Checked and Unchecked Resourcefulness: A Structural Theory of Sustainable Human Systems

Preprint Version 1.0 – March 2026
This manuscript is a preprint and has not undergone peer review.

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Suggested citation:

Steermann, R. J. (2026). *Checked and Unchecked Resourcefulness: A Structural Theory of Sustainable Human Systems* (Preprint, v1.0). Zenodo.
https://doi.org/10.5281/zenodo.18856793

Abstract

Contemporary sustainability challenges—including climate change, biodiversity loss, and pollution—are often framed as problems of excess scale or mismanagement. Beyond these considerations, this paper argues that they also reflect a structural divergence between human systems and wild ecosystems. It develops a cross-disciplinary evolutionary systems framework centered on resourcefulness: the adaptive capacity of a system to exploit available energy over time. Part 1 characterizes wild ecosystems as exhibiting checked resourcefulness, in which adaptation remains tightly coupled to ecological feedback through genetic inheritance, trophic structure, and energetic constraint. Part 2 argues that human gene–culture coevolution generated a distinct regime of unchecked resourcefulness, where cumulative cultural adaptation allows strategies to compound faster than ecological feedback can regulate them. This decoupling enabled unprecedented expansion while introducing delayed systemic risk. Part 3 derives a structural model of circular resourcefulness, in which rapid cultural adaptation is re-embedded within recovery-dominant material and energetic constraints. The framework redrafts sustainability as a problem of system architecture rather than self-limitation, clarifying why technological fixes or incremental efficiency gains are insufficient in isolation. By showing the structural conditions under which human adaptive power can persist without destabilizing its ecological foundations, it offers a unified theoretical lens for evaluating energy systems, material cycles, and land use in the context of planetary stability.

Keywords: sustainability theory; systems ecology; socio-ecological systems; gene–culture coevolution; planetary boundaries; circular economy; circular resourcefulness; feedback dominance

Introduction

Emissions, pollution, and biodiversity loss are typically framed as consequences of human excess, and the response is usually to scale them back. The planetary boundaries framework (Rockström et al., 2009; Steffen et al., 2015) identifies nine ecological thresholds whose transgression risks destabilizing Earth's life-support systems. The availability of quantified limits is invaluable. However, this framing implies that the underlying system is sound but overextended—that sustainability failures are primarily a matter of degree. A deeper structural divergence may remain obscured.

Most approaches to sustainability, therefore, emphasize efficiency, restraint, or technological substitution to curb excesses. While important, these responses do not address a more fundamental question: why did human adaptive capacity escape ecological limits in the first place? Answering this requires bridging ecology, anthropology, and systems theory. How do non-human species remain sustainable over millions of years, and how did humans become the exception within only thousands?

Wild ecosystems sustain themselves through feedback-bound resource use, in which production, consumption, and regeneration remain tightly coupled. Human systems, by contrast, have diverged from this pattern, expanding faster than ecological feedback can respond. This paper proposes shifting the sustainability conversation from a problem of scale or mismanagement to one of design. It identifies a structurally distinct evolutionary trajectory of the human system rooted in a unique biological and cultural development.

The three-part framework developed here is based on resourcefulness—the adaptive capacity of a system to exploit available energy. Conservation biologists have long emphasized how biodiversity underpins ecosystem stability through trophic interdependence and niche partitioning (Terborgh, 1992; Wilson, 2010). In wild ecosystems, what this paper terms checked resourcefulness binds species to narrow niches and reciprocal feedback loops. Research on cultural evolution and shared intentionality (Richerson & Boyd, 2010; Tomasello, 2014) shows how humans diverged by developing socially inherited, rapidly evolving strategies—such as tool use, symbolic communication, and cooperative norms—that enabled the engineering of environments and the circumvention of local constraints. Unlike wild species, which adapt through slow specialization and feedback-bound co-evolution, humans generalize, override ecological limits, and amplify their reach through external energy inputs. The result is unchecked resourcefulness: the capacity for self-reinforcing change at planetary scale (Meadows et al., 2004; Steffen et al., 2018).

The aim of this paper is not to idealize wilderness or vilify progress, but to show that our current trajectory cannot be corrected simply by scaling back certain systems or mitigating isolated excesses. These excesses reflect a deeper structural incompatibility between the sustainability-promoting logic of wilderness and the change-provoking logic of human systems.

In its third part, the paper infers a model of circular resourcefulness, integrating ecological constraints with human adaptive capacity to restore feedback dominance without forfeiting cumulative cultural innovation. This vision aligns with the circular economy's emphasis on closed material loops and regenerative design principles (Braungart & McDonough, 2008; Graedel & Allenby, 2010). The paper concludes by considering the implications of this framework for sustainability theory and future research.

The model developed here advances a structural evolutionary account of human sustainability. Rather than specifying optimal scales or prescribing institutional designs, the framework identifies the dominance relationships that determine whether adaptive capacity remains feedback-bound or becomes structurally decoupled from ecological self-restraint. By integrating systems ecology with gene–culture coevolution, the analysis complements circular economy and planetary boundary approaches: where those frameworks examine material flows or define ecological limits, the present theory clarifies how particular adaptive regimes generate, weaken, or restore feedback dominance. In this sense, circular resourcefulness is offered not as a normative ideal, but as an architectural condition under which cumulative cultural adaptation can persist without undermining its ecological foundations.

Part 1: Wild Ecosystems—Checked Resourcefulness

Wild ecosystems function through tightly coupled flows of energy and matter. These systems evolve slowly, stabilize through interdependence, and their living parts remain constrained by biophysical limits. This part examines the structural features of wild ecosystems and introduces the concept of checked resourcefulness to describe their characteristic mode of adaptation.

1.1 Wilderness

Wilderness refers to ecosystems characterized by minimal human influence and largely intact ecological processes (e.g., Watson et al., 2016). In this paper, wilderness functions as an analytical baseline: a system in which adaptive dynamics unfold independently of human-directed processes. This abstraction does not presuppose that such systems exist in pure form on contemporary Earth; rather, it provides a structural contrast that clarifies the distinctive properties of human systems. Throughout this framework, the term wild ecosystems refers to systems operating under this wilderness condition.

1.2 Feedback-Bound Resourcefulness

In this paper, resourcefulness refers to a system's adaptive capacity to mobilize and organize available energy and resources in ways that persist and, under certain conditions, accumulate over time. Within wild ecosystems, this capacity is structurally constrained: adaptation remains tightly coupled to genetic inheritance, physiological form, and proximate ecological feedback. This bounded mode of adaptation is what this paper terms checked resourcefulness. The sections that follow examine how genetic evolution, ecological specialization, and trophic interdependence together produce this condition.

1.3 How Genetic Evolution Constrains Adaptation

In wild ecosystems, species evolve through genetic variation and natural selection, often leading to increased ecological specialization. Niche breadth—the range of environmental conditions or resources a species can exploit—narrows as species adapt to particular ecological roles. Even a highly adaptable species such as the red fox, which is adapted to an exceptionally broad range of land surfaces, remains limited by its biological form: its feeding strategies, mobility, and behavioral repertoire must remain compatible with a body roughly one meter long and weighing 5–10 kg (Henry, 1996). Its versatility is real, but bounded.

