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Complex Earth–outer space systems and new spacetime for international law

Elena E. Cirkovic[1] and Danielle R. Wood[2]

[1]Department of Law, Aarhus University, Aarhus, Denmark and [2]Media Lab, Massachusetts Institute for Technology, Cambridge, MA, USA
Corresponding author: Elena E. Cirkovic; Email: elec8@law.au.dk

Abstract
Earth–outer space interactions challenge conventional legal structures through dynamics that transcend jurisdictional boundaries and temporal scales. International law historically operates through specific spatiotemporal assumptions: geometric space, chronometric time, and cartographic politics. These elements structure how legal authority is conceptualised and enacted. This study recognizes the interconnectedness between Earth and outer space, positioning legal thought and practice within planetary and cosmic contexts. This integrative framework moves beyond anthropocentric and state-centric paradigms to address the indeterminate nature of multifaceted systems. The research employs an interdisciplinary methodology that integrates legal theory and doctrine, systems engineering, and systems science to analyse emergent phenomena such as orbital debris dynamics. The study concludes that addressing Earth–outer space interactions effectively requires not merely integrating existing legal regimes but reconceptualizing core legal concepts to align better with complex, multi-scalar and emergent dynamics.

Keywords: complex systems; international law; earth system; EVDT; cosmolegal; environmental law; climate law; uncertainty

1 Introduction

This study responds to the symposium 'What is "the Global"? Reassembling legal authority across space and time', which invites critical reflection on concepts shaping legal perception and practice. International law requires reconceptualization of its spatiotemporal foundations to address complex Earth–outer space phenomena. It operates through specific spatiotemporal assumptions – geometric space, chronometric time and cartographic politics – that structure how legal authorities conceptualise and enact legal authority (Rajković 2025). These assumptions have co-existed with, and upheld, *dominium* and *liberum commercium* and power interests behind a façade of universal legality and morality (Koskenniemi 2001, 2005, 2021). Imaginaries of space and time became consolidated through legal practice and scholarship and have profound implications for how international law addresses ongoing planetary challenges.

Earth–outer space interactions challenge applicable law through complex dynamics that transcend jurisdictional boundaries and temporal scales. This article argues that these challenges stem not solely from regulatory gaps, but from conceptual limitations in the spatiotemporal foundations of law. These limitations require a reconceptualisation of how international law engages with complex planetary phenomena.

Contrasting the dynamics of the cosmolegal proposal – characterised by multi-scalar complexity, non-linearity, emergence, feedback loops, uncertainty and non-human factors – with

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the assumptions underlying anthropocentric legal spacetime reveals the latter's structural inability to adequately conceptualise or govern Earth–outer space phenomena. The cosmolegal approach recognises that Earth–space system interactions have always constituted the material reality within which human legal imagination operates. Our collaborative research does not describe law's expansion to a new frontier, but rather acknowledges complex Earth systems that transcend jurisdictional boundaries. The study equates critique with engaging with this complexity Koskenniemi demonstrates how international law developed through vocabularies that framed perceptions of the 'international' within a terrestrial, state-centric paradigm. This study demonstrates how radical uncertainty—distinct from calculable risk—necessitates reconfiguring traditional knowledge-action relationships. The cosmolegal proposal extends this critical understanding by revealing how these vocabularies have obscured physical realities. While Koskenniemi (2021) shows how legal imagination constructed the Global through imperial projects, the present research examines how such legal constructions have failed to account for complex systems that have always defined Earth's relationship to cosmic processes. Legal frameworks need to acknowledge the inherent complexities in which humans have always been embedded.

Anthropocentric legal spacetime refers to the legal paradigm that presupposes human-centred, linear, territorially bounded understandings of space and time that inform legal doctrine and practice. Our analysis responds to Koskenniemi's (2021) observation that prevailing legal 'vocabularies' constrain thought regarding planetary phenomena by engaging directly with the phenomena as relevant actors for legal thinking and acknowledging Earth's position within outer space (Cirkovic 2025). In his introduction to this symposium, Rajković identifies how the 'World Map' imagery obscures alternative spatial conceptions suited for transboundary phenomena. Earth–outer space interactions include the nature of atmospheric/orbital spaces, multi-scalar connections, extended temporalities (e.g. debris persistence) and non-human factors.

The analytical orientation reflects a methodological choice that Burke (1969) explained through his concept of 'circumference', describing how select focus determines what is considered relevant and shapes perception. Our research focuses on material interactions within the Earth–outer space system, foregrounding environmental and systemic contexts. We argue that legal theory benefits from engaging experiences beyond dominant institutional centres and requires a degree of reflexivity regarding the chosen analytical frame's participation in ideological production.

