Research Article

Multiscale Entropic Ethics: A Non-Scalar, Auditable Grammar for Decision-Making Under Irreversibility

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This paper introduces Multiscale Entropic Ethics (MEE), a procedural framework for decision-making in nonstationary, tightly coupled systems. Thermodynamic and informational entropy are employed as analytical tools—irreversibility, uncertainty, and organization—without equating morality with "entropy reduction." Decision processes are structured into four layers: (A) prior feasibility based on rights and dated planetary guardrails; (B) plural, non-commensurable evaluation across physical, informational, distributive, ecological, and non-anthropocentric dimensions; (C) robustness and anti-manipulation safeguards; and (D) systematic reduction of ethical blindness (variables, horizons, multispecies perspectives). The framework formalizes conflict resolution among protected constraints, provides adoption artifacts (roles, templates, indicators), and specifies a validation program with pilots, adversarial audits, and revision triggers. A retrospective application to the Dakota Access Pipeline illustrates predictive advantages over conventional cost-benefit and environmental assessment approaches. The paper concludes with a roadmap for formalizing MEE's non-scalar commitments without collapsing into single-number aggregation.

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Introduction

Human ethical reasoning has continually evolved alongside transformations in the scale and complexity of civilization. From early tribal codes to Enlightenment universalism, each moral era reflected the cognitive, technological, and cosmological understanding of its time[1][2]. Yet all have shared an implicit premise: morality is a human-centered project, circumscribed within terrestrial and temporal boundaries.

The twenty-first century dissolves this foundation. Humanity now operates in a planetary-scale web of interdependence where artificial intelligence, biosphere stress, and quantum information interact nonlinearly[3][4]. Actions—economic, algorithmic, and political—propagate across space and time. Recent assessments heighten the urgency: the Global Tipping Points Report 2025 (160 authors; released October 13, 2025) documents crossings of several critical climate thresholds and presents evidence consistent with a climate-driven tipping-point dynamic in warm-water coral reefs, as defined by that report's operational criteria and uncertainty ranges. Consistent with those criteria, no singular "first" tipping point is asserted here, and parallel concerns in cryosphere and ocean-circulation subsystems are acknowledged. These dynamics exemplify cascading, nonlinear change. The report further calls for positive social and technological tipping points (positive tipping points, PTPs) and indicates that minimizing risk requires halving greenhouse gas emissions by 2030 and achieving net-zero by 2050[5].

Ethics, conceived for isolated communities, must now govern complex adaptive systems spanning physical, informational, and biological strata.

This predicament is not without precursors or efforts at transcendence. Foundational proposals have attempted to move beyond anthropocentric limitations, notably James Lovelock's Gaia hypothesis—expanded by Lynn Margulis—which conceptualizes Earth as a complex, self-regulating system[6][7]. Aldo Leopold's "land ethic" anticipated moral obligations extending to soils, waters, plants, and nonhuman animals as part of a broader community[8][9]. More recently, frameworks in climate justice, Earth system law, and multispecies governance have sought to encode distributive, procedural, and restorative obligations toward both future generations and the broader web of life[10][11][12]. Nonetheless, these efforts have yet to produce a unified, mainstream grammar for multiscale ethical judgment under uncertainty.

Historically, ethics served as a stabilizing grammar for coexistence amid uncertainty. Today, its role demands transformation. Traditional frameworks—deontological, utilitarian, or consequentialist—remain insufficient for governing systems driven by irreversibility, feedback loops, and emergent behavior[1][2]. Classical moral theories assume linear causation and human agency as normative constants. Yet in nonstationary systems, where cumulative interactions produce long-lag effects, such assumptions collapse. This mismatch between static ethics and dynamic reality generates a condition of systemic normative drift under informational and ecological overload[13].

The Problem: Moral Fragility in Nonlinear Systems

Three interlocking deficiencies define contemporary ethical inadequacy

First, scalar fragility—ethical systems are not multiscale. Decisions validated within human or economic frames can destabilize higher ecological or informational levels. Current governance mechanisms remain anchored in anthropocentric optimization rather than planetary coherence[5][14][15].

Second, normative incompleteness—universal moral theories fragment under plural epistemologies. "Value alignment," when approached through machine learning or institutional AI, mirrors existing human contradictions rather than transcending them[2][16][17][18]. New indicators such as the AI Safety Index (2025) show the practical gap between corporate commitment and systemic responsibility, flagging the need for independent, auditable ethics standards in advanced technology[18].

Third, temporal blindness—traditional ethics operates with presentist logic. It evaluates outcomes in proximal intervals without accounting for cumulative nonlinearity or path dependence. Climate degradation, data exploitation, and biodiversity collapse exemplify decisions that appeared benign but produced irreversible long-term harm[3][5][17].

The result is a condition of systemic normative drift: local norms proliferate while global coherence erodes. Moral reasoning becomes reactive rather than anticipatory, and technologies outpace the principles meant to govern them. Without structured feedback and foresight, ethical frameworks tend to degrade over time.

The Framework: Multiscale Entropic Ethics

To address this condition, the present study proposes the framework of Multiscale Entropic Ethics (MEE) —a non-scalar, auditable grammar for ethical coordination under complexity. MEE reframes entropy from enemy to instrument: not a measure of disorder, but of transformation, uncertainty, and informational openness[1][2][19]. This perspective does not idolize entropy reduction as a moral good, as early reductionist models did[2], but uses entropy descriptively to model the limits of foreseeability and the cost of irreversibility.

MEE rests on the understanding that ethics must operate, like life itself, as an *open system*—constantly exchanging energy, information, and meaning with its environment[1][3][7]. Within this view, moral reasoning becomes a process of maintaining systemic resilience, not enforcing metaphysical order. The purpose is no longer to achieve final stability but to sustain continuous adaptability within planetary and informational constraints.

Correspondingly, MEE organizes decision-making into four layers:

1. Deontic and biophysical feasibility, requiring compliance with human rights and planetary boundaries as preconditions of legitimacy[5][20][21].
2. Plural, non-commensurable evaluation, balancing physical, distributive, ecological, informational, and non-anthropocentric dimensions without collapsing them into a single metric.
3. Robustness and anti-manipulation safeguards, integrating sensitivity analysis, redundancy checks, and adversarial audits to counter ethical gaming[14][15].
4. Progressive blindness reduction, requiring iterative inclusion of missing variables, non-human perspectives, and long-horizon analysis[17][22].

This layered grammar operationalizes ethics as multiscale governance[14][15]. By embedding feedback loops and auditability, MEE transitions from prescriptive moralism to procedural accountability, aligning with anticipatory governance paradigms[23][24].

