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Sustainability Knowledge and Governance in Environmental Problems. The cases of Illegal Wildlife Trade and National Park Systems Management

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Sustainability Knowledge and Governance in Environmental Problems. The cases of Illegal Wildlife Trade and National Park Systems Management

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by

Felber J. Arroyave B.

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DEDICATION

To all those who have supported and encouraged me in this process, and have contributed to my success. To my wife Estefania, my parents, my siblings, my friends. To my mentors, my professors and colleagues that have been part of me in this academic path.

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ABSTRACT OF THE DISSERTATION

Sustainability Knowledge and Governance in Environmental Problems. The cases of Illegal Wildlife Trade and National Park Systems Management

by

Felber J. Arroyave B.
Doctor of Philosophy in Environmental Systems

University of California Merced, 2023

Dr. Michael Dawson, Chair

The effective management of complex systems necessitates a fundamental understanding of the role of knowledge, especially in environmental systems comprising ecological and social complex dynamics and inherent uncertainties. The social dimension of environmental problems involves not only practices, symbolisms, and forms of organization around a particular resource, but also the dynamics of knowledge and its connection to collective action and decision-making. The interests, perceptions, and power dynamics inherent to the social construction of the problem are revealed by the knowledge produced for a given problem and who produces and uses such knowledge. However, the ways in which knowledge is purposely produced have been poorly explored in the analysis of environmental systems. This dissertation contributes conceptually and empirically to the understanding of knowledge in environmental systems – referred here as sustainability knowledge- by assessing the nature of such knowledge and its interconnection with management and policy of two environmental problems, namely, *"illegal trade of wildlife"* and *"National parks system management"*. To be specific, this dissertation addresses i) How knowledge enables illegal operation and its implications to tackle the activity. ii) How a problem's ill-definition and solution uncertainty affect the scholarly production of knowledge about environmental problems, emphasizing on illegal trade of wildlife. iii) In which ways the perceptions regarding illegal trade of wildlife differ between multiple stakeholders and how this affects possible strategies to manage the problem. iv) How the U.S. national parks are understood and represented by multiple

communication channels. v) To what extent the production of knowledge about national parks in multiple countries involves transdisciplinary teams (i.e. teams comprising of individuals from distinct sectors). vi) What is the potential of research about national parks to meet the managerial needs for knowledge-based governance. Altogether, these analyses show how knowledge is used in different management regimes. To be specific, the data-driven approach used here enables the characterization of distinctive features of sustainability knowledge. Overall, this dissertation indicates that sustainability knowledge about the two problems studied lacks proper conceptual and social consolidation at several scales, largely owing to the disparity in stakeholders' perceptions, preferences, and interests. These findings imply the existence of diverse knowledges that might result in difficulties to make them actionable. Furthermore, such difficulties can affect the capability of managers to deal with multiple, and sometimes conflicting, worldviews, priorities, and interests. As such, the findings suggest that achieving inclusive governance regimes might be hindered by the ability of managers to mobilize diverse actors towards common goals.

Chapter 1

Introduction

This dissertation studies different aspects of knowledge production regarding environmental problems characterized by high complexity and uncertainty at the nexus of social, political and ecological dynamics [3, 36, 86]. Environmental problems call for a combination of science and policy capable of accounting for their complexity and responding to societal demands regarding the necessary knowledge to cope with them [1, 74, 86]. Such knowledge, referred henceforth as **sustainability knowledge**, must therefore blend multiple disciplinary lenses into coherent cross-field synthesis and enable diverse actors to coalesce towards robust networks where the problems can be debated and understood [4, 22, 82, 148, 247]. Although significant advances have been made towards understanding and explaining the basis of such boundary-spanning problems [24, 82, 250, 249], it is unknown if problems addressed by sustainability knowledge have indeed comprised the necessary integration on cognitive and social dimension, as well as the physical and social aspects, that this type of problems entails. Furthermore, given the common ill-definition (i.e. lack of a comprehensive and broadly accepted conceptualization) of environmental problems and their difficulty to be studied, little is known about to what extent sustainability knowledge has met the societal demands for actionable knowledge.

In this regard, this dissertation evaluates what and how knowledge is produced/consumed in two domains (i.e. *'illegal trade of wildlife', 'national park systems'*) where environmental problems are of varying nature, while considering several contexts of knowledge creation and its implications for the management of the embedded natural resources. Considering the social and ecological nature of environmental problems, this dissertation is drawn from a systemic, relational, and complex systems approach that look at the dynamics of social actors producing and consuming relevant knowledge necessary for the problem solving. Although different studies have assessed some structural and dynamic properties of sustainability knowledge [35, 37, 25, 24, 249, 337], they frequently place emphasis on aspects regarding academic knowledge producers. Such studies commonly overlook other types of knowledge producers (e.g. governments, NGOs), topical and multidisciplinary differences between the myriad of environmental problems, and the relevance of knowledge dynamics in managing problems.

Understanding the governance of environmental problems beyond traditional institutional views requires assessing the interplay between knowledge and management as it relates to: how knowledge is produced and distributed among actors; how knowledge is leveraged to navigate the complexity of the problem; and how/why/by whom management strategies and priorities are developed. In other words, knowledge is an expression and a driver of power inasmuch as knowledge allows actors to define and steer a problem according to their attitudes and to take actions accordingly. Therefore, disentangling the intricate nature of power, knowledge production and its translation into management – owing to the diversity of knowledge producers and users, and their motivations – implies acknowledging the interconnection between what knowledge is being produced and its characteristics, who produce such knowledge, in which contexts the knowledge is produced, and how that knowledge is related to actual knowledge needs and possibilities of action.

In what follows, first, I detail the nexus between complexity, socio-ecological systems, knowledge dynamics and governance. Then, I briefly contextualize the environmental problems used as case studies and the most common approaches used to evaluate them. Finally, I describe motivation of this dissertation and introduce the six main chapters that constitute this document.

1.1 Background

Sustainability knowledge is a cornerstone element for addressing the challenges of our changing world. In fact, sustainability has become central to the mission of governments and corporations alike. This emerging and quickly evolving field has been of interest of many studies [24, 82, 316] that have shown some regularities also found in other knowledge domains (e.g. scaling rules, geographical biases). Notwithstanding, sustainability knowledge is a distinctive domain. For instance, environmental problems are characterized by high complexity and uncertainty owing to the dynamic and multidimensional characteristic features of the social and ecological systems that comprise this type of problems [36, 190, 338]. Identifying pathways for characterizing environmental problems and producing actionable knowledge becomes necessary, but not without challenges associated with integrating multiple disciplinary approaches and a variety of knowledge producers and users.

Environmental systems are host to a variety of ***"wicked problems"*** placed at the complex intersection between human societies and the ecosystems upon which they depend [92, 190]. Societies and ecosystems are inherently complex inasmuch as each one is composed by multiple parts connected via material and symbolic (e.g. meanings, rules) flows, producing collective behaviors (emergent properties) accessible only when the whole is assessed [227, 326]. At the intersection of these systems, they configure a collection of interacting parts from which emergent properties describe the inner complexity of the coupling [36, 35, 295]. Throughout this systemic view of coupled social and ecological interrelations, different properties have been described, such as non-linear responses, adaptability, resilience, tipping points, regime shifts and, governance regimes [35, 116, 128]. These properties have been associated with feedback loops, openness, path dependency, cross-scale linkages, self-organization, among other factors [3, 23, 261, 353]. Although different epistemic communities have contributed to the characterization of coupled social and ecological dynamics (e.g. political ecology, political economy, environmental economy, among many other), an important part of the knowledge is grounded in the developments of **socio-ecological systems** (SES) theory.

SES theory embeds social (sub)systems within ecosystems overcoming the human-nature dichotomy [63, 86] and emphasizing the coupled dynamics of societies and ecosystems. For instance, studies have shown how ecosystem services are affected by social dynamics leading to multiple outcomes on human wellbeing [36, 86, 239]. Most of the SES theory works embody evolutionary institutional economics approaches for which institutions include social organizations, markets, social norms, among others [86, 353].

The study of how sustainability knowledge is produced and assimilated by different social actors and organizations is rarely studied in SES, and in environmental systems in general. Furthermore, the relationship between sustainability knowledge and governance is frequently under-considered. To be specific, studies assessing the dynamics of sustainability knowledge commonly lack specificity and depth to properly inform decisionmakers and other stakeholders. This might affect the ability to steer knowledge systems towards solving pressing issues and to reduce associated uncertainties [150, 151]. High levels of task uncertainty could bolster controversies, limit the ability of managers and other stakeholder to make informed decisions, navigate the complexity of the problem, and form coalitions. Moreover, task uncertainty and deficiencies in the integration between knowledge producers and users might deepen the power imbalances between stakeholders and affect environmental governance. ***How knowledge systems affect governance regimes and management practices*** is therefore one the central element of this dissertation,

Governance refers to the different forms of purposeful collective action [209, 210] and the different mechanism employed to order, consult, negotiate and, handle a specific issue within a territory [7, 194]. Governance operates within networked socio-political systems in which actors and institutions interact and distribute power [164, 209]. Importantly, one element of governance and an expression of the exercise of power is how and who defines the knowledge necessary to assess a problem and its characteristics. However, little is known regarding what type of power actors have, how it was acquired and, and the knowledge that directs how/why power is exercised.

Governmentality is a key concept that connects governance, power, and knowledge, which refers to the mentalities through which subjects are governed. Governmentality was introduced by M. Foucault in his lectures on biopower [119, 120, 121], where he deconstructed how modern governments operate, develop technologies of control (e.g. violence, education, rewards, punishments), and create governmentalities to influence behaviors (e.g. steering, conducting, regulating). For Foucault, the power of modern governments lies on their capability of dominating the way we make sense to our lives and define what matters [7, 115, 158]. From this Foucaultian perspective, power is then understood as the knowledge, economy and politics used to create subjects or images of the world [115, 119, 121, 325, 332]. Overall, institutions and governments use power to reproduce governmentalities defining what it is (the subject) and how it is understood (knowledge), valuated (economy) and managed (politics). Therefore, collective actions (governance) are mediated by collections of specific knowledge institutionally constructed (governmentalities) by means of power.

Environmental sciences have been nurtured by discussions of biopower and governmentalities bringing up related concepts such as environmentality [1, 115, 274, 350]. Environmentality studies have addressed how power is used to create environmental subjects, addressing where the power lies and highlighting the role of NGOs, social organization and other institutions in favoring some forms of knowledge and content at expenses of other [1, 183]. Notably, these studies have been mostly restricted to studies framed from a political ecology perspective [274].

Considering that governance, power and governmentality are intimately tied concepts, in this dissertation I argue that understanding how natural resources are governed requires evaluating power/knowledge dynamics that enable governance regimes to implement a particular environmentality. In other words, it is necessary to understand how organizational and collective actions (governance) influence and are influenced by multiple knowledge corpora that might vary in terms of origin (i.e. knowledge producers), relevance, topical and disciplinary diversity, among other characteristics.

In summary, the analysis of governance of natural resources is inherently interdisciplinary and understanding socio-ecological dynamics involves more than social or ecological theories. Such socio-ecological approximation contributes to complex, holistic and systemic approaches. While there have been several advances towards characterizing the structure and functioning of socio-ecological systems, the interplay between knowledge and action (or the lack thereof) is still understudied. In this regard, this dissertation contributes to the understanding of the connections between sustainability knowledge and governance by providing novel characterizations of the structure and dynamics of knowledge production and consumption and their link with management and practice in two contrasting environmental problems, namely ‘illegal trade of wildlife’ and ‘management of national park systems’.

1.2 Environmental problems

In what follows I introduce each environmental problem and briefly motivate the research conducted for each. In addition, I point out some of the approaches used to analyze governance in these systems. Additionally, in each of the following six chapter I further detail some of the conceptual and theoretical approaches related to the specific research question evaluated in the chapters.

1.2.1 Environmental problem 1: Illegal wildlife trade

In wildlife markets species are either legal or illegally traded for many purposes such as bush meat, personal pets and collections, souvenirs, witchcraft, traditional medicine and many other products. **Illegal wildlife trade** involves at least the actors in the supply chain (i.e. poachers, middlemen, curriers, smugglers and, sellers), consumers and, agencies that regulate and curb the markets [256]. All these actors configure networks of different nature (e.g. commercial, surveillance) and with varying structures that enable markets to operate at local and global scales [12, 13, 244, 293]. Although wildlife trade has been practiced along most of the human history and represent valuable resources for rural livelihoods [333], the recognition of its current extent and impacts has committed governments to regulate and sometimes criminalize some forms of trade of vulnerable species. As such, illegal trade of wildlife could be considered mostly as a modern phenomenon.

Given the interdisciplinary nature of illegal wildlife trade, research regarding this phenomenon has included studies from the social and natural sciences, many of them framing illegal wildlife trade as a conservation concern. Overall, research is derived from three perspectives. First, a large body of literature have assessed the nature and extent of wildlife markets and supply networks [15, 51, 230, 285, 293] identifying the most-affected taxonomic groups and, the routes used by traders. Second, several works have evaluated the social and ecological implications of wildlife trade [226, 293, 308, 358]. Third, an increasing and recent research trend has explored the human dimension of wildlife trade showing how preferences, practices and livelihoods interplay in wildlife trade [2, 8, 17, 78, 102, 100, 131]. These latter studies also include deconstructions of discourses and criminality [101, 207, 357].

Recent studies seeking clarity on the question of how governance is produced around illegal wildlife trade, have started by evaluating how wildlife sovereignty shifts between global non-state actors and local communities [27, 65, 99, 322]. While this new direction is promising, governance of traded wildlife still requires a better understanding of how endogenous and exogenous factors influence the emergence of governance and power at several scales.

1.2.2 Environmental problem 2: Management of National Park systems

National parks are valuable treasures of cultural and historical heritage, with the potential for leveraging current global changes [113, 281]. In addition to being well-preserved ecosystems necessary for addressing challenges such as biodiversity loss and culture preservation, parks are valuable living laboratories supporting the broader scientific endeavor.

Research in parks is diverse and includes human and ecological aspects. As one could expect, ecological studies in parks are quite common, including analysis about wild species [132], floristic structure [280] and, the integrity of natural resources such as soil [257], water [216] and air [56]. Studies of climate change [279], fire [127] and pollution [177] provide valuable evidence regarding anthropogenic impacts in both within parks, and also relative to parks. Within the social domain, several studies have focused on managing human impacts [117], visitors [272] and other park's stakeholders [302], as well as human-wildlife conflicts [308], among other topics. Furthermore, an interesting focus has been placed around policy evaluation [281] and adaptive management [55, 213], as well as criticism of the model that some national park systems have followed [204, 299, 311].

Governance discussions around national parks have taken place on how they interact with other government agencies [75], local institutions [246] and the civil society [171]. These discussions have shown that national parks play an important role in articulating efforts through physical and institutional landscapes (e.g. connecting several agencies and institutions along the great Yellowstone ecosystem). However, little attention has been paid to the dynamics of governance within national parks. Some studies [144, 204, 299] have shown how the rationales used (governance regimes) to manage national parks have change over time as function of knowledge and politic disputes. For instance, some policies have been the result of academic inquiry and pressure, and a change in managerial advocacy based on visitors experience toward a one focused on ecosystem integrity [105, 299]. However, it is required to understand how current national parks stewardship paradigm have been produced as an interplay of power and knowledge.

1.3 Chapter overview

Overall, national parks management and wildlife trade are problems broadly discussed throughout multiple theoretical and empirical lenses. In both cases, the social and ecological dynamics of these systems as well as the dynamics at the socio-ecological intersection have been explored. In spite of the growing literature in these topics, governance analysis is still emerging and presently restricted to neo-institutional analysis that do not fully account for the complexity of socio-ecological systems.

Considering the relevance of knowledge about environmental systems to inform managers and decisionmakers, to guide multiple stakeholders towards pathways of action, and to integrate multiple perspectives and interest, in this dissertation I argue that characterizing the dynamics of sustainability knowledge is necessary to comprehend how our understanding of the phenomenon at hand (knowledge) guide collective actions or inactions creating regimes of management and policy (governance). Accordingly, this dissertation is based on the research question:

How is governance of natural resources influenced by the dynamics of knowledge and management?

From a theoretical standpoint, this dissertation contributes to the discussion of governance of natural resources by evaluating the dynamics of knowledge as a relevant element of management and practice. From an empirical perspective, this dissertation applies data-driven analysis to illustrate the interconnection between multiple stakeholders who simultaneously are producers and consumers of knowledge, and the knowledge that contributes to shaping and transforming governance regimes. To this end, this dissertation is comprised of two parts, each consisting of three chapters (Fig.1.1).

The first part addresses the knowledge production about illegal wildlife trade, considered at both local and global scales (Fig.1.1). To begin, Chapter 2 *"Multiplex Networks Reveal Geographic Constraints on Illegal Wildlife Trade"* addresses the characteristics of the knowledge and actions of traffickers and their implications to management. This chapter describes species-specific spatial patterns associated to traffickers' movements by using official government records of confiscations of wildlife illegally traded in Colombia. The superposition of routes used by traffickers describes the association between illegal wildlife trade and sociocultural and biophysical characteristics of the geography. Furthermore, such a superposition is also associated with the robustness of the wildlife trade phenomenon, which has several implications for tacking this practice. Importantly, results indicate that traffickers strategically leverage knowledge of the entire system. As such, the trafficking practice is a result of a collective knowledge that might affect the ability of authorities to control and combat illegal trade of wildlife.