The structure of this paper follows an interdisciplinary methodology that moves from legal theory to systems engineering applications and back to legal analysis. It traverses legal theory, engineering, and doctrine, acknowledging that this work represents a cross-section of ongoing research. This structure reflects both the collaborative research process and the integration of diverse disciplinary perspectives. The methodology builds upon conceptual work regarding the need to integrate outer space within Earth's planetary boundaries, as well as collaborative research introducing the environment-vulnerability-decision-technology (EVDT) approach to international law (Cirkovic and Wood 2025).

While transdisciplinarity proves necessary for addressing complex Earth–outer space interactions, it presents challenges related to differing expertise and training across disciplines. The first section focuses on the expertise of the paper convenors and the implications this has for our perspective on legal theory. It details the overall structure elaborating on the contrast between anthropocentric legal spacetime and the 'cosmolegal' understanding of the law. The cosmolegal learns from complex systems (Ruhl, 2008; Ruhl and Katz, 2015; Cosens et al. 2018, 2021) and identifies the tensions between human-created legal systems and the agencies that exist beyond human control.

Section 3 represents a collaborative 'reaching out' to systems engineering and includes studies on the application of the EVDT framework as a methodological tool for analysing system dynamics. Proposals for, and applications of, EVDT as a method, have involved various actors and

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stakeholders including legal and policy decision-makers. The section describes systems engineering tools, primarily through the EVDT tool, that provide approaches for systems architecture analysis, data integration and complex system modelling, enabling examination of interactions across disciplinary boundaries. This section provides a glimpse into transdisciplinary problem solving of specific Earth–outer space complex systems interactions.

Section 4 returns to the law and examines developments in international law and regime interactions relevant to climate change mitigation. It analyses how developments, such as the 2024 ITLOS Advisory Opinion on Climate Change (ITLOS 2024) acknowledge systemic interconnections and the interpretive challenges facing legal principles when confronted with phenomena characterised by distributed causality and systemic effects.

The paper concludes that significant gaps remain in knowledge production and transdisciplinary work, where 'collaboration' achieves the level of 'inclusion'. The internal dynamics of each discipline often remain unchallenged. Beyond disciplinary differences and respective training, an additional step requires internal self-critique within disciplines.

By examining spatiotemporal assumptions, this study contributes to discussions on reassembling legal authority for planetary challenges. It offers specific analytical resources from Earth system science, complexity theory and systems engineering – critically filtered through the cosmolegal perspective – for developing governance approaches suited to the interconnected, non-linear and multi-scalar realities of Earth–outer space interactions.

2 Complex systems and the law

When probabilistic frameworks fail due to fundamental unpredictability, legal analysis requires approaches that recognise the limits of predictive knowledge rather than merely improved models. This is a normative engagement with complexity and indeterminacy where prioritization is oriented towards environmental protection. At the same time, it avoids building an ontology of relations that imposes human sentiment on other biotic and abiotic entities—including ideas of 'kinship' (Paulson 2019).

While our previous collaborative work examined specific impacts of space activities on planetary boundaries (Cirkovic and Wood 2025), this study explores how complex systems science offers analytical resources that challenge assumptions embedded in international legal analysis. Prior research has demonstrated that effective governance of Earth–outer space interactions involves reconceptualising the ontological foundations of law itself (Cirkovic 2025). The cosmolegal approach positions legal thought and practice in relation to planetary and cosmic contexts to recognise the indeterminate nature of complex systems. It proposes a reconceptualisation of law's relationship to natural systems through the integration of complex systems science, plural ontologies and transdisciplinary research (Cirkovic 2025).

The analytical tools of complex systems science reveal indeterminacy, non-linearity and emergence – attributes that challenge legal constructs predicated on certainty and causation. Indeterminacy refers to the inherent unpredictability of system outcomes despite known initial conditions. Emergent properties are phenomena that arise from non-linear interactions among components rather than from the linear sum of individual behaviours (Bradbury and Vehrencamp 2014). Non-linearity describes disproportionate relationships between inputs and outputs, where small changes can produce large effects. Emergence characterizes the appearance of system-level properties that are not reducible to individual components. Complex systems comprise interconnected components whose collective behaviour cannot be predicted from the properties of individual parts (Rechtin and Maier 2010; De Weck, Roos and Magee 2011; Mitchell 2011; Crawley et al. 2016).

The orbital environment exemplifies the complex system characteristics. European Space Agency (ESA) data (2025) document an increasingly congested orbital space, where operational satellites, defunct spacecraft, rocket stages and fragmentation debris interact through orbital

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mechanics influenced by gravity, solar radiation pressure, atmospheric drag, space weather and collision probabilities. The Kessler Syndrome – a potential cascade of collisions in which an initial collision might trigger a chain reaction affecting orbital regions – represents an emergent property that cannot be attributed to any single satellite, but emerges from the system's collective, interactive dynamics (Kessler and Cour-Palais 1978).

