

The poleward expansion of the Hadley cell further reinforces this trend by redistributing climatic belts and extending zones of subsidence and reduced rainfall (Lu et al., 2007). Although

recent projections indicate that only a limited fraction of drylands may undergo full desertification, the intensification of aridity remains a robust and globally significant pattern with far-reaching ecological and socio-economic implications (Berg et al., 2024).

This emerging reality exposes the limitations of the dominant development paradigm, historically grounded in the assumption of abundance. Agricultural systems, urban infrastructures, and economic models have been designed under conditions of relative climatic predictability and resource availability. As these conditions deteriorate, the logic of abundance reveals its structural fragility, demanding a shift toward frameworks that prioritize adaptability, efficiency, and resilience under constraint.

In this context, resilience has gained prominence as a central analytical and normative concept in the study of social-ecological systems. Rather than implying mere resistance to disturbance, resilience encompasses the capacity to adapt, reorganize, and transform in response to continuous environmental pressures (Folke, 2006). This perspective challenges linear models of development and introduces a dynamic understanding of sustainability, one that acknowledges variability, thresholds, and systemic reconfiguration as inherent features of complex systems.

Despite the growing recognition of resilience, a critical gap persists in the global scientific discourse. Semi-arid regions remain largely framed as spaces of deficiency, vulnerability, and marginality, rather than as repositories of adaptive knowledge. This epistemic bias obscures the ecological sophistication and socio-technical innovations that have emerged in these environments, limiting their incorporation into global adaptation strategies.

The Brazilian Caatinga offers a compelling counterpoint to this dominant narrative. Characterized by extreme climatic variability, high solar radiation, and seasonal water scarcity, this biome has developed intricate ecological and social mechanisms of persistence and regeneration. Its biological systems operate through pulses of productivity, dormancy strategies, and efficient resource use, while its human populations have historically constructed adaptive practices rooted in coexistence with environmental constraints. Such features position the Caatinga not as an exception,

but as a system that anticipates the conditions increasingly observed across the planet.

This article advances the argument that the Caatinga should be understood as a global blueprint for climate adaptation in the Anthropocene. Through an integrative review of the literature, it seeks to reposition the Brazilian semi-arid region from a peripheral ecological condition to a central reference for understanding and navigating planetary change. In doing so, it challenges entrenched assumptions about development, resilience, and environmental value, proposing that the future of global adaptation may already be embedded in the lived realities of semi-arid systems.

METHODOLOGY

This study was designed as an integrative literature review with a theoretical and analytical orientation, aimed at synthesizing empirical and conceptual contributions capable of supporting an original interpretive proposition regarding the Brazilian Caatinga as a global model of adaptation in the Anthropocene. The choice of the integrative review method was justified by its ability to combine findings from studies with different methodological designs, while also enabling the articulation of dispersed evidence into a broader analytical framework.

In this sense, the review was not restricted to descriptive aggregation of results, but was structured as a critical synthesis oriented toward conceptual production and interdisciplinary interpretation, in line with the methodological assumptions proposed for integrative reviews in health and applied social research (Mendes; Silveira; Galvão, 2008; Souza; Silva; Carvalho, 2010; Torraco, 2005).

From an epistemological standpoint, the review adopted a critical theoretical perspective. This orientation was essential because the research problem did not concern merely the identification of isolated findings on dryland expansion, biodiversity, or adaptation strategies. Instead, it required the construction of an interpretive bridge among climatic, ecological, and socio-technical dimensions that are usually treated separately in the literature.

The methodological approach therefore sought to move beyond a fragmented reading of the evidence and toward a higher-order synthesis capable of revealing convergences, tensions, and conceptual absences across different disciplinary traditions. Such an approach is consistent with integrative review designs that privilege theory development and conceptual refinement, particularly when the objective is to respond to complex questions situated at the intersection of environmental change, social-ecological resilience, and territorial knowledge systems (Torraco, 2005).

The bibliographic search was conducted between November 2025 and March 2026 in four major sources selected for their complementarity and analytical relevance: Scopus, Web of Science, JSTOR, and NASA Earth Observations. Scopus and Web of Science were used as the main multidisciplinary indexing platforms for retrieving peer-reviewed scientific literature on climate change, dryland dynamics, resilience, biodiversity, and adaptation. JSTOR was included to strengthen the theoretical and interpretive dimension of the review, especially for works related to environmental thought, social-ecological systems, and critical perspectives on adaptation. NASA Earth Observations was consulted as a complementary source for climate and environmental data relevant to the discussion of global dryland expansion, aridity trends, and planetary-scale environmental transformations.

The search strategy was guided by the central research question of the study, namely how the biological, technological, and social model of the Brazilian Caatinga may serve as a paradigm of adaptation in an increasingly arid world. To address this question, the search process combined descriptors and thematic expressions associated with four analytical axes previously defined in the study design: dryland expansion, climate adaptation, Caatinga biodiversity, and social technologies for semi-arid regions. These descriptors were combined using Boolean operators and adapted according to the indexing logic of each database. The search process prioritized publications that offered either direct evidence on the selected themes or theoretical support for understanding adaptation under conditions of climatic stress and socioecological instability.

The initial search retrieved 336 references. After this stage, all records were exported, organized, and subjected to a systematic screening process. The first procedure consisted of identifying

and removing duplicates, followed by a preliminary reading of titles, abstracts, and keywords to assess thematic relevance. In this phase, studies that were manifestly unrelated to the research problem, that addressed aridity or biodiversity without analytical connection to adaptation, or that treated semi-arid regions in purely technical terms detached from broader climatic or socioecological implications were excluded. The remaining references were then subjected to full-text reading, allowing a finer evaluation of conceptual density, methodological consistency, and effective contribution to the argument developed in this article.

The inclusion and exclusion process was conducted according to explicit analytical criteria, with the aim of ensuring thematic coherence and conceptual robustness throughout the review.

Inclusion criteria:

- Studies addressing the expansion of drylands, aridity intensification, or atmospheric dynamics associated with climatic drying.
- Studies examining climate adaptation, resilience, adaptive capacity, or transformability in social-ecological systems.
- Studies focused on the biodiversity, ecological strategies, functional traits, or adaptive responses of Caatinga species and seasonally dry tropical forests.
- Studies analyzing social technologies, local knowledge, water management, or coexistence strategies in semi-arid regions, particularly in the Brazilian semiarid context.
- Publications with theoretical, empirical, or methodological relevance to the central thesis of the article.
- Works published in peer-reviewed journals or, when appropriate, in consolidated academic sources of recognized scientific relevance.