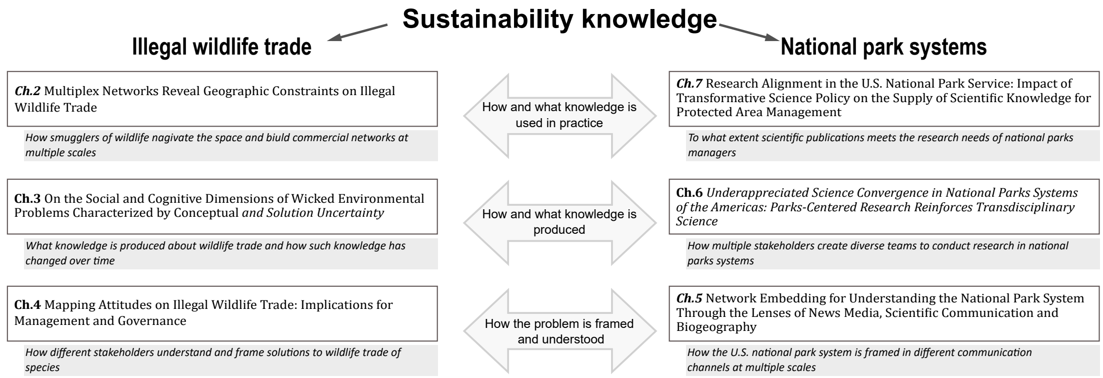

Figure 1.1: **Structure of the dissertation.** This dissertation is divided in two main parts, each one composed by three chapters. While each part addresses different cases, chapters are interconnected by guiding questions.

Chapter 3 *"On the Social and Cognitive Dimensions of Wicked Environmental Problems Characterized by Conceptual and Solution Uncertainty"* addresses what knowledge is produced by academia around different problems and how it is integrated. This chapter characterizes the structure and dynamics of scholarly knowledge related to three environmental problems, namely, wildlife trade, deforestation, and invasive species. I argue that environmental problems are wicked problems (i.e. ill-defined and lacking adequate solutions) by definition, which limit the ability of academics and other stakeholders to deal with task uncertainty and consolidate consensus around the problems. To address the dispersion in social and cognitive dimensions of the problems -a proxy of the wickedness of the problem- this chapter develops a quantitative framework that enable the evaluation of the evolution of knowledge in and around the problem. Results show that environmental problems suffer from ill-definition (low cognitive integration) and solution uncertainty (low social integration), which are accentuated in wildlife trade. These results are indicative of the multiplicity of lenses used to understand wildlife trade, that nevertheless lack cohesion and integration. As such, I argue that the academic community producing knowledge about wildlife trade has failed -comparatively speaking- to provide integrative knowledge, to reduce task uncertainty and therefore, to provide the necessary knowledge to design pathway solutions to manage the problem.

Chapter 4 *"Mapping Attitudes on Illegal Wildlife Trade: Implications for Management and Governance"* addresses how knowledge about the problem vary between and within stakeholders, and the implication of such a variation to management. This chapter uses mixed (qualitative and quantitative) methods to characterize the perceptions, believes, interests, and practices (i.e. attitudes) of different stakeholders regarding illegal trade of wildlife. Considering that the management of the problem, and ultimately the governance of wildlife, requires multiple actors – and at times, even opposing ones- to form consensus around fundamentals of the phenomenon, this chapter addresses how and to what extent the attitudes of stakeholders vary at geographical and organizational scales. Results suggest that the institutionalization of knowledge is lacking, as evidenced by the mismatching of attitudes between stakeholders from similar organizational and geographical scales. Such a mismatching could be explained by stakeholders' experiences and governance preferences. As such, the divergence in attitudes at multiple scales might affect the control of illegal wildlife trade inasmuch as there is a lack of consensus on what are, and how to combat the drivers of the problem.

The second part of this dissertation addresses elements of the production and consumption of knowledge about national park systems at national and supranational scales (Fig.1.1). Chapter 5 *"Network Embedding for Understanding the National Park System Through the Lenses of News Media, Scientific Communication and Biogeography"* addresses how different stakeholders -proxied by their corresponding communication channels- understand and represent the same system. This chapter evaluates the U.S. national park system through the lens of **emergent geographies**, which are defined as the interrelation between parks net of their geographic fixture. Emergent geographies in two complementary communication channels, news media and academic publications, are defined according to the co-occurrence of parks within individual articles. These emergent geographies are compared relative to the biophysical embedding which is used as a natural benchmark. The principal research question is whether different emergent geographies produce different forms of understanding the U.S. national park system and also whether correspondences between the geographies point to coordination between the forms of representing the system. Results indicate the the understanding of the elements of the system (park units) differs between communication channels -likely owing to the communicative interest of the producer-, whereas representations of the whole system are robust and consistent between communication channels and the biophysical embedding baseline. Because national parks are governed at multiple organizational and geographical scales, management should account for the varying objectives and constrains that dominate each scale.

Chapter 6 *"Underappreciated Science Convergence in National Park Systems of the Americas: Parks-Centered Research Reinforces Transdisciplinary Science"* addresses the integration of multiple stakeholders in the knowledge production and how teams diversity affects research consumption. This chapter evaluates the abundance of knowledge produced by diverse teams of stakeholders, as an advantageous and inclusive form of science. Considering that stakeholders are motivated by different interests, and they might have different perceptions regarding the same phenomenon, this chapter characterizes the dynamics of transdisciplinary teams (i.e. cross-stakeholder) producing knowledge in and about the national parks in eight countries in the Americas (i.e. Argentina, Chile, Colombia, Costa Rica, Ecuador, Mexico, Peru, and USA). Results indicate that for most of the countries, occurrence of cross-stakeholders teams is suboptimal as stakeholders of the same type tend to be work together more than what could be expected from a random associations, evidencing therefore preferences when forming teams. Importantly, research featuring national parks scientists as coauthors has greater research impact, and transdisciplinary teams are frequently more cited by other cross-stakeholder teams than mono-stakeholder publications. As such, this chapter illustrates that research at the science-policy interface is highly influential as it has high notoriety and bolsters downstream cross-stakeholder research. Nevertheless, such a process of transdisciplinary reinforcement is not evidenced in knowledge produced outside national parks.

Finally, chapter 7 *"Research Alignment in the U.S. National Park Service: Impact of Transformative Science Policy on the Supply of Scientific Knowledge for Protected Area Management"* addresses the relation between knowledge production and the demand for knowledge for managerial purposes. This chapter evaluates to what extent the scientific knowledge produced about the U.S. national parks have met the research needs of the parks (i.e. research alignment). Furthermore, this chapter assesses the effectiveness of an epochal policy shift occurring circa 2000 aimed at bridging science and management in the U.S. national parks by testing whether the policy shift have enhanced the research alignment. The analysis indicates a fair alignment in several topics at both system and park levels, where complex topics (e.g. Climate change) tend to be under-researched. Additionally, results show when policy enforces the research of some topics (e.g. air quality), those topics tend to be more aligned. Although results indicate that most of the research developed in parks meet the knowledge required for management, the policy shift has not affected what research is supported in parks.

At time of the time of publication of this document, Chapter 2 and Chapter 3 were published in the journals *Applied Network Science* [13] and *Advances on Complex Systems* [14], respectively. Chapter 4 and Chapter 5 were submitted in 2022 to the journals *Conservation & Society* and *Annals of the American Association of Geographers* respectively, and they are presently under review. Finally, Chapters 6 and Chapter 7 are in the final stages of being prepared for submission.

Chapter 2

Multiplex Networks Reveal Geographic Constraints on Illegal Wildlife Trade

Illicit wildlife trafficking poses a threat to the conservation of species and ecosystems, and represents a fundamental source of biodiversity loss, alongside climate change and large-scale land degradation. Despite the seriousness of this issue, little is known about various socio-cultural demand sources underlying trafficking networks, for example the forthright consumption of endangered species on different cultural contexts. Our study illustrates how wildlife trafficking represents a wicked problem at the intersection of criminal enforcement, cultural heritage and environmental systems management. As with similar network-based crimes, institutions are frequently ineffective at curbing wildlife trafficking, partly due to the lack of information detailing activities within illicit trading networks. To address this shortcoming, we leverage official government records documenting the illegal trade of reptiles in Colombia. As such, our study contributes to the understanding of how and why wildlife trafficking persists across robust trafficking networks, which are conduits for a broader range of black-market goods. Leveraging geo-spatial data, we construct a multiplex representation of wildlife trafficking networks, which facilitates identifying network properties that are signatures of strategic trafficker behavior. In particular, our results indicate that traffickers' actions are constrained by spatial and market customs, a result which is apparent only within an integrated multiplex representation. Characteristic levels of sub-network coupling further indicate that traffickers strategically leverage knowledge of the entire system. We argue that this multiplex representation is essential for prioritizing crime enforcement strategies aimed at disrupting robust trade networks, thereby enhancing the effectiveness and resources allocation of institutions charged with curbing illicit trafficking. We develop a generalizable model of multiplex criminal trade networks suitable for communicating with policy makers and practitioners, thereby facilitating rapid translation into public policy and environmental conservation efforts.

2.1 Introduction

2.1.1 Concerning dimensions of illegal wildlife trade

Wildlife trafficking is a wicked problem affecting thousands of wild species [277, 285] and communities [237, 357], and with the potential to expand toward new species and countries [293] as a multi-scalar phenomenon [12, 27, 51, 244]. The convergence of ecological and socio-cultural dimensions of wildlife trafficking give rise to a management paradox at the intersection of wildlife conservation and cultural sustainability.

On the conservation dimension, trafficked species are commonly overharvested in response to strong demand, resulting in higher extinction risk [16, 51, 230, 293]. Indeed, species overexploitation is one of the most common causes for recent and future species extinction, alongside climate change and human-driven land degradation [259, 258]. The spread of diseases [167, 308] and emergence of invasive species [67, 129] constitute additional threats for biodiversity, both related to wildlife trade. Negative effects of wildlife trafficking also pose concerns for other species, and ultimately entire ecosystems [1].

On the sociocultural dimension, human communities rely on biodiversity products for their livelihood and development[2], especially in poor and malnourished countries[3] [201]. However, where wildlife trafficking takes place communities are frequently exposed to violence, corruption, cooptation of institutions, and additional forms of criminality [17, 131, 285, 357]. Institutions at national and global scales committed to combating wildlife trade[4] are frequently weak and overflowed [363], and alternatives to tackle wildlife trafficking seem to be insufficient [51, 357]. Alternative approaches include market manipulation [98, 219], and community-base management of species [27, 277], however the problem at large scales is unfrequently addressed.

Actors involved in wildlife trafficking and their roles (e.g. poachers-harvesters, middlemen, smugglers, retailers, buyers) are poorly defined and might vary in time, and in contextual and physical landscape [102, 226, 256]. Moreover, actors are involved in social structures where wildlife trafficking and other crimes unfold [131]. These considerations manifest in our study in two particular aspects. First, information regarding criminal networks, in particular individual behavior and collective social structures, are difficult to gather, if not inaccessible [108, 290]. Second, wildlife traffickers are not necessarily members of the underlying criminal organization, and so an additional challenge is the limited knowledge of traffickers' activities and strategies [256, 293], which are not necessarily coinciding with the activities and strategies of the overarching criminal organization. Together, a lack of information on the individual and social factors contributes to a resilient persistence of wildlife trafficking. Furthermore, despite best intentions, ineffective on-the-ground policing of wildlife trade may further impair both species recovery as well as the ability of communities to conduct traditional practices.

To address these multiple elements simultaneously, here we show how relatively simple techniques of multiplex networks analysis can be used to unveil patterns of trafficker action and to identify data-driven strategies for dismantling wildlife trafficking networks. Due to the difficulty that comes with tracking criminal structures such as wildlife traffickers' organizations, we thereby propose to evaluate trafficker behavior using spatial proxies. In particular, we leverage official government data recording the confiscation of wildlife products to evaluate illegal reptile trade in Colombia. We use a multiplex framework in order to evaluate how criminal activities, aggregated across multiple species, are projected across geographical space – understanding this not only as a representation of physical space, but also as the social, ecologic and economic landscapes that coincide. As such, our study contributes to the understanding of how criminal activity persists across illicit trade networks, its internal co-dependence, and its robustness.

2.1.2 Multiplex features of wildlife trafficking

Wildlife trafficking networks are fundamentally social structures. As such, they can be understood as ensembles of family ties, communication channels, money flux, formal and informal organizational agreements, and species flux [230, 49]. In particular, ties in criminal structures, as well as in other social systems, involve material and symbolic contents [40, 188]. This multiplicity of content embedded in social ties has been called diffuseness [139]. Such intrinsically diffuse characteristics of criminal operations (e.g. secrecy, security handling, risk management, see [103, 231, 328, 363]) impede an in-depth analysis of social tie multiplicity. Fuzzy roles, diffuseness and otherwise hidden characteristics of criminal networks render information pertaining to the structure of the social organization incomplete [51, 103, 237]. However, alternative representations could inform how criminal structures operate and constitute criminal networks, and allow one to extract part of the content embedded in diffuse ties. For instance, spatial signatures of the operation (e.g. where crimes take place) may illuminate how criminal activities are developed, and across which physical and cultural structures they depend upon, among other characteristics [62, 137].

Another defining feature of wildlife trafficking networks we analyze is the multi-type links connecting different regions (nodes). We argue that it is essential to model these networks using a multiplex network representation, whereby multiple networks coexist, being interdependent yet synergistic [34]. In the present case, multiple relations (e.g. communication, business ties) that differ in structure and dynamics converge in such a way that facilitates illicit trade across species, geographic landscapes. As such, different regions can play different roles in the trafficking network of different species, giving rise to a fully connected system when viewed all together.

Of particular relevance to our study, recent work shows that multiplex networks are more tolerant to random failures than their monoplex counterparts [88, 215]. This insight highlights the importance of assessing the vulnerability (resistance to errors) and robustness (resistance to attacks) of networks in a multiplex perspective, especially in the context of multidimensional wicked problems that require broad approach across multiple facets. Recently, frameworks for evaluating multiplex and multilayered networks have been developed. For example, see [34] and related work for differences between multiplex, multilayered and interconnected networks, and conceptual foundations. Such frameworks have allowed for the description and improved understanding of processes embedded in layered systems. These approaches are quite relevant to multi-faceted problems deriving from criminal systems, such as wildlife trafficking.

Public and private interest in addressing wildlife trafficking has increased in recent years, as funder donors and researchers come together to develop strategies for policy enforcement and wildlife demand reduction [17, 27, 256, 357]. Yet, there is an incomplete picture about the structure of the crime as well as in which ways wildlife

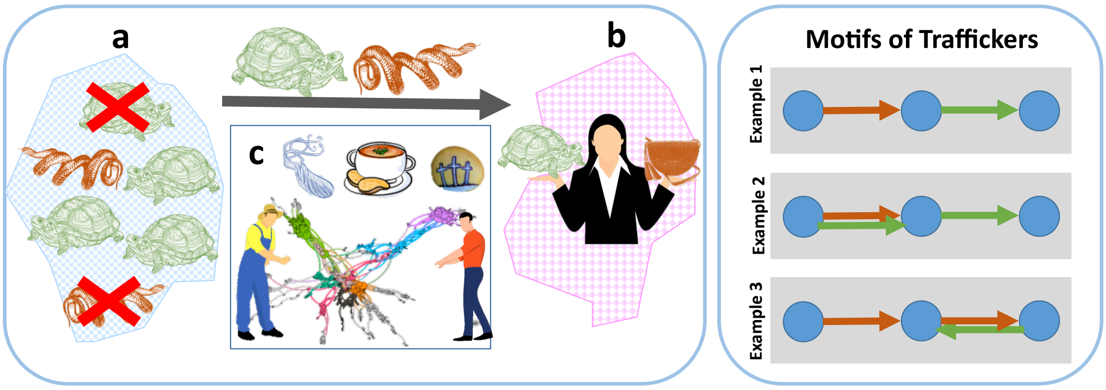

Figure 2.1: **Schematic model of wildlife trade of multiple species.** (Left panel) Species are harvested from place “a” and smuggled to place “b”. In the process, populations of species are depleted in “a” and individuals are consumed (e.g. pets or derived products) in place “b”. Typically, only the mobility of species is considered; however here we also account for material and symbolic fluxes, as indicated in subpanel c. Traditional and religious customs, as well as diseases, are examples of material and symbolic content. Furthermore, species flux also depends on various social networks that facilitate trafficking. (Right panel) Shown are three proposed motifs that represent how traffickers could move between places (blue circles) trading multiple species (species1 flux = orange, species2 flux = green) across a generic path. Example 1 illustrates a trafficker exchanging species. Example 2 illustrates a trafficker trading multiple species simultaneously. Example 3 illustrates a trafficker trading multiple species at different times by way of returning via the same path.

trafficking can be effectively disrupted. Although political and technical resources have been deployed for tackling trafficking, asymmetries in terms of capabilities, resources and information between traffickers and institutions have led to the persistence of black markets of wildlife. Because increasing institutional capabilities is costly and politically demanding, henceforth often perceived to be infeasible in the short term, then novel strategies for enhancing the effectiveness of organized crime are both timely and relevant [103].