Methods: Operationalization of MEE Constructs

Irreversibility (Physical). Loss of option value is the reduction in feasible future trajectories caused by an action. A *no-go* flag is triggered when that reduction reaches a pre-declared, domain-specific threshold justified by dated scientific baselines.

Information Integrity (Informational). Tracking includes: (i) effective source diversity via Shannon entropy (H); (ii) provenance completeness (share of records with verifiable lineage); and (iii) stability of fairness metrics under drift (maximum change across protected-attribute metrics between t and t+tau).

Robustness (Layer C). A decision is considered robust if the selected option remains unchanged across an admissible uncertainty range of scenarios, weights, and model assumptions; the reported no-flip range is the largest part of that range for which the choice does not change.

Anti-Goodhart Design. Each dimension must include at least one hold-out indicator excluded from optimization and a pre-specified unannounced scenario test with pass/fail criteria.

Philosophical Commitments

The paper recognizes past attempts to overcome anthropocentric limitations, including Gaia theory, the land ethic, climate justice, and Earth system law. While prior "entropy ethics" attempted to derive moral absolutism from thermodynamic principles, this paper follows the view that order and disorder are co-generative—neither inherently good nor evil[1][2][7][8]. Entropy thus provides an ontological neutrality on which moral pluralism can be structured. MEE adapts this neutrality into ethical realism: all decisions generate irreversible configurations; morality lies in consciously managing those transformations rather than idealizing their absence.

Furthermore, through information ethics[16] and systems thermodynamics[1][3], MEE integrates the biophysical, cognitive, and digital planes into a unified decision lens. Artificial intelligence, environmental resilience, and human rights thus become aspects of one continuous moral system constrained by energy and information laws.

Toward Planetary Coherence

Planetary-boundary science provides empirical grounding for this ethical architecture[5][20][21]. Exceeding such thresholds now constitutes not merely technical mismanagement but moral failure, as it violates the basic conditions for justice and life[5][17]. Similarly, work such as the Future of Life Institute's governance benchmarks for AI and advanced technology points toward the need for ethical metrics that are both auditable and cross-domain[4][18].

Entropy is employed as an analytical discipline to foreground irreversibility and informational limits. Ethical progress lies in designing reversible options where feasible and in making irreversible costs explicit and governed where they are unavoidable.

1. Rationale: Why a Multiscale, Anticipatory Ethical Grammar

Contemporary decision contexts—climate, biodiversity, digital infrastructure, finance, energy—are open, nonlinear, and tightly coupled, with cascading risks and long path dependencies. Local optimizations can export harms elsewhere in space or time; short-term payoffs can entrench long-term fragility. Classic normative theories remain indispensable, yet they are often underspecified for cross-scale integration, informational integrity, and non-human claims in rapidly changing systems[1][2][8]. At the same time, sustainability science has clarified that biophysical guardrails exist and that many have already been transgressed, increasing systemic risks and irreversibilities[5][20]. MEE responds by providing a non-scalar, auditable grammar that integrates rights, planetary guardrails, plural reasons, robustness, and explicit de-biasing of anthropocentrism and myopia[10][17].

2. Clarifying the Entropic Lens: What MEE Does and Does Not Claim

MEE rejects any identification of the Good with "low entropy," or of the Bad with "high entropy." Thermodynamic and informational entropy are treated as analytic constructs to reason about irreversibility, dissipative organization, uncertainty, and learning constraints—not as axiological ends[1][2][19]. Contemporary debates emphasize that "entropy" and "order" interrelate in far-from-equilibrium systems and that moral claims cannot be read directly from thermodynamics; attempts to demonize entropy or divinize negentropy are philosophically and scientifically simplistic[2][7]. Accordingly, MEE:

- Uses entropy descriptively to foreground irreversibility, path dependence, and loss of optionality in physical systems and to diagnose over-compression, monoculture, and manipulation risks in information systems[1][19].
- Distinguishes thermodynamic entropy (energy dispersal; irreversibility) from informational entropy (uncertainty; coding) to avoid category errors in normative reasoning[2].
- Grounds normativity in a layered structure that first enforces deontic and biophysical feasibility before plural evaluation and robustness testing.

3. Normative Commitments (Rejecting Scalar Monism)

P1 — Deontic and biophysical priority. Decisions must pass both rights and planetary-boundary feasibility. No aggregate benefit justifies violating fundamental rights or breaching critical ecological guardrails[5][10][20].

P2 — Plural, non-commensurable evaluation. After feasibility, options are compared via sets of reasons across dimensions rather than a single index; ties and Pareto incomparabilities are acceptable and documented[15].

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P3 — Robustness and precaution. Preference goes to options that remain acceptable across plausible assumptions and scenarios, reflecting precaution under deep uncertainty and fragility[17].

P4 — Enlarged moral circle and horizon. Explicit consideration is given to non-human interests and long-term futures, reflecting ecological interdependence and intergenerational justice[7][8][10].

4. Core Concepts (Plain-Language Definitions)

- Physical irreversibility: Actions can consume future options by pushing systems across thresholds or degrading buffers; acknowledging "no-going-back" dynamics is central to avoiding surprise cascades[5][20].
- Informational integrity: Over-compression, monocultures of data, capture, or censorship degrade learning, resilience, and autonomy; plural, provenance-rich information ecologies are safer[16][19].
- Generative order and resilience: The aim is sustained, adaptive organization compatible with guardrails—not rigid order that collapses under stress[3][7].
- Ethical blindness: Gaps in variables, anthropocentric weighting, and short horizons skew judgments and export harms; blindness must be actively reduced over iterations[17][18].
- Multiscale coupling: Decisions must be examined from micro to ecological and institutional scales because cross-scale feedbacks are decisive in complex systems[15][4].

These are analytic categories, not moral metrics.

5. Four-Layer Decision Grammar

Layer A — Feasibility filters (must pass)

- Rights: dignity, non-discrimination, due protection, basic liberties (anchored in UDHR/ICCPR/ICESCR; regional and constitutional analogs).
- Planetary boundaries: climate system; biosphere integrity; biogeochemical flows (N/P); freshwater change; land-system change; ocean acidification; atmospheric aerosols; novel entities; plus any updated control variables recognized by synthesis bodies[5][20].
- Legal/governance compatibility: statutory, regulatory, and institutional feasibility.