Evolutionary transitions also carry costs. When environments shift, specialists often lose fitness due to negative genetic correlations (Kassen, 2002). Rather than accumulating entirely new abilities, species typically trade one specialization for another. Generalist strategies evolve only when the cost of broader functions is low or where they confer a clear fitness advantage (Ma & Levin, 2006). These constraints help explain why generalists like the red fox remain relevant across diverse conditions: beneficial mutations could arise without sacrificing prior functionality; new traits remained compatible with the same claws, teeth, and overall morphology.

The red fox serves as a representative example of ecological generalism within undisturbed wilderness. As a highly adaptable consumer species, it illustrates that even broad niche breadth does not dissolve ecological constraints. Its adaptability does not translate into overabundance. Its carrying capacity—defined as the maximum population size an environment can support without degradation—is relatively high for a mid-sized carnivore, presumably due to its versatility. However, this adaptability does not spare it from regulation by prey fluctuations, disease, and predation by apex carnivores such as wolves, coyotes, and lynx.

Physical traits carry a cost. This is best illustrated with a counterexample. Vestigial structures, such as pelvic bones in whales or wings in ostriches, are features that once served a function but have lost most or all of their original utility. These structures still require energy to maintain, however. Unless secondary functions prove advantageous, selection would favor their reduction. The abundance of vestigial structures in biology shows how slowly evolution removes outdated traits and how strongly historical constraints shape organisms. Across evolutionary timescales, functional change is gradual, and adaptive potential is limited by the rate at which genetic variation can accumulate (Futuyma & Kirkpatrick, 2017).

1.4 Ecological Niches Shift Slowly

Because genetic adaptation unfolds over thousands or tens of thousands of generations, ecosystems typically change slowly. Most systems depend on long-term climatic stability, allowing evolutionary specialization, trophic diversification, and tight nutrient cycling to emerge over millennia. Abrupt environmental shifts can exceed a species' capacity to adapt, as illustrated by the desertification of the Sahara roughly 6,000 years ago, when shifts in Earth's axial tilt disrupted rainfall patterns and triggered ecological collapse (deMenocal et al., 2000). Rising air temperatures, capable of holding more moisture and altering precipitation patterns, altered abiotic conditions too drastically for many plant species. Their collapse in turn disrupted the food and energy base for both decomposers and consumers. These cascading dependencies set the stage for the next section, which explores the interdependencies of wild systems. At their base lie the narrow fitness ranges of individual life forms.

1.5 Trophic Structure and Dependencies

To analyze biomass creation and flow, this paper groups all components of an ecosystem into four functional categories, defined here for conceptual clarity:

1. Source Energy and Matter (Source E&M)—Abiotic inputs such as sunlight, water, minerals, and atmospheric gases that enable the creation of biological matter. These constitute the starting point of all biomass in wild ecosystems.
2. Producers—Organisms that convert Source E&M into organic biomass. Producers also use organic matter for their own growth, reproduction, and metabolism, but

they are the only organisms capable of creating new biological material from inorganic sources.

3. Decomposers—Organisms that feed primarily on dead organic material. In this framework, the term is used functionally to encompass microorganisms and detritivores that process dead biomass. Collectively, these organisms enable nutrient recovery and system-level material cycling, returning elements to the Source E&M pool accessible to producers. This grouping abstracts from taxonomic distinctions in order to highlight their shared role in ecological recovery processes.
4. Consumers—Organisms that feed mainly on living biomass. They cannot create biomass from inorganic sources or process dead biomass into forms of nutrients accessible to producers.

These four categories form a hierarchy of energetic dependencies:

- Producers rely on Source E&M.
- Decomposers rely on dead organic matter.
- Consumers rely on living biomass.

Although producers may indirectly benefit from consumers or decomposers (e.g., seed dispersal or nutrient recycling), they remain energetically dependent solely on Source E&M.

Together, these dependencies define the structural organization of biomass creation and transformation in wild ecosystems.

1.6 Biomass Limits, Energy Dissipation, and Checked Growth

Given these energetic dependencies, ecosystem structure does not merely constrain individual species but also regulates the distribution of total biomass across trophic roles. The quantity and composition of Source E&M set the upper limits of total ecosystem biomass. Tropical rainforests, which cover only 6–7% of land yet hold roughly 40% of terrestrial biomass, illustrate how abundant sunlight and moisture intensify producer productivity, enabling rich decomposer networks and dense trophic specialization (Chapin et al., 2011). By contrast, ecosystems with severely limited Source E&M show markedly reduced biomass potential. Even if genetic adaptation had kept pace with the Sahara's loss of rainfall, producer growth would still have been constrained by water scarcity. At the poles, prolonged darkness restricts photosynthesis and compresses biomass production into short seasonal windows, forcing food webs to rely on highly seasonal growth or migration. Regardless of evolutionary capacity, primary producers set the energetic ceiling of ecosystems, and total biomass is ultimately bounded by the availability of Source E&M.

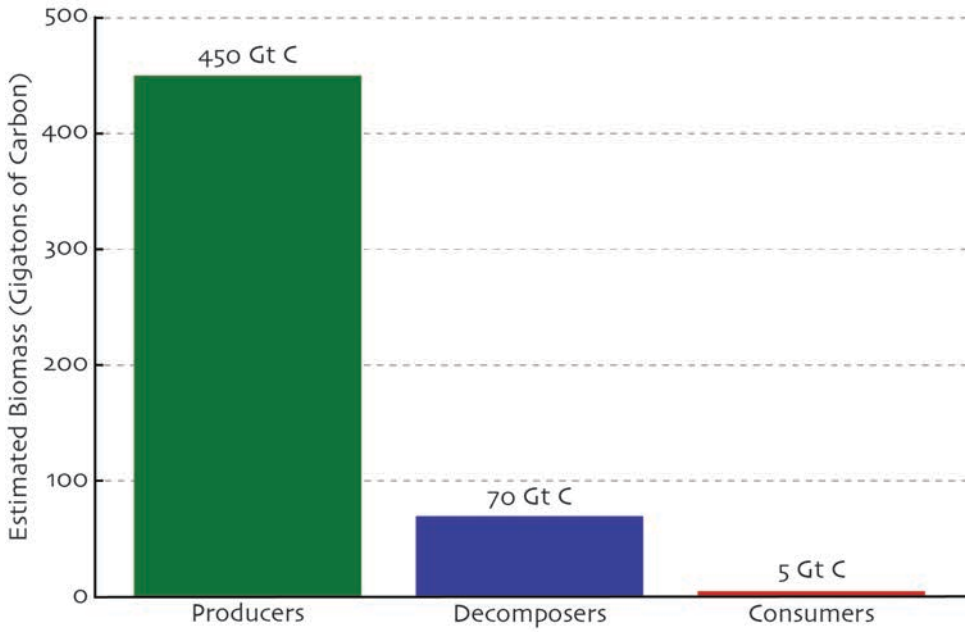
Consumers primarily feed on living biomass, and most of their prey allocate at least some tissue to chemical or structural defense. Upon death, these defenses degrade

irreversibly. This provides a broad array of ecological niches for decomposers, feeding on the dead organic matter of all three organic ecosystem categories.

Empirical estimates consistently show a steep biomass hierarchy. Bar-On et al. (2018) find a global terrestrial producer:decomposer:consumer ratio of approximately 225:13:1, consistent with trophic energy dissipation and the 10% energy transfer rule (Lindeman, 1942) —see Figure 1 below.