The structure of our study is as follows. We first motivate the relevance of this case study, detail the data used, and define how we model this complex system using a multiplex representation based on spatial proxies. We then introduce the multiplex network framework and methods that are necessary for quantifying the structure and robustness of wildlife trafficking networks in Colombia. We then show empirical results compared with theoretical null models, which together facilitate identifying particular multiplex properties that give important insights into topological and structural properties related to the functioning of wildlife trafficking. Finally, we conclude with policy implications related to our findings. Overall, this work develops a technical strategy for improving the effectiveness of environmental institutions charged with controlling and disrupting wildlife trafficking, with the larger mission of social and environmental conservation.

2.2 Methods

The criminal nature of wildlife trafficking implies that social structures embedded in this kind of system can hardly ever be traced properly. Nevertheless, some operational traces of crime organizations can be identified, thereby facilitating the reconstruction of particular behavior and activity patterns. For example, how wildlife traffickers operate could be determined in part by characterizing those places where poaching and sales take place. In addition, relations between places emerge according to the routes that traffickers used when smuggling. Therefore, within our geographically embedded context, the trafficking network arises as a collection of spatial points (nodes) connected through movement of traffickers (links), as illustrated in Figs.2.1-2.2. Since traffickers navigate between these spatial nodes, there are physical, logistic, economic and social structures that support such activity. Thus, the connectivity of nodes configures a diffuse state in which several interactions are condensed (Fig.2.1.

One can reasonably assume that nodes differ in their capabilities to support the supply and demand of a variety of species. Indeed, species are not homogenously distributed through space, and the same goes for factors that usually have been described as drivers of wildlife trafficking, such as cultural customs, economic disparities, and weak governance [17, 27, 102, 48]. Accordingly, it could be expected that traffic routes differ between harvested species. Nevertheless, correlations in traffic routes across species can be expected due to variable specialization among traffickers, which could give rise to specific motifs of multispecies trafficking (see Fig.2.1). Importantly, traffickers are frequently characterized as opportunistic actors [237, 48, 309]. The trafficking of each species constitutes a network (plex), and several networks form a connected hyper-network (multiplex) due to the ability of traffickers to switch between species, and smuggle or sell multiple species simultaneously. Such simultaneous or exchange-based trade may arise from a lack of consumer preference reflecting a perceived substitutability between species [237, 293]. Therefore, the multiplex behavior of wildlife trafficking comes from shared identical nodes across plexes, and connectivity and interdependence between plexes.

2.2.1 Case study

Colombia is one of the most biodiverse countries in the world. Climatic, topographic and historical factors explain such diversity, and at the same time contribute to the uneven and patchy distribution of species [258]. This biodiversity is also expressed in the cultural gradient that persists across the country [9, 195]. Relatively high levels of wildlife diversity, spatial heterogeneity, human mobility, cultural diversity and economic disparity are factors contributing to the prevalence of wildlife trade [48, 309, 191]. Wildlife trafficking in Colombia is one of the most pressing conservation concerns for many groups of species, in particular for reptiles and birds [282]. In this study we focus our attention on reptiles, the most trafficked group and one of the most threatened ones in the country and worldwide [277]. Frequently, reptiles are traded in bulk quantities numbering in the thousands [277, 285, 282] as many reptiles play a central role in Colombian myths and beliefs, translating into gastronomic and economic demand [90, 112].

Regional environmental authorities and police corps, have been charged with developing control activities against wildlife trafficking throughout the country, resulting in confiscation of wildlife products, and administrative and punitive actions against traffickers. Yet information about environmental offenders is scattered and typically not accessible because of privacy and legal constraints within the punitive process. In contrast, records of confiscations are compiled by the Ministry of Environment and Development of Colombia (MEDC). These records include information about the source and destination of shipment seized, as well as the taxonomic identity of the species confiscated. Here we analyze available records spanning the 5-year period 2005-2009. While the MEDC is currently developing an information system for improved mapping and monitoring wildlife trafficking, such developments are resource intensive; as such, the data used here is the latest data released.

Based upon these confiscation records, we are able to construct a multiplex network of reptiles trafficking in Colombia. To be specific, nodes correspond to departments (equivalent to states or provinces), links correspond to source-destiny record of shipments, and each plex corresponds to the traffic of a taxonomic family of reptiles. We use taxonomic families (hereafter referred to as families) to reduce uncertainties associated with misidentification of specimens, while also considering that members of the same family typically share uses and cultural meaning. Families of reptiles analyzed here accounts for more than an 80% of all reptile trafficking in Colombia and include tortoises (5 families), iguanas (1 family), snakes and vipers (3 families), and Caymans (1 family). More information about the families is provided in Supplementary Note 1 (SN 1).

All together, this multiplex network is composed by 34 nodes and 10 plexes. Fig.2.2 illustrates an aggregated representation of this multiplex. Trafficking statistics and network measures by department of the aggregated representation can be found in Supplementary Table 1. The climate zones shown in Fig. 2.2b represent 5 larger biogeographical regions, each with characteristic cultural, ethnic, social, economic and climatic similarities within. Overall, species are mostly trafficked from lowlands (e.g. Caribbean and Amazon regions) to the Andean region, where population, wealth and infrastructure are more concentrated, and where abundance of reptiles is low. The number of families trafficked by department is weakly correlated with the network's properties (R^2 <0.32) or the number of confiscations (R^2 <0.13) (see SN 2), which indicates that the data is appropriately capturing trafficking dynamics, and at most only weakly biased by department-specific policing and reporting factors.

2.2.2 Network framework and metrics

Different multiplex frameworks have been developed to address different assumptions and contexts. The relevant framework implemented here is based upon the adiabatic projection, introduced by Cardillo et al. [64]. This framework consists of evaluating changes within the structure of aggregated (projected) networks constructed from different permutations of plexes. In our case, reptile trafficking is composed by $N = 34$ nodes and $M = 10$ plexes, where m_i is a projected network defined as $g^{m_1}(N, L^{m_i})$, being g^{m_i} a graph with N nodes and L^{m_i} directed links between nodes. Plexes are aggregated across m levels, each one containing $\binom{m}{M}$ m_i projections obtained by merging m plexes. In each level of combination, several network metrics are calculated over all possible combinations. Further details on adiabatic projection of multiplex networks can be found in Cardillo et al. [64] and Lotero et al. [196].

Recent advances in the analysis of multiplex networks have incorporated tensorial representations of the multiplex [34, 88, 89]. This improvement facilitates considering the role of inter-plex connectivity, thereby preserving the relative independence and iden-

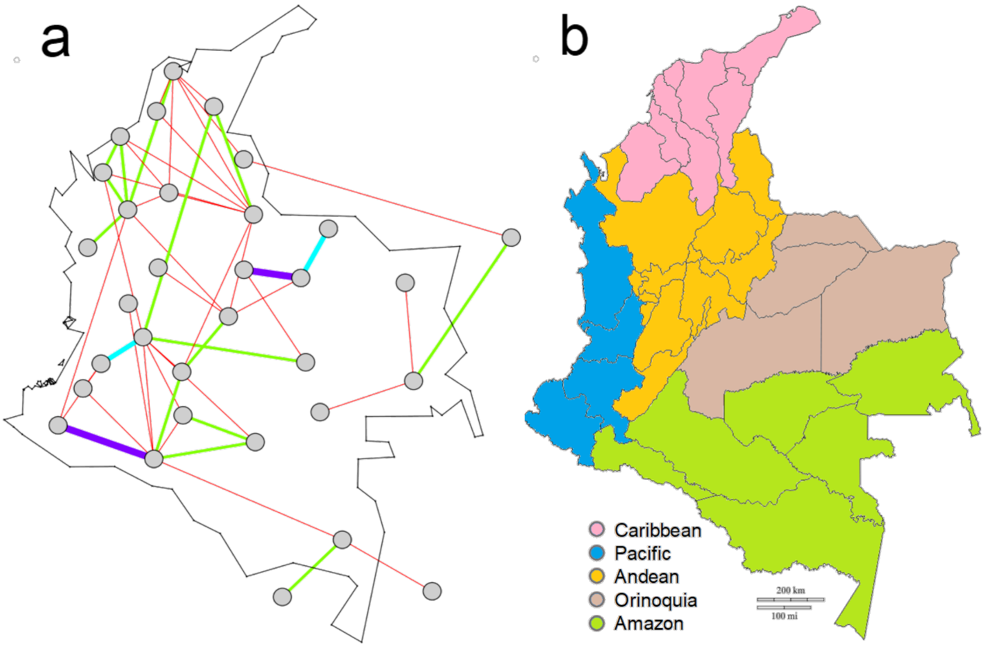

Figure 2.2: **Network representation of reptile trafficking in Colombia.** (a) Nodes correspond to departments (national geopolitical subdivisions) and links indicate the number of reptilian families traded across each border, as indicated by the color scale. Nodes outside of the map border represent neighboring countries. (b) Administrative division of Colombia into departments. Colors indicate the dominant climate zone in each department. Social, economic and biotic similarities between departments is higher within than between regions.

tity of each plex. These advances have promoted new ways of undertaking the centrality of nodes (see nodes versatility in De Domenico et al.[89]) and emerging dynamics such as synchronization or multiplex diffusion [34, 134]. Despite the valuable contribution of this novel tensorial representation, we followed Cardillo et al. [64] approach for two main reasons. First, the adiabatic projection framework allows us to easily characterize the effect of increasing the set of species analyzed. Typically, anti-trafficking policies are based upon single or aggregates of small groups of charismatic species [244]. We argue that such species do not necessarily have an umbrella effect over other relevant and largely traded species, and so it is crucial to consider all species simultaneously. Second, technical and conceptual simplicity of adiabatic projections is more accessible for a broader set of stakeholders, such as environmental policy makers, wildlife trafficking police, and other potential audiences. Nevertheless, we include some tensorial metrics into our analysis in order to compare the effect of incorporating more complex measures as strategies for attacking networks, as we describe below.

For all m_i projected network we calculate a set of metrics that account for structural and topological properties of the graph. Although significant advances in defining measures of weighted networks have been made, we consider the projected networks as unweighted graphs so as to simplify the interpretation of the analysis. Metrics included in the analysis are: Density (D), Clustering coefficient (C), Average path length (l), Diameter (d), Size of giant component (S), maximum Degree centrality (k_{Max}) (differentiating between in-degree and out-degree), Degree centralization (C_k), Betweenness centralization (C_b), Link overlapping (O) and reciprocity (R). Descriptions and mathematical formulations of network metrics used are provided in SN 3.

In addition, we compare the result of empirical projections with three null models. These null models consist of random networks that conserve some properties of the empirical ones. Model 1: is constituted by simulations of M Erdos-Renyi random networks [109] of size N, each one preserving the same amount of edges than the empirical networks. The M random networks were projected without additional randomization. This model evaluates whether our empirical networks and the projections lack topological structure, and whether our results are spurious manifestations related to graph density. Model 2: projects random networks equivalent to the empirical one in terms of their degree sequence (in/out). This second model assesses the effect of degree distribution on the overall structure across all projections. Model 3: is produced by random networks in which the origin of trade flux is conserved, and the links are traced to a neighboring department according to the physical adjacency of departments. This model represents a limited ability of traffickers to reach long distances and a prevalence of trading in the vicinity. We produce 2500 simulations for each model and report every realization across all synthetic configurations.

In addition to the null models we compare the inter-annual aggregated behavior of the multiplex with the multi-annual aggregates so as to identify temporal consistency of our results. As such, we project the networks using the cumulative sequence of years in which we aim to detect how the trafficker's behavior is related to pre-existing routes and structures.

We further evaluate the robustness of the multiplex network by producing sequential attacks or node removals on the projected networks. We use different strategies of disruption based on nodal centrality, including degree, betweenness, closeness, eigenvector and Pagerank centralities. In spite of many strategies having been proposed for dismantling networks [347, 271] we limit our exploration to the most common strategies. Furthermore, these strategies constitute feasible cases for implementing real-world scenarios, which are thus largely valuable to public policy. In addition, a random removal strategy was implemented.

Sequential attacks consist of removing the node with the largest centrality in the projected network and after each attack the centrality is recalculated, then the process is repeated until all nodes become disconnected. In each step we calculated the fraction of nodes intentionally removed and the fraction of nodes disconnected. Previous works that have assessed the robustness of networks only consider the fraction of nodes connected to the largest component instead to any connected component [347]. We consider that small connected components representing local or regional markets still might foster overharvesting of reptiles and promote diffusion of information and goods [103]. In our case we define robustness as the area under the curve produced by the fraction of nodes removed and the fraction of disconnected nodes. This approach enables us to reduce the effect of attacking diads and triads.

Finally, in order to compare the effectiveness of strategies commonly used in monoplex networks (centrality metrics) and strategies based on the multiplex connectivity of nodes (versatility), we combine adiabatic projections and tensorial representation of multiplex networks. In this regard, at each level of combination $m \geq 2$, the networks were not aggregated but represented as a tensor instead. Following the previous rationale, node versatility (using Eigen Tensor and Multiplex PageRank forms, see De Domenico et al.[89]) is calculated, and the most versatile node is removed across all the plexes. This is repeated up to the point that all nodes become disconnected within all plexes. For each metric we run 2500 simulations. All the methods described were conducted in R [324] using the packages "igraph" [85] and "muxVizR"[89].

2.3 Results and Discussion

2.3.1 Underlying wildlife trafficking mechanisms - Multiplex insights

In what follows, we identify and discuss relevant characteristics of the empirical multiplex wildlife trafficking network that are not reproduced by the null models considered here. While some metrics are largely explained by our null models, such as density (Fig. 2.3a) and the size of the largest component (Fig. 2.3b), which increase systematically[5], we do identify informative properties belonging principally to the empirical multiplex. Such distinguishing characteristics offer valuable insights into the role of geographic constraints and the strategic behavior of traffickers, together pointing to feasible mitigation strategies.

We start with network metrics such as average path length (Fig.2.3d), degree centralization (Fig.2.3e) and maximum degree (Fig.2.3g-i), which are well explained only by null Model 2, indicating that part of the behavior of the system is the result of idiosyncratic features of departments (i.e. nodal connectivity). In contrast, clustering coefficient (Fig.2.3c), diameter (Fig.2.3j) and betweenness centralization (Fig.2.3f) metrics show that at a low levels of plex combination (m) the empirical multiplex structure can be fully explained by the null models; nonetheless, for large m there are notable differences. In particular, the empirical multiplex exhibits more triangles (except for comparisons with model 3), larger paths between the most distant nodes in the multiplex structure, and the importance of high throughput nodes (or "bridges") are more evenly distributed. Since such characteristics become evident only when multiple families are considered into the analysis, our results highlight the importance of integrating all available trafficking data for all species in the analysis of wildlife trafficking.

Interestingly, metrics such as link overlapping (Fig.2.3k) and reciprocity (Fig.2.3l) exhibit large deviations from most null model predictions, even for small m. This result suggests that traffickers use common routes for smuggling reptiles as well as back and forth trading.

We find that null models 2 and 3 are able to reproduce great part of overlapping links but not all of them, suggesting that the use of common routes for trafficking species may largely be captured by the empirical vicinity structure of departments and the amount of connections that they have. Although model 3 is able to explain part of the link overlapping, it largely fails to reproduce link reciprocity, instead overestimating this metric. Similar patterns are observed for other metrics. Model 3 suggests that the spatial organization of departments is relevant for the navigability of traffickers; yet, we observe strong directionality toward high demand departments, mostly located in the Andean region. Consequently, we argue that back-and-forth trading and alternative routes are less prevalent than what is expected in a predominantly regional market.