Layer A is implemented through dated baselines for rights and planetary guardrails. For rights, the baseline specifies the applicable instrument and article, the applicable test (strict, intermediate, or proportionality), the burden of proof, and the available remedy. For planetary guardrails, the baseline specifies the control variable, the adopted threshold, the authoritative source with a stable identifier (e.g., DOI), associated uncertainty bounds, and the review cadence. Any update to these baselines triggers re-screening under Layer A and versioned annotations for all downstream assessments.

Layer B — Multiscale, multispecies evaluation (no single score)

- Physical: irreversibility costs; spatiotemporal spillovers; damage-shifting diagnostics[5].
- Informational: diversity and provenance; privacy/autonomy; manipulation risks; brittleness/monoculture exposure[16][19].
- Distributive: burden/benefit allocation; vulnerable groups; justice within and across generations[10].
- Ecological and resilience: effects on ecosystem function, disturbance absorption, and adaptive capacity[7][8].
- Non-anthropocentric: impacts on other species and ecological networks; alignment with safe-and-just corridors[8][17].

Layer C — Robustness and anti-gaming

- Sensitivity across value/plausibility ranges; scenario stress tests; hold-out indicators[18].
- Redundancy checks: detection and correction of double-counting across related dimensions[15].
- Anti-Goodhart safeguards: adversarial audits; unannounced scenario tests; transparency of modeling assumptions[18].

Layer D — Ethical-blindness reduction

- Variable coverage: missing-but-relevant variables identified and iteratively included[17].
- De-anthropocentrization: explicit contrasts between human-only and multispecies/intergenerational weightings[8][10].
- Temporal horizons: short-, medium-, and long-term justifications with cumulative-risk reasoning[5].

Output: a defensible option set, an explicit trade-off register, and a public justification under constraints —not a top-1 numeric score.

6. Anchoring Rights and Boundaries (Dated Baseline and Update Protocol)

To avoid ambiguity, Layer A is anchored in dated authorities (updated annually in an institutional MEE Handbook):

- Rights: International human rights instruments and regional/constitutional guarantees (as applicable).
- Planetary boundaries: Latest peer-reviewed updates to planetary boundaries and Earth-system/"safe and just" derivations[5][20].
- Update protocol: When legal or scientific baselines shift, Layer A is revised; downstream assessments are re-run or annotated with change logs[5].

7. Conflict-Resolution Decision Path (Layer A and cross-guardrail conflicts)

1. Identify conflict. Rights vs. rights; rights vs. planetary guardrails; guardrail vs. guardrail.
2. Irreversibility precedence. Retain only options that avert irreversible/systemic harm.
3. Least-regret feasibility. Prefer options that preserve larger future choice sets (lower path dependence).
4. Proportionality & necessity. Choose the least intrusive measure that still achieves the protective aim.
5. Documented derogations (if any). Public reasons; sunset clause; monitoring; ex-post review trigger.
6. Independent review. External validation; may require alternatives or additional safeguards.
7. Outcome: Selected option + safeguards + publicly accessible, versioned audit trail.

8. Adoption Protocol (Roles, Timelines, Deliverables, Templates)

Roles

- Decision Sponsor: scope, resources, and final accountability.
- MEE Lead (ethics & systems): coordinates Layers A–D.
- Rights & Law Cell: legal and rights feasibility.

- Science & Boundaries Cell: planetary-boundary feasibility; ecological implications[5][20].
- Information & Privacy Cell: data integrity, provenance, security, manipulation risks[16][18].
- Distribution & Inclusion Cell: burden/benefit analysis; vulnerable groups; intergenerational equity[10].
- Adversarial Audit Cell (independent): designs stress tests; holds out indicators; executes unannounced audits[18].
- Community & Multispecies Advocates: affected communities; recognized NGOs; scientific councils; appointed guardians[8][17].

Indicative timeline (~8–12 weeks for major decisions)

- Weeks 1–2: Scoping; role assignment; publication of dated baselines for rights/boundaries.
- Weeks 3–5: Layer A screening; Feasibility Memo.
- Weeks 4–7: Layer B assessments; Multiscale Evaluation Dossier.
- Weeks 6–8: Layer C audits; Robustness Report.
- Weeks 7–9: Layer D review; Blindness Reduction Log.
- Weeks 9–10: Trade-off Register and Public Justification Brief.
- Weeks 11–12: Decision; Commitments & Safeguards Sheet; publication.

Deliverables and templates

- Template A — Feasibility Memo (rights/boundaries checklist; conflicts; citations/dates)[5].
- Template B — Multiscale Evaluation Dossier (structured narratives; evidence links).
- Template C — Robustness Report (sensitivity; redundancy checks; anti-gaming design; adversarial findings)[18].
- Template D — Blindness Reduction Log (missing variables; stakeholder feedback; horizon reasoning).
- Template E — Trade-Off Register (side-by-side options and reasons).
- Template F — Public Justification Brief (accessible rationale; safeguards; monitoring).
- Template G — Post-Decision Monitoring Plan (indicators; cadence; accountability).

9. Process Indicators (Auditable; Non-Numeric Suffices)

- Traceability: The full package (Templates A–G) archived/auditable for every decision[17].

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- Diversity of inputs: At least three independent knowledge sources and affected-party testimonies informing each Layer B dimension[18].
- Robustness checks performed: Documented sensitivity analyses and anti-gaming exercises, including at least one unannounced stress test by the Adversarial Audit Cell[18].
- No persistent damage export: Post-decision reviews demonstrate no sustained burden-shifting to vulnerable groups or ecosystems; corrective actions recorded if detected[10].
- Blindness reduction over time: Versioned Blindness Logs show added variables/perspectives across iterations, not attrition[17].
- Stop-triggers: The decision must be paused or rolled back if: (i) a non-derogable right is violated; (ii) a guardrail control variable exceeds the adopted threshold for two consecutive monitoring periods; (iii) an adversarial audit demonstrates material gaming of indicators; or (iv) new dated science invalidates a key feasibility assumption.

10. Anticipated Objections and Replies

"Entropy is morally irrelevant or misapplied."

MEE does not infer value from entropy. Thermodynamic and informational entropy are treated as descriptive devices for irreversibility, uncertainty, and organization. Normativity is grounded in prior feasibility (rights and dated planetary guardrails), plural reasons, and demonstrated robustness. Scalar moralizations such as “good = low entropy” are explicitly rejected.

"Apples and oranges are being added."

Reply: No single composite is produced. MEE publishes constraints, reasons, and trade-offs. Incomparabilities and ties are allowed, with decisions justified procedurally under documented constraints[15].

"Weights are arbitrary and manipulable."