Figure 1

Approximate Biomass Distribution in Terrestrial Ecosystems



Note. Data adapted from Bar-On et al. (2018). Groupings are aggregated into the producer, decomposer, and consumer categories defined in the main text.

In terrestrial ecosystems, the consistent pattern is:

Producer biomass > Decomposer biomass > Consumer biomass.

Nutrient cycling tightly couples aboveground production to below-ground decomposer processes, reinforcing this interdependence (Wardle et al., 2004). However, what ultimately structures ecosystems are rates of production and transformation rather than the amount of biomass present at any given time. Standing biomass accumulates because of these rates, but it does not set their limits. This distinction matters especially when including marine ecosystems, where short organismal lifespans prevent large standing stocks from forming despite very high rates of primary production and nutrient turnover.

For this reason, the structural relationship in wild systems is best expressed in flow terms, where upstream input rates constrain downstream transformation and consumption:

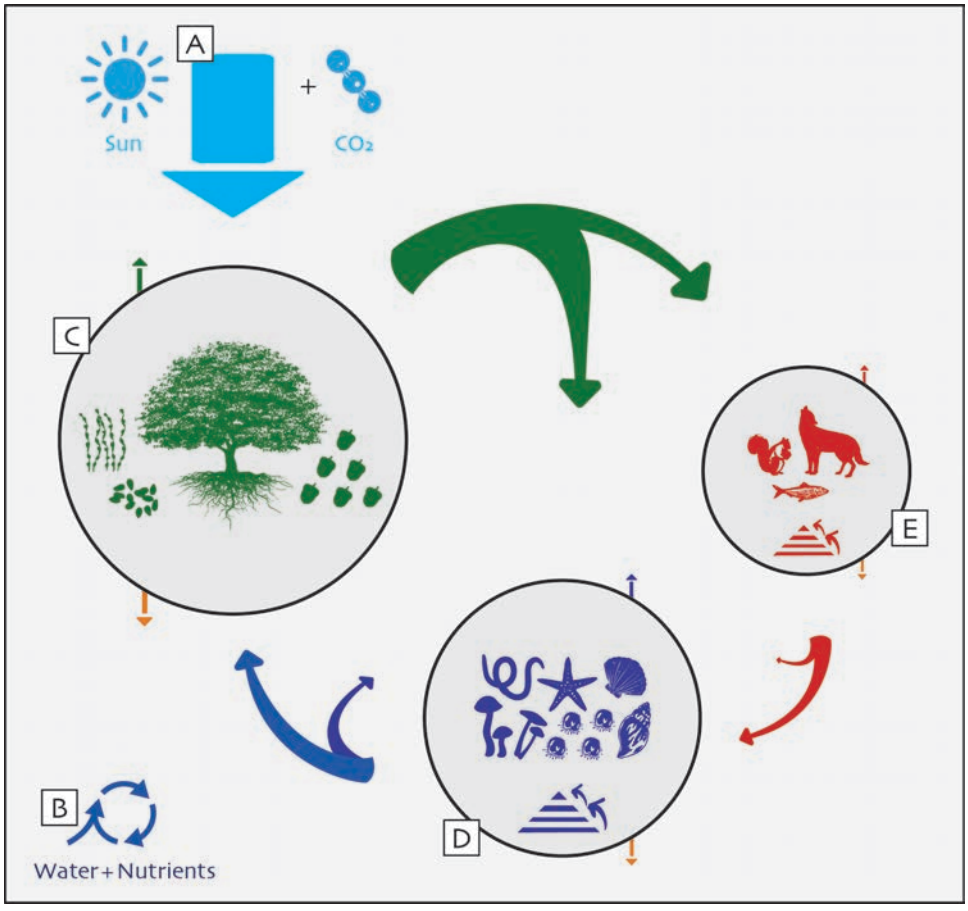
Source E&M potential (input rate) > Producer throughput >
Decomposer throughput > Consumer throughput

Here, Source E&M potential refers to the maximum sustainable rate at which usable energy and material enter the ecosystem from abiotic sources (e.g., solar radiation, water, mineral nutrients). Producer throughput denotes the rate at which primary producers convert these inputs into organic matter. Decomposer throughput refers to the rate at which dead organic matter is processed and nutrients are returned to biologically accessible forms. Consumer throughput represents the rate at which living biomass is consumed and transformed by consumers.

This ordering reflects the fundamental energetic logic of wild systems: total biomass and trophic structure are bounded by input rates and energy-transfer losses, and no category can expand independently of the flows that sustain it. Within the bounds set by interdependent niches and thermodynamic dissipation, an individual species' carrying capacity shapes its selection pressure. All actors are checked, not by choice, but by consequence. Figure 2 visualizes wild ecosystems' checked resourcefulness.

Figure 2

Throughput Structure of Wild Ecosystems (Checked Resourcefulness)



Note. This figure summarizes the structural relationships that characterize energy and material throughput in wild ecosystems exhibiting checked resourcefulness. Component sizes represent relative throughput (rates of energy and material transformation), not static biomass. Standing biomass reflects the long-run balance of these flows and is depicted proportionally, but the structural emphasis is on throughput rather than static mass. (A)

Atmospheric components of Source Energy and Matter (Source E&M), such as solar radiation and carbon dioxide. (B) Terrestrial components of Source E&M, including water and mineral nutrients. (C) Producers, which convert abiotic inputs into biological matter. (D) Decomposers, which process dead organic matter and return nutrients to forms accessible to producers. (E) Consumers, which feed primarily on living biomass. Arrows indicate dominant flows of energy and matter; energy flows one-way and dissipates as heat, while nutrients cycle through decomposition. Small vertical arrows represent unavoidable system leakage.

The relative sizes of the components reflect a consistent pattern in wild systems: producer capacity exceeds decomposer throughput, which in turn exceeds consumer biomass. This dependency structure ensures that no category can expand independently. Adaptive capacity remains tightly coupled to ecological feedback, keeping total system scale bounded and preventing runaway growth. The relative sizes and flows shown here are schematic and vary across ecosystems, but the dependency structure they represent is consistent.

1.7 Feedback-Regulated Growth and Population Dynamics

Wild species exhibit variation along what has traditionally been described as an r–K continuum, producing either many offspring with low survival (r-strategists) or fewer offspring with higher parental investment (K-strategists) (MacArthur & Wilson, 2001). Yet regardless of where a species sits on this sliding scale of reproductive strategy, all remain constrained by ecological carrying capacity, resource availability, predation, competition, and disease—typical forms of density-dependent regulation.

Even when species migrate into favorable environments, growth remains checked: populations expand only until they reach either their biotic potential or the ecological limits of the new habitat. Feedback is proximate and inescapable.

1.8 Disturbance, Recovery, and System Stability

Ecosystems experience periodic disturbances—fires, storms, volcanic activity, or invasive species. Smaller disturbances create temporary gaps that can be filled by existing variation or colonizers. Larger disturbances require longer recovery, but reassembly still depends on primary producers, followed by decomposers and consumers.

As ecosystems diversify through specialization and more efficient resource capture, they tend to become increasingly resilient to internal or external shocks (Holling, 1973). At the same time, moderate disturbance can even foster diversity by periodically creating ecological space for new or previously rare species (Connell, 1978). Greater diversity, in turn, increases functional redundancy across trophic roles; the loss of one or a few species has less impact in a highly interconnected system. Ultimately, the slow, feedback-bound evolution of wild ecosystems fosters structural stability—a hallmark of checked resourcefulness.