Exclusion criteria:

- Publications unrelated to the four thematic axes established in the study design.
- Studies focused on arid or semi-arid environments without conceptual contribution to

climate adaptation or resilience.

- Works whose scope was strictly local or descriptive, with insufficient analytical density for integration into the theoretical synthesis.
- Texts with duplicated records across databases.
- Studies with inaccessible full text during the review period.
- Publications whose content did not contribute substantively to the interpretive construction proposed in the article.

At the end of the screening and eligibility procedures, 29 references were selected as the final analytical corpus for the content development of the article. This corpus was considered sufficient not because of numerical representativeness alone, but because of its capacity to sustain a dense and articulated synthesis across scales, disciplines, and analytical traditions. The final set of studies was distributed across the major argumentative axes of the paper, allowing the review to preserve internal balance between climate science, biodiversity and functional ecology, socioecological resilience, and social technologies of coexistence with the semi-arid environment.

The analytical procedure unfolded in three complementary stages. The first stage consisted of thematic categorization. Each selected study was read in full and coded according to its primary contribution to one or more of the following analytical nuclei: global dryland expansion and atmospheric dynamics; biological and functional adaptations in the Caatinga; social technologies and semi-arid coexistence; resilience and social-ecological systems; and conceptual implications for adaptation in the Anthropocene. This step made it possible to identify thematic recurrences, epistemological gaps, and areas of potential articulation among bodies of literature that are often compartmentalized.

The second stage involved interdisciplinary synthesis. Rather than presenting the selected studies in isolated blocks, the review sought to establish analytical connections among climatology, ecology, and socioecological theory. This procedure was fundamental to demonstrating that the adaptive logic observed in the Caatinga cannot be reduced either to a purely biological phenomenon

or to a merely social response to scarcity.

What emerged from the synthesis was a multilevel adaptive system in which climatic variability, evolutionary strategies, and collective technologies interact in a coherent pattern of persistence under stress. This interpretive movement is central to integrative review methodology when the purpose is not only to summarize evidence, but to generate broader explanatory insight from heterogeneous literature (Mendes; Silveira; Galvão, 2008; Souza; Silva; Carvalho, 2010).

The third stage consisted of conceptual construction. Based on the convergences identified during the interdisciplinary synthesis, the review developed the concept of the Epistemology of the Thorn as an original interpretive proposition. This concept did not emerge as an a priori theoretical imposition, but as an analytical result derived from the reviewed literature and from the recognition of recurrent adaptive principles across ecological and social domains in the Caatinga.

These principles include economy of resources, strategic defense, tolerance to pressure, cyclical regeneration, and functionality under conditions of scarcity. The concept therefore serves as a higher-order theoretical formulation that integrates the evidence reviewed and offers an epistemic alternative to development models still grounded in assumptions of climatic stability and material abundance.

Methodological rigor was ensured through transparent definition of the review stages, explicit selection criteria, systematic screening, full-text reading, and analytical coding guided by the research question. At the same time, the study preserved the flexibility that characterizes integrative reviews aimed at theory building, particularly when addressing complex interdisciplinary problems that demand both empirical grounding and conceptual innovation (Torraco, 2005).

For this reason, the methodological pathway adopted here was not limited to cataloguing findings, but was intentionally structured to support a robust, coherent, and critical reinterpretation of the Caatinga as a central reference for global adaptation debates.

CAATINGIZATION AND GLOBAL DRYLAND EXPANSION

The ongoing reconfiguration of the Earth's climate system reveals a structural shift toward conditions historically associated with semi-arid environments. This section synthesizes evidence indicating that the global climate is progressively converging toward patterns of aridity, variability, and hydrological instability, thereby reinforcing the central thesis that the Caatinga represents not an ecological exception, but a climatic preview of broader planetary trajectories.

Expansion of Hadley Cells

One of the most robust indicators of large-scale atmospheric transformation is the expansion of the Hadley circulation. Traditionally confined to tropical latitudes, the Hadley cells have exhibited a consistent poleward expansion over recent decades, altering precipitation regimes and redistributing zones of atmospheric subsidence. This process directly contributes to the widening of subtropical dry zones and the intensification of aridity in regions previously characterized by temperate climates.

Lu, Vecchi and Reichler (2007) identified a statistically significant expansion of the Hadley cell under global warming scenarios, highlighting that "the poleward expansion of the Hadley circulation is a robust feature of climate model projections." This shift implies that regions located at the margins of these circulation systems are increasingly subjected to descending dry air masses, reducing precipitation and increasing evapotranspiration rates.

More recent analyses based on CMIP6 climate models reinforce this trend. Staten et al. (2020) demonstrate that the expansion of the Hadley cell is not only persistent but also intensifying, with implications for long-term hydroclimatic stability. In parallel, Xian et al. (2021) question the uniformity of this expansion, yet confirm its occurrence as a dominant feature of contemporary climate dynamics, noting that "most observational and modeling studies support a widening of the tropical belt."

The latitudinal displacement of these atmospheric systems has profound implications. It effectively shifts climatic boundaries, exposing new regions to conditions of water deficit and thermal stress. This phenomenon does not merely alter weather patterns; it redefines the ecological and agricultural viability of entire territories, suggesting that semi-arid dynamics are no longer geographically confined but are instead becoming structurally embedded in the global climate system.

Global Dryland Expansion

The expansion of drylands constitutes one of the most consequential outcomes of these atmospheric changes. Empirical evidence indicates that arid and semi-arid regions are increasing both in extent and intensity, driven by a combination of rising temperatures, altered precipitation patterns, and land-atmosphere feedback mechanisms.

Huang et al. (2016) estimate that more than 40% of the global land surface already falls within dryland categories, with projections indicating continued expansion under future climate scenarios. The authors emphasize that "drylands have expanded significantly during the last decades," underscoring the rapidity of this transformation. Complementing this perspective, Yao et al. (2020) demonstrate that dryland expansion exerts measurable impacts on global primary productivity, revealing that "accelerated dryland expansion regulates global productivity," particularly in ecosystems sensitive to water availability.