Despite a relatively high clustering of reptile trade (with respect to models 1

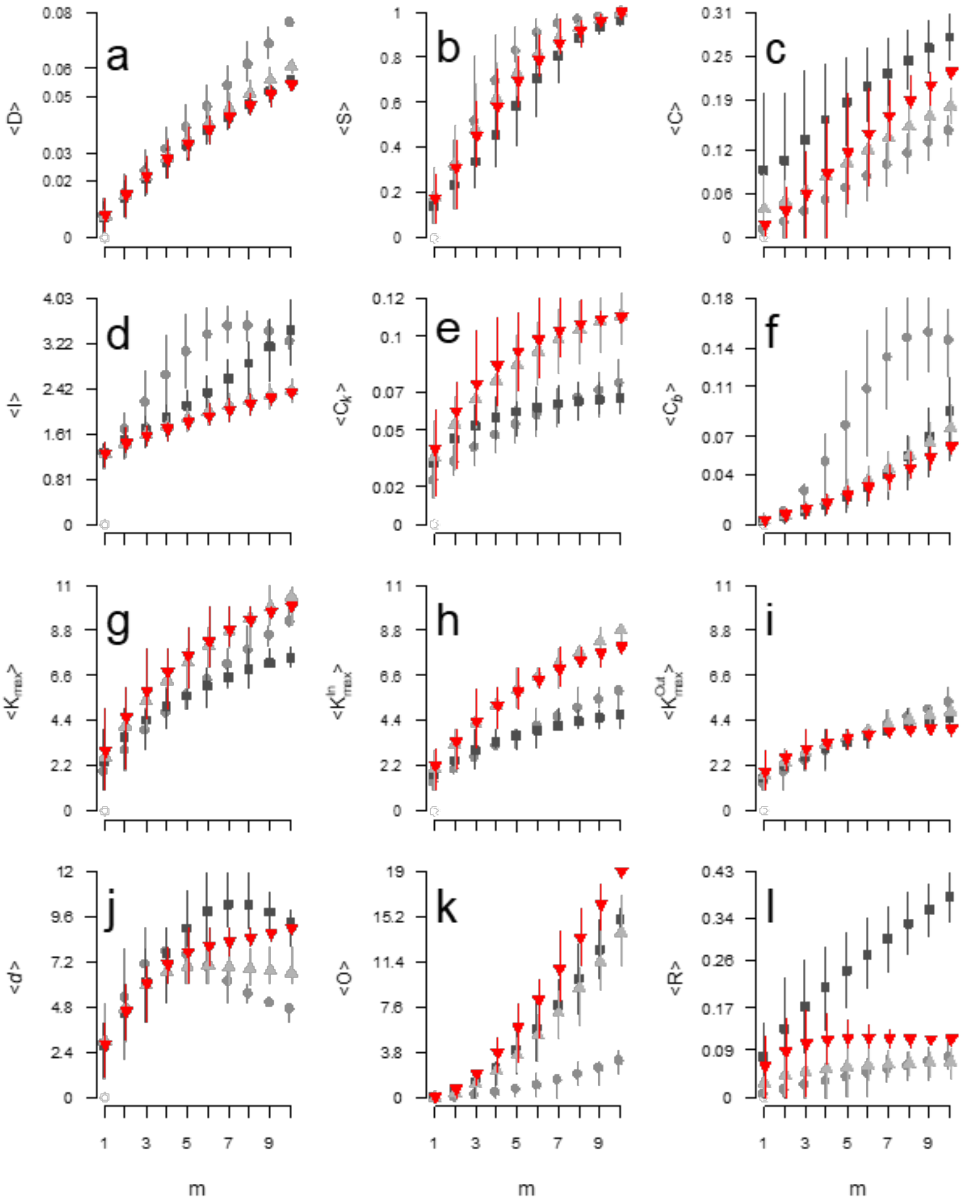

Figure 2.3: **Comparison between metrics of the multiplex reptile trafficking in Colombia and null models** across different levels of plex combination (m); each plex represents a different reptile family. Shown are empirical data (red triangle down) along with predictions of models 1 (diamonds), 2 (triangles up), and 3 (boxes). Metrics shown in each panel are: density (a), clustering coefficient (b), size of the largest component (c), average path length (d), centralizations by degree and betweenness (e, f), maximum degrees (g-i), network diameter (d), link overlapping (e), and reciprocity (f). Data points are slightly displaced in the x axis to improve visual clarity.

and 2), which suggests the use of alternative routes for trafficking reptiles, comparisons based on link overlapping and reciprocity metrics indicate that there are some routes extensively used in this regard. Similarly, the difference in clustering between the empirical data and model 3 suggest that some routes are avoided by traffickers. The clustering could be also explained by commercial circuits formed by the trade of multiple species, in particular in the northern region (Fig.2.2).

In general, we show that the three archetypical motifs of multi-species trafficking introduced in Fig.3.1 can be identified in our case study and play an important role in defining the multiplex structure. Indeed, these three motifs are supported by the most meaningful metrics assessed. To be specific, the enlargement of network diameter supports the idea of sequential trading (Example 1), while the trafficking of multiple species simultaneously (Example 2), and the back and forth trading (Example 3) are well supported by link overlapping and reciprocity, respectively.

Considering that wildlife trafficking networks could be dynamic and adaptive, as other criminal organization, we performed a temporal analysis of the empirical multiplex (Fig.2.4). For most of the cases, all the cumulative time windows follow a similar growing behavior and the differences between windows correspond to discrepancies in magnitude, indicating that there are not dramatic changes in the system over time that deform the aggregate behavior. However, noticeable discrepancies between windows are shown in the lasts ones, as such the system become more connected and clustered. Such difference can be attributed to imbalances in the amount of records and families traded in each year (see ST 2). The temporal structure of density (Fig.2.4a), betweenness centralization (Fig.2.4f), link overlapping (Fig.2.4k) and reciprocity (Fig.2.4l) are particularly interesting, while other metrics do not show large differences between the windows 2005-2008 and 2005-2009, these metrics indicate noticeable changes in the traffickers behavior in 2009 that consist on the more extensive use of pre-existing routes and an increase in the back-and-forth trading. As such, bridges, common paths and reciprocal links emerge through the inter-annual relation of the multiplex. This result suggests some ability of traffickers to identify accessible routes and make decisions accordingly.

We argue that the quantity of information when disaggregated by years may influence some of the results, especially in the period 2005-2006 when the information is less abundant. As such, temporal dynamics of trafficking require further investigation, in particular with regard to the reinforcement and generation of routes. In addition, we

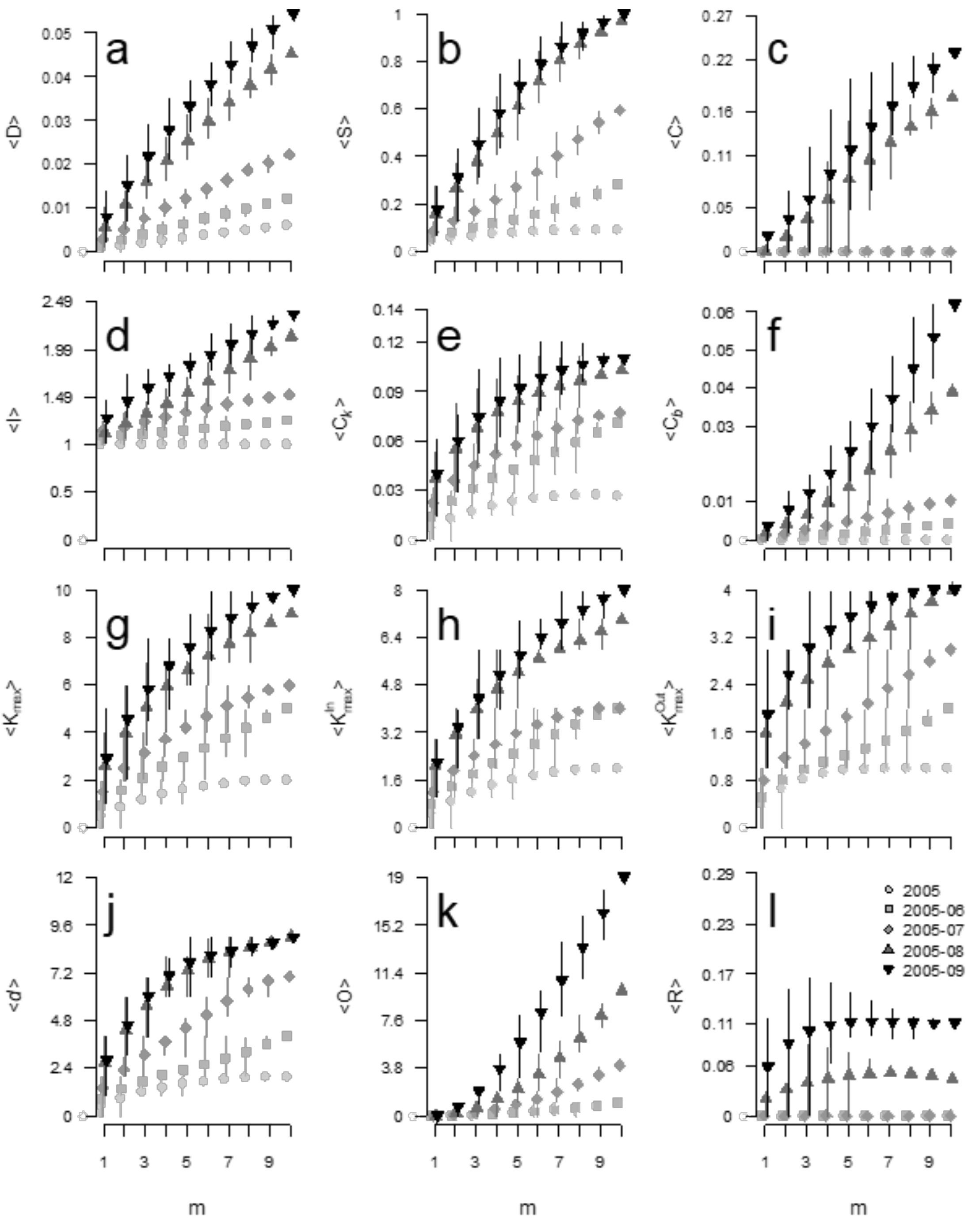

Figure 2.4: **Metrics calculated for the empirical multiplex using wildlife trafficking data for cumulative sequence of years.** Metrics shown in each panel are: density (a), clustering coefficient (b), size of the largest component (c), average path length (d), centralizations by degree and betweenness (e, f), maximum degrees (g-i), network diameter (d), link overlapping (e), and reciprocity (f). Elements are slightly displaced in the x axis.

run the null models for the time window 2005-2008 (SF. 1) and our result are consistent with the 2005-2009 aggregate, tough differences between the empirical multiplex and the predictions of the null models are smaller than the observed in the 2005-2009 window. This suggests that patterns shown are descriptive of the system, and significant part of the system's structure is observed in the largest part of the dataset.

In summary, differences between empirical data and null models, along with the temporal variation in multiplex characteristics indicate: (1) traffickers may know and prefer some routes, upon which smuggling species could be expedited, and there is some collective memory that enables participants to traffic more species along such routes. This idea is supported by the large link overlapping and the inter-annual composition. (2) Reciprocal trading involving multiple species indicates some degree of substitutability-complementarity[6] between species, especially in sub-regional markets. However, small marginal differences in reciprocity when more and more species are considered suggests an incomplete substitutability between species; this may be related with either the differences in their uses or their disjoint distribution. (3) Idiosyncratic connectivity might be caused by geographical features (e.g. neighborhood structure, infrastructure available, species distribution, "barriers" imposed by strong institutions, social landscape) that restrict traffickers' operation. Indeed, vicinity structure notably influences some dynamics of trafficking between neighboring departments, probably conducted by terrestrial and fluvial means, reinforcing regional markets that ultimately expand to adjacent regions. (5) Considering the trafficking of each reptile family in isolation can yield misleading results, since for many metrics null models are able to explain quite well the empirical data for small m; thus, a multiplex approach is required for revealing meaningful patterns. In addition, adequate temporal frames and longitudinal analysis are needed to capture relevant dynamics as repeated (overlapping) and back-and-forth (reciprocity) trading, that otherwise could be highly underestimated.

Additional characteristics of the system could serve as explanatory factors of the dynamics of trafficking. For instance, it has been reported in analysis based on single-species trafficking that market structure is associated with geographic distribution of species, regional cultural heritage, and economic disparities between supply and demand places [48, 309, 12, 38]. Increasing the number of families (plexes) considered within our analysis contributes to the understanding of a larger picture of wildlife trafficking in the country. Although analysis developed independently for each family could reveal some nuances of species uses and trafficking dynamics, such approaches do not capture the breadth of variation, which may result in an incomplete representation.

2.3.2 Multiplex robustness and strategic policing for optimal trade disruption

We implemented various network attack strategies motivated by different rationalities for disrupting criminal structures. Strategies based upon prominence of nodes (Eigenvector centrality, EigenTensor versatility) address places closely connected to strategically connected markets. Attacks based on the nodal prominence and the directionality of fluxes (PageRank centrality and Multi-PageRank versatility) focus on those places that receive illegal trade from strategic markets. Other strategies rely on attacking places with high ability to connect distant places (betweenness and closeness centralities) or that act as bridges or gateways. Finally, one strategy focuses on highly connected nodes (degree centrality) independent of the network's neighborhood structure.

Consistent with expectations, we find that plex aggregation (corresponding to increasing m) increases the multiplex robustness (Fig.2.5), mainly due to increasing link density [215, 103, 60, 87]. In all cases, strategies performed better than random strategies and the surplus gained by strategies increases with m (Fig.2.5). For most of the cases, centrality measures such as Degree or PageRank have the best performance, even though there are not noticeable differences between strategies. In general, strategies based on node versatilities did not outperform strategies based on centralities, as expected. Closed walks or trapping nodes could contribute in explaining this behavior. We notice also that there is not a strong correlation between Multi-PageRank versatility and degree centrality in projected networks (see SF. 2) which implies that removing largely versatile nodes is not necessarily conducive to disconnecting a great fraction of nodes, but it might contribute to fragmenting the network (i.e. produce a larger number of small connected components frequently under-considered in analysis of robustness).

Our findings suggest that all strategies evaluated for disrupting illegal trade of reptiles in Colombia are almost equally useful in that regard. Despite that the simplest strategy based on the total degree of nodes do not show the largest performance, it produces similar outcomes when compared with more sophisticated strategies, specifically Pagerank centrality. Similar to Wandelt [347], strategies based on degree sequences are

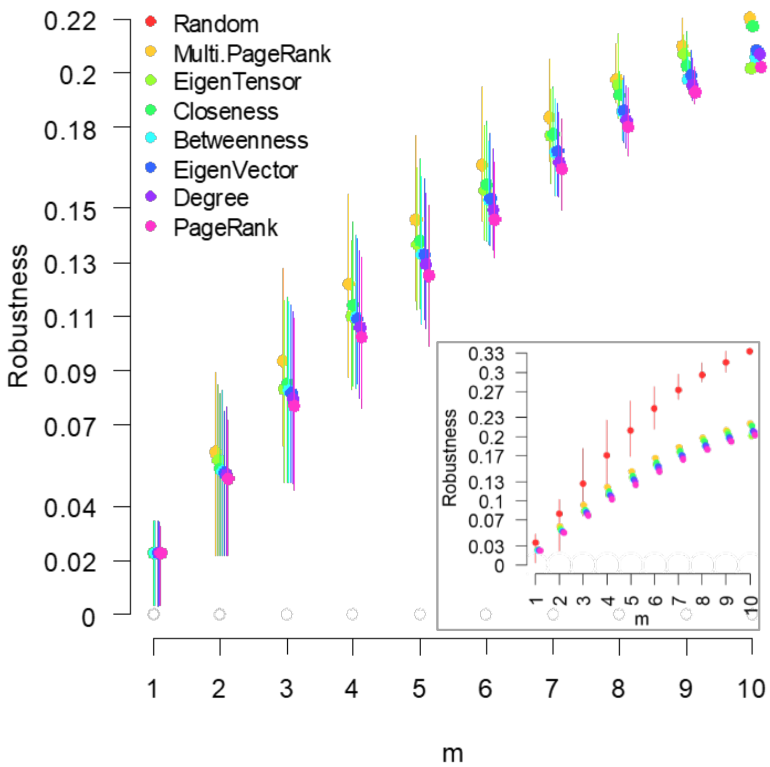

Figure 2.5: **Robustness of multiplex networks of reptile trafficking in Colombia.** The resistance to targeted network attack is shown across all levels of plex combination (m) for different disruption strategies based on node centralities and versatilities. Elements are slightly displaced in the x axis. Subpanel shows the average result of the strategies in comparison to random node-deletion interventions (i.e. attacks).

not necessary optimal solutions, but they are quite efficient. Highly connected nodes correspond to places with both incoming and outgoing trade flux, but with predominance of large in-degree; thus, these nodes correspond to departments where species are consumed. Most of these departments are located in the Andean region or its interface with other regions. Although those regions may function as both suppliers and consumers of reptiles, it is more likely that they correspond to places devoted to consumption of species due to the fact that incoming links tend to contribute the most in the total degree (see Fig.2.3g-i). As such, departments in the border of the Andean region result in good candidates for intervention due to the fact that they contribute largely to the vulnerability of the multiplex.

Our analysis also points to the value of strategies based on simple metrics, such as degree centrality, as the information required to identify highly connected nodes is easily accessible by either using data derived from policing activities and reports, as implemented here, or by gathering experiences and knowledge from institutions and their staff, who are involved daily in monitoring and controlling wildlife trafficking. As such, regional policing activity aimed at disrupting traffickers by way of simple metrics should be prioritized, as it does not require large investments in training skilled staff, and could produce similar outcomes to more demanding strategies. In contrast, lack of knowledge related to the structure of the network could lead to ineffective interventions (closely aligned to random interventions). However, we recognize that the cost of intervention in nodes is not homogeneous and that could affect the implementation of dismantling strategies. Solutions such as those proposed by [271] need to be assessed in the future.

Targeted intervention (policing) of nodes where demand for reptiles is concentrated, in particular those in the border of the Andean region, seems to be effective for disrupting trafficking networks at the departmental scale in Colombia, though concrete actions are necessary to achieve such a goal. Literature in criminology and networks disruption has conceptualized elements for dismantling illegal structures [87, 103, 363, 108, 357, 276, 290]. In particular, Roberts and Everton [276] show that multiple actions are needed for imposing long-lasting effects on criminal networks, including kinetic (e.g. identifying and processing heads of organizations, disrupting channels of communication by capturing supporters) and non-kinetic approaches (e.g. rehabilitation of members like providing economic alternatives can disengage participation; discouraging the consumption of wildlife). In the present case, this represents prosecution of traffickers and vendors, identify stocking places and discouraging species consumption and even harboring. In other words, policies and interventions that leverage the diffuseness of trafficking networks to significantly perturb the embedded social and human capital are needed [103]. To this end, identifying valuable targets and their supporting structures (e.g. infrastructure, communication, social ties) can be developed if concerted efforts are prioritized toward those places where the system is most susceptible.