Consider, finally, an invasive producer species that outcompetes native vegetation for sunlight while remaining inedible to local herbivores due to chemical defenses. Such a disruption can slow decomposition, alter nutrient cycling, and increase greenhouse gas emissions. However, its impact remains spatially and temporally bounded: the invader can

thrive only within the geographic and climatic conditions compatible with its ecological strategy. From a global systems perspective, these disturbances do not constitute self-amplifying systemic transformations because their impacts remain spatially confined.

Even the five major mass extinction events are widely understood to have been triggered by large-scale geophysical disturbances—such as massive volcanism, rapid climate shifts, or extraterrestrial impact—that overwhelmed existing ecological organization (Erwin, 2006). Wild systems can collapse, but collapse has historically been associated with large-scale exogenous disturbance rather than cumulative endogenous trophic decoupling.

1.9 Conclusion to Part 1: The Logic of Checked Resourcefulness

Wild ecosystems exhibit checked resourcefulness: adaptive capacity is bounded by genetic inheritance, physiological form, and ecological feedback. Across wild systems:

- Adaptation proceeds slowly and is constrained by genetic and morphological limits.
- Energy and biomass flows remain tightly coupled across trophic levels.
- Population growth is regulated by ecological carrying capacity.
- Feedback loops are unavoidable and binding.
- Disturbances trigger rebalancing rather than runaway expansion.

Because innovation remains embedded within these feedback-bound relationships, wild ecosystems tend to accumulate diversity, reinforce internal resilience, and move toward structural stability between major disturbances. Over evolutionary timescales, adaptive change remains aligned with the environmental conditions that sustain it.

In this sense, checked resourcefulness is not a limitation imposed by choice or foresight, but a consequence of ecological interdependence. Adaptive strategies cannot decouple from the systems that support them. This constraint underpins the structural sustainability of wild ecosystems.

Part 2: Human Systems—Unchecked Resourcefulness

Human ecosystems are organized around culturally mediated adaptation. Cumulative cultural evolution enabled rapid expansion in energy use, production, and coordination, reinforcing and compounding adaptive strategies. These dynamics enable growth to continue even as ecological constraints are displaced, delayed, or externalized. This part outlines the structural features of human systems that produce what this paper terms unchecked resourcefulness—the capacity for self-reinforcing adaptive change that is not readily constrained by ecological feedback.

2.1 The Coevolution of Human Culture

Cognitively advanced animals such as our closest relatives—chimpanzees and bonobos—hunt and forage in groups, maintain stable social networks of dozens of kin and non-kin, use tools, transmit behaviors socially, and communicate. At a behavioral level, these capacities can give the appearance of robust cooperation. On closer inspection, however, such activities are best understood as organized around individual intentionality: coordinating with others increases one's own chances of success, social ties enhance individual standing, and socially learned behaviors serve personal ends (Tomasello, 2014). Communication likewise remains oriented toward influencing others' behavior—gaining access to food, recruiting aid, or deterring aggression—rather than toward establishing a shared frame of understanding. Even cases that appear overtly altruistic, such as primate alarm calls or sentinel behavior in other species, lack evidence of shared mental representations of joint action; they coordinate behavior, but do not constitute cooperation grounded in jointly represented intentions (Seyfarth & Cheney, 2014; Tomasello, 2014).

The crucial evolutionary split between nonhuman primates and humans occurred when success in key survival tasks became genuinely interdependent. Activities such as confronting or hunting much larger game could no longer be achieved through parallel or opportunistic action but required tightly coordinated cooperation: I needed my partner to succeed for me to succeed; we had to succeed together. Where tasks required close coordination, selection favored joint mental representations, joint attention, and sustained sensitivity to a partner's perspective. Communication expanded beyond directive signaling to include informative acts aimed at aligning perspectives toward a shared goal (Tomasello, 2010, 2014). Informative communication thus provided a foundation for increasingly abstract and intersubjective representations. Increased interdependence also made partner evaluation consequential: individuals had to monitor not only others' reliability, but their own standing as cooperative partners (Hrdy, 2011; Henrich, 2017). Self-evaluation helped stabilize cooperation beyond immediate tasks and enabled the expansion of larger, more stable social groupings.

Collective intentionality emerges when cooperation is no longer organized primarily around particular partners and tasks, but around group-level norms, roles, and shared

practices. As social groups expanded and interactions became more frequent and less personal, coordination increasingly depended on expectations independent of any specific joint activity. Collective intentionality allowed human sociality to scale beyond the cognitive limits of relationship-based cooperation. While nonhuman primates are constrained to maintaining on the order of 150 stable social relationships (Dunbar, 1992), norm-governed groups could coordinate among far larger numbers of relative strangers. As such, individuals increasingly moved from loosely organized bands of cooperative partners toward clearly defined groups, bound by socially recognized standards of conduct. These norms sustained cooperation by making conformity predictable and deviations sanctionable, allowing coordination to extend beyond the limits of direct reciprocity or personal reputation (Henrich, 2017; Tomasello, 2014).

Critically, collective intentionality transformed social learning into a stable inheritance system alongside genetic transmission by enabling cumulative cultural "ratcheting," whereby successful solutions were preserved and incrementally refined rather than lost (Tomasello, 2001, 2014). Such horizontal cultural transmission allowed practices to be maintained and built upon across generations, rather than being restricted to vertical genetic inheritance from parent to offspring. Shared rituals, narratives, and symbolic markers reinforced in-group conformity and out-group distinction, preserving cultural differences even as people moved between groups. This stood in sharp contrast to genetic evolution, where migration typically outpaces adaptation and tends to homogenize populations. As a result, human societies came to function as semi-isolated, parallel experiments in adaptation, allowing responses to environmental challenges to emerge far more rapidly than genetic evolution alone would permit (Boyd & Richerson, 2010).

2.2 The Virtual Niche

Humans' primary adaptive niche is culture: cooperation based on socially learned, transferable knowledge. Over human evolutionary history, culture shifts the dominant locus of adaptation from the physically based domain of genes and anatomy to a virtual domain—socially real but not biologically instantiated—composed of norms, practices, and shared expectations. What keeps us alive is not what is *within* us, but what exists *between* us. Culture here is not treated merely as shared behavior, but as a structured adaptive niche with its own dynamics of inheritance and selection.

Building on Tomasello's (2014) account of cumulative cultural development, the claim that the primary adaptive niche of modern humans is cultural can be clarified through a simple hypothetical scenario. Imagine a small group of human infants raised to adulthood in an environment entirely devoid of cumulative cultural knowledge—no inherited techniques, no established language, no tools or practices transmitted across generations. Cooperation may emerge, but its adaptive potential would remain limited to what could be developed within a single generation. Without drawing on accumulated knowledge such as fire use, complex tool-making, or coordinated subsistence strategies, their ecological niche would

likely resemble that of other highly social primates rather than that of technologically organized human societies. In such a case, adaptation would remain tightly coupled to genetic inheritance and immediate ecological feedback. Resourcefulness, in other words, would remain checked.