Recent projections further highlight the persistence and spatial heterogeneity of aridification processes. Zhang et al. (2025) show that land aridification continues even in regions not traditionally classified as drylands, suggesting a diffusion of semi-arid conditions across climatic zones. The study notes that "aridification persists in vulnerable drylands," reinforcing the notion that climatic drying is not a transient anomaly but a structural trend.

However, the relationship between aridity and desertification is not linear. Berg et al. (2024) argue that although aridity is increasing globally, less than 4% of dryland areas are projected to

undergo full desertification. This finding introduces an important nuance, indicating that while ecosystems may not collapse entirely, they are nonetheless subjected to intensified stress, requiring adaptive responses at both ecological and societal levels.

In the Brazilian context, recent remote sensing analyses reveal a consistent intensification of aridity across the semi-arid region. Silva et al. (2026) document climate-driven increases in aridity indices, emphasizing that "climate change is intensifying aridity in the Brazilian semiarid region," with direct implications for water availability, vegetation dynamics, and agricultural systems.

The convergence of these findings suggests that the global expansion of drylands is not merely a spatial phenomenon, but a systemic transformation affecting ecological productivity, food security, and human livelihoods. It raises a critical question: if increasing portions of the planet are becoming functionally semi-arid, which existing systems are best equipped to inform adaptation strategies?

The Caatinga as a Climate Analog

In light of these transformations, the Caatinga emerges as a compelling climate analog for future global conditions. Characterized by highly variable rainfall regimes, intense solar radiation, and prolonged dry periods, this biome operates under environmental constraints that are becoming increasingly common worldwide (Silva et al., 2026; Fernandes et al., 2022). Its ecological configuration reflects a long-term evolutionary response to climatic instability, resulting in a system structured around unpredictability and resource limitation rather than equilibrium.

Rainfall in the Caatinga is not only scarce but also temporally irregular, often concentrated in short, intense events followed by extended dry spells. This pulsed hydrological regime challenges conventional agricultural and ecological models based on predictability and continuity, which are typical of humid and temperate regions. Instead, it favors systems capable of rapid response, dormancy, and efficient resource use, as observed in the functional strategies of woody species and seedling

dynamics in the biome (Lopes et al., 2017; Rufino et al., 2024). Such dynamics reinforce the idea that variability, rather than stability, constitutes the organizing principle of these ecosystems.

High levels of solar radiation further exacerbate water loss through evapotranspiration, intensifying selective pressures on vegetation and soil systems. Under these conditions, survival depends on adaptive strategies such as phenological plasticity, deep and efficient root systems, and water storage mechanisms, both above and below ground (Silva et al., 2022). Functional trait analyses indicate that these characteristics are not incidental, but rather systematically distributed across species, reflecting convergent evolutionary solutions to chronic water deficit. In this sense, the Caatinga reveals a high degree of ecological optimization under stress, where energy and water use are tightly regulated.

At the same time, the biome sustains remarkable levels of biodiversity and endemism, challenging traditional assumptions that associate environmental harshness with biological impoverishment. Floristic surveys and updated plant checklists demonstrate a rich assemblage of species adapted to seasonal dryness, indicating that resilience in this context is not synonymous with simplification, but with diversification under constraint (Fernandes et al., 2020; Santos et al., 2024; Soares; Loeuille, 2024). This complexity suggests that semi-arid systems may harbor underexplored adaptive potential, particularly relevant in a context of global climatic stress.

The concept of the Caatinga as a climate analog gains further relevance when considering the increasing variability observed in global climate systems. The combination of irregular precipitation, thermal stress, and resource limitation is no longer restricted to semi-arid regions. Instead, it is becoming a defining characteristic of multiple biomes undergoing climatic transition, as evidenced by the intensification of aridity in different parts of the world (Huang et al., 2016; Zhang et al., 2025). This convergence indicates that environmental conditions historically associated with the Caatinga are progressively being reproduced at broader spatial scales.

Such alignment suggests that the Caatinga embodies a form of ecological and climatic foresight. Its environmental dynamics mirror the conditions toward which many regions are evolving,

positioning it as a living laboratory of adaptation. Recognizing this role requires a critical departure from deficit-based interpretations of semi-arid systems and an epistemological shift toward valuing their adaptive intelligence. Rather than being perceived as marginal landscapes, these systems should be understood as repositories of strategies that anticipate and respond to the emerging configuration of the Earth system in the Anthropocene.

Table 1 synthesizes the main global patterns associated with dryland expansion, integrating atmospheric drivers, regional expressions of aridification, and their socioecological consequences. The table highlights that the processes driving climatic drying are not isolated phenomena, but rather interconnected mechanisms operating across multiple regions of the globe. By juxtaposing different territories, it becomes evident that semi-arid conditions are emerging as a structural component of contemporary climate dynamics.

Table 1 – Global Trends of Dryland Expansion and Climatic Drivers

Region	Climatic Mechanism	Observed/ Projected Trend	Primary Impacts	Key References
Mediterranean Basin	Hadley cell expansion; reduced precipitation	Increased aridity and prolonged drought periods	Agricultural decline; water scarcity	Lu et al., 2007; Huang et al., 2016
Southwestern United States	Subtropical dry zone expansion; warming	Intensification of drought frequency and severity	Soil degradation; reduced crop yields	Yao et al., 2020; Staten et al., 2020
Central Asia	Continental drying; temperature increase	Persistent aridification trends	Vegetation loss; desertification risk	Zhang et al., 2025; Xian et al., 2021
Sub-Saharan Africa (Sahel)	Rainfall variability; land-atmosphere feedback	Oscillating drought cycles with long-term drying tendency	Food insecurity; ecosystem instability	Huang et al., 2016; Berg et al., 2024
Brazilian Semiarid (Caatinga)	Climate change-driven aridity; variability	Intensification of aridity indices and rainfall irregularity	Water stress; adaptive ecological and social responses	Silva et al., 2026

Source: Developed by the authors.

The comparative perspective reveals a clear convergence toward increased aridity across

distinct climatic zones, albeit through region-specific mechanisms. The expansion of the Hadley cell appears as a recurrent driver, particularly in subtropical regions, reinforcing the redistribution of dry conditions toward higher latitudes (Lu et al., 2007; Staten et al., 2020). Simultaneously, feedback processes involving soil moisture, vegetation cover, and atmospheric circulation intensify local drying trends, as observed in Africa and Central Asia (Huang et al., 2016; Zhang et al., 2025).

