On the social and cognitive dimensions of wicked environmental problems characterized by conceptual and solution uncertainty

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We develop a quantitative framework for understanding the class of wicked problems that emerge at the intersections of "natural", social, and technological complex systems. Wicked problems reflect our incomplete understanding of interdependent global systems and the hyper-risk they pose; such problems escape solutions because they are often ill-defined and thus mis-identified and under-appreciated by problem-solvers and the communities they constitute. Because cross-boundary problems can be dissected from various viewpoints, such diversity can nevertheless contribute confusion to the collective understanding of the problem. We illustrate this paradox by analyzing the development of both topical and scholarly communities within three wicked domains: deforestation, invasive species, and wildlife trade research. Informed by comprehensive bibliometric analysis of both topical and collaboration communities emerging within and around each domain, we identify symptomatic characteristics of wicked uncertainty based upon quantitative assessment of consolidation or diversification of knowledge trajectories representing each domain. We argue that such knowledge trajectories are indicative of the underlying uncertainties of each research domain, which tend to exacerbate the wickedness of the problem itself. Notably, our results indicate that wildlife trade may become a neglected wicked problem due to high uncertainty, research paucity, and delayed knowledge consolidation.

Emergent phenomena associated with interconnected systems underlay many global challenges [1], such as climate change, biodiversity loss, and epidemic containment. Indeed, the source problems that can trigger systemic failures often reside at the intersection of environment and socio-technical systems [2–4], nexuses that tend to foster out-of-equilibrium phenomena owing to anthropogenic conflict rather than systemic synergy.

Our understanding of interdependent complex systems requires integrating diverse bodies of scientific knowledge. Such understanding can better enable responsible strategies to resolve, mitigate and manage such boundary-spanning problems – as in the case pursued in this work regarding biodiversity loss in environmental systems, and the potential downstream impact it may have on global food security, climate change, and human security and wellbeing, among other issues [5–7].

A particular class of problem we are motivated by are wicked problems, typified as untamed, dynamically complex, and ill-structured problems, similar to other 'gray rhino hazards' that are highly likely and ignored [8]. Wicked problems tend to be intractable and elusive given the multiple interdependencies and the absence of a 'correct' view [9]. Therefore, wicked problems commonly lack of unique and definitive solution which is particularly chilling when systemic hyper-risk [1] is appropriately included when estimating the full societal cost associated with candidate pathways that do not address the fundamental problem, e.g., as in the case for eliminating extreme poverty [10, 11].

In order to fully appreciate the multifaceted nature and implications of wicked problems, communities of problem-solvers must construct robust knowledge structures around them. Lacking clarity and solution uncertainty do not absolve policy makers from deciding about policy alternatives, allocate resources and evaluate metrics [9, 12]. Knowledge structures imply bridging knowledge across domains, representing the challenge of integrating multi-disciplinary lenses and triggering common visions regarding the properties of wicked problems [13], and manners to address and manage them – i.e., the constitution of scientific agendas. Over time, consistent knowledge constructs and persistent knowledge production give rise to robust *knowledge trajectories* that reflect the state and development of a research domain [14]. Against this backdrop, this work contributes to the discussion on the nature and properties of wicked problems by assessing: *in what ways do knowledge trajectories indicate the maturation of scientific understanding around a wicked problem?* To this end, we analyzed three relevant domains of 'Invasive species', 'Wildlife trade' and 'Deforestation' research. A common criterion for selecting these domains is lack of technically well-posed objectives, as multiple disciplinary lenses might prioritize different components of the system and therefore the ways to address the problem. We argue that such a flaw is sufficient to give rise to a coherence failure within social and cognitive realms of knowledge construction.

We address these issues by drawing on literature providing insights into the emergence and dynamics of cohesive research communities [5, 14–20]. In addition to analyzing collaboration networks as a measure of social cohesion, we also analyze cognitive trajectories that are indicative of persisting

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topics in these communities. Notice that we refer to cognitive domain as the topic-specific similarities that arise in research in which common frameworks are discussed [17, 21, 22]. To quantify these relationships, we employ data-driven network science methods to measure the knowledge dynamics according to: (a) cognitive similarity between research and (b) collaboration among scholars. By simultaneously comparing networks capturing (a) and (b), in a similar vein to prior research identifying emerging research areas [23–26], we seek to identify emerging knowledge production patterns that characterize wicked problem domains.

Given a wicked problem, a fundamental question that can be asked is whether there is a common vision or leading topics among problem-solver subcommunities. We posit that research areas lacking consolidation in collaboration and cognitive domains fail to delineate a clear pathway for addressing the target problem, which then reduces potential for investment in intellectual, human, social, institutional capabilities. This declination further hinders the consolidation of support systems (e.g., extramural funding, high impact journals, course releases, diversity and inclusion governance, other forms of institutional support) that incubate early-stage researchers and sustain long-term collaboration and leadership. Hence, a better understanding of the cognitive and social dimensions of wicked problem-solving is necessary to fully comprehend the complexity of dealing with this type of problems, though these elements are poorly explored in literature.

The remainder of this paper is structured as follows: in section I we detail the anticipated relationship between a cognitive/collaboration trajectory, and the lack thereof, and the emergence of research trajectories about wicked problems. Section II introduces the data and methodology for assessing the proposed relationships. Section III investigates knowledge trajectories by analyzing knowledge communities and collaboration trajectories in tandem. Finally, we discuss the connection between the social and cognitive dimensions of research dynamics and the symptomatic characteristics of wicked problems.

I. Conceptual Background

Dimensions and defining characteristics of wicked problems

This paper gravitates around several characteristics of wicked problems, which are defining elements of the "wickedness" of a problem, as it has been previously described [13, 27]. 'Wicked' is a concept that emerged from public policy research (also frequently used in studies of science dynamics) referring to particular characteristics of a research domain. However, we are unaware of literature exploring the relationship between this concept and its implication on research dynamics, particularly as it relates to nascent or otherwise understudied research fields.