Operating within this virtual niche, human groups can develop distinct adaptive strategies that coexist, compete, fuse, or transfer on ecological timescales far faster than genetic evolution permits. Because these strategies operate at the level of socially organized practices rather than biological traits, they can accumulate without the fitness tradeoffs inherent to genetic evolution, and can be abandoned at relatively low biological cost. Crucially, in this parallel adaptive landscape, maladaptation is not fatal at the species level: unsuccessful strategies disappear through cultural loss, replacement, or absorption, while others persist. In effect, humans subjected their cultures to a non-genetic analogue of natural selection, operating on timescales far faster than genetic evolution.

While niche construction theory applies to humans by explaining how culturally mediated modifications of environments feed back into genetic selection (Odling-Smee et al., 2003; Laland et al., 2015), the virtual niche highlights adaptive dynamics that operate primarily through socially instantiated norms and practices, often without corresponding genetic change. Within the broader framework of gene–culture coevolution, these dynamics suggest that humans occupy a distinct adaptive niche—one that is virtual rather than biological, and whose selective pressures operate primarily through social norms and practices.

2.3 Cultural Expansion Beyond Biological Constraints

Cumulative cultural transmission enabled humans to survive in environments that genetic adaptation alone would not have permitted (Tomasello, 2014). Fire use, clothing and shelter, dietary expansion through food processing, and cooperative subsistence practices made deserts, tundra, high-altitude regions, or arctic coastlines habitable.

Much later, this same cultural capacity was amplified by agriculture, long-distance trade, and writing, allowing knowledge to be preserved, coordinated, and scaled across growing populations. Over time, increasingly powerful technologies—most notably fossil fuels and the internet—vastly expanded human energy use and coordination, while antibiotics and related innovations weakened constraints imposed by disease. Together, these developments enabled societies to grow and reorganize at an unprecedented scale. All of this occurred through cultural amplification rather than biological transformation, with bodies not substantially different from those of our closest primate relatives.

2.4 From Checked Resourcefulness to Structural Decoupling

The logic of checked resourcefulness described in Part 1 reflects a general property of wild systems: adaptive success remains tightly coupled to the ecological feedbacks that regulate energy, matter, and population dynamics. Innovation is constrained by biophysical limits and

trophic dependencies. A species' resourcefulness may increase, but it cannot escape its interdependence with the system to which it is adapted.

The human case does not initially depart from this logic through scale, intent, or complexity, but through a subtle structural shift. Over evolutionary time, adaptive strategies increasingly accumulated outside the direct constraints of genetic specialization and local ecological feedback. Ecological limits were not removed; their effects were delayed, displaced, or externalized. It is this altered relationship between adaptive action and ecological response—not resource use per se—that distinguishes human systems from wild ecosystems.

2.5 Unchecked Resourcefulness

When adaptive strategies begin to expand faster than the ecological feedbacks that regulate them, growth no longer self-corrects. This paper describes that condition as unchecked resourcefulness. In humans, unchecked resourcefulness arises when cognition, cooperation, and cumulative cultural inheritance enable adaptation beyond immediate biophysical limits, relocating survival and innovation from genetic specialization into a shared, culturally constructed niche.

In humans, unchecked resourcefulness first became visible when culture, in the specifically cumulative and cooperative sense, began to function as an enabling mechanism for adaptation. Culturally mediated subsistence and territorial strategies relaxed dietary and environmental constraints that otherwise bind closely related primates. This shift did not initially confer an unambiguous advantage over genetic adaptation, but it altered the logic of adaptation itself: rather than relying on morphological adaptation, human survival increasingly came to depend on socially transmitted solutions.

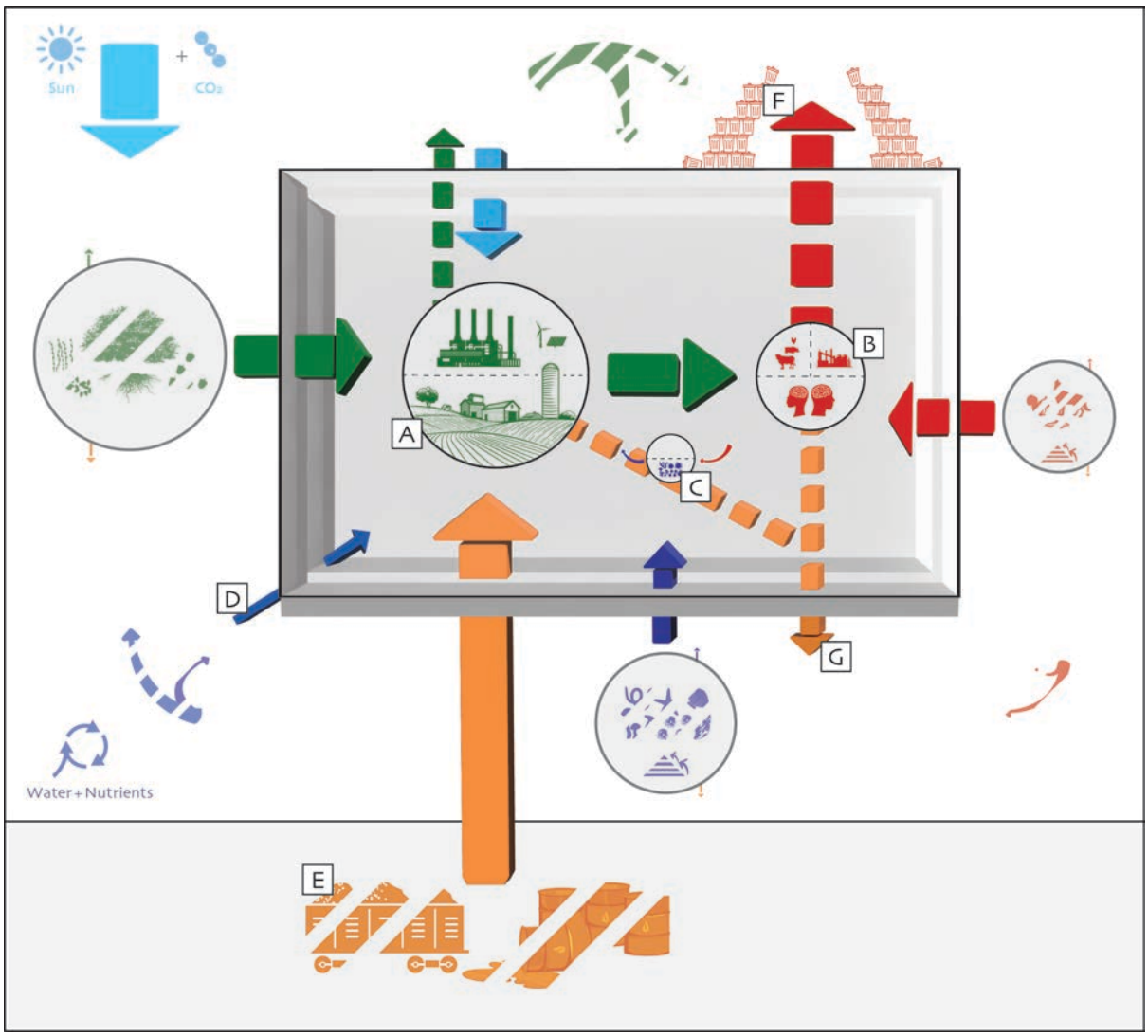
One may imagine a small hunter–gatherer group during the early stages of cumulative culture, where coordinated hunting techniques and crafted weapons allowed pairs or small teams to take down large prey that would otherwise be inaccessible. In such a system, predator and prey populations would ordinarily fluctuate around ecological carrying capacities. However, if within only a few human generations hunting techniques improved or new tools expanded the range of exploitable species, the effective carrying capacity of the human group could increase before prey populations or broader ecological constraints adjusted. Cultural innovation thus alters the relationship between adaptive action and ecological response, delaying the feedback that would otherwise regulate expansion.