A critical insight emerging from the table is that the Brazilian semiarid does not occupy an isolated position within this global pattern. On the contrary, its climatic dynamics align closely with processes observed in other regions undergoing aridification, particularly in terms of rainfall variability and increasing water stress (Silva et al., 2026). This alignment reinforces the central argument of the article, suggesting that the Caatinga should be interpreted as a functional analog of future climatic conditions rather than as an exception.

Furthermore, the impacts identified across regions converge on key dimensions such as food security, ecosystem stability, and water availability, indicating that the consequences of dryland expansion are systemic and transboundary. This convergence challenges conventional adaptation strategies and underscores the urgency of rethinking development models in light of semi-arid realities.

BIO-SOFTWARE OF RESILIENCE IN THE CAATINGA

The ecological configuration of the Caatinga cannot be adequately understood through deficit-based frameworks that associate semi-arid conditions with biological limitation. On the contrary, this biome represents a highly sophisticated system of evolutionary solutions shaped by long-term exposure to climatic instability, water scarcity, and thermal stress. From this perspective, its biodiversity constitutes a form of "bio-software of resilience," encoding adaptive strategies that are not only ecologically functional but also potentially translatable into biotechnological and agricultural innovations under global climate change.

Evolutionary Assembly and Biodiversity

The Caatinga is widely recognized as the most biodiverse semi-arid region in the world, hosting a remarkable number of endemic species adapted to seasonal dryness. Its evolutionary assembly reflects complex biogeographical processes, including climatic oscillations, isolation mechanisms, and lineage diversification over geological timescales. Fernandes et al. (2022) highlight that the biome's formation involved "a long history of climatic fluctuations and floristic exchanges," which contributed to its current structural and functional heterogeneity.

Updated floristic inventories reinforce this interpretation by revealing high levels of species richness and endemism. Fernandes et al. (2020) report that the Caatinga includes thousands of plant species, many of which are restricted to this biome, emphasizing that "the Caatinga flora is more diverse than previously assumed" (p. 104082). This finding challenges persistent narratives that portray semi-arid environments as biologically impoverished, instead positioning them as reservoirs of evolutionary innovation under constraint.

Recent studies on floristic composition corroborate this pattern at regional scales. Santos et al. (2024) document a diverse assemblage of species in the semi-arid region of Paraíba, demonstrating that local communities are structured by both environmental filtering and adaptive specialization. Similarly, Soares and Loeuille (2024) identify significant diversity within the Asteraceae family, one of the most ecologically important plant groups in dry environments, reinforcing the idea that taxonomic richness is maintained even under conditions of chronic water limitation.

Functional Traits and Survival Strategies

The resilience of the Caatinga is fundamentally rooted in the functional traits of its species. These traits reflect adaptive responses to recurring environmental stress, particularly water scarcity and high evapotranspiration rates. Among the most prominent strategies is deciduousness, which

allows plants to shed leaves during dry periods, reducing water loss and metabolic demand.

Lopes et al. (2017) demonstrate that functional groups of seedlings in the Caatinga are closely aligned with ecological strategies adapted to seasonal water availability. The authors note that "seedling functional groups reflect ecological strategies of woody plants," indicating that adaptation is expressed from early developmental stages (p. 112). Complementing this perspective, Rufino et al. (2024) identify distinct functional groups among woody species, emphasizing that trait diversity plays a central role in ecosystem resilience.

Root system architecture constitutes another critical adaptive feature. Deep and extensive root networks enable access to water stored in deeper soil layers, while shallow roots can rapidly absorb moisture during short rainfall events. Silva et al. (2022) highlight that "functional traits above and below ground are tightly coordinated" (p. 5), suggesting that resource acquisition strategies are integrated across plant structures. This coordination enhances water-use efficiency, allowing species to survive under highly variable hydrological conditions.

Water-use efficiency itself emerges as a defining characteristic of Caatinga vegetation. Physiological mechanisms such as stomatal regulation, reduced leaf area, and specialized photosynthetic pathways contribute to minimizing water loss while maintaining metabolic activity. These traits collectively represent optimized solutions for survival under chronic stress, reinforcing the idea that the Caatinga operates as a system of ecological precision rather than limitation.

Microbial and Symbiotic Adaptations

Beyond plant-level adaptations, the resilience of the Caatinga is also mediated by microbial and symbiotic interactions. Endophytic fungi, in particular, play a crucial role in enhancing plant tolerance to environmental stress, including drought and nutrient scarcity.

Lima et al. (2020) investigate the diversity of endophytic fungi associated with Poincianella pyramidalis, a key species in the Caatinga, revealing a complex microbial community with potential

functional benefits. The authors report that these fungi “may contribute to host plant adaptation to environmental stress” (p. 512), suggesting that resilience is not solely an intrinsic property of individual organisms, but emerges from multi-species interactions.

These symbiotic relationships expand the adaptive capacity of plants by improving nutrient uptake, enhancing resistance to pathogens, and modulating physiological responses to drought. From a broader perspective, they illustrate that resilience in semi-arid systems operates at multiple biological scales, from cellular processes to ecosystem-level dynamics. This multilayered adaptability reinforces the conceptualization of the Caatinga as a bio-integrated system of resilience.

Climate Vulnerability and Adaptive Limits

Despite its high adaptive capacity, the Caatinga is not immune to the accelerating pressures of climate change. Projections indicate that increasing temperatures and prolonged drought periods may exceed the resilience thresholds of certain species, leading to shifts in community composition and potential biodiversity loss.

Silva et al. (2019) provide evidence that climate change poses significant risks to endemic plant species, noting that “many Caatinga endemic species are projected to experience range contractions” (p. e0217028). This finding highlights the existence of adaptive limits, beyond which even highly specialized systems may face destabilization.

At the same time, the intensification of aridity observed in the region suggests that existing adaptive strategies may be pushed toward critical thresholds. Silva et al. (2026) demonstrate that climate-driven aridity is increasing in the Brazilian semi-arid region, reinforcing the urgency of understanding both the strengths and vulnerabilities of these ecosystems.