Problems in general can be defined, among other things, by the degree in which related clear-cut concepts and solutions are identifiable. Heifetz & Heifetz [27] propose that with difference to tame problems (Type I), wicked problems can be divide between those conceptually definable but without clear-cut solution (Type II), and those conceptual and technically ill-defined (Type III). In other words, not all wicked problems are equally complex and suffer from the same type of ill-definition. On the one side, Type II wicked problems are conceptually clear but appear 'fuzzy' to problem solvers, as they lack exact solution or have a compendium of degenerate (multiple equivalent) solutions embedded in high uncertainty [10, 28]. On the other hand, Type III wicked problems are inherently resistant to clear and unique definitions, and consequently, predefined solutions [10, 13, 29], and are delineated by definition and solution uncertainty [see, 9, 27, 30, 31]. In contrast to tame problems, wicked problems result in thorny issues for which common top-down, silos, and expert-driven approaches are insufficient to cope with the complexity of wicked problems [3, 10, 27, 32]

Beyond conceptual and solution ill-definition, and the multiplicity of conceptual and solution approaches, wicked problems are also exacerbated by social factors. Indeed, the underlying problems do not occur in a vacuum, but are socially situated [13, 29]. Addressing complex and wicked problems facing society and the planet requires research spanning traditional disciplinary boundaries that leverages convergent integration of expertise across multiple research fields and stakeholders[23, 31, 33–36]. The variety of stakeholders, interests, and objectives embedded in the social context may involve a large collection of opinions and ideas about the problem itself and its causes [9, 10, 13, 29, 32, 37] that could result conflicting and therefore hampers consensus formation or shared visions. The greater the disagreement among stakeholders, the more wicked the problem. Confusion, discord, and lack of progress are telltale signs that an issue might be wicked [29]. However, different studies [e.g., 15, 19, 38] suggest that long term social interactions between stakeholders might increase knowledge diffusion, second-order learning and favor co-creation; altogether enablers of agreements [3, 39]. Although some authors suggest that the multiplicity of stakeholders define wicked problems, we argue that social and cognitive cohesion between them might foster coherent consolidation of research areas, policy agendas, and shared vision [5, 10, 14, 17, 26, 40] reducing therefore concept and solution uncertainties. However, that may increase transaction cost of engaging and aligning stakeholders [32].

To help bridge the nature of wicked problems and the research dynamics behind them, we explore the role of social-networks and knowledge-networks as structural elements of social and cognitive cohesion [17], inasmuch as they relate with the nature of wicked problems in at least two dimensions. First, where uncertainty obfuscates the clarity of problem definitions. Such lack of agreement around concepts, their relationships, and manifest objectives are characteristic of endeavors calling on multi-disciplinary problem-solving. Consequently, wicked problems may fail to consolidate permanent and incremental cognitive trajectories with low conceptual uncertainty [14, 20].

The second dimension of wicked problems is where uncertainty obscures the set of feasible solutions. We posit that returns on social capital investment, understood as collaboration trajectories, are reduced in a research community lacking clearly delineated forward pathways, and so sustaining consequential leadership and research agendas, which serve to maintain social and knowledge-network cohesion, may become untenable in such scenarios. As such, wicked problems fail to alert, activate, orient, and incentivize the vast field of candidate problem solvers [37] who help the institutionalization of research by addressing 'grand challenges' and other conceptual leverages that serve as a lighthouse to guide trajectories that might not otherwise provide a promising approach to address such failures [1]. Wicked problems are by definition intractable in the sense of a single 'closed-form' solution, so 'better' solutions are fostered instead of a 'correct' one; which is mostly feasible when stakeholders converge, agree over, and institutionalize research agendas to cope with these problems [9, 13, 29, 32, 36, 41] . As such, wicked problems can be managed instead of solved, a situation that requires agreements between stakeholders, solid research agendas, and inter and transdisciplinary approaches, as Masterson [42] shows for the case of malaria coping.

The relation between problems and knowledge trajectories

Following the concept of Schumpeterian patterns of innovation, we argue that knowledge trajectories facilitate uncertainty reduction by increasing cognitive dependencies and fostering collaborations trajectories [14, 25]. We argue that wicked problems deal with high levels of task, conceptual, and solution uncertainty associated to the production of unrelated and fragmented knowledge [13, 14, 30]. Lacking leading structures in the cognitive domain might therefore exacerbate further uncertainties within cognitive trajectories, whereas high fluctuation of knowledge-producing actors and the lack of collaboration can result in a lack of agreement of possible solutions and manners to deals with intervention uncertainty [17, 40]. While long term interactions are highly relevant to build up common vision, trust, and to challenge uncertainty [43, 44], temporary and short-run collaborations can lead to lacking or flawed solution frameworks [22, 45, 46]. We suggest that the lack of both cognitive and collaboration trajectories may hamper the development in knowledge trajectories.

How new knowledge is produced and how paradigm shift might happen have been relevant enquiries addressed by several studies that posit the relatedness between knowledge topics and fields as a main mechanism of diversification [14, 18, 20, 25]. Cognitive relatedness as disciplinary and language coherence or, in other words, permanence and continuity of research in disciplinary subfields and keywords, relates to the strong path dependency of knowledge production, and the entry and exit of knowledge building-blocks accumulated in the system [14].

Similar to cognitive relatedness, we posit collaboration trajectories as proxy of partnership relatedness and therefore indicator of knowledge consolidation. Long-term collaborations underly established process of academic debate [22, 38] that assist consolidated agendas, and are enablers of deep learning across researching communities [5, 43, 44]. Besides relational events of research interactions, long-term collaborations contribute to the establishment and consolidation of knowledge trajectories, frequently shown through authorship, collaboration between authors and institutional permanence and continuity.

The analysis of cognitive and collaboration structures frequently involves the use of networks and synthetic indices [e.g., 5, 15, 17, 19, 20, 22, 40, 46–51] that bring detail of the structure and dynamic of research systems. Building up on that, we use a diversity model based on disparity that identifies the emergence of leading communities and established collaborations. This approach is similar to previous works [e.g., 14, 20, 25, 40] but bases diversity as heterogeneity rather than richness or differentiation. We leverage the understanding of diversity in the taxonomy proposed by Harrison & Klein [52], which differentiate varieties, separation and disparity. Variety refers to possible states of a system (richness), while separation alludes to the differences between existing varieties, and disparity addresses the dominance of one or few varieties over the other. In addition, our model has a "memory effect" represented by the evaluation of disparity over temporal aggregates of knowledge trajectories, facilitating therefore the identification of fluctuations on the diversity of cognitive and collaboration trajectories, as we further describe in the next section.