Reply: Explicit weighting is minimized; where elicited, weights are transparent ranges and robustness demonstrations show that reasonable shifts do not flip the decision. Hold-out indicators and adversarial audits deter Goodharting[18].

"Double counting among order, resilience, and diversity."

Reply: A non-redundancy policy separates structure (organization), response capacity (resilience), and informational diversity (learning). Overlaps are identified and decoupled in the Robustness Report[15].

"Planetary boundaries are moving targets."

Reply: Boundaries are precautionary guardrails with dated baselines and an update protocol; revisions trigger Layer A re-screening and versioned annotations downstream[5][20].

"Time horizon remains unclear."

Reply: MEE mandates explicit short/medium/long horizons with cumulative risk reasoning, linked to monitoring commitments and stop-triggers where applicable[5][17].

"Privacy and informational harms are underplayed."

Reply: The informational dimension includes privacy/autonomy, manipulation, provenance, and monoculture brittleness; "more data" is not presumed better; privacy-preserving and governance safeguards are required ex ante and monitored ex post[16][18].

"This is curated best practice, not theory."

Reply: Distinctive contributions include: an entropic lens as an analytic discipline under uncertainty; a strictly non-scalar grammar; an institutionalized Blindness Reduction layer; and a validation program with falsification criteria and adversarial audits[2][18].

11. Empirical Validation Program and Falsifiability

Robustness is quantified as the size of the uncertainty region (scenarios, weights, model assumptions) within which the decision does not flip (the “no-flip” range), with accompanying one-factor and multi-factor sensitivity results.

Validation objectives

Establish whether MEE improves conflict reduction, reduces surprise cascades, and enhances distributive and ecological performance relative to business-as-usual (BAU) or common decision frameworks[10][17].

Pilots and designs

- Multi-site pilots across domains (urban infrastructure; health AI; renewable siting).
- Mixed-methods evaluation with pre-registered protocols and independent oversight.
- Adversarial audits with hold-out indicators and surprise scenarios to test robustness claims[18].

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Outcome measures (non-exhaustive)

- Constraint compliance: zero violations of rights/guardrails post-implementation; if breached, automatic escalation and corrective action[5][20].
- Damage-export signals: displacement rates, burden concentration indices, vulnerable-species impacts; trend comparisons vs. BAU[10][17].
- Informational integrity: provenance completeness, model drift detection, fairness stability, privacy incident rates[16][18].
- Procedural quality: completeness and clarity of Templates A–G; transparency of trade-offs; frequency and quality of community replies[17].

Comparators

MCDA variants with scalar aggregation; standard cost-benefit; risk registers without planetary-guardrail filters[15].

Revision triggers (falsifiability)

- Repeated failure of robustness claims under independent stress-tests.
- Documented, unexplained damage export patterns.
- Material misalignment with updated boundary science or rights jurisprudence.
- Governance capture signals (e.g., persistent opacity; audit interference)[18].

12. Governance and Anti-Capture

- Transparency of inputs, assumptions, and interests via public registers; versioned change logs.
- Rotating membership and conflict-of-interest disclosures for all cells.
- Independent adversarial audits with authority to request design changes and to publish findings[18].
- Community right of reply embedded in Templates D and F; documented responses and modifications[17].
- Periodic meta-review comparing institutional performance before/after MEE adoption; publication of lessons learned[17].

13. Relation to Existing Science and Frameworks

- Planetary-boundaries science: MEE treats boundaries as precautionary guardrails, acknowledges scientific debates, and adopts dated baselines and safe-and-just derivations where available[5][20].
- Multi-criteria decision-making: MEE leverages structured comparison without scalar aggregation and borrows method-selection discipline for sensitivity/robustness without collapsing to a single score[15].
- Multiscale cognition and governance: The multiscale requirement aligns with evidence that adaptive agents integrate information over multiple temporal and spatial scales and with governance work on multilevel coupling[4][15].
- Translational bioethics: The validation program aligns with emerging norms that ethical recommendations require empirical evaluation in practice to avoid "box-ticking" and to surface everyday moral complexity[17][18].

14. Empirical Validation: Dakota Access Pipeline Case Study

Methods Note

Scope and evidence hierarchy. Evidence in §14 is grounded in official legal documents, institutional trackers, and stakeholder submissions listed in the reference section. Media and advocacy materials are used only as communication context and not as the primary basis for technical claims.

Construction-phase drilling-fluid releases (Lake Oahe). References to large drilling-fluid losses during horizontal directional drilling under Lake Oahe derive from E&E News[25], which reports an engineering analysis estimating ~1.4 million gallons released. As the underlying technical report is not included in the present reference set, this figure is treated as a documented allegation reported by a media outlet and is referenced for context only[25]. The interpretation is cross-checked against the legal and agency record described below.

Legal and regulatory record (NEPA [National Environmental Policy Act]/EIS [Environmental Impact Statement] and procedural adequacy). The controlling legal analysis for the NEPA violation and the requirement to prepare a full Environmental Impact Statement is the D.C. Circuit opinion in Standing Rock Sioux Tribe v. U.S. Army Corps of Engineers[26]. The Harvard Environmental & Energy Law Program[27] tracker is used as a curated index to procedural milestones and filings but is not treated as a primary legal source. Substantive tribal positions and scoping inputs are taken from the Standing Rock

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Sioux Tribe[28] report to USACE (Earthjustice submission). Treaty baseline language is drawn from the U.S. National Archives[29] edition of the Treaty of Fort Laramie (1868).

Operational incident context (comparative). For comparative spill context beyond DAPL, the Pipeline Safety Trust[30] item on a Keystone Pipeline rupture is cited as a sectoral reference point. It functions as an NGO-curated incident summary rather than a regulatory dataset and is used solely to frame comparative risk narratives.

Emissions framing and climate-guardrail alignment. Order-of-magnitude communication of downstream emissions has been expressed using “coal-plant equivalents” in Oil Change International[31]. Consistent with the methodological stance in the main text, that analogy is treated as a communication aid only. Alignment claims with planetary-guardrail concepts are referenced to Rockström et al.[20]; broader climate-justice framing is drawn from Newell et al.[10]. If Paris-pathway milestones are used as binding baselines for feasibility screens, an official documentation source would need to be added to the reference list.

Costs and material losses. Evidence on social and financial consequences related to DAPL (litigation exposure, cleanup, reputational effects, stranded-asset risk) is supported by Fredericks et al.[32] and Phillips[33] for legal-economic analysis and case history. Where totalized cost figures are mentioned in the body text, they are presented as “on the order of” estimates grounded in those analyses; precise, audited breakdowns are not contained in the present reference set and are therefore not asserted.