The complex system dynamics challenge legal frameworks predicated on establishing clear causal connections between specific actions and resulting harms (Cosens et al. 2021; Cirkovic, 2025). Traditional legal analysis relies on identifying causal chains linking actors with outcomes. This approach is effective for discrete events but limited when addressing distributed causality and emergent harm in complex, non-linear systems. As Fisher (2013) observes, even conventional environmental law struggles with multi-causal harm untraceable to singular actions.

For instance, position and trajectory predictions for space objects incorporate uncertainty margins that increase over time (Es Haghi et al. 2024). Legal systems designed to assign responsibility face difficulties when addressing probabilistic risks whose manifestation remains uncertain. This uncertainty reflects a property of complex, non-linear systems where precise prediction often remains unattainable, regardless of available information.

The understanding of complexity in physical systems provides a foundation for considering legal systems through a similar lens. Barbara Cosens, Robin Kundis Craig, Brian Chaffin and J. B. Ruhl, among others, have argued that traditional governance approaches are insufficient for handling modern challenges that are characterised by rapid change, uncertainty and complex system interactions (Ruhl 2008; Cosens et al. 2021). This scholarship identifies the emergence of adaptive governance as a critical development. Adaptive law and governance typically emerge in situations marked by conflict and high uncertainty in environmental management outcomes. It is characterised by collaboration across multiple scales, sectors and jurisdictions, involving both private and public actors in networked decision-making processes. Rather than trying to control this emergence, they argue that law and government should play a facilitative role – ensuring legitimacy and accountability and creating space for innovation while maintaining stability. Enabling adaptive governance requires several key elements: legal authority for government agencies to implement adaptive management; adequate resources for monitoring and responding to change; flexibility to adjust course based on new information; mechanisms for cross-jurisdictional and public–private collaboration and processes to ensure legitimacy and accountability. Central to their argument is the critical balance between stability and flexibility in governance systems. However, legal governance does not necessarily require temporal acceleration or enhanced adaptive capacity, but rather ontological reorientation and methodological integration of multiple knowledge systems.

Adaptive management, adaptive governance, and adaptive law approaches have gained prominence in addressing complex social–ecological challenges. These concepts are rooted in a variety of disciplines and approaches including economics, ecosystem science and public choice theory. The Social-Ecological Systems Framework (SESF), for instance, tends to focus on 'common-pool resources' (resources that are difficult to exclude users from but subject to depletion through overuse) and oversimplifies complex interactions within social-ecological systems, embodying a managerial approach rooted in classical liberal economics (Ostrom 2007). SESF's claim of theoretical neutrality carries implicit assumptions about institutional design and resource management (Cirkovic 2025). The adaptive law approach, derived from these frameworks, is implicated in this managerialist turn, potentially limiting its ability to address the full complexity of environmental and social challenges (Ostrom 2007).

Our proposed and ongoing research relies more on the Socio-Ecological-Technical Systems (SETS) framework, which sometimes becomes conflated with SESF in adaptive law literature (Cirkovic 2025). SETS emerged primarily from urban planning and incorporates technological components alongside social and ecological elements. It builds on urban ecosystem services research to better understand four core challenges associated with urban nature-based solutions

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multi-functionality, systemic valuation, scale mismatch of ecosystem services and inequity and injustice. It incorporates elements from various disciplines, including urban planning, engineering and environmental science. SETS raises several questions relevant for our argument: What is the present status of a pertinent environmental variable? How is the change in this environmental state impacting people's socio-economic well-being? What legal and policy options are under consideration by decision-makers? Is the currently available data adequate for addressing these questions, or is there a requirement for advanced data collection technologies?

2.1 Uncertainty and value judgments in Earth–space system modelling

The modelling of complex, interrelated dynamics of the Earth system and the cosmos, as well as the projection of the results of human decisions into the future, inherently involves significant uncertainty. Attitudes towards uncertainty range from denial to acceptance as an element of scientific inquiry. The modelling of the complex Earth–space system necessitates numerous decisions regarding which factors to include, how to weight various variables, and how to interpret results. Space technology impact factors include rocket emissions, the deposition of debris in orbit, or the potential for uncontrolled re-entry of space objects. The selection of factors to include in climate and environmental models should consider the evolving understanding of the life-cycle of space technology, from launch to disposal or re-entry. Decisions about which launch-related emissions to prioritise – such as greenhouse gases, particulates or chemical by-products – can have significant implications for the model's outputs and the resulting policy recommendations. Similarly, the modelling of the impacts of orbital debris and the risks posed by uncontrolled re-entry events requires ongoing refinement as new data and understanding emerge.