In order to study the nature of the research about wicked problems, we test whether the research of three specific problems, namely, Deforestation, Invasive species, and Wildlife trade, exhibit high fluctuation levels regarding cognitive and collaboration trajectories. In particular, we are motivated by the following propositions regarding each problem domain:

P1. *Invasive species.* Given the clear task and conceptual definition of Invasive species, we anticipate a persistent growth of cognitive research and collaboration trajectories.

P2. *Wildlife trade.* Contrarily, we expect a turbulent pattern of cognitive and collaborative research associated to wildlife trade because of the high task and solution uncertainty of this problem.

P3. *Deforestation.* We expect that this domain suffers from solution uncertainty; the definitions of the problems are clear, but a lack of effective solutions, and furthermore multiple players, and localization of the problem might generate a turbulent pattern of collaboration related to this problem.

II. Methods

Evaluating the nature and extent of change in knowledge trajectories requires characterizing the composition and structure of scientific knowledge, operationalized by assessing structural changes in diversity (separation or disparity) related to the emergence or consolidation of cognitive trajectories and leading authors [5, 14, 50]. In what follows we first detail the case studies addressed and then we describe our proposal for assessing structural changes in research domains, which is sufficiently general to be applied beyond the three case studies explored.

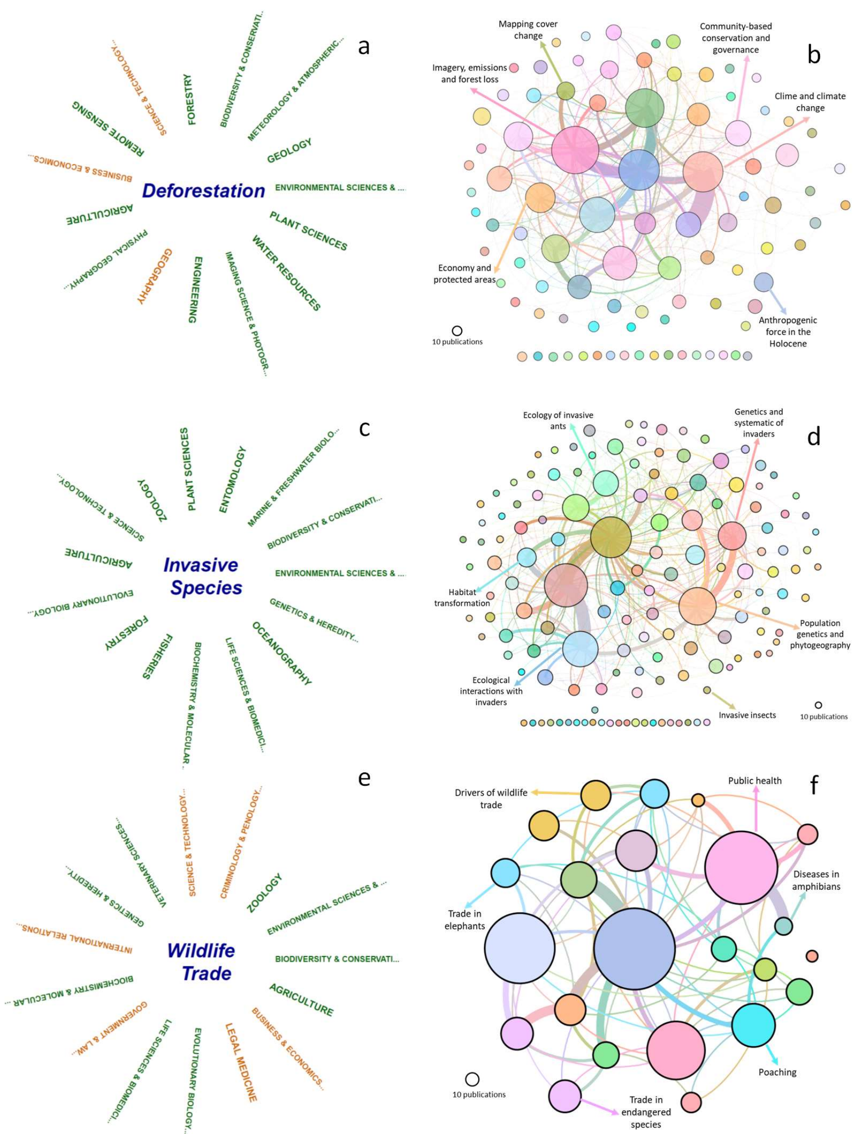

FIG. 1: **Disciplinary and cognitive composition of three environmental problems.** The 15 most frequent WoS subject categories (SC) for each problem are shown (a, c, e), ordered counterclockwise. Subject categories are colored for physical (green) and social sciences (orange). Co-bibliography networks (b, d, f) showing (circles) knowledge communities (groups of publications) and their cognitive relation (see Supplementary note 2). Some communities are labeled according to the topics addressed by the group. The size of the circle represents the number of publications within.

Study cases

Global challenges facing the environment exist at the crossroads of scarcity and uncertainty. Natural resources, conservation efforts, and ecosystem preservation exist in a state of scarcity; either economically, spatially, or functionally – there is always less or something markedly different left today than the day before. This scarcity means that any social, technical, or environmental solution is necessarily crisis-driven. That is, a conservation biologist, as one disciplinary example, may have to make decisions or recommendations about design and management before they are completely comfortable with the theoretical underpinning, methodological approach, or empirical bases, let alone the totality of the problem at hand [12, 13, 53]. Therefore, tolerating epistemic uncertainty in terms of what the best available knowledge and other sources of uncertainties to confront a challenge may be is a necessary component of environmental science, particularly when dealing with wicked problems [10].

Holistic approaches are therefore needed to confront underlaying uncertainties and the complex nature of interconnected global environmental challenges, but the boundaries of what disciplinary knowledge may be best suited to address the problem cannot entirely be known a priori to identification of the issue. A multi-disciplinary or trans-disciplinary approach [23, 54] is thus needed in order to address environmental problems like the cases discussed here. The knowledge networks that the melding of natural and social scientific relies on can be used to overcome the previously siloed nature of disciplinary approaches, especially with both vertical and horizontal integration. However, interdisciplinarity is possible only when there is sustained interaction between members of different disciplines because it leads to new ways of thinking about complex issues [5, 12, 13, 47]. It is only with the explicit recognition of the tight coupling of social and natural systems that scientists may collaborate to identify both the problem and potential solutions to best inform practical decisions and management outcomes [36, 55].