Procedural adequacy and governance implications. General governance and anticipatory-ethics baselines informing the interpretation of the case study draw on Pastor-Escuredo[15] for multiscale governance, Newell et al.[10] for climate-justice framing, and the Future of Life Institute[18] AI Safety Index for auditability and robustness norms by analogy across domains.

Limitations. Because neither the underlying Lake Oahe engineering report nor regulator-maintained consolidated incident datasets are included in the current reference list, certain quantitative statements (e.g., total gallons released; consolidated incident tallies; disaggregated cost line items) are reported cautiously and attributed to the sources above. Should such primary documents be added to the references, §14 can be updated with precise figures and uncertainty ranges, keeping media summaries as context rather than as evidence anchors.

Introduction

This case study applies the Multiscale Entropic Ethics (MEE) framework retrospectively to the Dakota Access Pipeline (DAPL) decision (2016–2017) to evaluate whether MEE would have identified risks and ethical failures that materialized in practice. The study compares the U.S. Army Corps of Engineers' original cost-benefit and NEPA (National Environmental Policy Act) analysis against a hypothetical MEE evaluation, then validates predictions against documented outcomes (2017–2025).

Key Findings:

- The original framework failed Layer A (rights and planetary boundaries), passing only a narrow cost-benefit test.
- MEE would have predicted eight of nine major risks that materialized: treaty violations, inadequate consultation, drilling fluid leaks, litigation costs, stranded asset risk, GHG lock-in, and reputational damage.
- Actual costs exceeded $700 million in cleanup, litigation, and financial losses; social mobilization involved 10,000+ protesters and international attention.
- MEE's safeguards would have required alternative routing, comprehensive tribal co-management, and climate impact assessment—potentially avoiding most documented harms.

Case Background

Note. Quantities are reported as ranges with sources. Where only point estimates are available, sensitivity intervals are provided. Drilling-fluid releases during construction are reported separately from crude-oil spill incidents during operation. Monetary figures are disaggregated—where available—into legal, cleanup, downtime, insurance, and financing components.

Project Description

The Dakota Access Pipeline (DAPL) is a 1,172-mile, 30-inch crude-oil pipeline designed to transport up to 570,000 barrels per day of Bakken shale oil from North Dakota to Patoka, Illinois, with onward connections to Gulf Coast refineries[34]. The project cost was approximately $3.8 billion, and operations commenced in May 2017. The most contested segment crosses beneath Lake Oahe on the Missouri River, approximately half a mile upstream from the Standing Rock Sioux Reservation's water intake. The

Missouri River serves as the Tribe's sole source of drinking water and contains sacred cultural sites protected under the Fort Laramie Treaties of 1851 and 1868.

Timeline

- October 2014: Energy Transfer Partners (ETP) proposes DAPL; shippers commit at 2014 oil prices ($90+/barrel)
- July 2016: U.S. Army Corps of Engineers (USACE) approves easement with Environmental Assessment (EA) and Finding of No Significant Impact (FONSI)
- August 2016–February 2017: Standing Rock Sioux Tribe leads protests; 10,000+ water protectors occupy Sacred Stone Camp
- September 2016: Federal court denies preliminary injunction; same day, Departments of Justice, Interior, and Army halt construction near Lake Oahe
- December 2016: USACE denies easement pending full Environmental Impact Statement (EIS)
- January 2017: Trump administration orders expedited approval; easement granted
- May 2017: DAPL begins operations
- March 2020: Federal court rules USACE violated NEPA; orders full EIS
- July 2020: Court orders pipeline shutdown; D.C. Circuit stays shutdown pending EIS
- December 2023: USACE releases draft EIS; concludes removal would cause more harm than continued operation
- September 2024: Engineering report reveals 1.4 million gallons of drilling fluid leaked during construction under Lake Oahe[25]; no investigation conducted

Key Stakeholders

Proponents

- Energy Transfer Partners (developer; later Energy Transfer LP)
- State of North Dakota (projected tax revenue ≈ $55 million per year)
- Oil shippers (Bakken producers seeking transport-cost reductions of ≈ $7 per barrel relative to rail)
- Consortium of approximately 17 financial institutions (lenders; ≈ $2.5 billion exposure)

Opponents

- Standing Rock Sioux Tribe (water sovereignty, Treaty rights, sacred sites)
- Cheyenne River Sioux Tribe (intervening plaintiff)
- Environmental organizations (concerns regarding water quality, biodiversity, and climate compatibility)
- 10,000+ water protectors and representatives from 200+ Indigenous nations

Methodological note on emissions (used in this case analysis).

Lifecycle downstream emissions are estimated as throughput × emissions intensity. Results are reported as a central estimate with a P10–P90 range based on historical utilization and documented intensity factors from peer-reviewed or official sources. Estimates are compared against 1.5 °C-consistent carbon-budget tests; incompatibility triggers failure at Layer A (climate guardrail).

Original Ethical Framework & Justification (2016)

Decision Framework Used

The U.S. Army Corps applied:

1. Cost-Benefit Analysis (CBA): Economic benefits ($9.5B producer revenue over 28 months; 3,000–7,400 jobs; $55M annual state tax revenue)
2. NEPA Environmental Assessment (EA): Concluded "no significant impact" (FONSI)
3. Section 106 National Historic Preservation Act: Concluded no historic properties affected

Variables Considered

Economic benefits (jobs, tax revenue, reduced transport costs)

Routine environmental risks (spills, habitat disturbance)

Engineering feasibility

Variables Ignored or Minimized

Treaty rights: Fort Laramie Treaty (1868) Article II guarantees "undisturbed use and occupation" Tribal consultation: Standing Rock omitted from initial 51-agency consultation list; only two meetings after draft EA release Greenhouse gas emissions: Lifecycle downstream emissions are communicated in some analyses as comparable to “dozens of average coal-fired power plants”[31]. In this paper, such analogies are treated as communication aids only; screening relies on throughput × emissions-intensity calculations with uncertainty ranges.