In environmental governance (and arguably the lack thereof in outer space), the prevailing view holds that uncertainty, to some extent, is unavoidable but should be quantified and communicated clearly. It is also always evaluated in the context of multiple interests and, in law, vertical (scale) and horizontal (plurality of states and sectors) regime interactions. The concept of 'situated objectivity' or 'strong objectivity' acknowledges that scientists – those who study phenomena with significant societal implications – are influenced by their context and values. The choice of research focus, methodologies and interpretation of results all involve some degree of value judgment. For instance, a climate scientist's decision to study sea-level rise might be influenced by concerns about coastal communities, reflecting a value placed on human welfare and environmental preservation.

Legal systems and engineered structures can have fault lines or weaknesses, often rooted in historical circumstances. In law, such fault lines might appear as loopholes, inconsistencies or outdated regulations that fail to address current technological and environmental realities. In space technology, fault lines could be structural weaknesses, design flaws or operational vulnerabilities, and even traced to circumstances such as violence, dispossession, destruction, or faulty construction. For example, laws or technologies designed to assert dominance or exclude certain groups from space activities reflect how legal frameworks can reinforce exclusion and inequality. Similarly, technologies or laws that enable – or fail to prevent – harmful activities, such as the creation of space debris, exemplify destructive elements within the architected or designed law. The systemic barriers, unequal access and limited diversity within the space sector represent not merely technical failures, but also socio-political and historical legacies. While the space industry is highly regulated, it is not immune to the impacts of broader societal inequities and power dynamics.

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2.2 Deep time and multi-scalar dynamics

To reiterate, Earth–outer space interactions operate across spatial and temporal scales that exceed conventional international law. Surpassing regulatory challenges, these extended scales reveal conceptual limitations in how law conceives time and space. While international law typically addresses timeframes reflecting human-scale temporalities – from immediate effects to generational transitions – Earth–outer space dynamics involve temporal scales extending far beyond human experience, resembling what geologists term 'deep time' (Hutton 1788; Lyell 1830; McPhee 1981).

The concept of 'radical unknowability' (Cirkovic 2025), provides a foundation for addressing these extended temporalities. This formulation acknowledges that uncertainty is not merely a knowledge gap to be filled, but an inherent characteristic of complex Earth–space systems. It suggests that the ontology of law benefits from embracing indeterminacy as a central consideration, rather than an obstacle to be overcome.

Space debris persistence exemplifies these extended temporalities. Objects in geostationary orbit have effective lifetimes measured in thousands of years, while those in medium Earth orbit may persist for centuries, according to orbital decay models. These timeframes extend beyond not only the operational lifespans of the entities creating the debris, but also beyond the existence of the legal regimes, companies and potentially even states involved in their creation. This temporal extension creates a mismatch with laws designed around human-scale temporalities and near-term causal relationships. Rather than the traditional legal/scientific approach of trying to reduce uncertainty through better prediction and control, the cosmolegal idea, or the research we discuss, argues for designing legal systems that can function within and alongside unknowability.

Multiple spatial scales intersect in Earth–outer space systems in ways that transcend traditional legal conceptions of territory and jurisdiction. Activities in specific terrestrial locations create effects distributed throughout global orbital space and potentially throughout the atmosphere. Conversely, global phenomena like climate change affect specific objects in particular orbits (Cirkovic and Braun 2025; Parker, Brown and Linares 2025).

The multi-domain character of Earth–outer space environments introduces additional complexity. Orbital mechanics define object trajectories within six-dimensional phase space, where gravitational, atmospheric, and radiative forces continuously perturb orbital elements. This dynamic spatial distribution transcends conventional three-dimensional territorial concepts and challenges surface-based demarcations and fixed jurisdictional boundaries.

The disjunction between multiple domains and international law represents more than a regulatory gap, or the need for speed – it constitutes an ontological challenge. Socio-technical imaginaries (Jasanoff 2015) that shape space activities – including notions of space as a frontier for exploitation or as an extension of state power – conflict with the physical realities of orbital congestion and environmental interdependence. The law's attempt to separate Earth and space into distinct regulatory domains appears increasingly at odds with the physical reality of their integration.

Anthropocentric legal spacetime reflects the prevailing conception of space and time within international law – a historically constructed worldview shaped during European modernity and imperial expansion. In this symposium, Rajković (2025, pp. 3–4) identifies these foundations of international legal thought in his introduction. He demonstrates how international legal thought is grounded in 'misplaced concreteness' in the visualisation of global space and time. While 'the Global' is often taken for granted in legal scholarship, it is in fact 'as much a historical, social and legal construction, as it is a geological thing' (2025, pp. 1–2).