Environmental problems typically encompass multiple social, technological, and ecological dimensions; thus, they are multidisciplinary and complex by construction. Although environmental problems are placed at the intersection of natural and social sciences, what specific disciplines or fields compose the research of a particular environmental problem might vary (see **Fig.1**).

Accordingly, we focus on 3 human-driven environmental problems (Deforestation, Invasive species, Wildlife trade) tied to human history and development [56], though recognized as global problems only recently. Since the late 1970s several studies have suggested that the 3 problems are drivers/symptoms of global change, biodiversity loss and the asymmetric relationship between the global North and South [57–59]. These global challenges are therefore incorporated into political actions through international conventions and accords that deal with the interconnected nature and boundary crossing aspects of the phenomena at hand; examples include the Convention on International Trade in Endangered Species of Wild Flora and Fauna (CITES) of 1973, the Convention on Biological Diversity (CBD) of 1992, and the Reducing Emissions from Deforestation and Forest Degradation (REDD) of 2008.

Our first case study is Deforestation, which refers to the intentional reduction of forest cover in both legal and illegal contexts. Deforestation has been tied to the expansion of commercial and subsistence agriculture frontier, legal and illegal logging for paper or hardwood industry, urbanization, desertification, and climate change [59–61]. The impacts of deforestation on vulnerable populations can be wide ranging and degrade human wellbeing [61, 62]. Drawing on the disciplinary composition of the scientific research on deforestation (see **Fig.1a**) we show that such understanding is strongly dependent on natural sciences aimed at assessing land cover change and its impacts, as well as forest/agriculture management. Social sciences contribute understandings of the behavioral, economic, sociocultural and psychological drivers and consequences of deforestation.

Besides disciplinary approaches, scientific understandings are formed within communities of practice and expertise interlinked by conceptual and methodological frameworks that facilitate cognitive proximity and coherence [17, 22, 51, 63]. Such communities of practice, or communities of knowledge henceforth, are here identified through co-bibliography networks as we further explain in the next subsection, being them a central methodological approach in this study. Consequently, we identify several communities of knowledge that represent different cognitive domains within deforestation inquiries (**Fig.1b**; see also Supplementary Figure 1 -SF.1-), such as the relation between land cover and water quality, fragmentation and habitat use, human impacts on habitat integrity, the role of forest in economic growth and equity, and the relationship between production of sustainable energies and deforestation, among other domains.

The second case study is Invasive species, which refers to biological invasions or the unnatural demographic growth of species. Invasive species are frequently nonnative species introduced to an ecosystems a) intentionally (e.g., in an active, deliberate manner) or b) unintentional (e.g., in passive, accidental manner), though some native species can also become invasive [64, 65]. The mechanisms and consequences of biological invasions differ across species, organisms, and economics. The rate at which invasive species change their distribution and affect their recipient ecosystems is often determined by natural scientists using various forms of risk assessments, many of which have pointed invaders out as potentially harmful and destabilizing forces in natural and anthropogenic ecosystems [66]. The economic impacts of controlling or coping with existing, or preventing new, invasions are significant, frequently exceeding hundreds of billion dollars per year [67].

Biological invasions are mostly human driven, though ecologically shaped and filtered which reflect the disciplinary composition of the research in this problem that is notably focused on biological sciences and zoology, in particular (**Fig.1c**). From a disciplinary perspective, biological invasions are mostly addressed through the lenses of natural sciences despite the known consequences of invasive species in the livelihoods and economy of the inhabitants of the recipient ecosystems [68]. The cognitive domains or knowledge communities (**Fig.1d**, SF.1b) formed by the scientific research on invasive species include, for instance, the genetic structure of invasive populations, comparative biology between invasive and non-invasive species, management of invasions, dispersion and spatial structure of invasion, and invasions in human-dominated ecosystems.

Finally, the third case study is Wildlife trade, or alternatively wildlife trafficking, which refers to the legal and extralegal commercialization and use of wild fauna and flora, as well as their derived products. Both, legal and illegal wildlife trade frequently suffer of fuzzy boundaries highly debated in academia and practice. Wildlife trade spans through local and international scales encompassing complex social networks that supply the increasing demand for medicines, souvenirs, pet markets, wild meats, and cultural customs [56, 58, 69]. One aspect of the problem that is frequently highlighted is the illegal dimensions of wildlife trade, which is recognized as one of the most profitable illicit supply chains in the world [70] with profound ecological and social impacts [69] such as biodiversity loss, corruption, and violence.

In contrast to the previous cases, Wildlife trade is further characterized by an inextricable social sciences involvement. More specifically, Fig.1e shows that besides biological sciences, this problem domain is co-dominated by human sciences such as criminology or government. Cognitive domains or communities of knowledge regarding wildlife trade (**Fig.1f**, SF.1) include invasive species derived from trade, epidemiology and public health, the relationship between wildlife trade and social media, law enforcement and policy, among others.

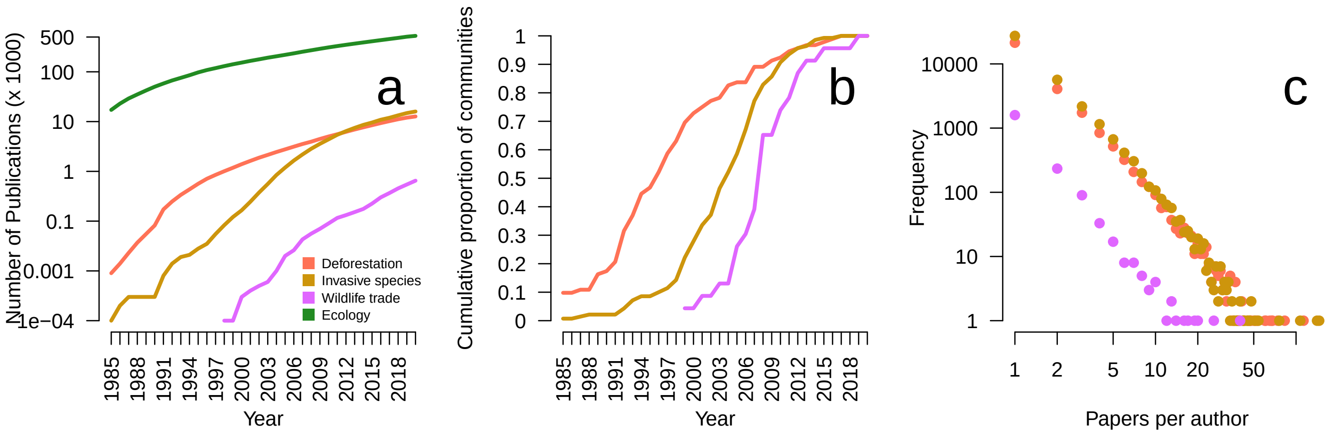

FIG. 2: **Characteristics of the source sets defining the 3 case studies.** It is shown deforestation (orange), invasive species (brown), wildlife trade (purple). (a) Cumulative number of sources including data for Ecology (green) for benchmarking purposes. (b) Cumulative proportion of knowledge communities emerged. (c) Author productivity distribution, indicating common scaling despite underlying differences in domain size.