In order to curb wildlife trafficking, there is increasing need for improved cooperation between environmental authorities, criminal investigators and law enforcement, combined with extensive consumer-side education, which has been implemented with demonstrated success [98, 219]. Although these actions are demanding and hard to address at large scales, our findings provide a framework for defining priority sites for initial actions. In addition, we recommend that local supply-side interventions should be implemented in sync with demand-side education programs in order to disrupt the entire supply chain. Some of these initiatives (e.g. [27, 78]) could contribute to reducing the market for wildlife products and at the same time reinforce and recognize cultural values, promote sustainable uses of wild species and strengthen different forms of governance, in particular those community oriented [52].

In summary, we identify several relevant elements of wildlife trafficking that may contribute to the understanding of network-based green crimes, and criminal activity in general. First, reptile trafficking in Colombia is constrained by physical, social and market elements that provide structure. These geographic constrains are similar to what has been reported for cocaine smuggling in Central America [199], showing some similarities across crimes. As such, demand-supply interactions draw the routes that traffickers use and enable an up-scaling of their activities from regional to national levels. This is supported to a great extent by considering the simultaneous trade of multiple species, which is driven in part by the vicinity structure of departments and their idiosyncratic connectivity, and the knowledge that traffickers apparently have about market structure and routes for smuggling, that are used across species and time. The superposition of routes not only indicates an associated knowledge or preference, but also geographical elements (e.g. weak institutions, infrastructure that lacks official control labor, particular ecosystems with abundant species) that could enable/constrain the action of traffickers. The market's demand side contributes to this superposition mainly because trafficking routes converge where consumption of wildlife products is focused. This indicates the presence of an oligopolistic organization, as Harvey et al. [146] previously suggested for the case of ivory trade in China. Market constraints can be attributed to the uneven distribution of species at the country scale, which causes the system to be poorly connected, giving rise to long path lengths. Regional affinities in biotic and cultural heritage terms, as well as the physical connectivity, support small scale clusters of trafficking for many species showing that drivers of wildlife use and trade are relevant elements for traffickers' operations. Indeed, economic asymmetries between source/destination places leverage the trafficking at national scale.

Second, similar conditions contribute to the robustness of the system, which increases when more species are considered (i.e. increasing m). Multiple strategies are useful for attacking the underlying social structure of traffickers, even though simple strategies based on the number of market partners are as effective as more sophisticated ones. This is important because these findings could be easily translated into public policy. However, the inter-annual variation on reptile trafficking indicates that strategies should be permanent and target many species.

By way of example, simple information about trafficking dynamics gathered through official records or to some extent by compiling experiences of practitioner could have a significant impact on the ability of institutions to define places of interest and to henceforth disrupt illicit trafficking. Our analysis allows institutions to focus efforts like law enforcement and education on the demand side where the system as a whole is most susceptible, whereas community-based strategies could be implemented as alternatives for local development, engagement and cultural heritage conservation. As Duijn et al. [103] and Roberts and Everton [276] suggest, multiple actions of diverse nature must be taken repeatedly in order to achieve long-lasting disruptions. Reducing wildlife trafficking represents a significant advance in human and animal well-being, nonetheless it requires planned actions.

Here we show why it is necessary to include many species into the analysis and abandon the idea of umbrella species as a key element for understanding inner structures of wildlife trafficking networks. Similarly to Scheffers et al. [293], we show that species-based policies could result in a large set of unattended issues due to oversimplification and unconsidered interactions between trafficking groups and species substitutability. As a result, we highlight the importance of systematically analyzing multiple species simultaneously – including non-charismatic – in order to fully appreciate the multiplex structure of the entire system.

2.4 Conclusions

One of the major hindrances to analyzing and curbing criminal activity is limited access to information concerning the crime itself. Here we show that spatial proxies are relevant for undertaking structural elements of crimes that account for general patterns of action of criminals as well as physical, biological, social, cultural and economic constraints. The multiplex methods utilized in this work facilitate identifying characteristics of the criminal operation that could be either inaccessible due to limited data availability or otherwise indistinguishable from randomly generated information.

Moreover, this work highlights the importance of including multiple facets of the criminal practice and its real-world implications – in both society and nature. Even the use of simple techniques for the analysis of multiplex networks such as adiabatic projections in addition to null models prove relevant for understanding the emergence of structural and dynamic characteristics of illegal systems such as wildlife trafficking. Actually, the simplicity of the method applied here may contribute to assessing the weaknesses of the criminal structure and therefore provides a useful and straightforward framework for designing interventions to disrupt organized crime networks. This is not only advantageous for translating science into societal outcomes, but also for improving our capabilities to understand other crimes, including green crimes like illicit logging or dumping, among others.

Increased efforts and methods to curb wildlife trafficking are needed, in particular to address idiosyncratic country- and species-specific factors that may limit the generalizability of certain approaches. Here we contribute to these efforts by applying methods of network science to a large temporal dataset capturing a real-world 'wicked' problem existing at the nexus of organized crime, cultural preservation and wildlife/environmental conservation. The results of our analysis provide support for basic network-based strategic interventions that prioritize the finite resources present in many regions of the world facing illicit black-market trafficking.

Supplementary Material

Supplementary materials are available at this link and include: **Supplementary Note 1**. Socio-ecological description of taxonomic families of reptiles included in the analysis. **Supplementary Note 2**. Correlations between confiscation records, diversity trafficked and network properties. **Supplementary Note 3**. Networks metrics implemented in the analysis. **Supplementary Figure 1**. Comparison between metrics of the multiplex reptile trafficking in Colombia (2005-2008) and null models across different levels of plex combination (m). **Supplementary Figure 2**. Correlation between degree centrality and PageRank versatility.

Notes

[1]Many diseases such as the Chytrid fungus are spread globally due to wildlife trade [174]. This disease have been reported as one of the major causes of decline in natural populations of amphibians globally [193]. Similarly, species such the lionfish have been introduced in ecosystems causing considerable reduction of native species [224]. Both examples illustrate derived effects of wildlife trafficking that affect

other species beyond those actually traded. Due to the inter-dependency of ecosystems, it is expected that species and diseases introduced might cause impacts in the ecosystems as a whole.

[2]Species play a major role in local economies, rural gastronomy, and for cultural practices and beliefs [269]. Although demand for species is usually associated to traditional medicines and bush meat, there are also large markets for trophies, pets, and other sumptuary uses [12, 244]. There is not a consensus regarding the value of these markets, estimations vary from some tens to hundreds of billions, annually [73, 285].

[3]Biodiversity is not homogeneously distributed around the globe. There is a strong correlation between biodiversity and poverty [201]. Typically, diversity constitutes a temporary or permanent income for rural communities that commonly get trapped in the "tragedy of commons" [80]. In those cases, species tend be harvested up to exhaustion.

[4]International Agreements such the Convention on International Trade in Endangered Species of fauna and flora (CITES) were developed to control species trade and prevent overexploitation, however black markets and species laundering still threaten species [244, 285]. Similar initiatives can be found in a country-base, even though they have not succeeded in tackling wildlife trade. Two factor that could explain this are the ratio traffickers/institutions officers, and the fact that wildlife trade is wrongly considered as a minor issue in many countries [357].

[5]Aggregation enlarges network metrics such as density (Fig.2.3a), the size of the largest component (Fig.2.3b), clustering coefficients (Fig.2.3c), and maximum degrees (Fig.2.3g-i) due to inherent increases in the number of edges in projected networks, indicating differences between the trafficking of each family (i.e., individual plexes). This systematic result of aggregation has been previously reported in analyses on other systems [64, 196].

[6]For instance, species as "hicotea" or "Colombian-slider" tortoise and iguana are used as dishes during the Easter celebration in northern regions of Colombia. Despite that they share geographical distribution and given meanings, trafficking networks at the regional scale are developed to supply the demand of urban areas from neighboring places. In this case, species show complementary uses.

Chapter 3

On the Social and Cognitive Dimensions of Wicked Environmental Problems Characterized by Conceptual and Solution Uncertainty

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 systemic risk they pose; such problems escape solutions because they are often ill-defined, and thus mis-identified and under-appreciated by communities of problem-solvers. While there are well-documented benefits to tackling boundary-crossing problems from various viewpoints, the integration of diverse approaches can nevertheless contribute confusion around the collective understanding of the core concepts and feasible solutions. We explore this paradox by analyzing the development of both scholarly (social) and topical (cognitive) communities – two facets of knowledge production studies here that contribute towards the evolution of knowledge in and around a problem, termed a knowledge trajectory – associated with three wicked problems: deforestation, invasive species, and wildlife trade. We posit that saturation in the dynamics of social and cognitive diversity growth is an indicator of reduced uncertainty in the evolution of the comprehensive knowledge trajectory emerging around each wicked problem. Informed by comprehensive bibliometric data capturing both social and cognitive dimensions of each problem domain, we thereby develop a framework that assesses the stability of knowledge trajectory dynamics as an indicator of wickedness associated with conceptual and solution uncertainty. As such, our results identify wildlife trade as a wicked problem that may be difficult to address given recent instability in its knowledge trajectory.

3.1 Introduction

Scientific knowledge production is a necessary input for better responding to the direct consequences, downstream impacts, and systemic risk associated with complex problems [24, 33, 92, 152, 245]. Environmental problems in particular, such as climate change or biodiversity loss, happen at the multidisciplinary intersection of ecological, social and technological systems, and are therefore inherently complex [267, 307]. Managing such challenging boundary-spanning problems calls on the convergence of knowledge and expertise across disciplines and inter-sectoral organizations [249]. Although different studies have addressed how knowledge is produced and integrated within well-stablished disciplinary domains (e.g., astronomy), little is known regarding scientific knowledge production about emerging environmental problems within the broad envelope of sustainability science [24].

In particular, we are motivated by *wicked problems*, typified as untamed, dynamically complex, and ill-structured problems, that lack clear-cut conceptual and solution definition [273, 4, 61, 147]. Note that not all problems suffer the same degree and type of ill-definition, or are equally 'wicked', as we further discuss. These known but largely unattended problems [356] are elusive given the multiple interdependencies and the absence of a 'correct' view [22].

In order to fully appreciate the nature and implications of wicked problems, communities of problem-solvers are needed in convergence to bridge knowledge across disciplines, thereby triggering a common vision regarding the properties of the core problems, and the means to address and manage them [4]. Such knowledge integration depends upon blending existing concepts and social structures (e.g., formal communities of researchers) that collectively and intentionally delineate an encompassing *knowledge trajectory* that defines the scope of knowledge around a given domain [150]. Knowledge trajectories are thus defined as the characteristic dynamical pathway followed by a domain in both its cognitive (i.e., ideas and concepts) and social dimensions [43, 150, 342, 37]. Although the study of knowledge trajectories has advanced towards identifying how knowledge converge, diverge and eventually stabilize [37, 25, 24, 43, 150], few studies have explored how knowledge trajectories emerge within the scope of ill-defined or wicked problems, where paradoxically, the multiple approaches can nevertheless contribute confusion around the collective understanding of the core concepts and feasible solutions.

Against this backdrop, we seek to provide a better understanding of knowledge production around wicked problems starting with the question: *do knowledge trajectories emerging around wicked environmental problems differ according to their cognitive and social dimensions?* As such, for a given problem domain, we seek to elaborate on the association between the emergence and stabilization of its knowledge trajectory, as it relates to the overall wickedness of the underlying problem.

We develop this framework by constructing a representation of the knowledge trajectory for each of three environmental problems – Deforestation, Invasive Species, and Wildlife trade. These three problem domains were selected due to the great risks for negative ecological and societal impact they pose, owing to manifest systemic-risk associated with interdependent natural, social and technological systems [92, 152, 317, 71, 116]. Specifically, a common criterion for selecting these three problems is the 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 these three environmental problems lack certainty regarding the core concepts and possible solutions, and that such flaws are sufficient to give rise to instability in the knowledge trajectory dynamics which manifests in exacerbating conceptual and solution uncertainty.

This work contributes to the literature on the emergence and dynamics of collective knowledge production[24, 25, 42, 97, 150, 265, 319, 248]. To assess the emergence and stability of the knowledge trajectory for each problem domain, we develop an empirical data-driven framework focusing on the diversity of topics, disciplines, collaboration, and geographic coordination. We associate each empirical facet with either (a) cognitive dimension or (b) the social dimension. By simultaneously comparing networks representing (a) and (b), in a similar vein to prior research characterizing knowledge domains

[303, 151, 249], we seek to identify patterns of scientific knowledge production related to wicked problems.

The remainder of this paper is structured as follows in Section 3.2 we describe the relationship between cognitive and social dimensions of a knowledge trajectory, in the particular context of wicked problems. Sections 3.3 introduces the data and methodological framework for assessing the proposed relationships. Section 3.4 presents our analysis on the cognitive and social dimensions of knowledge trajectories. Finally, we conclude by discussing how observed (in)stability in the social and cognitive dimensions relates to the 3-level typology of wicked problems developed by Heifetz & Heifetz [149].

3.2 Conceptual background

3.2.1 Defining the characteristics of wicked problems

' Wicked' is a concept that emerged from public policy research (also frequently used in studies of science dynamics) referring to particular characteristics of a knowledge domain [4, 149]. However, we are unaware of literature exploring the relationship between 'wickedness' and its implications on scientific knowledge production. Hence, we seek to develop statistical methods for measuring, evaluating and better understanding wicked problems.

Problems can be defined, among other notions, by the degree to which related clear-cut concepts and solutions are identifiable. Heifetz & Heifetz [149] propose that in respect to the baseline of tame problems (Type I), wicked problems can be divided between those with well-defined conceptual definitions but with ill-defined solutions (Type II); and those lacking both well-defined conceptual definitions and solutions. (Type III).

In essence, not all wicked problems have the same degree of wickedness. On the one hand, Type II wicked problems are conceptually clear but appear 'fuzzy' to problem solvers, as they lack a single exact solution, or alternatively, are faced with multiple solution pathways characterized by uncertainty [68, 92, 147, 148]. On the other hand, Type III wicked problems are inherently resistant to clear and unique definitions [4, 61, 92], and are characterized by definition and solution uncertainty [22, 147, 149, 190]. In contrast to tame problems, wicked problems result in thorny issues for which common top-down expert-driven approaches can be insufficient to cope with their complexity [92, 149, 125, 296, 273]. In the present context, we acknowledge that environmental problems aren't simply differentiated as tame or wicked, but given their tendency to be situated at the nexus of interdependent complex systems, they are distributed in a spectrum of ill-definition or wickedness [4, 147, 148].

Beyond the issues of ill-defined concepts and solutions, and the multiplicity of conceptual and solution approaches, wicked problems are also exacerbated by social factors. Indeed, problems derived from anthropogenic drivers are socially situated [4, 61]. Hence, addressing wicked problems facing society and planet requires convergent research spanning traditional disciplinary boundaries that leverages cross-sectoral integration of expertise [19, 82, 190, 192, 249, 317]. Consequently, the variety of stakeholders, interests, and objectives engaged in the social context may involve a large collection of opinions and ideas about the problem itself and its causes that can hinder consensus formation around a shared vision [4, 22, 61, 92, 125, 273]. For this reason, it is commonly appreciated that the greater the disagreement among stakeholders, the more wicked the problem is likely to be. Confusion, discord, and lack of progress are telltale signs that an issue might be wicked [61]. However, different studies [25, 253, 342, 343] also indicate that long term social interactions between stakeholders is critical to the consequential diffusion of knowledge, second-order learning and co-production of stable agreements [297, 316, 296]. And while some scholars argue that the multiplicity of stakeholders is the primary factor contributing to wicked problems, we argue that such multiplicity is not a sole determinant. Instead, we posit that social and cognitive integration plays a dominant role in fostering the consolidation of knowledge domains, policy agendas, and shared vision, which together can reduce conceptual and solution uncertainties [24, 92, 142, 150, 265, 316].

We seek to provide clarity around this point by analyzing cognitive and social dimensions of knowledge trajectories [265]. Regarding the first dimension, we posit that cognitive factors are most likely to obfuscate the clarity of problem definitions. Such lack of agreement around concepts and their relationships is characteristic of endeavors calling on multi-disciplinary problem-solving. Consequently, wicked problems may fail to consolidate into stable trajectories because new efforts fail to constructively leverage and contribute to existing knowledge [43, 150].

Regarding the second dimension, social factors tend to contribute uncertainty concerning the set of solution pathways. We posit that the benefits of collaboration are less potent in research communities lacking clearly delineated pathways forward, and conversely, that problems lacking identifiable pathways forward are less likely to elicit stable community formation. Indeed, establishing and sustaining consequential leadership may be untenable in wicked scenarios if there is a failure to alert, activate, orient, and incentivize the vast field of candidate problem solvers [273]. Ideally, critical scientific agendas become institutionalized as ' Grand Challenges' that serve as a lighthouse beacon to guide trajectories toward a clearly identifiable objective [152, 249]. Another important consideration is that wicked problems are by definition intractable, thereby lacking a single 'closed-form' solution; hence, ' better' solutions are converged upon instead of a unique 'correct' one. Such a process is typically feasible when stakeholders iteratively converge in agreement on how to institutionalize agendas that best address the problem [4, 22, 61, 125, 126, 317]. As such, wicked problems are commonly managed, as opposed to being solved, giving rise to a situation that requires long-standing agreements between stakeholders, robust research agendas, and inter- and trans-disciplinary approaches – e.g., as Masterson [208] shows for the case of managing the malaria crisis in global tropical and subtropical zones.