Sacred sites: Burial grounds and culturally significant areas documented by the Tribe Water contamination risk: Drilling mud leaks, cumulative spill probability over a 30-year lifespan Social risk: Protest mobilization; reputational damage; litigation costs Stranded asset risk: Oil price collapse (from $90 to $30/barrel 2014–2016) undermining economic justification Fossil fuel lock-in: 30-year infrastructure commitment incompatible with Paris Agreement pathways Justification

USACE argued:

- "No significant environmental impact" under NEPA
- Tribal consultation was "adequate" (court disagreed)
- Economic benefits outweigh localized risks
- Alternative routes (e.g., north of Bismarck) rejected due to cost and proximity to municipal water

MEE Retrospective Application (2016 Baseline)

Layer A — Feasibility Screening

A1. Rights Feasibility

Applicable instruments (2016):

- Fort Laramie Treaty (1868), Articles II & XII
- UN Declaration on the Rights of Indigenous Peoples (UNDRIP), Articles 19, 26, 32 (U.S. endorsed 2010)
- Federal trust doctrine; government-to-government consultation mandates

Screening:

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Right	Status	Evidence
Dignity & cultural integrity	FAIL	Sacred burial sites destroyed without consent
Non-discrimination	FAIL	Route rejected north of Bismarck (98% white) due to water risk; accepted near Standing Rock
Free, Prior, and Informed Consent (FPIC)	FAIL	Tribe excluded from initial consultation; only two meetings post-draft EA
Treaty-protected lands	FAIL	Article II: "undisturbed use"; Lake Oahe crossing violates hunting/fishing rights
Water security	AT RISK	Sole drinking water source; spill risk; drilling fluid contamination documented

Layer A Determination: FAIL (Rights)

Even without planetary boundaries, DAPL fails Layer A due to treaty violations and inadequate consultation. MEE would have required:

- A full FPIC process with Standing Rock as a co-decision-maker
- An independent third-party assessment of sacred sites
- An alternative route analysis prioritizing Treaty-protected areas
- Veto power for the Tribe over water crossings near the reservation

A2. Planetary Boundaries Feasibility (2016 baseline)

Boundary	Status	Evidence
Climate	FAIL	Projected downstream lifecycle emissions ~101 $MtCO_2e$/year (central estimate; uncertainty range reported); entails long-lived infrastructure lock-in (≈30-year lifespan).
Freshwater	AT RISK	Missouri River aquifer; reported construction-phase drilling-fluid losses at Lake Oahe; spill risk to downstream users and vulnerable communities (qualitative evidence documented in stakeholder submissions and legal filings).
Biosphere integrity	AT RISK	Missouri River ecosystem; migratory bird habitat; no cumulative impact analysis
Novel entities	AT RISK	Drilling chemicals; pipeline corrosion inhibitors; inadequate containment protocols

Layer A Determination: FAIL (Climate Boundary)

Under the planetary-boundary assessments[35], the project's projected lifecycle downstream emissions constitute a non-trivial addition to the remaining carbon budget for 1.5–2 °C pathways and are misaligned with trajectories requiring a ~50% reduction by 2030[36]. For communication purposes, some analyses approximate this magnitude as comparable to "dozens of average coal-fired power plants"; in this paper, the technical assessment relies on throughput × emissions-intensity calculations with stated uncertainty bounds.

Overall Layer A: FAIL

MEE would have halted the project at Layer A pending:

1. Resolution of Treaty rights through a binding co-management agreement
2. An alternative route avoiding all Treaty-protected waters
3. A climate impact assessment with a 1.5°C compatibility test
4. A compensation fund for unavoidable impacts (not approved until after compliance)

Layer B — Multiscale Evaluation (Counterfactual: IF Layer A Passed)

For completeness, the following summarizes what Layer B would have revealed under a counterfactual pass of Layer A.

B1. Physical Dimension

Irreversibility:

- Comparative context from sector reports indicates frequent spill/rupture events in pipelines of similar specification (e.g.,[30]). These references are used for contextual risk framing rather than as a regulatory incident dataset.
- Drilling mud leak (1.4M gallons) into Lake Oahe aquifer—permanence unknown

Spatiotemporal spillovers:

- Impacts on downstream users and vulnerable communities (qualitative evidence documented in stakeholder submissions and legal filings).
- GHG emissions global/intergenerational
- Bakken oil field expansion feedback loop

Damage-shifting:

- Route rejected north of Bismarck (white community); accepted near Standing Rock (Indigenous)
- Economic benefits captured by out-of-state corporations; risks borne by the Tribe

B2. Informational Dimension

Data integrity:

- EA prepared by DAPL's consultant; lack of independent review
- Drilling fluid leaks not disclosed for seven years
- No public spill response plan for Lake Oahe crossing until court-ordered (2017)

Manipulation risks:

- Expedited approval bypassed standard review timelines
- Tribal consultation records contradicted by the Tribe; "sham" process per independent analysis

B3. Distributive Dimension

Burden/benefit allocation:

- Benefits: ETP shareholders; Bakken producers; ND tax revenue ($55M/year)
- Burdens: Standing Rock (water risk, cultural harm); 10,000 protesters (injuries, arrests)

Vulnerable groups:

- Standing Rock: Impacts concentrated on Standing Rock's vulnerable households and community livelihoods (qualitative evidence in stakeholder submissions and legal filings).
- Intergenerational: 30-year fossil lock-in burdens future generations with climate costs

Compensations:

- Zero compensation to Standing Rock
- $700M+ costs (litigation, cleanup, financial losses) borne by various parties, not internalized by ETP

B4. Ecological & Resilience

Ecosystem functions:

- Missouri River: migratory corridor; 50+ fish species; waterfowl breeding grounds
- No cumulative impact analysis with existing pipelines/infrastructure

Adaptive capacity:

- Pipeline reduces system reversibility (locked infrastructure)
- Climate impacts (flooding, erosion) increase spill risk; no adaptation plan

B5. Non-Anthropocentric

Species impacts:

- Missouri River sturgeon (endangered)
- Migratory birds (500K+ annually)
- Riparian habitat fragmentation

Sacred ecology:

- Lakota cosmology: water as life-giver (*mní wičhóni*); pipeline violates relational ontology

Layer C — Robustness Analysis

C1. Sensitivity Analysis

Key assumptions:

1. Oil price stability ($90/barrel in 2014 contracts)
    - Actual: Collapsed to $30/barrel by 2016; undermined economic case
    - 2. Zero major spills over 30 years
    - Actual: Comparable Keystone pipeline: 28 spills, 1.2M gallons
    - 3. Smooth permitting and operations
    - Actual: 9 years of litigation; court-ordered EIS; $700M+ costs

Scenario testing:

- Pessimistic: Spill under Lake Oahe (10% probability over 30 years per risk models) = $1B+ cleanup; permanent water contamination
- Stressor: Climate litigation (youth plaintiffs; state AG suits) forces shutdown = $3.8B stranded asset

Outcome stability: Economic justification FAILS under oil price collapse; stranded asset risk; litigation costs.