Rajković (2025, pp. 3–4) identifies three assumptions underlying the prevailing conception of 'the Global' in international law: geometric space, which conceptualises the Earth as a divisible sphere upon which distinct territorial boundaries can be inscribed; chronometric time, which assumes time as a linear, uniform, measurable progression; and cartographic politics, where maps

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emphasising state territoriality become the dominant representations of global order. These three elements – geometric space, chronometric time and cartographic politics – form what Rajković calls a 'triadic concept' that has structured how international lawyers see, know and act upon 'the Global' (2025, 3).

Rajković identifies the architecture (geometric space, chronometric time, cartographic politics) shaping international legal thinking about 'the Global,' while Koskenniemi traces its historical emergence. Koskenniemi (2021) conceptualizes his work as examining 'the legal imagination as it operates in relationship to the use of power' through bricolage—employing familiar legal vocabularies to address new problems and justify power distributions. Since 'bricolage begins at home' (Koskenniemi 2021, pp. 8–9), European legal concepts become foundations for global constructs. This framework produces a legal spacetime that is state-centric (viewing states as the primary actors and spatial units and facilitators of both public and private local, transnational and global powers), linear in its temporal logic, bounded by territorial divisions, oriented towards maintaining stability and predictability within those boundaries, and anthropocentric in its focus on human intention, agency and sovereign control.

In contrast, the cosmolegal lens portrays Earth not as an isolated sphere but as an interconnected component of the larger cosmic environment, defined by interacting physical, chemical and biological processes across its 'spheres' and influenced by its position within the solar system (Steffen 2004; McDowell 2018). Humans cannot 'escape' or 'transcend' this environment. And the 'environment' is non-linearity and emergence, where interactions involve feedback loops with causes and effects often disproportionate to one another. The relationship between anthropogenic CO_2 emissions, lower atmosphere warming, upper atmosphere cooling and the resultant decrease in atmospheric drag (Cnossen et al. 2016), which affects orbital debris lifetimes, and generally demonstrates feedback mechanisms spanning planetary and orbital domains. System-level behaviours, such as potential satellite collision cascades or crossing of planetary boundary thresholds, can emerge from the aggregation of numerous individual actions and interactions.

Cosmolegal recognises (instead of 'includes') beyond-human agency and materiality. Earth system processes governed by physical laws and influences from the cosmos possess dynamics that interact with, constrain and shape the outcomes of human activities. Solar activity fluctuations influencing atmospheric density and altering satellite trajectories demonstrate agency external to human intention or control. This complexity and interconnectedness lead to uncertainty, where precise long-term prediction often remains unattainable due to chaotic dynamics, sensitivity to initial conditions and incomplete knowledge.

Addressing these Earth–outer space interactions requires recognition of plural ontologies that can challenge dominant narratives, concepts, and constructs. Plural ontologies enable the redirection of current paradigms beyond dominant space governance narratives (Cirkovic 2025). While these narratives often reflect specific experiences and mainstream imaginations, recognising multiple ways of knowing and being strengthens engagement with the unknown and with the more-than-planetary scales involved. The mismatch between these contrasting spacetimes demands vocabularies that can engage with beyond-human agency and material processes that shape outcomes regardless of human intention.

A central limitation lies in the dominance of a linear, forward-moving and uniform conception of time – 'chronometric time' (Rajković 2025). This model traces its origins to specific theological traditions later secularised and institutionalised through developments like the mechanical clock, the centralised state and modern legal systems (Le Goff 1960; Greenhouse 1989). The global hegemony of linear time was achieved through colonial expansion and the standardisation of time (e.g. Greenwich Mean Time), which served imperial interests and projects of capitalist expansion (Fabian 2014; Ogle 2015; Gordon 2019). The linear temporality appears inadequate for grappling with phenomena characterised by non-linearity, emergence, feedback loops or deep temporal scales extending beyond human or typical legal horizons. It

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struggles to account for cyclical ecological rhythms or harms that manifest gradually as 'slow violence' or 'slow emergencies', lacking the immediacy often required for legal recognition (Nixon 2013).

While scholars increasingly challenge the grand narrative of Progress, notions of incremental progress remain embedded in legal discourse. This appears particularly visible in international environmental law, which often portrays itself as developing progressively since the 1972 Stockholm Conference, despite mounting evidence of ecological collapse. Environmental legal concepts like 'sustainable development' reproduce this forward-looking temporality, promising future improvement while potentially masking present failures or inequalities (Skouteris 2010). Sustainable development inherited the temporal assumptions of economic growth while attempting to reconcile it with conservation. The orientation towards the future as an 'open' horizon of possibility appears problematic in environmental contexts. It obscures how past actions, and enduring structures have already constrained future pathways (Folkers 2021). Given the accumulated fossil residuals in air, water and earth, the future cannot simply be viewed as an 'open horizon of infinite options'. Modern societies cannot fully escape the past to seize an open future of progress and possibilities. Dominant legal conceptions of the future often overlook what Grove et al. (2022) term the 'uneven distribution of futurity' – how the modern experience of an anticipatory orientation to the future as potential for change and development has been conditioned by practices that deny these same possibilities to racially marginalised communities. Legal framings of the future as open can obscure the foreclosed futures of those living with ecological devastation.