Data

Multiple scientific repositories have been widely used for understanding scientific dynamics. We use Web of Science (WoS), one of the most prominent sources of indexed literature [48], to collect the scientific literature associated with each case study. The information was downloaded in November 2020 using general queries designed to capture each problem (see Supplementary Note 1 -SN.1-). For each article we tabulate several characteristics, including journal (SO), authors (AU), keywords (DE), year of publication, country of authors' affiliation (CU) and, WoS research subject category (SC, similar to WoS disciplinary category (WC), SC is indicative of a journal-specific ontology). Furthermore, for each source we also tally two co-occurrence measures, one for co-author (C-AU) dyads and another for co-keyword (C-DE) dyads.

Scientific repositories systematically compile, store, and make accessible vast quantities of information regarding scientific productivity, nevertheless their supporting search engines might be sensitive to misidentifications and synonyms. To avoid the intrusion of non-related publications within our analysis we focus on publications cognitively coherent and consistent with at least part of the rest of the literature. We identified such publications by reconstructing the corresponding co-bibliography network [21, 22, 63] as we further describe in SN.2. The co-bibliography networks (see SF.1) are composed by nodes (publications) interconnected by links that indicate the similarity between the references used by the publications, or the cognitive proximity [21, 22]. The networks comprehend only clusters or knowledge communities (groups of coherent publications cognitively proximal) of a minimum size of 10 nodes, providing high modularity (0.88 for Deforestation, 0.95 for Invasive species, and 0.85 for Wildlife trade) indicative of the robustness of the knowledge communities identification method (see SN.2). Differing from other studies, we include all the knowledge community (KC) in the analysis rather than limiting it to those in the main or giant component in the network. With this, we include nascent and contesting frameworks and ideas, but exclude inconsistent, non-related, isolated, and poorly coherent publications.

After the filtering process (see SN.2), the number of publications in each case study are: 12,674 for Deforestation; 15,947 for Invasive species; and just 650 for Wildlife trade. **Fig.2a** shows the cumulated number of sources included in our analysis, including the number of papers published in the domain of ecology, useful for benchmarking as an overarching discipline spanning the three case studies. We note differences in the growth rate of each domain. When fitting the annual number of sources to an exponential distribution, we determine the doubling time for each case as follows: Deforestation=6.12 years, Invasive species=5.67y, Wildlife trade= 5.48y, and ecology=6.64y.

Importantly, we also note differences in the timing of consolidated knowledge to emerge for each domain, indicated qualitatively by the year of the first publication, as illustrated in **Fig.2a** and **Fig.2b**. Notice that here we refer to consolidated knowledge rather that publications in general. Although the three domains are relatively contemporary (the earliest observation is in the 1960-70's for the three cases), consolidated knowledge for Deforestation and Invasive species emerges in the early 1980's, whereas for Wildlife trade it emerges in the late 1990's. Figure **Fig.2b** and SF.1 provide further indication of when and how knowledge communities arise. For each case we observe a sigmoidal curve, frequently found in science studies [e.g., 71], indicating more precisely the onset of problem space diversification.

To assess the numerosity and productivity of researchers in each domain, we applied a simple name disambiguation method by collecting articles authored by common surname and first initial, an approach that is remarkably robust in studies of this scope [72]. As well documented in the literature [16, 38, 71, 73], we observe an extremely right-skewed productivity distribution **Fig.2c**, indicating that each domain supports just a few highly productive authors, whereas the vast majority of scholars publish just a few research articles. Despite the differences in domain size, estimation of the skew using the single-parameter power law distribution model $P(x = \text{sources per author}) = x^a$ indicates similar scaling exponents ($a = 2.495$ for Deforestation; $a = 2.494$ for Invasive species; $a = 2.246$ for Wildlife trade). In sum, we show that the 3 case studies are not extraordinarily different in their general characteristics, thus we argue that they are comparable and further differences reflect problem features, as opposed to idiosyncratic differences arising from variation in sample size and scholar productivity.

Analytical approach

We differentiate the variables described within cognitive (i.e., KC, DE, C-DE, SC, SO) and collaboration trajectories (i.e., AU, C-AU, CU), to which we quantify their diversity by means of two disparity measures: the "Shannon Evenness" index [74], a common metric use in ecological studies of diversity, and the Gini index expressed as its complement (1-Gini). These disparity measures are aimed at evaluating the dominance of some or few varieties (e.g., authors, knowledge communities) over the general pool. In order to assess temporal shifts in diversity, the metrics are calculated using intra-annual and inter-annual (cumulative) approaches. More precisely, we calculate disparity (i) in the first based upon sources published in year t; and (ii) in the second case using all sources up to and including year t.

We first clarify how to interpret inter-annual disparity changes. Note that changes in inter-annual disparities in year t are relative to cumulative disparities measured up to year $t-1$. Second, changes in inter-annual disparities in year t can arise even in the absence of significant changes in successive intra-annual disparities; this could occur if the varieties included in years $t-1$ and t differ. Hence, inter-annual measurement indicates change in the temporal relatedness of research by accounting for system 'memory' necessary to evaluate how new research fits into the existing trajectories, as Funk & Owen-Smith [49] argue. Contrariwise, the comparative baseline for intra-annual disparity is a random configuration of variable categories appearing in the same year. Hence, for both cases we develop a null model in which the temporal footprint of sources is shuffled. The null model is constituted by 5000 iterations, which yields confidence intervals in addition to average values representative of diversity values that could arise from random temporal configurations of the data, with source-level features otherwise held constant.