3.2.2 The relation between problems and knowledge trajectories

Various studies have addressed the knowledge trajectories for well-stablished domains (e.g., astrophysics; organic chemistry) identifying that they eventually reach stable trajectories reflecting the steady-state accumulation of intellectual development [37, 150, 151, 343]. Such stability emerges from the incremental addition of coherent knowledge; in other words, knowledge based upon the preexisting. Although emerging fields (e.g., computer sciences) show a more turbulent pattern characterized by fluctuations owing to disruptive innovations, and therefore less related knowledge. Such fields nevertheless eventually achieve stability in their richness, e.g. proxied by descriptors like the rate of new keywords used – e.g., see Bonaccorsi [37]. Similarly, research on social dimensions [26, 24, 248] show that social cohesion manifesting as consolidated collaboration is a common characteristic of synergistic cross-disciplinary integration; alternatively, if persistent collaboration is lacking, then it is less likely that consequential blending of concepts and methods will succeed.

A common theme in knowledge trajectory research is what role relatedness plays in knowledge diversification [43, 97, 151, 150]. Implied in this definition of relatedness is the strong path dependency regarding the entry and exit of knowledge building-blocks accumulated in the system [150]. We argue that cognitive relatedness thus captures to the permanence, continuity, and integration (with the preexisting) of concepts and ideas.

Similar to cognitive relatedness, social relatedness refers to the permanence and reinforcement of pre-existing associations between partners. Long-term collaborations underly established process of academic debate [140, 342] that assists in consolidating agendas, enables deep learning within and across academic communities [24, 138, 270], is associated with higher-impact research outcomes [253]. Stable collaboration is therefore an indicator of social consolidation of knowledge trajectories [24].

Cognitive and social networks provide a well-established framework for defining synthetic indices for analyzing the structure and dynamic of scientific knowledge production [24, 25, 42, 59, 111, 123, 124, 140, 140, 265, 316, 330, 249]. Building up on these efforts, here we focus our analysis around the dynamics of two complementary characteristics – the *diversity* and the *relatedness* of the entities comprising the aggregate knowledge trajectory. This approach is similar to previous research using diversity measures to characterize knowledge trajectories and relatedness [43, 150, 151, 265, 316].

To distinguish our approach to measuring diversity, we first define diversity using the typology proposed by Harrison & Klein [145], which differentiates between three alternative perspectives: variety, separation, and disparity. Unlike previous studies, here we seek to evaluate the emergence of diversity in problem-solving approaches by measuring disparity, as opposed to variety (also referred to as richness) or separation. To be specific, while variety refers to counting the total number of varieties of entities (or richness of a system), and separation measures the characteristic differences between expressed values (differentiation), here we choose a measure of disparity because it directly measures the dominance of one or few varieties over the remaining varieties (i.e., heterogeneity in concentrations of varieties). We posit that saturation to a problem-specific diversity level is a robust indicator of whether or not a knowledge trajectory is confounded by conceptual and/or solution uncertainty.

To develop this assessment framework, we systematically analyze disparity levels for three research areas – Deforestation, Invasive Species, and Wildlife trade – motivated by the following postulations:

P1. *Invasive Species.* Given the clear task and conceptual definition of what is an invasive species, we anticipate stable knowledge trajectory dynamics for both cognitive and social dimensions (i.e., closer to a tame problem).

P2. *Deforestation.* While the definitions regarding deforestation are clear, this problem suffers from a lack of effective solutions, in part owing to multiple global stakeholders, despite being a problem that is highly localized. Hence, this problem suffers primarily from solution uncertainty (i.e., Type II wicked problem). As such, we expect such conditions to generate unstable or turbulent collaboration patterns.

P3. *Wildlife Trade.* In contradistinction to P1 and P2, we suspect that instability in both cognitive and social dynamics results from relatively high conceptual and solution uncertainty (i.e., typical of a Type III wicked problem).

3.3 Methods

We analyze knowledge trajectory change by assessing structural changes in diversity (disparity) among the constituent components of the research corpus in and around each problem domain [24, 111, 150]. In what follows we first detail the environmental problems addressed and then we describe our proposal for assessing structural changes in a given research domain, which is sufficiently general to be applied beyond the three case studies explored in this work.

3.3.1 Environmental problems

Grand environmental challenges involve high degrees of uncertainty in cognitive, social, and technical dimensions. By way of example, a conservation biologist may have to make decisions or recommendations about ecosystem management before a complete theoretical, empirical or methodological foundation have been established [4, 147, 148, 312, 313]. Therefore, tolerating epistemic uncertainty in terms of what the best available knowledge may be an unavoidable component of environmental science [92, 317].

Three environmental problem examples

We focus on three environmental problems of global extent (Deforestation, Invasive species, Wildlife trade) with origins in human development [334]. Since the late 1970s several studies have suggested that the three problems are both drivers and symptoms of global change, biodiversity loss and the asymmetric relationship between the global North and South [21, 293, 354]. These problems 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.

The first problem studied 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 and industrial hardwood, urbanization, desertification, and climate change [20, 202, 354]. The impacts of deforestation on vulnerable populations can be wide ranging and degrade human wellbeing [20, 66]. Figure 3.1a shows the disciplinary composition of the scientific research on deforestation, illustrating a background context involving both the natural sciences (in the endeavor to assess land cover change and its impacts), as well as the social sciences (relating to forest/agriculture management, as well as efforts to understand the sociocultural and economic impacts of deforestation).

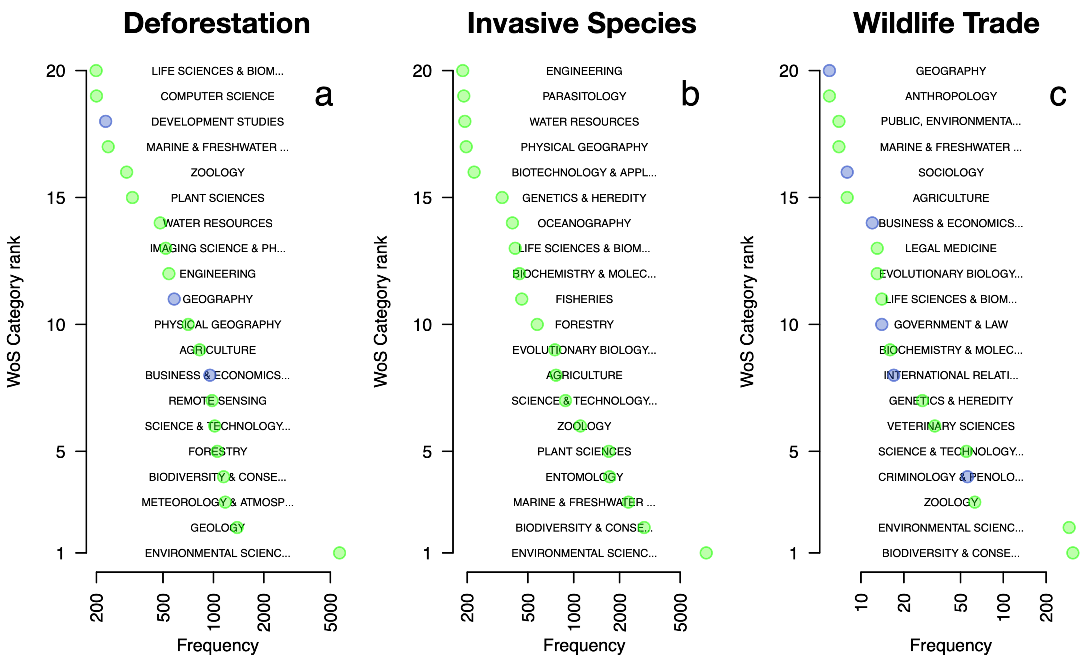

Figure 3.1: **Disciplinary composition of environmental problems.** Disciplinary composition of the three environmental problems domains: (a) Deforestation; (b) Invasive Species; (c) Wildlife Trade. Shown are the top 20 most frequent WoS categories associated with each. Data point colors indicate physical sciences (green) and social sciences and humanities (blue).

The second problem studied is Invasive Species, which refers to biological invasions or the unnatural demographic growth of species. Invasive species are frequently nonnative species introduced to an ecosystem either intentionally (e.g., in an active, deliberate manner) or unintentionally (e.g., in passive, accidental manner), though some native species can also become invasive [69, 159]. The mechanisms and consequences of biological invasions differ across species, organisms, and economic settings [159]. The economic impacts of controlling or coping with existing, or preventing new, invasions are significant, frequently exceeding hundreds of billion dollars per year [218]. 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, in particular zoology Fig.3.1b. From a disciplinary perspective, biological invasion is mostly addressed through the lenses of natural sciences, with little social sciences imprint despite the known consequences of invasive species in the livelihoods and economy of the inhabitants of the recipient ecosystems [300].

Finally, the third environmental problem 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 from fuzzy boundaries that are highly debated in academia and practice [71]. 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 [13, 293, 334]. One aspect of the problem frequently highlighted is its profound ecological and social impacts [13] such as biodiversity loss, corruption, and violence. In contrast to the previous two problem domains, Wildlife Trade has prominent research streams in the social sciences. More specifically, Fig.3.1c shows that besides biological sciences, this problem is co-dominated by human sciences such as criminology and government.

3.3.2 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 [186], to collect the scientific literature associated with each one of the environmental problems here studied. The information was downloaded in November 2020 using general queries designed to capture each problem (see Supplementary

Note 1 -SN.1-). For each publication we extracted various metadata fields, 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), both of which are journal-specific ontologies). Furthermore, for each source we also tally two co-occurrence measures, one for co-author (C-AU) and another for co-keyword (C-DE), in which we tally the frequency of dyads, i.e. the number of publications featuring author (alternatively keywords) A & B.

Data refinement using co-bibliography networks

Scientific repositories systematically compile, store, and make accessible vast quantities of information regarding scientific productivity. However, these information search and retrieval engines might be sensitive to misidentifications and synonyms. To avoid including unrelated publications within our analysis we focus on publications cognitively related with at least part of the core literature associated with each problem domain. We identified such publications by reconstructing the corresponding co-bibliography network [140, 284, 336].

Co-bibliography networks (CBN) synthetize the association of a pool of publications through the literature they cited. CBN are composed by nodes (publications) connected by links that indicate the bibliographic similarity or bibliographic coupling between them. Publications with high similarity share a large proportion of bibliographic references, thus they are expected to address similar problems, or use similar frameworks [83, 242]. Therefore, links in CBNs represent cognitive proximity between publications. As such, clusters of densely connected publications in a CBN represent groups of topic-specific publications. Note that we consider publications within these groups as consolidated knowledge since it underlies communities of researchers where the knowledge is discussed and diffused [83, 111, 178]. While there are other extant methods for mapping publication topics, we choose CBN being that it produces maps similar to other methods [336] and it is amenable to including recent literature that has not yet had sufficient time to be itself cited [140].

We assess the bibliographic coupling between pairs of publications by using the bibliographic coupling distance[1] proposed by Kesser [170] and implemented by Grauwin & Jensen [140], which defines the coupling as the normalized intersection of the cited references, varying from 0 (no coupling) to 1 (identical bibliographies). Following Romero et al. [284], we exclude from the analysis those links that represent low cognitive proximity between papers (i.e., small coupling) by defining a threshold that maximizes the formation of highly cohesive clusters of papers (i.e., network's modularity). We use the Louvain algorithm to identify these clusters [140], which we term knowledge communities (KC). The threshold is defined by iteratively removing the links weighted lesser than a given value, and then measuring general properties of the resulting network such as the resulting modularity, as described in S.N.2. By removing weak links, we seek to retain the maximum of information (i.e., nodes and links) while exposing the structure defined by strong links [138, 253] defined here as communities forming around high cognitive proximity. Consequently, several nodes might become disconnected and form small components corresponding to tangential research. Note that studies using networks frequently rely on analyzing the giant component of the network and excluding the smaller components [227]. Here we include communities larger than an arbitrary threshold of 10 nodes, which maintains our ability to capture emerging topics [284]. As such, we include nascent frameworks and ideas, but exclude inconsistent, non-related, and isolated publications.

Data characteristics

Using threshold values of 0.167 (Deforestation), 0.177 (Invasive Species), and 0.181 (Wildlife Trade), we obtain core CBN networks comprised of: 12,674 publications for Deforestation; 15,947 for Invasive Species; and 650 for Wildlife Trade. The resulting networks are highly modular (0.88 for Deforestation, 0.95 for Invasive species, and 0.85 for Wildlife trade) indicating that the communities identified are highly cohesive and well-defined.

Importantly, we note differences in the onset of knowledge consolidation for each problem domain, indicated by the year of the first publication and the time to reach half maximum, as illustrated in Fig.3.2a and Fig.3.2b. Note that we refer to consolidated knowledge (or strongly connected CBN) rather that publications in general. Although the three problems 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. In Fig. S1(a,b,c) we provide additional network visualizations showing the emergence of select knowledge communities. For each case we observe a sigmoidal curve, similar

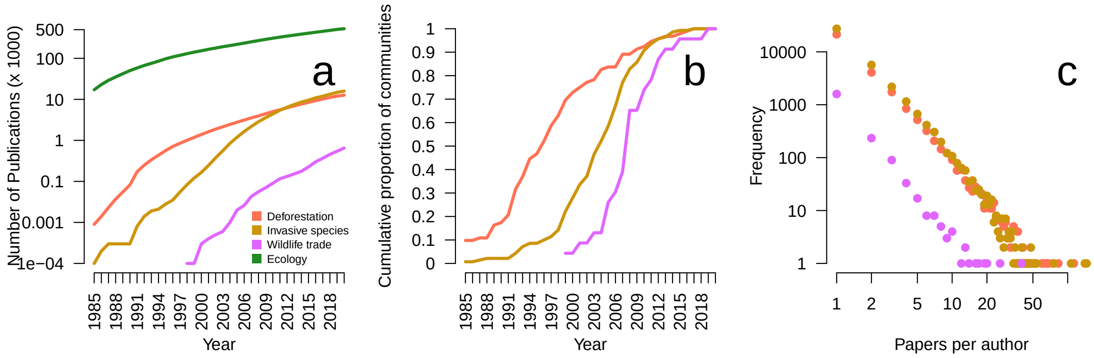

Figure 3.2: **General characteristics of the source sets defining the 3 case studies.** Deforestation (orange), Invasive species (brown), wildlife trade (purple). (a) Cumulative number of sources including data for Ecology (green) for benchmarking purposes. (b) Cumulative number of knowledge communities emerging through a given year, reported as the proportion of the total in 2020 to better facilitate comparison. (c) Author productivity distribution, indicating common scaling despite underlying differences in research domain size.

to other studies of collaboration networks [26], here indicating the onset of knowledge diversification since each community represents a collection of research articles that are highly coupled in terms of their knowledge inputs (see also Fig.3.2).

To assess the numerosity and productivity of researchers in each problem 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 [214]. As well documented in the literature [26, 251, 319, 342], we observe an extremely right-skewed productivity distribution Fig.3.2c, indicating that each problem supports just few highly productive authors, whereas the vast majority of scholars publish just few research articles. Despite the differences in the publications abundance for each problem, 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 summary, we show that the 3 case studies are not markedly different in their general characteristics, thus we argue that differences are defining features of the problem domains, as opposed to idiosyncratic differences associated with variation in sample size and scholar productivity.

3.3.3 Analytical approach

In this section we distinguish research article metadata categories used as proxies for either cognitive or social dimensions. For the cognitive dimension we include the size of knowledge communities (KC), the frequency of keywords (DE), keywords co-occurrence or dyads (C-DE), subject categories (SC), and journals (SO). For the social dimension we include the frequency of authors (AU), coauthors dyads (C-AU) and countries (CU). Then for each variable we measure the disparity, using two measures that both correspond to greater disparity the smaller the value: Shannon Evenness index [211] and the Complementary Gini index (or simply $1 - G$, where G is the traditional Gini index). We measure the diversity over the publications retained in the CBN.

In more detail, Shannon evenness[2] is a normalized version of the Shannon entropy which measures the average level of information contained in the variable [211]. Alternatively, the Gini index[3] is an inequality coefficient that measures the pairwise difference between all the data values in the sample normalized by the value expected of this quantify for a uniform distribution. We use the complementary Gini (1- Gini) to simplify the comparison with Shannon. In general, these two indices measure diversity according to the disparity within the distribution of distinct varieties. Low diversity (corresponding to high disparity) is associated with a system dominated by few varieties or high homogeneity; while high diversity (low disparity) represents high heterogeneity in the system since varieties are uniformly distributed a no one dominates. Both metrics vary from 0 (representing homogeneity, low diversity, high disparity, high concentration) to 1 (heterogeneity, high diversity, low disparity, low concentration).