3 The EVDT framework

This section explores the EVDT methodological tools. The EVDT framework has evolved beyond conventional systems engineering applications to address methodological challenges of analysing complex socio-environmental-technical systems.

The integration of the EVDT tool with the cosmolegal approach moves beyond binary legal thinking to accommodate uncertainty as a fundamental characteristic of complex systems (Cirkovic 2025, pp. 63–64). The integration provides both analytical tools for understanding system dynamics and normative foundations for developing governance approaches aligned with the nature of Earth–space interactions. Challenges facing Earth–outer space systems require transdisciplinary approaches, as well as diverse knowledge systems of local and Indigenous communities, a perspective that EVDT methodology facilitates through its multi-domain analysis.

The EVDT framework's foundation in systems architecture analysis provides approaches to identifying system components, relationships, and emergent properties across physical, social and technological domains (Crawley et al. 2016; Rechtin and Maier 2010). The systems architectural approach examines Earth–outer space interactions as integrated systems. By identifying connections and information flows between system components, the EVDT methodology reveals interfaces between domains traditionally analysed separately: between orbital and atmospheric processes, between technological systems and environmental impacts, and between regulatory mechanisms and system behaviours.

Its integrated treatment of uncertainty helps envision and propose regulation that can account for unpredictable outcomes. EVDT modeling provides approaches for incorporating uncertainty explicitly into analysis and decision support, rather than attempting the challenging endeavor of eliminating uncertainty through more precise prediction in complex, non-linear systems (Lombardo et al. 2023; Haghi et al. 2024). For the purpose of this study of international law and Earth-outer space environments, ensemble modelling, scenario analysis, sensitivity testing and adaptive management approaches offer tools for addressing the uncertainties.

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3.1 Applications to Earth–outer space governance challenges

Orbital debris dynamics resist analysis through traditional legal approaches focused on discrete actions and bilateral relationships. It offers a practical tool for the more theoretical cosmolegal proposal. The EVDT approach enables integrated examination of orbital mechanics, regulatory frameworks, stakeholder behaviours and environmental impacts to identify system-level interventions that conventional legal analysis might overlook. Initial examples of this analysis address the experience of NASA's Conjunction Assessment and Risk Analysis (CARA) team by modeling how they coordinate with both public and private actors to avoid collisions between active satellites. The analysis also considers how the socioeconomic value of the spacecraft and the services provided could be a factor in collision avoidance strategies (Haghi et al. 2024). A second example of an EVDT application considers the complex dynamics when one commercial actor provides satellite servicing for another commercial actor while a public actor implements continuing supervision of the servicing event (Smith, Jah and Wood 2024). This work highlights that the technical capabilities of space situational awareness and the uncertainty caused by the physics of orbit dynamics and space environment place severe limitations on the capability for governments to implement Continuing Supervision consistently during servicing scenarios. Article VI of the 1967 Outer Space Treaty (OST) states that countries bear international responsibility for national space activities and must provide "continuing supervision" of those activities, whether conducted by governmental or non-governmental entities. These examples illustrate the multifaceted insights that can be gained when combining analysis from engineering, physics, social science, law and policy while being sensitive to uncertainty and time scales.

The EVDT approach provides tools for analyzing space-enabled Earth observation systems as integrated socio-technical arrangements rather than merely technical infrastructure. This analysis examines information flows between observation systems and decision-making processes, identifies gaps between available data and user needs, and evaluates potential system improvements to enhance decision support capabilities. Several example studies have taken this approach, including work in cooperation with the Yurok Native American Tribe in California to use satellite data to inform participation in carbon markets (Lombardo et al. 2023), work to map and quantify the experience of people living in US prisons as they are exposed to environmental hazards such as air pollution and extreme temperatures (Ovienmhada et al. 2021, 2024), and work to map the relationship between protected areas and human settlement areas in Mexico (Montes et al. 2024). A recent study applied EVDT to support the City Government of Rio de Janeiro to use newly available high-resolution commercial satellite data to monitor methane emissions from the city's largest landfill (Ajisafe 2025). In each of these projects, research teams collaborate with decision makers who are working in the context of specific legal regimes drawn from local indigenous nations' government, municipal government, or national government context. The EVDT analysis provides both quantitative and qualitative findings visualised based on the needs of the decision makers.