III. Results

Despite across-domain similarities in growth rate, author productivity distribution, and modularity of the co-bibliography networks (**Fig.2**, SF.1), we identified marked differences in the temporal structure of cognitive and collaboration trajectories. Our results are robust to the diversity measure used, as indicated by comparing trajectories calculated using Shannon evenness entropy (SF.2-5) and Gini complement (SF.6-9). Henceforth, we focus our analysis on the results obtained using the Gini index, and provide further details of knowledge trajectories in supplementary materials.

Cognitive trajectories

In this subsection we analyze network measures of cognitive disparity for each research domain. **Fig.3** illustrates the concentration of knowledge community (KC) sizes, with higher Gini complement values corresponding to higher disparity levels. Hence, while Deforestation and Invasive species research are characterized by high disparity levels, Wildlife trade is characterized by markedly lower concentration levels, corresponding to more even distribution across its cognitive communities. Furthermore, both Deforestation and Wildlife trade show significant diversification periods as oppose to Invasive species who shows an ever-growing disparity, indicative of incremental growth. First focusing on the intra-annual level (**Fig.3a**; SF.2, 6), results show a generic increasing trend that saturates, indicating that scientific productivity becomes increasingly focused on fewer knowledge communities over time. Interestingly, for Invasive species and Wildlife trade, the empirical trajectories are typically only slightly greater than the expected values yielded by the randomized null model (see SF.3, 7). Hence, neglecting historical correlations reinforcing the formation of each community, concentration within communities is consistent with cognitive trajectories established by random ensembles. On the other hand, applying a cumulative sampling that accounts for aggregate historical correlations, **Fig.3b** shows more rapid ordering (increasing concentration upon fewer communities) in cognitive structure, with earlier periods showing larger deviations from the null model (see also SF.4-5 and SF.8-9). We posit that higher concentration derives from higher coherence or relatedness within the communities, indicative of agendas becoming prioritized. However, ever time, the empirical levels approach the null model expectations for each domain, indicating a saturation and decay of coherence over time. Such decay is notable for Deforestation and Wildlife trade, which show important diversification after saturating. Moreover, Gini values are consistently smallest for Wildlife trade, indicating the absence of dominant cognitive communities leading the field forward. As such, results indicate that cognitive trajectories are firstly characterized by knowledge consolidation in specific domains that define the *status quo* like the case of Invasive species; nevertheless, for Deforestation and Wildlife trade it is also shown periods of diversification or attention more evenly distributed between multiple foci.

To test for robustness, we performed this disparity analysis using other source-level characteristics for all the metrics assessed in the cognitive domain (SC, SO, DE, C-DE) that corroborate that the main differences between the case studies lay in the distribution of cognitive relatedness in the formation of knowledge communities (**Fig.4a-b**), as the differences between the empirical data and the results yield by the null model suggest (see SF.6, 9). Other aspects as the generic high diversity of Wildlife trade and differences between Deforestation and the null model at early stages are also consistent (**Fig.4a-b**, SF.2-9).

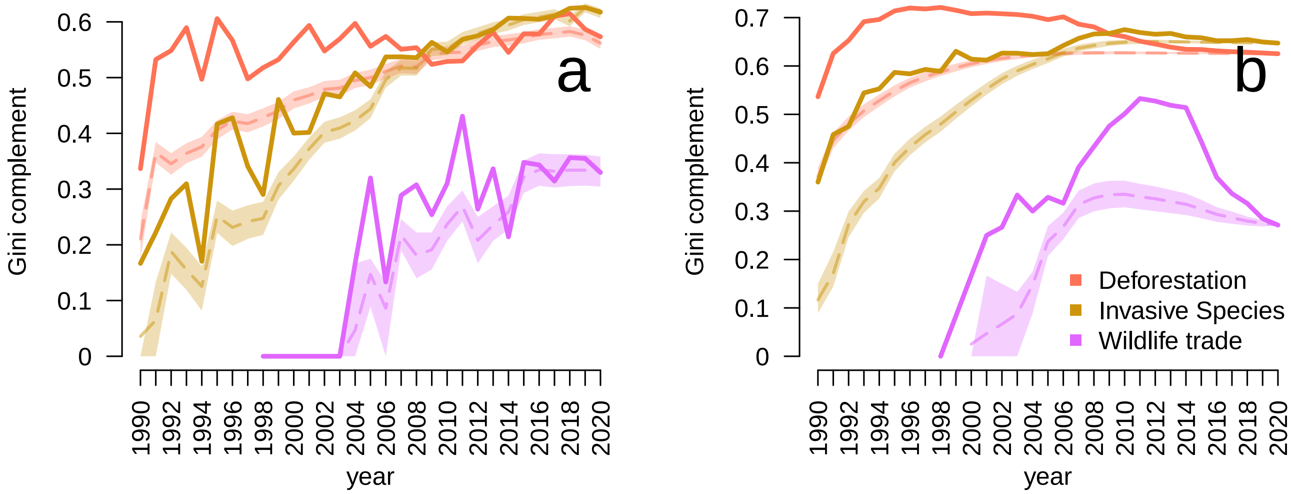

FIG. 3: **Temporal variation in disparity of cognitive community sizes.** Measurements are expressed as the Gini complement (1-Gini) for: Deforestation (orange), invasive species (brown), and wildlife trade (purple). (a) Intra-annual variation. (b) Cumulative variation. Shadows denote the interquartile range for data generated by randomized null model, applied to each domain separately; dashed lines indicate the mean null model realization value.