Over time, a confluence of conditions—including extended periods of climatic stability, the emergence of sedentary lifeways, and the adoption of agriculture—shifted cumulative culture from a contingent advantage to a dominant adaptive strategy. These conditions supported increasing specialization, coordination, and knowledge retention, allowing cultural solutions to accumulate and compound. Together, these shifts enabled human societies to grow, reorganize, and transform environments at rates that increasingly exceeded the capacity of local ecological systems to respond.

Cultural inheritance ceased to be a feature of human adaptation and became a systemic property. Once this threshold was crossed, growth and transformation became self-reinforcing, setting the conditions for the global dynamics observed today. When adaptive expansion compounds faster than balancing ecological feedback can accumulate and constrain it, delay-induced overshoot becomes structurally likely (Meadows et al., 2004; Steffen et al., 2018). Figure 3 schematically represents this transition by extending the checked-resourcefulness model from Part 1 to include a distinct human adaptive sphere, illustrating how cultural and technological innovations restructured energy and biomass flows.

Figure 3

Throughput Structure of the Human System (Unchecked Resourcefulness)



Note. This figure extends the throughput structure of wild systems shown in Figure 2 by depicting the human system as a distinct adaptive sphere that appropriates and redirects energy and material flows. Component sizes represent relative throughput (rates of transformation per unit time), not static biomass. (A) illustrates the human production sector. Above the dashed line, the technical cycle generates electricity and heat from concentrated

energy sources, including fossil fuels and renewables. Below the dashed line, the biological cycle produces food and biomass through agriculture, drawing on air- and soil-based Source Energy and Matter (Source E&M), with modern yields increasingly subsidized by technical energy inputs (e.g., Haber–Bosch fertilizer production). (B) represents the human consumption sector, including humans, livestock, pets, and manufactured goods. (C) depicts the human recovery sector. Organic waste from food systems is partially recovered below the dashed line, whereas the technical cycle lacks a comparable systemic recovery loop. (D) and (E) indicate external soil-based inputs of Source E&M, including water, nutrients, mineral resources (e.g., copper, lithium, cobalt, rare earth elements), and fossil energy. (F) and (G) show above- and below-ground outputs, including emissions, waste products, particulate matter, and nutrient runoff. Dashed markings through wild-system components indicate progressive depletion of wild producer, consumer, and decomposer throughput capacities through land conversion, extraction, and pollution.

2.6 Human-Controlled Biomass and Linear Material Flows

Human activity now occupies and reshapes ecological space at an unprecedented scale. Roughly 44% of Earth's habitable, ice-free land surface is used for agriculture, the majority of it supporting livestock grazing and feed production (Ritchie & Roser, 2019). Through biomass harvest, grazing, forestry, and land-use change, humans appropriate an estimated 25–40% of terrestrial net primary production, substantially constraining the energy available to wild systems (Haberl et al., 2007). Humans and their domesticated mammals account for roughly 95–96% of global mammalian biomass (Bar-On et al., 2018). Biological productivity on land is thus increasingly organized around the needs of a single species.

Equally significant is the rise of technical materials. Over the past century, anthropogenic material stocks have increased more than twentyfold, with built infrastructure now constituting one of the planet's dominant physical structures (Krausmann et al., 2017). Human industry transforms fossil carbon, minerals, metals, and sand into substances—plastics, alloys, concrete, and synthetic chemicals—that ecosystems cannot readily decompose. Because producing virgin materials remains cheaper than high-fidelity recycling, fewer than 10% of technical materials are recycled, most of them through down-cycling that merely delays their accumulation as terminal waste (Oberle et al., 2019). The result is a strictly linear material flow without precedent in ecological history: an influx of substances that serve the utility of a single species while remaining largely external to ecological cycles.

This linear structure stands in direct contrast to wild ecosystems, where decomposition throughput structurally constrains consumption. In human systems, this relationship is effectively inverted: material consumption throughput exceeds recovery throughput, and production is organized primarily around consumer demand while recovery remains marginal, externalized, or absent altogether. This inversion can be expressed schematically in flow terms as:

$$C(human) > R(human)$$

where C(human) denotes the rate at which biological and technical systems consume and transform materials, and R(human) denotes the rate at which materials are recovered and returned to usable form, the functional analogue of decomposition in wild ecosystems.

2.7 Conclusion to Part 2

Taken together, these contrasts show that unchecked resourcefulness is not defined by any single technology, behavior, or moral failing, but by a systemic reconfiguration of adaptation itself. Human systems differ from wild ecosystems in how quickly they adapt, how weakly they are regulated by feedback, how globally they mobilize energy, and how linearly they process materials. Figure 4 summarizes this regime shift. The resulting system is extraordinarily productive and flexible, yet structurally exposed to delayed risk. The question, then, is not whether unchecked resourcefulness can be restrained, but whether its adaptive power can be re-embedded within feedback structures that restore long-term viability.

Figure 4

Unchecked Resourcefulness Table

Feature	Wild (checked)	Human (unchecked)
Adaptation Type	Physical	Cultural (virtual) + Physical
Adaptation Speed	Slow (genetic)	Fast (cultural + genetic)
System Feedback	Strong	Weak (delayed/externalized)
Energy Regime	Local, mostly renewable	Fossil + renewable
Material Cycling	Mostly closed loops	Predominantly linear
Structural Dominance	Producers > Decomposers > Consumers	Consumption > Recovery