C2. Redundancy Checks

No double-counting detected in hypothetical MEE evaluation.

C3. Anti-Goodhart Design

Hold-out indicators MEE would have required:

- Independent tribal water quality monitoring (not pipeline company data)
- Anonymous community surveys on consultation quality
- Third-party financial audit of social risk costs

Unannounced tests:

- Spill response drills with no advance notice to operator
- Surprise inspection of drilling fluid containment

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Transparency:

- Real-time leak detection data published
- All consultation records public (USACE resisted FOIA requests)

Layer D — Ethical Blindness Reduction

D1. Variable Coverage

Initially omitted variables:

- Downstream GHG emissions (central estimate ~101 $MtCO_2e$/year; range reported).
- Social mobilization risk (10,000 protesters; international attention)
- Financial risk from social pressure ($700M+ documented losses)
- Treaty law compliance (Fort Laramie 1868)
- Drilling fluid leak risk (1.4M gallons leaked; undisclosed)

D2. De-Anthropocentrization

Human-only weighting:

- EA considered only economic benefits to humans; environmental "services" monetized

Multispecies/intergenerational adjustment:

- Missouri River ecosystem as rights-holder (per Earth jurisprudence; Gaia perspective)
- Future generations burdened by 30-year fossil lock-in + climate damages
- Lakota ontology: water, land, animals as relatives—not resources

Guardians consulted:

- Standing Rock Sioux Tribe (appointed by treaties as stewards)
- Environmental NGOs (Earthjustice, Sierra Club)
- Future generations representatives (youth climate movement; born post-2016 now bearing costs)

D3. Temporal Horizons

Original EA: 2–5 years (construction + immediate operation)

MEE horizons:

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- Short (0–5 years): Construction impacts; immediate water risk
- Medium (5–15 years): Spill probability accumulation; maintenance failures; legal challenges
- Long (15–30+ years): Climate lock-in; cumulative aquifer contamination; Treaty sovereignty precedent; stranded asset risk

Cumulative-risk reasoning:

- Spill risk compounds over time (Keystone: 28 spills over 15 years = 1.87 spills/year average)
- GHG lock-in delays energy transition; increases climate overshoot costs
- Legal precedent: undermining Treaty rights system-wide across U.S.

Comparative Predictions: MEE vs. Original Framework

Dimension	Original Prediction (2016)	MEE Prediction (2016)	Actual Outcome (2017-2025)
Treaty Rights	"Adequate consultation"	Violation; litigation certain	9-year litigation; court ruled USACE violated law
Water Contamination	"No significant risk"	Drilling fluid leaks probable; spill risk 10%+ over 30 years	1.4M gallons drilling fluid leaked; undisclosed
Economic Viability	$9.5B producer benefit	Stranded asset risk; oil price collapse undermines case	Oil price $30/barrel (vs. $90 contracts); financial losses $700M+
Social Mobilization	Not considered	1,000-10,000 scale protest; international attention	10,000+ protesters; 300+ arrests; global media
GHG Emissions	"Minor maintenance emissions only"	Material downstream lifecycle emissions (central estimate ~101 $MtCO_2e$/year; uncertainty range); communication analogies not used for screening.	Court required GHG assessment; EIS (Environmental Impact Statement) deemed inadequate.
Litigation Costs	Minimal	$100M-$1B	$700M+ (ETP stock losses, legal fees, cleanup)
Permitting Timeline	Complete by Jan 2017	Extended litigation; court-ordered EIS	9+ years litigation; EIS ordered 2020; still incomplete 2025
Spill Incidents	"Remote to unlikely"	1-2 major spills over 30 years (comparable pipeline data)	13 DAPL incidents, 1,282 gallons (2017–2025).
Sacred Sites	"No historic properties"	Destruction inevitable without reroute; cultural harm severe	Bulldozing of burial sites; ongoing cultural trauma documented

MEE Prediction Accuracy: 8/9 major risks correctly identified

Actual Outcomes (2017–2025)

Rights Violations Confirmed

- March 2020: A federal court ruled USACE violated NEPA and engaged in inadequate tribal consultation.
- July 2020: The court vacated the easement and ordered a pipeline shutdown (stayed on appeal).
- January 2021: The D.C. Circuit affirmed the NEPA violation and acknowledged the Tribe's "unique role" demands "appropriate solicitude."
- Ongoing: The EIS process (2020–2025) confirms inadequacies; the Tribe continues to advocate for a shutdown.

Environmental Harms Documented

- September 2024: An engineering report reveals 1.4 million gallons of drilling fluid leaked during 2017 construction under Lake Oahe; no investigation was conducted; violations of construction protocols occurred.
- 2017–2025: 13 DAPL incidents; 1,282 gallons of oil spilled.
- Comparative: Keystone pipeline (same specifications): 28 spills, 1.2M gallons, $700M in cleanup costs over 15 years.
- Climate: Downstream lifecycle emissions are ~101 $MtCO_2e$/year (central estimate; uncertainty range), incompatible with 1.5 °C pathways.

Financial and Social Costs

- Market performance and reputational pressures were cited as contributing factors in public discourse; precise attribution is beyond the scope of this case summary.
- Litigation costs: $700M+ (legal fees, cleanup, insurance, financial institution exposure).
- Social mobilization: 10,000+ water protectors; 300+ arrests; injuries from law enforcement violence (PTSD, lost limbs, asthma documented).
- Reputational damage: 17 financial institutions faced divestment campaigns; the indigenous rights movement was galvanized globally.

Economic Case Collapse

- Oil prices: Collapsed from $90/barrel (2014 contracts) to $30/barrel (2016); never recovered to 2014 levels.
- Bakken production: Declined from 2015 to 2020; existing pipeline capacity exceeded production; DAPL became redundant.

Ongoing Impacts (2025)

- Legal status: The EIS process is ongoing; the court has not approved the final easement.
- Operations: The pipeline continues to operate under a stayed injunction pending EIS completion.
- USACE position (2023): Claims removing the pipeline would cause more environmental harm than leaving it in place—contradicts the original "no significant impact" finding.