Launch impacts on atmospheric systems illustrate EVDT's capacity to address cross-domain environmental effects. The methodology can be used to create an integrated examination of how launch activities affect atmospheric chemistry, connecting atmospheric science, launch technology assessment, regulatory analysis, and environmental policy evaluation. This transdisciplinary approach provides analytical tools for examining the multi-scalar impacts of space activities on Earth's environmental systems, addressing dimensions of Earth-Outer Space System Spacetime that conventional legal analysis struggles to conceptualize.

This study demonstrates how integration of methodologies provides a tool for the spatiotemporal challenges identified in Section 2. It is an example of a transdisciplinary tool for examining legal concepts and approaches in light of the complex, uncertain, and multi-scalar dynamics characteristic of Earth-outer space interactions. It also facilitates critical examination of how legal concepts themselves might evolve to better address uncertain and multi-scalar dynamics

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characteristic of Earth-outer space interactions. This is a critical examination and transdisciplinary mapping process that does not rely only on critical legal history and theory, but aims to engage directly with multiple domains.

Complex systems approaches reveal additional analytical dimensions when applied to legal principles such as prevention, precaution, sustainable use and intergenerational equity. The EVDT framework is one technique for multi-domain analysis that may have broader applicability here, we combine it with the cosmolegal proposal to offer an approach that can help observe and evaluate how legal principles function within systems characterised by non-linear dynamics, emergent properties and uncertainties. Law does function 'within' those complex systems since anthropogenic laws exist in the broader planetary context. Transdisciplinary methods can identify limitations in conventional interpretations and suggest adaptations that better address complex system characteristics. The EVDT tool is built on creating simulations of potential future scenarios, visualising interconnections between physical and nonphysical dynamics and describing sources of uncertainty.

The integrative methodology enables examination of whether jurisdictional constructs align with system boundaries and interfaces. EVDT tools for boundary analysis reveal how legal jurisdiction might align with the cross-boundary characteristics of Earth–outer space systems by identifying jurisdictional gaps, overlaps and misalignments that create governance challenges when addressing phenomena that transcend territorial boundaries.

Section 4 applies the integrative approach to legal concepts of liability and responsibility. Contemporary liability regimes presuppose direct causal connections between actions and resulting harms – a presumption challenged by the distributed causality and emergent damages characteristic of complex systems. EVDT methodologies for analyzing causal relationships can identify limitations in existing liability doctrine and suggest adaptations that account for system-level interactions and emergent outcomes.

4 Legal developments

The ITLOS 2024 Advisory Opinion constitutes a judicial attempt to address how international law can manage systemic environmental harm. The Opinion responded to questions from the Commission of Small Island States on Climate Change and International Law regarding state obligations under UNCLOS with respect to greenhouse gas emissions and the impacts of climate change on the marine environment. The Opinion takes an evolutionary approach to precaution and scientific evidence in international environmental adjudication. Although the Opinion acknowledges 'the all-encompassing nature of climate change', the tribunal operates within institutional structures that require translating systemic environmental problems into discrete legal duties and compliance standards (Cirkovic 2025).

The Tribunal's interpretation of marine pollution under UNCLOS Article 1(1)(4) to encompass anthropogenic greenhouse gas emissions responds to systemic environmental harm. By recognising that emissions originating largely from land-based sources ultimately affect ocean chemistry through carbon absorption processes, the Opinion recognised environmental processes occurring within the volume of the ocean, driven by diffuse atmospheric inputs rather than traditional point-source discharges tied to specific territorial locations.

The Opinion acknowledges that greenhouse gas emissions from diverse sources, globally combine in the atmosphere and subsequently affect marine environments through physical and chemical processes that transcend jurisdictional boundaries. This is an institutional recognition of environmental processes that operate through multi-dimensional space rather than along territorial boundaries. The Tribunal's emphasis on using 'best available science' engages implicitly with complex system dynamics (ie. the phenomenon of climate change). Paragraph 46 states that 'the phenomenon of climate change is central to the Request and the questions contained therein necessarily have scientific aspects'. The Opinion draws on scientific assessments from the IPCC

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and other bodies to establish the factual basis for its legal analysis. The data sets represent multi-domain analysis and incorporate climate models that integrate processes across multiple Earth spheres and timescales.

The Advisory Opinion's interpretation of UNCLOS as a 'living instrument' (para. 130) reflects an attempt to adapt legal doctrine to evolving scientific understandings of Earth system dynamics. The Tribunal states that 'coordination and harmonisation between the Convention and external rules are important to clarify, and to inform the meaning of, the provisions of the Convention and to ensure that the Convention serves as a living instrument'. This interpretive approach demonstrates how legal doctrine should evolve in response to changing scientific understanding.