We evaluate the temporal changes in the diversity in two ways – intra-annually and inter-annually. In the first case we calculate the intra-annual diversity using just the varieties that exist in each given year. Changes in intra-annual diversity indicate whether the disparity varied in a particular non-overlapping time-frame. For instance, a decrease in intra-annual authorship diversity indicates that the publications in a given year increasingly concentrated on just a few productive authors. Note that successive intra-annual diversity values might be the same, indicating for instance certain degree of concentration in a particular author, but the disparity can be produced by different varieties (e.g., author a dominates in year 1 and author b in year 2).

We complement the intra-annual perspective with a second cumulative perspective on diversity change, calculated by accumulating varieties from the beginning of the data up through the specific year being analyzed. In this way, an increase in the inter-annual diversity indicates that varieties included in year t were marginally represented in the past, and possibly non-existent. We argue that this inter-annual perspective accounts for the temporal change in path-dependent or relatedness of the varieties existing up through year t, since variations depend upon the intra-annual diversity of a given year and the previously existing varieties. In other words, the inter-annual diversity evaluates how varieties in time t fit into the existing trajectory [124].

Finally, we assess the degree to which a given disparity value could arise from random configurations of the same empirical varieties, calculated by estimating the average diversity values obtained through a random null model. In this way, the null model captures patterns representing a baseline for a particular problem, where the variables of interest have no effect [321]. Our null model is comprised of 5000 random ensembles, where each ensemble of varieties is obtained by shuffling the publication years (i.e., intertemporal resampling), followed by the calculation of the intra- and inter-annual diversities. We then represent the estimated null diversities as the mean diversity across 5000 realizations along with the corresponding inter-quartile range. In this way, we conserve the number of research articles analyzed in a given year, but allow for variation in their other covariates. The objective of this comparative baseline is to assess to what degree temporal patterns can be explained by phenomena in excess of the intrinsic fluctuation level associated with the entry and exit of varieties, as well as their frequency dynamics.

Note that in cases where there is little difference between the empirical intra-annual diversity and the null model suggests that the diversity is a product of the number of varieties included, but not of their distribution. Moreover, small differences between the empirical inter-annual diversity and the null model indicates the absence of temporal sorting and sporadic bursts in the underlying data. If the temporal distribution of varieties has some order (e.g., some prolific author only published in early years and then were replace by new prolific authors) it is unlikely that the null model captures such order. Note also that in the last year of evaluation differences in the inter-annual diversity between the null model and the empiric data are not expected since the distribution of varieties in the last year is the same for both. All the calculations were made in R 3.6 [324] using the package igraph [85].

3.4 Results

In the previous sections we document the similarities in growth rate, author productivity distribution, and modularity of the co-bibliography networks (CBN) shown in Fig.3.2. In what follows, we first further describe the CBNs for each of the three environmental problems, and then we assess the disparity dynamics, used as proxies for the temporal structure of the cognitive and social dimension of the overall knowledge trajectory. Importantly, the observed dynamics are consistent regardless of the diversity measure used, as indicated by comparing calculations using Shannon Evenness (Fig.S2-S5) and Complementary Gini indices (Fig. S6-S9). Thus, we choose to focus the remainder of our analysis on the results obtained using the complementary Gini index.

Knowledge communities (KC) are natural elements for analyzing the structure of CBNs, given their co-bibliographic construction. In Fig.3.3 we show a simplified representation of each CBN (for detailed networks see Fig. S1) in which nodes represent KC and links between them represent the number of articles connected (representing bibliographic coupling) between the papers included in each pair of KCs. Note that the number of KC between each problem analyzed vary. Differences in the sizes of KC (number of papers included) within each problem are evident, showing that the BCNs are composed of a few very large communities and a (relatively) large collection of small communities, some of which are disconnected from the network's fully connected (giant) component.

As mentioned, KC are clusters of publications cognitively proximal research publications. Such clusters represent conceptual and methodological frameworks, developed by scholarly communities incrementally over time for the purpose of forming a coherent scientific discourse [59, 140, 265, 284]. By manual assessment of titles and abstracts we can identify the topics covered in each KC. For example, we find that Deforestation KC encompass a variety of topics 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 topics (see Fig.3.3a, Fig. S1a). KC topics for Invasive Species include 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 (Fig.3.3b, Fig S1b). Finally, Wildlife Trade is characterized by KC topics associated

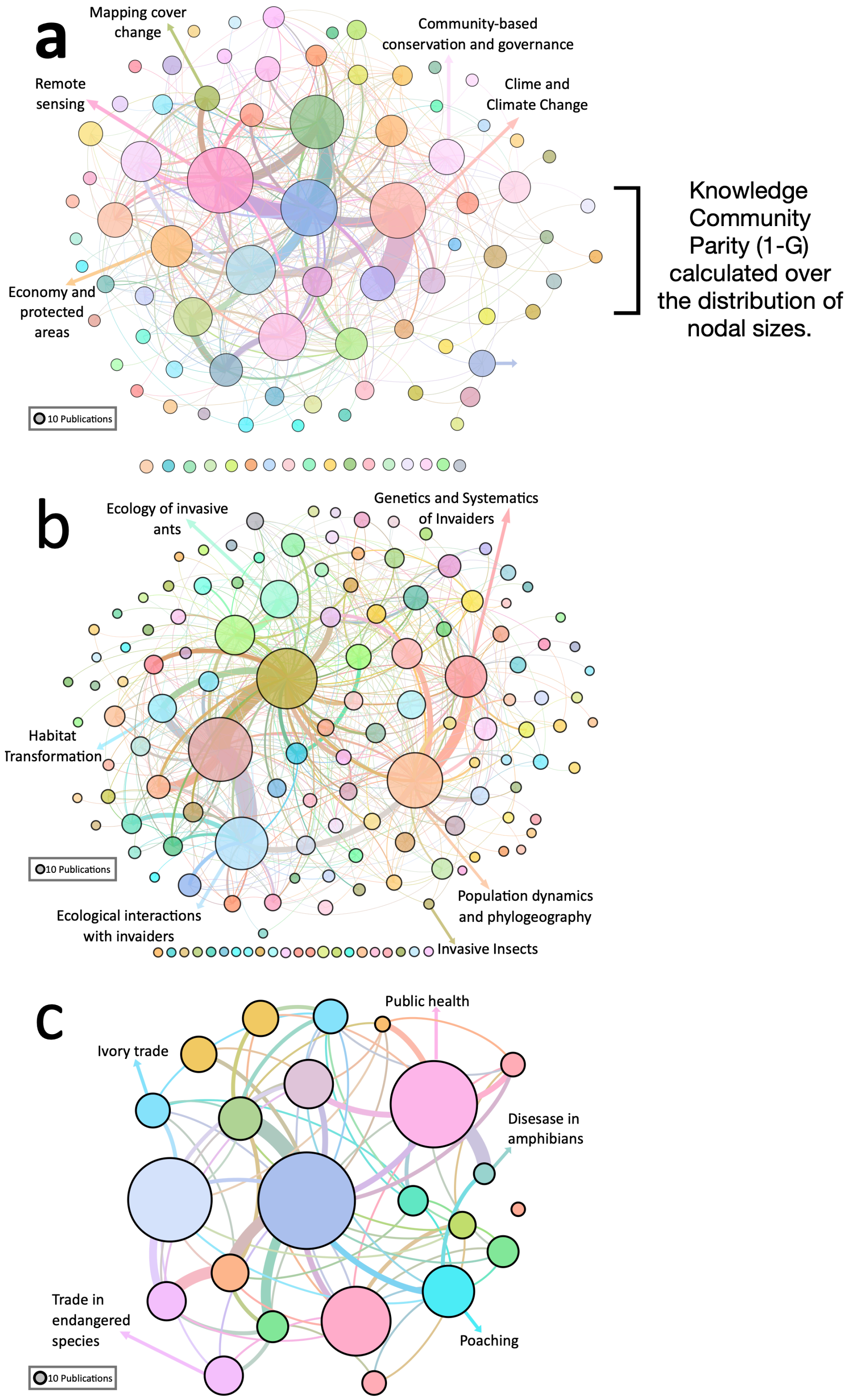

Figure 3.3: **Cognitive composition of the three environmental problems.** Co-bibliography networks showing knowledge communities (groups of publications represented by circles) connected by links conveying their cognitive relation (see Supplementary Note 2). We manually labeled several communities according to the topics addressed by the group. The size of the circle represents the number of publications, and the thickness of links is proportional to the number of connected publications

with criminology, invasive species derived from wildlife trade, epidemiology and public health, the relationship between wildlife trade and social media, law enforcement and policy, among other topics (Fig.3.3c, Fig. S1c). Note that the collection of topics included in each problem reflect the multiple views that researchers develop. Although many views can be complementary, it is likely each one emphasizes specific elements (concepts) of the problem, and therefore also addressing possible solution pathways.

3.4.1 Cognitive dimension

We analyze the cognitive dimension of each knowledge trajectory by assessing the changes in the disparity – for both intra and inter-annual levels. First, Fig.3.4a shows the intra-annual variation for knowledge community sizes, which indicates a sustained increase in diversity (increasing parity) across all problem domains. However, we note for Invasive Species and Wildlife Trade that the trajectories are only slightly greater that the expected values yielded by the null model. This suggests that the intra-annual diversity for these two problems is consistent with the random expectation and the changes in the diversity are the product of the increase in the volume of publications. In contrast, the KC diversity for Deforestation prior 2008 can't be explained by the abundance of publications, suggesting the existence of some internal process associated with the temporal distribution of efforts across multiple KC that lead such high initial diversity.

On the other hand, analysis of inter-annual variation, which better accounts for inter-temporal correlations manifesting in burstiness, shows a rapid increase in the diversity with large deviations from the null model, especially during early periods (Fig.3.4b). However, Wildlife Trade, and also Deforestation to a lesser degree, feature prominent decreases in diversity corresponding to higher concentration levels (i.e., smaller Complementary Gini index values). Additionally, complementary Gini index values for Wildlife trade are consistently smaller than the rest of the problems, indicating in general a lower baseline diversity, which is indicative of higher concentration of knowledge within certain KC. We posit that both saturation around a stable value, as well as higher concentration levels, can be associated with higher relatedness. In such a case, as more recent publications are incorporated, they tend to disproportionality contribute to the growth of a few existing KC, as opposed to creating new KC or being homogeneously distributed across existing KC. As such, results for KC indicate that topical diversity emerges through diversification of varieties which tend to grow equitably towards a stable saturation point at which point the system of knowledge is coherently related, as it is the case of Invasive Species.

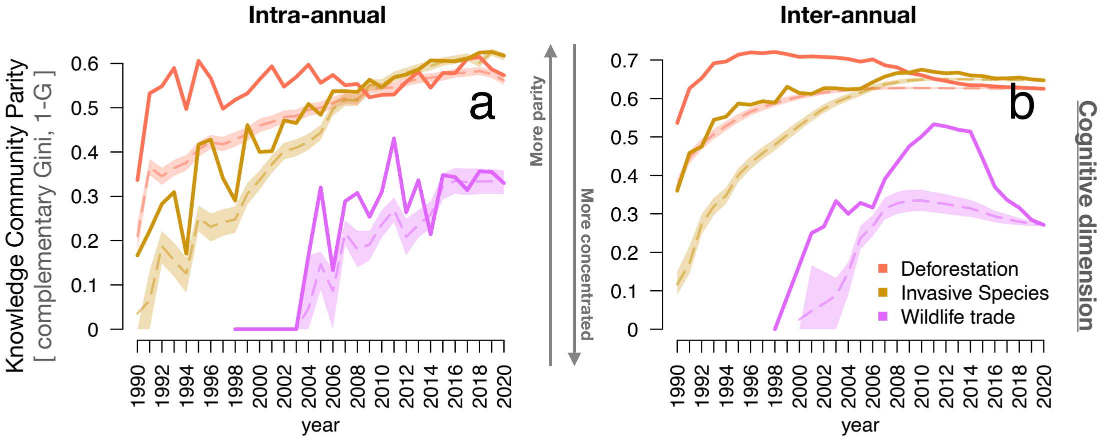

Figure 3.4: **Temporal variation in parity in cognitive dimension.** Temporal parity measured as the complementary Gini index (1-Gini) in knowledge community sizes for three problem domain areas: Deforestation (orange), invasive species (brown), and wildlife trade (purple). (a) Intra-annual variation. (b) Cumulative (inter-annual) variation. Larger (smaller) parity values (reported as 1-Gini Index) correspond to lower (higher) concentration levels. Shaded intervals 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

In addition to KC, we also computed the disparity time series for several other cognitive dimension variables (Fig.3.5a-b), including subject category (SC), journal (SO), keywords (DE), and keywords dyads (C-DE); for simplicity we present only a subset of these results, and the rest are presented in Figs. S2-S9. Results for intra- and inter-annual variation in the diversity of the mentioned variables indicate that the variables are mostly indistinguishable from the null expectation at the intra-annual level; the inter-annual variables follow a generic increase in diversity that coincides the null expectation, except for Deforestation which features a relatively high initial diversity (Fig.3.5a-b); Wildlife Trade features relatively high concentration levels for inter-annual dynamics (Fig.3.5a-b, Figs S2-S9). As such, we corroborate that the main differences in the cognitive dimension between the problem domains is in the analysis of KC disparities (Fig.3.4a-b).

3.4.2 Social dimension

In order to analyze the social dimension of each knowledge trajectory, we present results for co-author and country disparity, as indicators of the relatedness of social communities (see Fig. S2-S9 for results derived from other social dimension variables). In particular, we focus on results corresponding to inter-annual diversity.

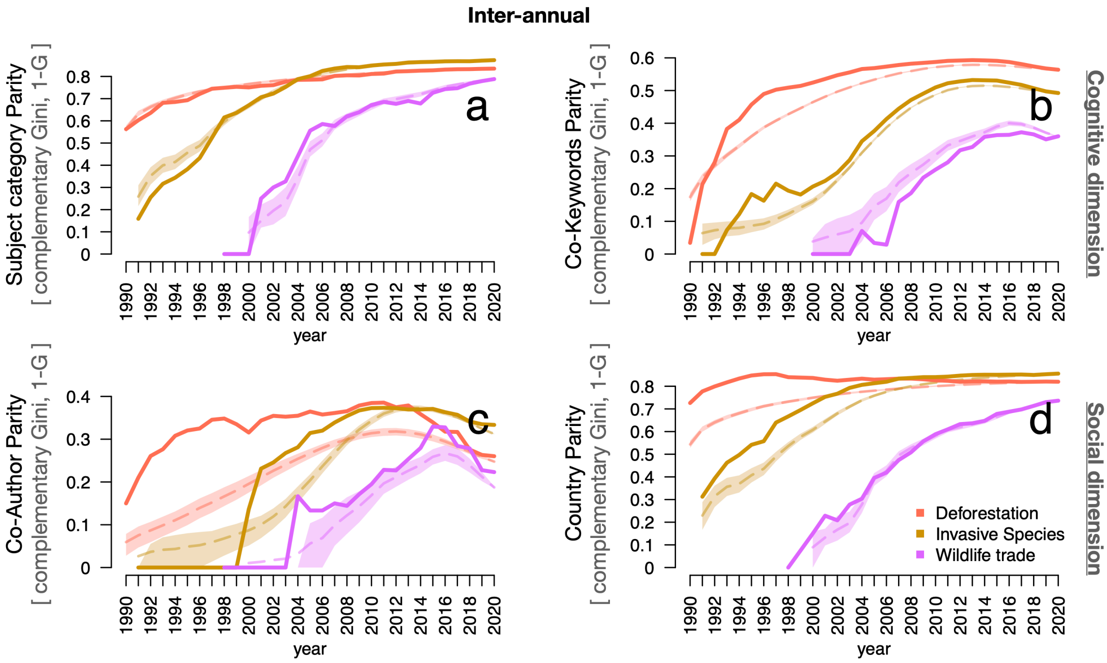

Figure 3.5: **Temporal variation in parity in cognitive and social dimensions.** Cumulative (inter-annual) parity calculated for three problem domain areas – deforestation (red), invasive species (blue), wildlife trade (purple) – and 4 different types of cognitive and social networks: (a) WoS Subject categories; (b) co-keywords dyads, (c) co-authors dyads, and (d) author affiliation country. Shaded intervals 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.

Figure Fig.3.5c shows the results for C-AU (which are nearly identical to the results obtained for the authorship variable), which indicate that collaboration is a variable that largely differs from the expectations of the null model for Deforestation and Invasive Species, but less so for Wildlife Trade. Although we identify prolific authors (Fig.3.3c) in the research domain of Wildlife Trade, their impact is diminished in the case of inter-annual variation where we account for their temporal ordering. Interestingly, for Wildlife Trade and Deforestation we note a reversal towards higher concentration during the past decade, indicating an increase in the social relatedness possibly owing to a greater exploitation of existing collaborations. This suggests, at least for Deforestation, that the research activity has recently concentrated in a subset of authors and their collaborators.