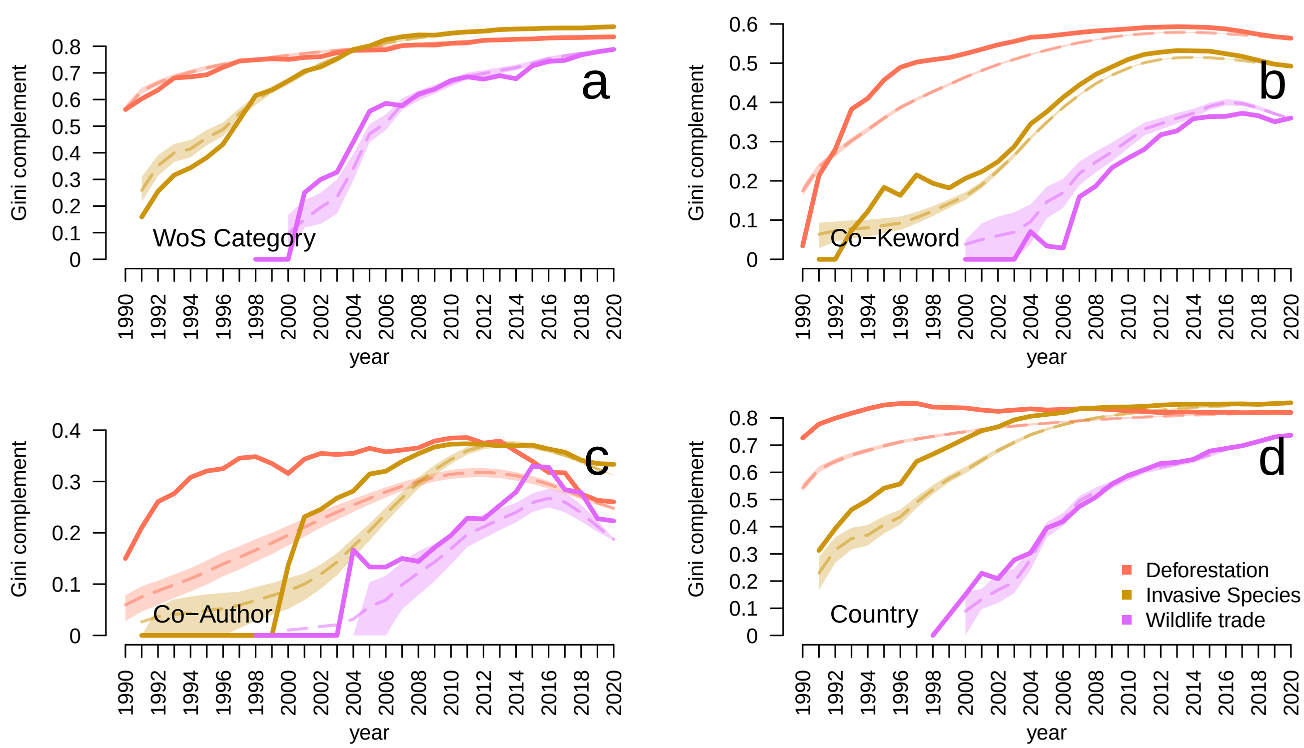

FIG. 4: **Temporal variation in concentration in cognitive, social, and geographic coordination networks.** Gini index calculated using cumulative data sampling for: deforestation (red), invasive species (blue), wildlife trade (purple). (a) WoS Subject categories. (b) co-keywords dyads, (c) co-authors dyads, and (d) author affiliation country. Shadows denote the interquartile range for data generated by randomized null model, applied to each domain separately; dashed lines indicate the mean null model realization value. For comparison, intra-annual analysis is provided in the SM.

Collaboration trajectories

In this subsection we analyze network measures of social coherence. Results based upon Authorship (AU) and co-authorship dyad (Co-AU) networks show similar results (**Fig.4c**, SF.2-9(e-f), respectively). Deforestation and Invasive species communities are highly concentrated and differ from the random model, while Wildlife trade follows random expectation. Together, these results consistently indicate that Wildlife trade research lacks continuity and leadership. Although we identify prolific authors (**Fig.2c**) in the research of Wildlife trade, their impact is diminished if we account for their cross-temporal footprint. Interestingly, for Wildlife trade and Deforestation we notice a diversification in the co-authorship in the last decade, indicating a significant influx of new researchers in these problem domains.

Analysis of concentration disparity between countries serves as a proxy for the role of institutional factors (e.g., national science funding). For Deforestation and Invasive species, we find the empirical data to deviate from random expectation (**Fig.4d**, see also SF.6, 9). Such excess concentration levels indicate a high level of order reflecting a small set of countries leading each domain. In contrast, concentration disparity between countries in Wildlife trade research does not differ from the random expectation, suggesting a lack of national-based leadership. To further support this result, we also measured productivity disparity between the global South and North (SF.5i-9i), and we found similar results – Deforestation yield values in excess of the randomized null model showing high diversification or, in other words, a more balanced production between the global North and South.

In summary, we identified important differences across the 3 study cases. Invasive species research is characterized by an increasing concentration disparity in both cognitive and collaboration trajectories. Disparities generally increase in time, for each variable analyzed, indicating an increasing domination by few varieties. This trend indicates coherent consolidation of cognitive features and research leaders.

Similarly, Deforestation research is also characterized by high concentration disparity levels, also for both cognitive and collaboration measures. However, for some cognitive (KC) and collaboration (CU, C-AU) variables, we observe a slight reduction in disparity indicative of recent diversification. These suggests that deforestation is broadening in scope coinciding with the entry of new research subdomains, which perhaps are mainly from the global south.

Finally, Wildlife trade represents the most distinct domain of the three, showing important changes in cognitive (KC) and collaboration trajectories (C-AU) characterized by strong diversification (large reduction in Gini index) after periods of increased concentration around dominant themes (larger Gini index). In addition, this case shows ordering in the relevant variables (CU, C-AU) that is consistent with the randomized null model. These results indicate emerging vicariance in the cognitive and social domains, owing to 'fuzzy' delineation of the problem and the community lacking leadership.

IV. Discussion

We analyzed the social and cognitive dimensions of research trajectories emerging around three environmental problems – Deforestation, Invasive Species, and Wildlife Trade. Despite the common backdrop of sustainable development and conservation, we observe marked differences that we attribute to the role of uncertainty associated with problem and solution identification in each domain. First, we note different consolidation time scales and research publication volume between the three cases analyzed, indicative of differences in how research is prioritized [75] and the time required for the academic community to build a common understanding and agenda. Second, for deforestation and wildlife trade we observe a diversification of cognitive structures (mainly regarding Knowledge Communities, KC) indicative of an increasing task uncertainty, and perhaps also conceptual uncertainty. We observe a broad spectrum of conceptual approaches, which may indicate contested spaces where assumptions and knowledge are debated [5, 20, 49]. Finally, it is well understood that the influx of new researchers contributes to the diversification of collaboration trajectories. Yet in wicked problem domains where knowledge is poorly integrated, high levels of churning may impede the cohesive growth of the research community [33, 51]. Consequently, this may exacerbate solution uncertainty, limit the development of leadership roles, hamper the cross-fertilization between researchers and institutions, and reduce progress towards second order "deep learning" [2, 3].