The Opinion's analysis centers on individual state obligations under UNCLOS, examining how states 'prevent, reduce and control pollution of the marine environment from any source' (Article 194). This focus on individual state responsibility and due diligence struggles to encompass accountability for emergent risks within global systems characterized by complex feedback loops, uncertain thresholds, and diverse temporal lags between emissions and impacts. The Tribunal's treatment of temporal dimensions similarly reflects both adaptation and constraint. While acknowledging the extended temporal scale of climate change and noting that greenhouse gas emissions create effects persisting across generations, its remedial approach remains focused on prospective actions rather than confronting the deeper temporal dimensions of climate responsibility.

When legal analysis encompasses outer space, both juridical doctrine and outer space governance embody the geometric and territorial logic of anthropocentric legal spacetime. Article II of the OST establishes that '[o]uter space, including the Moon and other celestial bodies, is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means' conceptualizing space primarily as an area or surface governed by jurisdictional rules. Article VIII establishes a registry-based method of jurisdiction that 'retain[s] jurisdiction and control over such object, and over any personnel thereof, while in outer space or on a celestial body'. This creates a patchwork of jurisdictional authority linking individual space objects to their respective states of registry without considering the orbital environment as a multidimensional system. As orbital space becomes increasingly congested, the object-by-object approach reveals limitations when addressing risks and shared resources. The paradigm lacks conceptual resources for addressing the orbital environment as a system with emergent properties.

The environmental provisions in Article IX require states to 'conduct exploration of them so as to avoid their harmful contamination' and to avoid 'adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter'. The concept of 'harmful contamination', originally focused on contamination events, is currently insufficient for addressing the environmental risk posed by the effects of orbital debris, spacecraft deterioration or interventions in celestial environments. The Convention on International Liability for Damage Caused by Space Objects (The Liability Convention 1972) employs a fault-based liability standard for damage occurring in space, providing that 'the latter [launching State] shall be liable only if the damage is due to its fault or the fault of persons for whom it is responsible.' The probabilistic and emergent nature of orbital risks challenges this fault-based structure. In a congested orbital environment where multiple objects interact through orbital mechanics, determining fault for damage becomes difficult. The potential for collision cascades represents an emergent risk that cannot be attributed to any single actor but arises from the dynamics of the orbital system itself (Kessler and Cour-Palais 1978).

Recent developments in space governance represent attempts to overcome these limitations while remaining constrained by the assumptions of anthropocentric legal spacetime. The 2019 Guidelines for the Long-term Sustainability of Outer Space Activities (LTS Guidelines) represent an effort to establish governance approaches for the orbital environment. They focus on voluntary state actions rather than addressing orbital space as an environmental system with its own dynamics, thresholds and emergent properties. Integrated interpretation of existing outer space

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treaties could synthesise state pluralism and global interest sectors horizontally, while vertically connecting regime scales from local and domestic levels through to national, regional, transnational and international spheres. Such integration would allow for a more nuanced methodology and an understanding of the interconnections between Earth's systems and space activities, potentially leading to more effective legal instruments for confronting environmental challenges (Cirkovic and Wood 2025).

The historical development of outer space law exposes the practical barriers to regime integration. Signatory states drafted and ratified the OST in 1967 with minimal environmental integration despite ongoing debates about space environmental impacts throughout the 1960s (UNGA 1962; UNCOPUOS 1966). However, free access and use took priority over development of substantive environmental provisions (UNGA 1962; UNCOPUOS 1966). This history embodies choices that subordinated environmental protection to strategic and economic interests. While the OST contains provisions that could encompass environmental concerns (particularly Article IX's provisions on avoiding harmful contamination), as a product of its time, it does not address explicitly the space environment or provide mechanisms for assessing space activities' environmental impacts.

Scholars and practitioners committed to doctrinal positivism may question whether systems approaches can provide sufficient certainty and predictability for effective legal practice. The concern about certainty and predictability merits consideration, as legal systems require stability and coherence. The integrated approach offers methodological guidance for incorporating multiple forms of evidence – including Earth observation data and systems modelling – into legal arguments and treaty interpretation.

5 Conclusion

The transdisciplinary approach developed in this paper suggests the need for legal frameworks that can accommodate inherent uncertainty, multi-scalar dynamics, and emergent properties while maintaining sufficient stability and predictability to function as governance systems. The modelling of complex interrelated dynamics of the Earth system and the cosmos – as well as the projection of human decisions' results into the future – inherently involve significant uncertainty. The integration of multiple domains within a single framework advances previous approaches that addressed these elements in isolation. Together, these approaches suggest the need for more comprehensive and transdisciplinary learning practices, mapping, modeling, problem-solving, and an ontology of uncertainty and unpredictability.

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