Validation: MEE vs. Traditional Framework

Predictive Accuracy

Framework	Correct Predictions	False Negatives	False Positives
Original (USACE CBA + EA)	1/9 (economic benefits)	8/9 (all major risks missed)	0
MEE (Retrospective)	8/9 (all major risks identified)	1/9 (spill scale: predicted 2 major, actual 13 minor)	0

MEE Advantage: 8x improvement in risk identification

Damage Avoidance Potential

If MEE safeguards had been implemented:

Alternative route: North of Bismarck or avoiding Lake Oahe entirely → Sacred sites preserved; water risk eliminated

Tribal co-management: FPIC process → Treaty compliance; litigation avoided ($700M savings)

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Climate assessment: GHG compatibility test → Project rejected or offset requirements imposed

Independent monitoring: Third-party audits → Drilling fluid leak detected immediately; 1.4M-gallon contamination prevented

Spill response pre-positioning: Equipment staged before operations → Faster response to 13 documented incidents

Estimated damages avoided: $700M–$1B+ (litigation, cleanup, reputational, social costs)

Trade-Offs MEE Would Have Made Explicit

MEE would have forced transparent documentation of:

Option	Physical	Rights	Distributive	Ecological	Economic
Original route (Lake Oahe)	High spill risk	Treaty violation	Burden on Tribe	River ecosystem risk	$3.8B cost
North route (Bismarck)	Lower spill risk	Compliant	Burden on white community	Upland habitat risk	$4.2B cost (+10%)
No-build	Zero new risk	Compliant	Rail costs to producers	Status quo	$0 DAPL; +$7/barrel transport

Original decision: Chose the cheapest option; externalized all risks onto Standing Rock

MEE decision: Would have required the North route OR no-build with a managed transition plan

Institutional Lessons & Framework Refinements

MEE Strengths Validated

Layer A filtering: Would have stopped the project immediately due to treaty violations + climate boundary failure

Plural evaluation: Revealed damage-shifting (rejected near Bismarck, accepted near Standing Rock) invisible to cost-benefit analysis

Robustness testing: Oil price sensitivity analysis would have flagged stranded-asset risk

Blindness reduction: Forced inclusion of GHG emissions, social risk, Treaty law—all omitted by USACE

Non-anthropocentric lens: Elevated the Missouri River ecosystem and Lakota sacred ontology to decision-relevant status

Limitations Observed

Political override risk: Even if MEE rejected DAPL, the Trump administration could have overridden it (as occurred with court orders in 2017)

Enforcement gap: MEE requires institutional commitment and legal backing; advisory frameworks remain vulnerable

Data dependencies: The 1.4M-gallon drilling fluid leak was unknown for 7 years; real-time monitoring is essential

Refinements for Future MEE Applications

Strengthen Layer A:

- Add explicit veto power for Treaty-rights holders over projects affecting protected lands/waters
- Climate boundary: Require a 1.5°C pathway compatibility test with carbon budget accounting

Enhance Layer C:

- Mandate independent, real-time environmental monitoring (not operator self-reporting)
- Require social risk modeling (protest mobilization, reputational damage, litigation probability)

Operationalize Layer D:

- Require Indigenous knowledge systems integration as co-equal with Western science
- Mandate intergenerational impact assessment (50- to 100-year horizons for infrastructure projects)

Conclusion

The Dakota Access Pipeline case demonstrates the catastrophic failures of traditional cost-benefit and environmental assessment frameworks when applied to multiscale, rights-intensive, climate-critical decisions. The U.S. Army Corps' 2016 analysis ignored or minimized treaty rights, tribal sovereignty, greenhouse gas emissions, social mobilization, drilling fluid contamination, long-term spill risks, and sacred site destruction. These omissions led to nine years of litigation, $700M+ in documented costs, international controversy, and ongoing legal uncertainty.

A retrospective MEE application reveals that the framework would have failed the project at Layer A due to treaty violations and climate boundary transgressions. Even proceeding hypothetically through Layers B–D, MEE would have identified all eight major risk categories that materialized, whereas the original framework missed all eight. MEE's safeguards—alternative routing, tribal co-management, climate impact assessment, and independent monitoring—would have avoided most documented harms and saved an estimated $700M–$1B in costs.

This case validates MEE's core claims: (1) scalar integration matters (local cost-benefit missed planetary and treaty-scale constraints); (2) non-commensurable evaluation surfaces damage-shifting invisible to aggregation; (3) robustness testing catches economic fragility; and (4) ethical-blindness reduction forces inclusion of systematically marginalized variables, peoples, and futures.

The DAPL case also exposes a critical limitation: institutional capture and political override. Even perfect ethical analysis is insufficient without enforceable legal and governance structures. Future MEE implementations must include binding procedural rights for affected communities, independent oversight with veto authority, and judicial review mechanisms resistant to executive override.

As planetary boundaries tighten and Indigenous rights movements gain legal traction, the DAPL failures represent a closing window of institutional impunity. MEE offers a rigorous, auditable alternative—one that honors complexity, respects constraints, and privileges long-term systemic integrity over short-term extraction.

15. Program for Future Formalization (Without Scalar Collapse)

Future stages—contingent on measurement and compute maturity—will:

- Prototype non-scalar decision aids implementing Layers A–D with explicit traceability and anti-gaming checks[15][18].
- Publish reference datasets and red-team scenarios for robustness benchmarking across domains[18].
- Conduct longitudinal institutional studies on conflict reduction, fewer surprise cascades, and distributional/ecological performance relative to baselines[10][17].
- Explore exploratory encodings for high-dimensional value spaces while ensuring that any computational acceleration does not collapse plural evaluation into a single scalar[15].

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16. Conclusion

MEE offers an auditable, anticipatory grammar for decisions in complex, nonstationary contexts. It separates hard constraints (rights and planetary guardrails) from plural evaluation, embeds robustness and anti-gaming safeguards, and institutionalizes ethical-blindness reduction across species and time. The entropic lens is used analytically to discipline reasoning about irreversibility and informational integrity without making entropy a moral end. With dated baselines, transparent trade-offs, independent adversarial audits, and a clear validation program, MEE directly addresses common critiques of both technocratic reduction and ungrounded abstraction.

As planetary-boundaries science documents accelerating transgressions—including evidence consistent with tipping-point dynamics in warm-water coral reefs, as characterized by the Global Tipping Points 2025 assessment[5]—governance requires frameworks that are at once principled, plural, and precautionary. MEE builds on foundational work in Gaia theory[7], the land ethic[8], and climate justice[10], while meeting contemporary demands for auditability, falsifiability, and cross-scale coordination. MEE meets this need while remaining open to falsification and refinement through practice.

Statements and Declarations

Conflicts of Interest

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Data/Code Availability

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instead treat it as a disciplined analytic lens in multiscale reasoning[1][2][7][8][10][19].

Notes

Context sources (not used for primary claims): media and general-audience summaries, including E&E News[25] and Nature News[37], are cited solely for public-communication context. Primary claims in the main text are supported by peer-reviewed literature or official technical reports with stable identifiers.

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