This duality raises a fundamental question. If the Caatinga represents an advanced system of adaptation, what happens when the pace and magnitude of climate change exceed its adaptive capacity? The answer to this question is not merely ecological, but deeply connected to global

adaptation strategies. It suggests that while the Caatinga offers valuable lessons, these lessons must be interpreted within the limits imposed by accelerating environmental change.

Table 2 systematizes the principal functional adaptive traits identified in Caatinga species, highlighting their underlying biological mechanisms, ecological roles, and potential applications beyond their native context. By organizing these traits into a structured analytical framework, the table reveals that adaptation in the Caatinga is not based on isolated characteristics, but on integrated strategies that operate across multiple biological scales. This organization allows for a clearer understanding of how evolutionary solutions developed under semi-arid conditions may inform technological and agricultural innovation in a context of global climate stress.

Table 2 – Functional Adaptive Traits of Caatinga Species and Their Biotechnological Potential

Trait Type	Biological Mechanism	Ecological Function	Adaptive Advantage	Biotechnological Potential
Deciduousness	Seasonal leaf shedding	Reduction of transpiration during drought	Water conservation under prolonged dry periods	Development of drought-resilient crops
Deep root systems	Extensive vertical root architecture	Access to deep soil moisture	Survival during long dry intervals	Engineering crops with enhanced water uptake
Shallow opportunistic roots	Rapid surface root proliferation	Quick absorption of rainfall pulses	Efficient use of short, intense precipitation events	Soil moisture optimization systems
Water-use efficiency	Stomatal regulation; reduced leaf area	Minimization of water loss	Maintenance of metabolic activity under water stress	Genetic improvement for water-efficient agriculture
Phenological plasticity	Flexible growth and reproductive cycles	Synchronization with rainfall variability	Rapid response to environmental fluctuations	Climate-adaptive cropping calendars
Symbiosis with fungi	Endophytic fungal associations	Enhanced nutrient uptake and stress tolerance	Increased resilience to drought and poor soils	Bioinoculants for stress-prone agricultural systems
Functional trait integration	Coordination of above- and below-ground traits	Systemic resource optimization	Stability under multi-factor environmental stress	Systems-based ecological engineering

Source: Developed by the authors.

A critical reading of Table 2 indicates that the adaptive strategies of Caatinga species are characterized by efficiency, integration, and responsiveness to variability. Traits such as deciduousness and water-use efficiency demonstrate a consistent orientation toward minimizing resource loss, while root system diversity reflects the capacity to exploit both temporal and spatial heterogeneity in water availability (Silva et al., 2022; Lopes et al., 2017). This dual strategy, combining conservation and opportunism, suggests a highly optimized system of resource management under constraint.

The presence of phenological plasticity and symbiotic relationships further expands the adaptive repertoire, indicating that resilience is not limited to structural traits but also involves dynamic and relational processes (Lima et al., 2020; Rufino et al., 2024). These findings reinforce the notion that the Caatinga operates as a multi-layered adaptive system, in which survival emerges from the interaction between physiological, morphological, and ecological mechanisms.

From a broader perspective, the table highlights the translational potential of these traits. What emerges is not merely a catalog of ecological characteristics, but a repertoire of strategies that can be reinterpreted as biotechnological pathways for addressing water scarcity, soil degradation, and climate variability in other regions. This reinforces the central argument of the article, suggesting that the Caatinga embodies a functional blueprint for adaptation in an increasingly semi-arid world.

SOCIAL TECHNOLOGIES AND SERTANEJO KNOWLEDGE

The adaptive capacity of the Caatinga cannot be fully understood through ecological or biological lenses alone. Human populations inhabiting the Brazilian semi-arid region have historically developed complex systems of knowledge, practices, and technologies that enable coexistence with environmental constraints. These systems constitute a form of socially engineered resilience, grounded not in the control of nature, but in the strategic alignment between human practices and ecological variability. In this context, adaptation emerges as a collective, cumulative, and territorially embedded process.

From “Drought Combat” to “Living with the Semiarid”

The historical trajectory of public policies and development strategies in the Brazilian semi-arid region reveals a profound paradigmatic shift. For much of the twentieth century, drought was framed as an adversary to be overcome through large-scale hydraulic interventions, often disconnected from local realities. This approach, commonly referred to as “drought combat,” was based on a technocratic logic that sought to impose stability on inherently variable systems.

More recent approaches, however, have challenged this paradigm by proposing the concept of “living with the semiarid” as an alternative framework. This perspective recognizes that climatic variability is not an anomaly, but a structural condition that must be incorporated into adaptive strategies. Diniz; Piraux; Bursztyn (2016) emphasize that social technologies in the region are grounded in “a rationale that aligns with the environmental and social specificities of the semiarid” (p. 34), highlighting the importance of contextualized solutions.

This shift is not merely conceptual; it reflects a reorientation of development practices toward resilience, autonomy, and local knowledge. Rego et al. (2016) describe this transition as a movement from reactive interventions to proactive coexistence, noting that “convivência com o semiárido pressupõe adaptação às condições locais” (p. 45). Such a transformation challenges dominant development models and redefines the role of semi-arid populations from passive recipients of aid to active agents of innovation.

Water Technologies

Water management represents one of the most critical dimensions of adaptation in the Caatinga. In a context marked by irregular rainfall and prolonged dry periods, access to water becomes a central determinant of social and ecological resilience. Rather than relying on centralized

infrastructure, communities in the semi-arid region have developed decentralized technologies that capture, store, and manage water at the household and community levels.

Among these technologies, cisterns stand out as one of the most emblematic and widely disseminated solutions. Designed to collect and store rainwater during short precipitation events, cisterns enable families to maintain water security during extended dry periods. Duarte et al. (2023) highlight that cisterns function as "tecnologias sociais de convivência com o semiárido," emphasizing their role not only as technical devices but as instruments of social transformation (p. 8).

The Programa Um Milhão de Cisternas (P1MC) represents a large-scale effort to institutionalize this technology, demonstrating its effectiveness in reducing vulnerability and enhancing autonomy. Gomes; Heller (2016) argue that access to water through cisterns contributes to a "ruptura da vulnerabilidade," rather than merely mitigating drought effects (p. 628). This distinction is crucial, as it reframes water access as a structural condition for resilience rather than an emergency response.