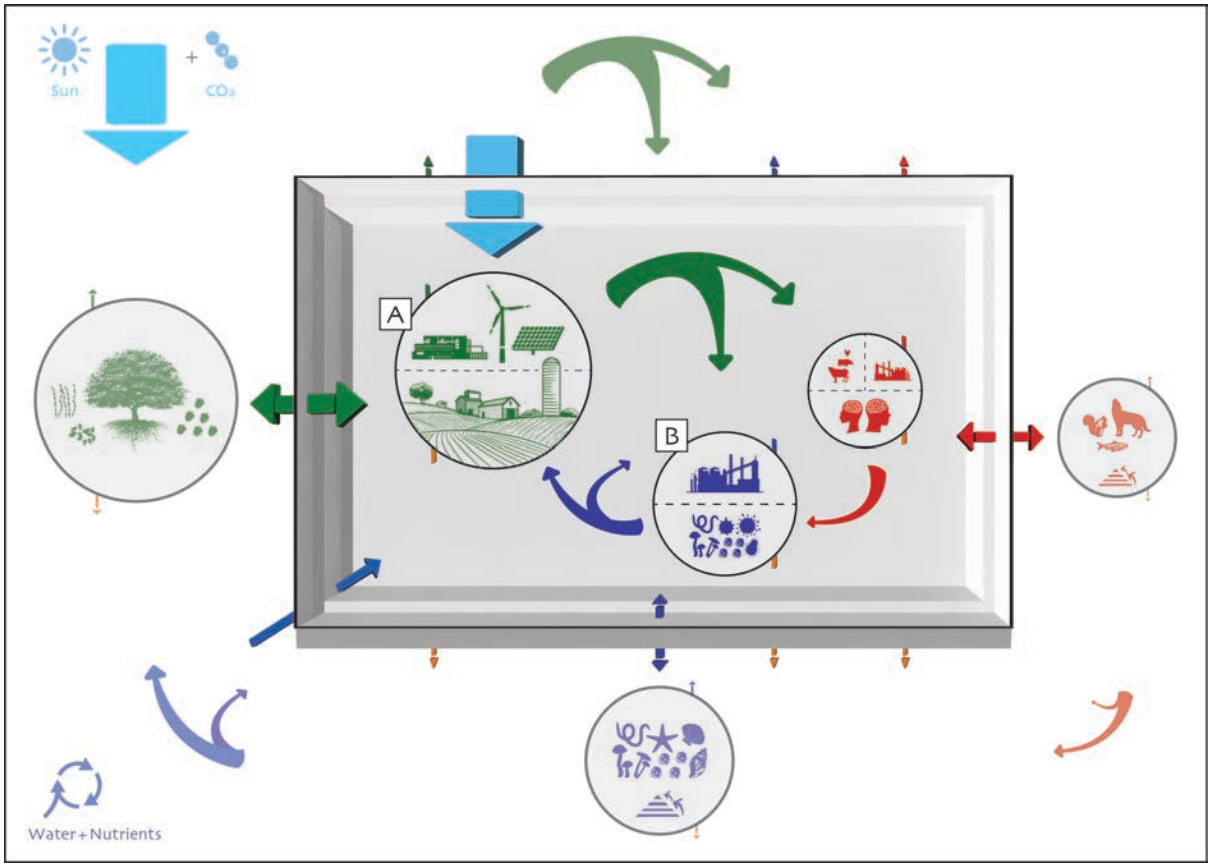
Part 3: Circular Resourcefulness—Synthesis and Outlook

Figure 5 integrates the feedback-bound logic of wild ecosystems with the adaptive power of human systems. It synthesizes the structural insights developed in Parts 1 and 2 into a conceptual model of circular resourcefulness—a regime in which human ingenuity is preserved while feedback dominance is reintroduced as a governing constraint.

Because this model is inferred from the preceding theoretical analysis, it is presented as a conceptual extension rather than a definitive solution, intended to clarify the conditions under which adaptive power could be re-coupled to recovery and long-term viability. In this sense, circular resourcefulness provides a framework for thinking about long-term sustainability in human systems.

Figure 5

Throughput Structure of a Circular Human System (Circular Resourcefulness)



Note. This figure integrates the throughput logic of wild ecosystems (Figure 2) with the adaptive capacity of human systems (Figure 3), depicting a configuration in which recovery structurally governs consumption. Component sizes represent relative energy and material throughput (rates of transformation per unit time), not static stocks. (A) Human production systems generate usable energy and food from recoverable Source E&M. (B) Recovery processes dominate consumption, so that material losses are incidental rather than systemic. The human system (foreground) and wild system (background) are shown as coexisting adaptive spheres linked through reciprocal exchange, indicated by bidirectional arrows.

Reduced and balanced exchange with wild systems reflects continued ecological interdependence without large-scale extraction or degradation.

3.1 Structural Logic of Circular Resourcefulness

Circular resourcefulness does not represent a return to wild ecosystems, nor a rejection of human adaptation. Instead, it describes a structural reconfiguration in which human systems retain their distinct adaptive mode while re-aligning material and energy flows with recovery processes. As in the unchecked model, humans remain a distinct adaptive sphere. Unlike unchecked resourcefulness, however, circular systems are organized such that all consumer mass—biological and technical—must remain recoverable within the system. This requirement restores a dependency characteristic of wild ecosystems but absent in the unchecked regime.

Circular resourcefulness requires that recovery throughput exceed consumption throughput. The asymmetry reflects unavoidable energy losses inherent to all material transformations and is necessary for maintaining system closure:

$$R(human) > C(human)$$

where R(human) denotes the rate at which materials are recovered and returned to usable form (e.g., recycling throughput, composting and anaerobic digestion rates, remanufacturing flows, material recovery infrastructure). It is the functional equivalent of decomposers in wild systems. C(human) denotes the rate at which biological and technical systems consume and transform materials, including humans, domesticated animals, and technical artifacts that draw on system resources without directly regenerating them.

Recovery must itself be energetically sustained, which creates a second dependency:

$$P(human) > R(human)$$

where P(human) denotes net usable energy production (heat, electricity, metabolic energy in food), generated by physical production systems such as crops, photovoltaics, wind turbines, and other primary energy-harvesting infrastructures, expressed as energy throughput per unit time.

Finally, production remains bounded by available Source E&M. Taken together, these relationships yield a structurally ordered system:

$$\text{Source E\&M potential} > P(human)\ \text{throughput} > R(human)\ \text{throughput} > C(human)\ \text{throughput}$$

Source E&M potential refers to the maximum sustainable rate at which usable energy and material can be drawn from environmental sources. These relationships are expressed in terms of system-level material and energy throughput rather than standing stocks.

While industrial ecology and circular economy frameworks analyze material flow closure at the level of products and industrial systems (e.g., Graedel & Allenby, 1995; Braungart & McDonough, 2002), the present framework establishes a necessary structural

condition: human adaptive systems must be organized such that recovery throughput structurally dominates consumption throughput.

Energy systems that irreversibly disperse their material basis—such as those that release stored carbon into the atmosphere—cannot satisfy this condition at scale, because recovery throughput cannot exceed consumption throughput under such dynamics (see Appendix A).

3.2 Continuity and Contrast with Checked and Unchecked Resourcefulness

Circular resourcefulness occupies an intermediate position between the two regimes examined earlier. Like checked resourcefulness, it is feedback-bound: growth and innovation remain coupled to recovery and regenerative capacity. Like unchecked resourcefulness, it preserves rapid adaptation, cultural inheritance, and global coordination.

What distinguishes circular resourcefulness from both is its selective recombination of features. From wild systems, it inherits tight material cycling and recovery dominance. From human systems, it retains cumulative cultural adaptation, intentional coordination, and innovation. It is neither regressive nor idealized, but structurally constrained.

Unlike unchecked resourcefulness, circular systems do not allow adaptive strategies to compound independently of recovery. At the same time, unlike wild ecosystems, circular resourcefulness does not rely on genetic specialization or slow evolutionary adjustment. Instead, it places design, coordination, and innovation under explicit feedback conditions. In this sense, circular resourcefulness is not a new adaptive mode, but a re-embedding of human adaptation within constraints that prevent unchecked accumulation and delayed systemic risk.

3.3 Balanced Exchange With Wild Systems

Even under circular resourcefulness, human systems remain functionally narrower and less resilient than wild ecosystems. Through dense niche filling, trophic redundancy, and long-term specialization, wild systems stabilize atmospheric composition, regulate hydrological cycles, and buffer climatic variability. These functions are not replicated by human-managed systems, which remain optimized for a single species and therefore, even under circular constraints, can at best avoid amplifying external shocks rather than absorb them.