Accordingly, we argue that for these domains – each differing in its set of task and conceptual uncertainties, and knowledge trajectories – symptomatic characteristics of their wickedness were unfolded and coincide with the typology of Heifetz & Heifetz [27]. As such, we posit that Invasive species corresponds to a Type II wicked problem (i.e., conceptually definable but without clear-cut solution) while Deforestation and Wildlife trade correspond to Type III wicked problems (i.e., conceptual and technically ill-defined). These assessments are based on diversification of cognitive trajectories being an indicator of increasing task uncertainty and conceptual ill-definition, as in the case of Deforestation and Wildlife trade.

In contrast, Invasive species appears to have organized around a well-posed problem, as indicated by its clear and consistent cognitive trajectories. However, there appears to be a relatively high level of KC diversity, indicating solution uncertainty balanced by large collaboration. These results provide support for our initial propositions [P1-P3] regarding the type of uncertainties associated with each domain. The Invasive species domain is characterized by well consolidated knowledge trajectories, indicative of low levels of uncertainty and/or large agreements about the fundamentals of the problem. On the contrary, knowledge trajectories for Wildlife trade are unconsolidated for both the cognitive and social dimensions. Interestingly, for deforestation we expected large uncertainty in the solution domain associated with a turbulent social (collaboration) trajectory. However, we also observe diversification in the cognitive domain, which may reflect increasing conceptual uncertainty.

Conceptual and solution uncertainties are tied to the dynamics of knowledge trajectories that may consolidate a particular set of views, while also forging alternative pathways by challenging and destabilizing the cognitive status quo when introducing disruptive or unconventional ideas [49, 76, 77]. As we have shown, consolidation of knowledge trajectories via reinforcement of (social and cognitive) status quo and diversification are not mutually exclusive. In fact, cognitive trajectories such as knowledge communities are characterized by diversification and cohesion (consolidation) processes [17] that enable the inclusion of multiple voices while triggering shared visions regarding concepts and technicalities [32]. For instance, in well-delineated problems such as Invasive species, mainstream knowledge communities can consolidate in parallel, thereby yielding cognitive diversification of co-evolving knowledge [51] without affecting the overall knowledge trajectory. We argue that knowledge trajectory consolidation is a paradox in which, on the one hand, it may foster the emergence of alternative trajectories where new actors and ideas can thrive without overwhelming prevailing knowledge [17, 25, 33, 40, 43, 44]. While on the other hand, locked-in or rigid trajectories can impede the integration of different voices that underpins interdisciplinary, holistic, and post-normal approaches [10, 18, 32, 53, 55].

Such problems call for better means to stimulate the research community by way of integrated diversification [33, 35, 51] in which multiple voices and approaches can be included while consolidation of existing research agendas and communities of expertise takes place [2]. Balancing this fundamental tension will help focus efforts and capabilities toward specific, albeit partial, solutions that iteratively converge to solutions addressing the underling complexity [10, 13, 31]. Without direct measures or consideration for the complexity of wicked problems, well-intentioned efforts may nevertheless result in research domains that are fragmented and uncoordinated, giving rise to untenable or unactionable solutions.

High levels of conceptual and solution uncertainty do not only pose a challenge to the scientific process. Such ill-definition also hampers the translation of science-based solutions into societal action. Hence, there is increased demand for shared visions at the academic-industry-government interface [78], in addition to the multi-disciplinary interfaces increasingly encountered in academia. In particular, long-term interactions may generate common visions and directions that facilitate identifying possible solutions and agendas between researchers, organizations, and funding agencies [5, 13, 22, 25, 30, 38, 41]. With this in mind, our results indicate that the integrative collaboration dynamics among biodiversity and conservation-related communities may be hindered by the confounding nature of ill-defined problems, producing fragmented and tangential diversification of knowledge trajectories [17, 20]. Prolonged failure to reach shared visions may hinder the development of cognitive and social trajectories that satisfy society's demand for actionable knowledge [75], as in the case of neglected diseases [11, 79–81]. As such, consolidation of cognitive and collaboration trajectories are necessary enablers to supply human, financial, and institutional capabilities needed to advance appropriate combinations of science- and policy-based problem solving, which otherwise may give rise to neglected problems. Within our proposed framework, highly wicked problems, as is the case of wildlife trade, might suffer from a broader societal disregard for pursuing further action owing to the lack of clarity regarding problem definitions and solutions.

Overall, we analyzed how knowledge trajectories, analyzed through complimentary cognitive and collaboration perspectives, evolved since they emerged within the corpus of scientific knowledge. By measuring the dynamics of knowledge diversity (disparity), we assessed how cognitive and social structures emerge, consolidate, and diverge over the life-course of a given problem domain. Identification of these dynamic motifs is essential for understanding how conceptual and solution uncertainties are digested by scholarly communities – as highlighted in our study of three wicked problem domains. Our study therefore provides guidance for identifying characteristics of wicked problems and some of their dimensions through the dynamics of their research and provides a straightforward method for evaluating the dynamics of research domains. We posit that enhanced conceptual and solution uncertainties increase (respectively, decrease) as a product of scope-broadening (respectively, lock-in) of knowledge trajectories [18], affecting ultimately the actionable value of knowledge. Comparison between the three problem domains indicates that wildlife trade is evolving along a distinct trajectory characterized by literature paucity, low disparity between dominant and peripheric cognitive structures, and a general lack of leadership in individual and institutional basis. Hence, this domain may suffer from ill-posed problem definition, which calls for increased alignment between knowledge supply and societal demand to address this critical wicked problem.

Finally, we acknowledge that our approximation to capturing the evolution of these problem domains is incomplete. For example, our focus on disparity measures does not provide insights into knowledge relatedness through the lens of separation diversity, as achieved in other approaches [e.g., 14, 20, 48]. In addition, while our operational framework illuminates the structure of research producing fundamental changes in each research domain, it does not provide any additional indication as to how the particular pathways connecting cognitive and leadership micro-changes translate into macro-level knowledge trajectories. A better understanding of the causal channels through which these dynamics operate will be critical to steering wicked problem domains away from the neglected research trap.

Supplementary Material

All supplementary materials are available at `https://doi.org/10.6071/M39106`. Supplementary materials include SN.1 Search queries, SN.2 Co-bibliography Networks construction, SF.1 Co-bibliography networks for the 3 case studies, SF.2-5 Dynamics of knowledge trajectories measured as Shannon evenness, and SF.6-9 Dynamics of knowledge trajectories measured as Gini Complement.

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