Medeiros; Silveira (2022) further interpret the program as an institutionalized social innovation, noting that it integrates technical knowledge with community participation, thereby enhancing its scalability and sustainability. The decentralized nature of these systems contrasts sharply with traditional large-scale infrastructure, suggesting that resilience in semi-arid environments is better achieved through distributed and context-sensitive solutions.

Agroecological Knowledge and Seed Sovereignty

Beyond water management, agricultural practices in the Caatinga reflect a deep integration between ecological knowledge and adaptive strategies. Agroecological systems developed in the region prioritize diversity, flexibility, and local adaptation, enabling farmers to cope with climatic variability and resource limitations.

One of the central elements of this system is the use of creole seeds, which are locally adapted

varieties maintained and exchanged within communities. These seeds embody a form of biological and cultural heritage, preserving genetic diversity and enhancing resilience to environmental stress. Lacerda et al. (2020) emphasize that social technologies in the semi-arid are based on "práticas e mecanismos que articulam conhecimento local e inovação" (p. 12), highlighting the role of community-based knowledge in sustaining adaptive systems.

Seed sovereignty, in this context, is not merely a technical issue but a political and ecological one. It involves the capacity of communities to control their own means of production, resist external dependencies, and maintain adaptive flexibility. This autonomy is particularly relevant in environments where external inputs may be unreliable or inappropriate for local conditions.

The integration of agroecological practices with local knowledge systems creates a dynamic form of resilience that operates across temporal scales. It allows communities to respond to immediate climatic fluctuations while preserving long-term adaptive capacity, reinforcing the idea that resilience in the Caatinga is both a biological and a socio-cultural phenomenon.

Institutionalization of Social Innovation

The effectiveness of social technologies in the Caatinga is not limited to isolated initiatives; it is increasingly supported by processes of institutionalization that enable their replication and scaling. Public policies have played a central role in this process, particularly through programs that integrate community participation, technical support, and financial resources.

The institutionalization of social technologies represents a critical step in transforming local innovations into broader development strategies. Medeiros; Silveira (2022) describe this process as the consolidation of "uma inovação social institucionalizada," emphasizing that scaling does not imply standardization, but rather the adaptation of core principles to diverse contexts (p. 61).

At the same time, the success of these initiatives depends on maintaining a balance between institutional support and local autonomy. Over-centralization risks undermining the flexibility and

contextual sensitivity that characterize effective social technologies. Diniz; Piraux; Bursztyn (2016) argue that the sustainability of these systems is closely linked to their alignment with local rationalities, suggesting that top-down approaches may compromise their effectiveness.

This tension between scaling and contextualization raises important questions for global adaptation strategies. Can the principles underlying Caatinga social technologies be transferred to other regions without losing their effectiveness? What forms of governance are required to support such transitions?

EPISTEMOLOGY OF THE THORN IN THE ANTHROPOCENE

The empirical and analytical evidence presented in the previous sections converges toward a central theoretical necessity. The current planetary condition cannot be adequately interpreted through conceptual frameworks grounded in stability, predictability, and resource abundance. Instead, the emerging climate regime demands a reconfiguration of how knowledge itself is structured, mobilized, and applied. It is within this context that the concept of the Epistemology of the Thorn is proposed as a new paradigm for understanding and navigating the Anthropocene.

Conceptual Definition

The Epistemology of the Thorn can be defined as a model of knowledge grounded in constraint, variability, and adaptive intelligence under pressure. It draws inspiration from the ecological and socio-technical dynamics of semi-arid systems, particularly the Caatinga, where survival depends on the efficient use of scarce resources, the capacity to withstand stress, and the ability to respond to pulsed environmental conditions.

Unlike traditional epistemologies rooted in abundance and linear growth, this framework assumes that scarcity is not a temporary disruption but a structural condition. Knowledge, in this

sense, is not oriented toward maximizing outputs under ideal conditions, but toward sustaining functionality under persistent instability. This shift implies a fundamental reorientation of scientific inquiry, technological development, and socioecological organization.

Core Principles of the Epistemology of the Thorn

Resource Economy

The first principle is the economy of resources. In semi-arid systems, efficiency is not a matter of optimization for growth, but a condition for survival. This principle aligns with the broader literature on resilience, which emphasizes the importance of maintaining system functionality under constraint rather than maximizing production (Folke, 2002). As highlighted in early discussions on resilience and sustainability, adaptive systems must operate within ecological limits, recognizing that "sustainable development requires the maintenance of resilience" (Folke et al., 2002, p. 437).

Defensive Adaptation

The second principle concerns defensive adaptation. In contrast to expansionist models of development, systems operating under scarcity evolve mechanisms of protection, buffering, and resistance to external shocks. Walker et al. (2004) conceptualize this as part of the adaptive capacity of social-ecological systems, defining it as "the capacity of actors in a system to influence resilience" (p. 3). In the context of the Caatinga, such defensive strategies are evident in both biological traits and social technologies, reflecting a proactive orientation toward risk management rather than reactive crisis response.

Pulsating Resilience

The third principle is pulsating resilience. Semi-arid systems are not characterized by continuous productivity, but by cycles of dormancy and rapid activation in response to environmental pulses. This dynamic challenges linear models of stability and introduces a temporal dimension in which resilience is expressed through oscillation rather than equilibrium. Folke (2006) emphasizes that resilience involves "the capacity to absorb disturbance and reorganize while undergoing change" (p. 259), suggesting that adaptability is inherently linked to temporal variability and systemic reconfiguration.

Theoretical Anchors: Resilience, Adaptability, and Transformability

The Epistemology of the Thorn is not an isolated conceptual construct, but is anchored in a well-established body of literature on social-ecological resilience. Over the past decades, resilience thinking has evolved from a descriptive ecological concept to a comprehensive analytical framework for understanding complex systems under stress.

Folke, Colding and Berkes (2003) argue that building resilience involves the integration of ecological knowledge with social institutions, emphasizing that adaptive capacity emerges from the interaction between human and natural systems. This perspective is further expanded by Folke et al. (2010), who introduce the concept of transformability as a critical dimension of resilience, defined as the capacity to create fundamentally new system configurations when existing conditions become untenable.