Circular resourcefulness, therefore, does not eliminate dependence on wild systems, but clarifies it. Human sustainability requires not only internal material closure, but a balanced exchange with ecologically intact, non-extractive wild systems that continue to perform essential planetary regulation. Biodiversity, in this sense, is not an ethical supplement to human systems, but a structural prerequisite for maintaining the environmental conditions within which human physiology and social organization remain viable.

3.4 Conclusion to Part 3

The contrast developed across Parts 1–3 reframes sustainability as a question of system architecture rather than restraint. Unchecked resourcefulness enabled unprecedented human expansion by weakening the coupling between adaptive capacity and ecological feedback.

Circular resourcefulness identifies the conditions under which that same adaptive capacity can persist without destabilizing the systems that support it. Figure 6 below summarizes.

Several contemporary debates—most notably those surrounding fossil energy, material circularity, and land use—take on a new structure when viewed through the lens of circular resourcefulness. Illustrative applications are discussed in Appendix A.

Figure 6

Circular Resourcefulness Table

Feature	Wild (checked)	Human (unchecked)	Human (circular)
Adaptation Type	Physical	Cultural (virtual) + Physical	Cultural (virtual) + Physical
Adaptation Speed	Slow (genetic)	Fast (cultural + genetic)	Fast (cultural + genetic)
System Feedback	Strong (by consequence)	Weak (delayed/ externalized)	Strong (by design)
Energy Regime	Local, mostly renewable	Fossil + renewable	Renewable, recoverable
Material Cycling	Mostly closed loops	Predominantly linear	Mostly closed loops, recovery-dominant
Structural Dominance	Producers > Decomposers > Consumers	Consumption > Recovery	Production > Recovery > Consumption

Conclusion

This paper has argued that sustainability failures are not primarily the result of excess, mismanagement, or insufficient technological sophistication, but of a deeper structural divergence. Wild ecosystems persist because adaptive success remains tightly coupled to ecological feedback. Human systems diverged from this logic through gene–culture coevolution, which enabled adaptive strategies to accumulate beyond the constraints of genetic specialization and local ecological response.

The framework developed here distinguishes three regimes of resourcefulness. In checked resourcefulness, all species are constrained not by choice but by consequence, producing structurally self-regulating systems. In unchecked resourcefulness, humans became unconstrained not by choice but by chance, enabling adaptive power to compound faster than ecological feedback can respond. Circular resourcefulness identifies the conditions under which feedback dominance can be restored without forfeiting the uniquely human capacities for cumulative culture, coordination, and innovation.

Circular resourcefulness does not imply reverting human systems to wild ecological conditions, nor does it assume that human-designed systems can replicate the buffering capacity of biodiverse ecosystems. Rather, it specifies a necessary structural condition for long-term viability: adaptive power must remain coupled to recovery. In this sense, circular resourcefulness reframes sustainability not as a restraint but as a condition for continued adaptive capacity. Under the framework developed here, no alternative structural configuration appears capable of sustaining cumulative adaptive power over long time horizons without restoring feedback dominance. How such re-embedding can be achieved remains a matter for institutional, technological, and political development; the structural requirement itself follows from the feedback dynamics outlined here.

Acknowledgments

The author used ChatGPT (OpenAI) as an editorial and research-support tool to improve clarity and conciseness. All arguments, interpretations, and conclusions are the author’s own.

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Appendix A: Illustrative Applications of Circular Resourcefulness

Appendix A shows how the framework of circular resourcefulness reshapes contemporary sustainability debates, without claiming empirical completeness or policy prescription. It examines three analytically distinct structural conditions required for circular resourcefulness:

(1) Producer and Source E&M Integrity,
(2) Recovery Dominance (R > C), and
(3) Balanced Exchange with Wild Systems.

Taken together, these conditions prevent systemic leakage—such as pollution, waste accumulation, and nutrient runoff—by re-establishing recovery as a governing structural constraint. Each subsection illustrates how familiar sustainability debates are reorganized when evaluated against one of these conditions.

Appendix A.1: Fossil Energy—Producer and Source E&M Integrity

Conventional framing: Fossil fuels are commonly portrayed as high-emissions energy sources whose impacts can be mitigated through efficiency gains, substitution, or carbon capture.

Structural assessment via circular resourcefulness: Under circular resourcefulness, all material carriers of energy must remain recoverable within the human system. Fossil energy fails this condition because combustion disperses its material carrier (reduced carbon) into low-concentration atmospheric CO_2, requiring substantial external energy inputs for re-concentration (Ayres, 1998). While re-capture is physically possible, it cannot be energetically self-sustaining within a fossil-based loop and therefore cannot support a recovery-dominant, closed material system at scale. By contrast, energy sources that do not irreversibly disperse their material basis when producing energy—such as renewables or, in principle, nuclear energy—do not violate circular criteria at the level of material closure.

Structural implication: The central limitation of fossil fuels is not emissions, but their incompatibility with circular recovery dominance.

Appendix A.2: Material Circularity—Recovery Dominance (R>C)

Conventional framing: Material sustainability is commonly framed in terms of recycling rates, waste reduction targets, or improvements in material efficiency, often assessed at the level of individual products or supply chains.

Structural assessment via circular resourcefulness: From the perspective of circular resourcefulness, the decisive question is not whether materials are recycled, but whether recovery capacity structurally exceeds consumer mass. Where recovery remains subordinate to consumption, recycling functions as a mitigating add-on rather than a governing constraint. In such systems, material throughput can continue to grow even as recycling rates improve, because recovery does not dominate system structure. This failure is reinforced when

recovery responsibilities are institutionally separated from production and consumption, preventing recovery from constraining system scale. Circular closure, therefore, depends less on optimizing recycling performance than on establishing recovery as a limiting condition on consumption.

Structural implication: Material circularity requires recovery dominance (R(human) > C(human)); without it, efficiency gains delay accumulation but do not prevent systemic leakage.

Appendix A.3: Land Use and Biodiversity—Balanced Exchange With Wild Systems

Conventional framing: Land use reversal and rewilding are widely justified by their contributions to climate regulation, carbon sequestration, water cycling, and other ecosystem services, often complemented by ethical arguments for the intrinsic value of non-human life. These framings correctly emphasize the importance of ecologically intact systems for planetary stability.

Structural assessment via checked and unchecked resourcefulness: The distinction between checked and unchecked resourcefulness adds explanatory weight by clarifying how wild and human systems operate on fundamentally different adaptive timescales. Wild ecosystems contribute to atmospheric, hydrological, and climatic stability through dense niche occupation, trophic redundancy, and layered ecological interdependence—features that generate resilience but unfold slowly, often over centuries or millennia, and far beyond the horizon of human perception. Human systems, by contrast, operate under unchecked resourcefulness, allowing rapid expansion and reorganization to continue even as ecological buffering capacity is incrementally degraded. This temporal mismatch explains how human systems can remain functional and dominant while progressively eroding the environmental conditions—temperature ranges, water availability, and atmospheric composition—within which human physiology and social organization remain viable.

Structural implication: Balanced exchange with wild systems is therefore a structural requirement arising from the asymmetry between rapid human adaptation and slow ecological recovery. Human dominance does not eliminate dependence on wild systems; it obscures that dependence, delays its consequences, and risks destabilization accumulating beyond the adaptive capacity of even an extraordinarily flexible species.