This triad of resilience, adaptability, and transformability provides the theoretical backbone for the Epistemology of the Thorn. It situates adaptation not as a static response, but as a dynamic process that includes learning, innovation, and systemic change. Reyers et al. (2018) reinforce this view by highlighting that navigating the Anthropocene requires "integrating knowledge across scales

and systems" (p. 270), pointing to the necessity of interdisciplinary and context-sensitive approaches.

From Abundance to Resilience: A Paradigm Shift

The contrast between the abundance paradigm and the resilience paradigm reveals a fundamental epistemological rupture. The former is based on assumptions of stability, control, and resource availability, which have historically guided industrial development and technological innovation. However, as environmental conditions become increasingly variable and constrained, these assumptions lose their explanatory and practical validity.

The resilience paradigm, by contrast, acknowledges uncertainty, limits, and nonlinearity as defining features of contemporary systems. It shifts the focus from growth to persistence, from control to adaptation, and from uniformity to diversity. This transition is not merely conceptual; it has direct implications for how societies organize production, manage resources, and design technologies.

Reyers et al. (2018) argue that the Anthropocene requires new ways of thinking about human-environment interactions, emphasizing that traditional approaches are insufficient to address complex global challenges. Similarly, Folke (2006) notes that resilience thinking "offers a framework for analyzing how to sustain development in the face of change" (p. 260), highlighting its relevance for contemporary sustainability debates.

Table 3 presents a comparative analytical framework contrasting the dominant paradigm of abundance with the proposed concept of the Epistemology of the Thorn. The table is structured across key dimensions that define how environmental systems are understood, managed, and transformed under conditions of climatic stress. By organizing these paradigms side by side, the table highlights not only their conceptual differences but also their practical implications for adaptation in the Anthropocene. This synthesis serves as a bridge between empirical findings and theoretical innovation, consolidating the central argument of the article.

Table 3 – Comparative Framework: Abundance Paradigm vs. Epistemology of the Thorn

Analytical Dimension	Abundance Paradigm	Epistemology of the Thorn	Implications for Adaptation	Associated Theoretical Basis
Ontological Assumption	Nature as stable and predictable	Nature as variable, unstable, and constrained	Adaptation requires flexibility and anticipation	Folke, 2006; Walker et al., 2004
Resource Logic	Maximization and extraction	Economy, efficiency, and conservation	Shift toward sustainable and optimized resource use	Folke et al., 2010; Reyers et al., 2018
Temporal Perspective	Linear growth and continuity	Pulsed dynamics and cyclical adaptation	Planning must incorporate variability and thresholds	Folke, 2002; Folke et al., 2003
Adaptation Strategy	Control and standardization	Coexistence and contextual adaptation	Local knowledge becomes central to resilience	Diniz; Piraux; Bursztyn, 2016
Technological Orientation	Centralized, large-scale infrastructure	Decentralized, modular, and socially embedded technologies	Greater autonomy and distributed resilience	Medeiros; Silveira, 2022
Knowledge System	Universal, technocratic, external	Situated, experiential, and collective	Recognition of plural epistemologies	Reyers et al., 2018
System Response to Stress	Collapse or external intervention	Reorganization, transformation, and persistence	Emphasis on adaptive capacity and transformability	Walker et al., 2004; Folke, 2006
Sustainability Model	Growth-dependent sustainability	Resilience-based sustainability	Redefinition of development under environmental constraints	Folke et al., 2010

Source: Developed by the authors.

A close examination of Table 3 reveals a profound epistemological rupture between the logic that has historically guided development and the framework required to navigate emerging climatic realities. The abundance paradigm is grounded in assumptions of stability, predictability, and resource availability, which are increasingly misaligned with the dynamics of a warming and drying planet.

Its emphasis on control, standardization, and large-scale infrastructure reflects a model designed for equilibrium conditions that no longer prevail.

In contrast, the Epistemology of the Thorn is structured around variability, constraint, and adaptive responsiveness. Rather than seeking to eliminate uncertainty, it incorporates it as a fundamental condition of system functioning. This shift is particularly evident in the transition from resource maximization to resource efficiency, and from centralized technological systems to decentralized and socially embedded solutions (Medeiros; Silveira, 2022; Diniz; Piraux; Bursztyn, 2016).

The table also underscores the centrality of knowledge systems in shaping adaptive capacity. While the abundance paradigm privileges universal and technocratic knowledge, the Epistemology of the Thorn recognizes the value of situated, experiential, and collective forms of understanding. This recognition aligns with contemporary approaches to social-ecological resilience, which emphasize the importance of local knowledge and adaptive learning in navigating complex systems (Folke, 2006; Reyers et al., 2018).

From a broader perspective, the comparative framework suggests that the transition toward resilience-based sustainability is not merely a technical adjustment, but a fundamental transformation in how development is conceptualized. It requires rethinking the relationship between humans and the environment, moving from domination to coexistence, and from predictability to adaptability. In this sense, the Epistemology of the Thorn does not simply describe an alternative model; it articulates a necessary paradigm shift for a world increasingly defined by semi-arid conditions.

Epistemological Implications for the Anthropocene

The introduction of the Epistemology of the Thorn carries significant implications for scientific research, policy design, and global adaptation strategies. It challenges the dominance of universalist models that disregard local variability and calls for the recognition of situated knowledge

systems, particularly those developed in historically marginalized environments.

Moreover, it redefines the role of semi-arid regions in global knowledge production. Rather than being treated as peripheral or deficient, these regions emerge as epistemic frontiers where adaptive strategies are continuously tested and refined. This inversion aligns with the broader argument of the article, positioning the Caatinga as a central reference for understanding and responding to planetary change.

At a deeper level, the Epistemology of the Thorn invites a reconsideration of what constitutes progress in the Anthropocene. If environmental stability can no longer be assumed, then progress cannot be measured solely by growth or expansion. Instead, it must be evaluated in terms of resilience, adaptability, and the capacity to sustain life under conditions of constraint.

GEOPOLITICS OF CAATINGA ADAPTATION

The recognition of the Caatinga as a socioecological system of advanced adaptive capacity carries implications that extend beyond ecology and climate science. It reconfigures geopolitical hierarchies of knowledge, technology, and development in the Anthropocene. If semi-arid conditions are becoming structurally embedded in the global climate system, then regions historically shaped by such conditions acquire strategic relevance. This shift demands a reassessment of which territories produce actionable knowledge for the future, and which remain anchored in obsolete paradigms of abundance.

The Caatinga as a Knowledge Export Platform

The Caatinga can no longer be interpreted solely as a recipient of development interventions. Instead, it must be understood as a platform for exporting adaptive knowledge, particularly to regions of the Global South facing similar climatic pressures. This repositioning challenges traditional North-

South knowledge flows, in which innovation is presumed to originate in industrialized countries and diffuse toward peripheral regions.

Empirical and theoretical evidence suggests that effective adaptation strategies are deeply contextual and often emerge from long-term interaction between communities and their environments. Reyers et al. (2018) argue that navigating the Anthropocene requires "integrating knowledge across scales and systems" (p. 272), which implicitly recognizes the value of localized and experience-based knowledge systems. In the case of the Caatinga, such knowledge is embedded in social technologies, agroecological practices, and water management systems that have evolved under conditions of scarcity.

Diniz; Piraux; Bursztyn (2016) emphasize that social technologies in the Brazilian semi-arid are not merely technical solutions, but expressions of a specific rationality aligned with environmental constraints. The authors note that these technologies are grounded in "a rationale that is coherent with the semiarid context" (p. 35), suggesting that their transferability depends not on replication, but on adaptation to local conditions.

This perspective opens space for South-South cooperation frameworks in which semi-arid regions in Africa, Asia, and Latin America exchange strategies, technologies, and knowledge systems. Rather than importing externally designed solutions, these regions can engage in horizontal learning processes, drawing on shared experiences of climatic variability and resource limitation. In this sense, the Caatinga emerges as a node in a global network of adaptive knowledge, capable of informing strategies far beyond its geographical boundaries.

Dryland Technologies and Global Inequality

The expansion of drylands also exposes and intensifies global inequalities. Regions most affected by aridification are often those with limited access to financial resources, technological infrastructure, and institutional capacity. This asymmetry creates a condition of climate injustice,

in which populations least responsible for global emissions are disproportionately affected by their consequences.

At the same time, dominant adaptation strategies frequently rely on capital-intensive technologies that are inaccessible to vulnerable regions. Large-scale irrigation systems, advanced climate monitoring tools, and genetically engineered crops are often presented as universal solutions, despite their limited applicability in contexts characterized by institutional fragility and economic constraints.

In contrast, the social technologies developed in the Caatinga offer an alternative model based on accessibility, scalability, and local participation. Medeiros; Silveira (2022) describe the institutionalization of cistern programs as an example of innovation that combines technical simplicity with social effectiveness, noting that such initiatives represent "uma inovação social institucionalizada" (p. 60). These technologies operate with low financial input while generating significant improvements in water security and resilience.

The implications of this contrast are profound. If adaptation strategies continue to be framed within high-cost technological paradigms, they risk reinforcing existing inequalities. Conversely, the recognition of low-cost, decentralized, and socially embedded technologies as legitimate forms of innovation may contribute to more equitable adaptation pathways. This raises a critical question: which forms of knowledge and technology are being prioritized in global climate governance, and whose interests do they serve?

Brazil as a Leader in Dryland Adaptation

The repositioning of the Caatinga as a global reference for adaptation also implies a strategic opportunity for Brazil. Historically associated with the Amazon in international environmental discourse, the country has the potential to assume leadership in a different domain: dryland adaptation and resilience under climatic stress.

Recent evidence indicates that aridity is intensifying within the Brazilian semi-arid region, reinforcing its relevance as a site of ongoing adaptation (Silva et al., 2026). This internal dynamic strengthens the argument that Brazil is not only a repository of adaptive knowledge, but also an active laboratory where such knowledge continues to evolve. In this sense, the country occupies a dual position as both subject and producer of adaptation strategies.

From a geopolitical perspective, this positioning can be translated into scientific diplomacy. By promoting research, technological exchange, and policy frameworks centered on semi-arid adaptation, Brazil can engage with other regions facing similar challenges, particularly in Africa and South Asia. Such engagement has the potential to redefine international cooperation, shifting it from a model of aid to one of mutual learning and co-production of knowledge.

Folke et al. (2010) highlight that adaptive governance requires "the capacity to deal with change and to continue to develop" (p. 3), emphasizing the importance of institutional flexibility and innovation. In the Brazilian context, this implies the need to strengthen policies that support social technologies, agroecological practices, and decentralized water management systems, ensuring their continuity and scalability.

At the same time, the pursuit of technological sovereignty becomes a central concern. Dependence on external technologies that are poorly adapted to semi-arid conditions may undermine long-term resilience. By investing in locally grounded solutions, Brazil can develop a portfolio of technologies aligned with its climatic realities, positioning itself as a global leader in adaptation science and practice.

CONCLUSION

The evidence synthesized in this study converges toward a compelling and, to some extent, unsettling conclusion. The conditions that have historically defined the Caatinga are no longer confined to a specific biome or region. They are progressively emerging as structural features of the

Earth system in the Anthropocene. Aridity, variability, and constraint are no longer anomalies; they are becoming the baseline of a changing planet.

Within this context, the Caatinga reveals itself not as a marginal landscape, but as an अग्र -garde system of adaptation. Its biological strategies, social technologies, and knowledge systems embody a form of intelligence forged under pressure, capable of informing responses to global climatic challenges. What has often been interpreted as limitation now appears as sophistication. What was once seen as scarcity now emerges as a condition that generates efficiency, innovation, and resilience.

The concept of the Epistemology of the Thorn, developed in this article, seeks to capture this shift. It represents more than a theoretical proposition; it is an invitation to rethink how knowledge is produced, valued, and applied in a world defined by uncertainty. It challenges the persistence of paradigms rooted in abundance and calls for the recognition of systems that have long operated within ecological limits.

Repositioning the Caatinga at the center of global adaptation debates is not merely an academic exercise. It is a political, epistemological, and ethical necessity. As climate change reshapes the geography of habitability, the future of adaptation may depend less on inventing entirely new solutions and more on learning from those who have long lived with instability as a condition of existence.

In this sense, the Caatinga is not a remnant of the past. It is a signal of what is to come. The ongoing process of planetary "Caatingization" signals not a crisis of exception, but a transformation of norm. The Caatinga is not the periphery of the world; it is its most advanced ecological frontier.

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