Analysis of author affiliation country data provides a proxy for diversity in organizational (e.g., Universities, Research centers, NGOs) and institutional factors (e.g., national science funding). Results reported in Fig.3.5d show that empirical diversity calculated for Deforestation and Invasive Species feature early excess parity with respect to null model levels. Over time these differences reduced as parity levels stabilized around steady values, indicating high geographic parity. Wildlife Trade features little deviation from random expectation, and parity has steadily increased over time, corresponding to a decreased concentration of geographic leadership. To further support these results, we also calculated productivity diversity between the global South and North (Figs. S5i-S9i) and also observe inequalities in the production of knowledge generally decreasing over the long run.

In summary, we identified important differences across the three environmental problems evaluated. Invasive Species is characterized by an increasing diversity in both cognitive and collaboration trajectories that saturates in recent times. Such a pattern describes homogenous growth across the different topics embodied, and the community of researchers as well as their supporting organizations, in addition to growth supported by preexisting structures (i.e., topics and researchers) fostering the recent stabilization of both cognitive and social dimensions.

Similarly, Deforestation is also characterized by high diversity levels, for both cognitive and social dimensions, and featuring an approach to a stable diversity level. However, for some cognitive (KC) and collaboration (CU, C-AU) variables, we observe a slight reduction in the diversity indicative of recent increase in concentration in some varieties (e.g., topics, authors). These suggest changes in the scope of the research in this problem either by increased emphasis or paucity in some topics and researchers. We also observe reduced productivity inequalities between the global North and South.

Finally, Wildlife Trade represents the most distinct problem of the three, showing important changes in cognitive (KC) and collaboration trajectories (C-AU) characterized by strong reduction in the diversity after periods of sustained increased. Observed parity values are typically less than those observed for other problems and are indistinguishable from the null expectation in many circumstances (DE, C-DE, AU, C-AU, CU). These results indicate that the knowledge about this problem has grown disproportionally within a few building blocks (e.g., topics, countries), thereby reducing the development potential for this wicked problem domain. Moreover, comparison of intra- and inter-annual dynamics shows heterogeneous growth, indicating that the knowledge trajectory is not consolidating into a stable core of research topics or research leaders (neither individual nor geographic).

3.5 Discussion

We analyzed the social and cognitive dimensions of knowledge trajectories emerging around three environmental problems – Deforestation, Invasive Species, and Wildlife Trade. Despite the common backdrop of sustainable development and conservation, we observe differences across the different problem domains that we attribute to the role of uncertainty associated with problem and solution identification. First, we note different time periods when these problems first emerged (Fig.3.2b) along with different subsequent total knowledge production as indicated by publication volumes in each problem domain (Fig.3.2a). Together, these observations illustrate how problem prioritization [74] reinforces the role of path-dependency in the evolution of knowledge production, and consequently also affects the time required for building a common understanding and agenda.

Second, we observe a broad spectrum of topical approaches (Fig.3.3), which may indicate contested spaces where assumptions and knowledge are debated [24, 43, 124]. In particular, Deforestation and Wildlife Trade exhibit a prominent period of decreasing parity across knowledge communities (Fig.3.4b). Third, we do not observe any indication that Wildlife Trade will achieve stability in the social dimension based upon the prominent decrease in parity observed in Fig.3.5c. Yet it remains to be seen if stability in the cognitive dimension of Wildlife Trade will spread into the social dimension, which is a potential avenue for change [19, 59]. However, stability in the social dimension may exacerbate solution uncertainty by reinforcing echo chambers in which a few highly productive authors (or collectives) dominate the discourse. Such a situation could limit the development of alternative leading roles, hampering the cross-fertilization between researchers and organizations, and reducing progress towards second-order ‘deep learning’ [267, 284, 297].

We posit that variability in knowledge trajectory dynamics indicate different wickedness characteristics [149]. When comparing our results with those previously reported for more well-stablished domains [25, 26, 24, 37, 43, 151] we identify some marked differences in the three domains evaluated here, which we associate with the characteristic ill-definition of each problem.

First, in contrast with our initial expectation, we found Invasive Species to more closely correspond to a Type II wicked problem (i.e., conceptually definable but without clear-cut solution) since cognitive dimensions stabilize in parity, whereas social dimensions are still changing. Until such a stable community forms, it will be challenging to settle disagreements concerning candidate solutions. Second, our initial expectations for Deforestation were also short, as this problem appears to be closer to a Type III wicked problem when considering the instability of both cognitive and social dimensions. And finally, in the case of Wildlife Trade, our analysis confirms our initial expectation of a Type III wicked problems. As such, these two Type III problems suffer from disparities that negatively affect the development of an integrated research domain.

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 reported in other work [43, 150, 186]. In addition, while our operational framework illuminates the structure of research producing fundamental changes in each problem, 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 unconsolidated, unactionable and eventually neglected research traps.

To address these extant challenges, we developed a generalizable framework that compares the intra-annual to the inter-annual parity dynamics, as a way to illustrate the nuances associated with the growth and saturation of diversity. In particular, our analysis of inter-annual parity indicates that growth and stability are not mutually exclusive. Indeed, cognitive trajectories often follow a process of diversification followed by consolidation and increased relatedness [150, 265], capturing the process by which multiple voices and meld and trigger a shared vision for moving forward [126, 19, 59, 151, 138, 270, 316]. Contrariwise, locked-in or highly concentrated trajectories, as exhibited in the case of

Wildlife Trade, can inhibit integrative, holistic, and post-normal approaches and instead may promote the emergence of conceptual echo chambers in which disproportionally few topics are mainly discussed by a reduced subset of voices [92, 97, 125, 126, 312].

As such, environmental wicked problems appear to necessitate integrated diversification [19, 59, 192] in which multiple voices and approaches can be included while consolidation of existing research agendas and communities of expertise takes place [267]. Balancing the tension associated with this paradox of cross-disciplinary integration will help distribute efforts and capabilities toward specific solutions that iterate towards addressing the underling complexity [4, 92, 190]. Failing to address the tension may give rise to untenable or unactionable solutions that hinder the translation of science-based solutions into societal action, particularly at the academic-industry-government interface [187], or neglected problems as in the case of some diseases [289, 292]. Indeed, extremely wicked problems are likely to suffer from a broader societal disregard for pursuing further action owing to the lack of or insufficient clarity or completeness regarding problem definitions and solutions.

Supplementary Material

Supplementary materials are available at https://doi.org/10.5281/zenodo.5205271. Supplementary materials include **Supplementary Note 1**: Search queries; **Supplementary Note 2**: Co-bibliography Networks construction; **Figure S1**: Co-bibliography networks for the 3 problem domains; **Figures S2-S5**: Dynamics of knowledge trajectories measured as Shannon Evenness; and **Figures S6-S9**: Dynamics of knowledge trajectories measured according to the Complementary Gini index.

Notes

[1]bibliographic coupling similarity w_{ij} is described by $|R_i \cap R_j| * (|R_i||R_j|)^{1/2}$. It evaluates the distance between publications i and j as the intersection of their references over the length of both list of references.

[2]The Shannon evenness E is represented by $-log(m)^{-1} \sum_{i=1}^{m} log(p_i)p_i$, and is a bounded version of the traditional Shannon entropy, normalized by the maximum entropy $log(m)$ associated with equally frequent varieties.

[3]The Gini inequality index G is calculated by $(2n^2\overline{x})^{-1} \sum_{i=1}^{n} \sum_{j=1}^{n} |x_i - x_j|$, which evaluates the absolute difference between all the pairs of values (denoted by x), normalized by the mean absolute difference

Chapter 4

Mapping Attitudes on Illegal Wildlife Trade: Implications for Management and Governance

Illegal wildlife trade (IWT) is a problem that affects societies and ecosystems alike. However, it remains unclear which management strategies are suitable for addressing this issue, particularly when one considers the diversity of actors, interests, and nuances of the problem. We argue that better management strategies require multiple – and at times, even opposite – actors to coalesce around the fundamentals of the problem. An initial step towards formulating management strategies is to identify how the multiple actors involved understand the problem and its possible solutions (i.e. their attitudes). Although previous studies have addressed actors' attitudes regarding IWT, they have rarely evaluated how attitudes vary between different actors. Against this backdrop, this study uses mixed methods to evaluate convergences in the attitudes of multiple actors (e.g. poachers, authorities, police forces and academics, among others) in Colombia. Importantly, this work has revealed that multiple IWT-related attitudes exist and are not necessarily shaped by contextual factors (e.g. social relations); instead, they are explained by actors' experiences and preferred governance forms. We argue that consensus formation between the multiple parties involved is required to overcome institutional weaknesses, perception divergences and the differences in governance preferences for an efficient management of IWT.

4.1 Introduction

Illegal trade of wildlife (IWT) is an environmental problem occurring at the intersection of cultural heritage, economic circuits and conservation [136]. IWT encompasses the illegal and extra-legal use of wild fauna or flora (or derivatives) and its associated activities (i.e. harvesting/poaching, smuggling, selling and possessing). From harvesting to final consumption many actors are involved in the IWT supply chain such as poachers, carriers, retailers and buyers [256, 181]. Additionally, other actors important to consider are the organisations that disincentivise, control, and judicialise this illegal activity. All these actors (those for and those against IWT) are defined by their role in the system (e.g. poacher/harvester, buyer or control authority) and by the information and narratives to which they are exposed [188, 36, 207, 168], which help them construct the attitudes necessary to navigate the social-institutional contexts of their own realities [178, 154, 350, 3, 160]. Therefore, the actors' understanding and framing of IWT, their possible solutions to the problem are expected to differ. However, little is known about these attitudes or how they differ between and within the actors related (for or against IWT).

Comprehensive characterisations of the attitudes are informative for conservation, management and policymaking [350, 160, 220, 338]. Although previous studies have addressed attitudes regarding IWT, they have rarely evaluated how multiple attitudes coexist between and within different types of actors [362, 8, 349]. Against this backdrop, this study uses IWT in Colombia as a case study that allow us to characterise the attitudes of a variety of actors (e.g. poachers, authorities, others). This work maps actors' perceptions and preferences (i.e. attitudes) associated with different dimensions of the problem to assess: how do attitudes regarding IWT vary between types of actors? We argue that effective management of IWT requires multiple actors to coalesce, share perceptions and negotiate preferences around the issue [92, 317, 14]. This work contributes to the discussion around IWT management and natural resources governance.

This paper is structured as follows. In the subsequent sections, we: first, detail the connections between IWT, narratives, attitudes and governance. We then, contextualise our case study, introduce our methods for data collection, characterise the actors addressed, and describe the analytical strategy for mapping attitudes. Next, we present our results summarising the actors' perceptions and characterising the attitude clusters. Finally, we discuss our findings and outline some elements necessary for IWT management.

4.1.1 Background

IWT presents a major threat to biodiversity and societies alike [293, 8, 13, 207]. Indeed, given the lack of control over the smuggling of species that is inherent to IWT, it has been posited that it is a vector for emerging diseases and invasive species [159]. Moreover, IWT has also been linked to violence, corruption and institutional weakening [334, 335, 360, 221, 358].

IWT is a highly profitable business for final sellers and intermediaries, whilst it is primarily the source communities that suffer the derived impacts [48, 47, 136, 256, 333]. These communities have cultural and economic connections with wildlife, and local species are important resources for household economy and livelihood [229, 47, 181, 27, 340]. Whilst wildlife trade is not a new phenomenon, its illegal connotation is recent; it is linked with colonial thinking, restricted use of species and conflict between the communities that benefit from wildlife and the government apparatus that is charged with species protection [333, 334, 168].

Legal and illegal wildlife markets develop on intricated and interconnected networks at multiple scales [293, 15, 13]. It is generally thought that IWT is unsustainable due to overharvesting, as opposed to legal wildlife trade; however, this is controvertible. Furthermore, the boundary between legal and illegal products might be diffuse, as illegal products are often laundered and consumers may not be able to (or care to) distinguish products' origins [229, 362, 181, 333, 15, 207, 360, 189].

ITW is an issue that must be curtailed. Unfortunately, domestic policy and law enforcement efforts commonly focus on poachers, the most visible – and typically the most vulnerable – part of a IWT operation [101, 256, 79]. Commonly accepted narratives criminalise poachers, smugglers and corporate traffickers alike, despite their fundamental differences. These narratives are linked to fortress conservation schemes that (*i*) dispossess communities from the ecosystems they have inhabited for generations [236, 334, 207], (*ii*) favours social stigma, (*iii*) have the potential to cause food insecurity and (*iv*) result in the securitisation of nature and consequential exclusion and violence [136, 102, 101, 135, 57]. Whilst we acknowledge that several studies on green criminology have rigorously discussed criminalising narratives by dissecting IWT operations [357, 358, 136, 360, 222], the relevance of species in local extra-legal economies has seldom been recognised in the literature.

Other narratives acknowledge the economic and cultural value of species in communities' identities by placing them at the heart of the problem [36, 283, 86]. For instance, community-based approaches emphasise community management as strategy for ameliorating the impacts of IWT and overharvesting [27, 79, 78, 3]. Notably, these narratives often avoid stigmatising communities, which nevertheless results in IWT not being fully addressed. In fact, IWT presents a major threat to the continuity of community-based approaches [229]. We acknowledge that narratives which are pro conservation and against IWT are more numerous than those mentioned here, but a deeper discussion about them is beyond the scope of this work.

Narratives are expressions of particular attitudes. Attitudes refers to the perceptions, beliefs and preferences that someone has regarding a subject [160]. Narratives and attitudes therefore emphasise specific goals (e.g. disrupting supply), parts of the market (e.g. online vendors) or law enforcement mechanisms (e.g. international cooperation) that together frame how to curtail the problem and govern the involved species. Drawing upon governmentality [119, 119] and environmentality [1, 115, 350, 57], we describe how governance models are built and how they connect with narratives and attitudes. Governmentality and environmentality refer to the mechanisms used to govern – or control and guide – a (environmental) system and how (and which) power is used. In this work, power is understood as the knowledge (disseminated by the circulating narrative) and the influence of institutions and markets.

Governmentality and environmentality in the context of IWT and conservation can be understood through Fletcher's [115] four non-exclusive mechanisms. The first mechanism, 'biopower' is sustaining life through the creation of incentives that influence individual preferences. Biopower manifests, for instance, by encouraging in situ preservation and turning poachers into park rangers. The second mechanism, 'discipline', refers to the internalisation of norms and values as behavioural changes driven by social punishment and avoidance of labels such as 'criminal'. Discipline is incentivised by education and propaganda. The third, 'sovereignty', is the top-down control that results from the formulation and enforcement of regulations and domestic laws. Sovereignty could also be seen as the local empowerment produced by community-based management. Finally, 'neoliberalism' refers to the manipulation of markets by creating substitutes, imposing sanctions and incentives such as fines or informant rewards. Overall, each mechanism uses power to create particular notions (e.g. species must be protected; poachers are criminals), define how rules are designed and enforced (e.g. law enforcement, local control) and by whom (governmental organisations, social pressure) and which economies are put into place (e.g. fines or employment provision).

The different forms of governing natural resources, from individuals to organisations, relate to the ways in which the complexities involved in the problem, as well as its causes and consequences, are perceived, understood, prioritised, framed and envisioned [1, 220, 160]. In explanation, a given form of governance is tied to a particular attitude. IWT, as a wicked problem, suffers from a lack of consensus regarding the multiple dimensions of the problem and the approaches that might be used to solve it [61, 92, 14] . Indeed, we posit that the multiplicity of attitudes contributes to the lack of shared vision between actors and the duality conservation-use of species, which is particularly conflicting when top-down sovereignty does not distinguish communities who opportunistically engage in IWT networks, from those that are inherently proactive components of such networks.

The analysis of attitudes has gained momentum in natural resources management because it promises to reveal the complexities of the problem at hand and inform policy and inclusive governance [154, 350, 220, 160, 163, 320]. Recent studies have detailed the awareness of wildlife consumers [362], community attitudes towards IWT and livelihood sustainability [349], gender-based attitudes regarding poaching [320, 2] and the drivers of the misconduct and perceptions of rangers [8, 221]. However, a comparative and comprehensive assessment of the attitudes of different types of actors has not yet been performed. Most existing studies have evaluated homogeneous groups of actors, which do not reveal what controversies between and within different types of actors exist. Consequently, this study focuses on the similarities in attitudes that arise between different actors involved in the development or control of illegal wildlife trade in Colombia. We hypothesise that the actors' roles, interests and idiosyncrasies affect their perceptions and preferences of the problem, thereby their attitudes.

4.2 Methods

Understanding the social, institutional (i.e. organisations) and functional (i.e. role) contexts in which actors are embedded is necessary for assessing how they perceive and frame a problem [154, 178, 220, 338, 160]. In the section that follows, we first contextualise the case study, then we introduce our method of data collection and describe the type of actors addressed in the study (i.e. rural communities, control authorities, others). Finally, we introduce the analytical approach we used to map the attitudes.

Contextualization of the wildlife trade in Colombia

Colombia is a megadiverse country whose biological diversity parallels its ethnic diversity (i.e. indigenous, afro, raizal and mestizo). As with other diverse countries, Colombian species face multiple anthropogenic threats,[1] including IWT, which represents one driver of diversity loss [293, 331], particularly for taxonomic groups such as birds and reptiles [293, 38].

While the study of IWT dynamics in Colombia is still incipient, research has thus far indicated that it is a growing problem [282, 38, 39, 10, 136, 331]. Similar to the native species themselves, IWT phases (i.e. poaching/harvesting, smuggling and consumption) are located in regional hotspots that bring structure to the market and coincide with socioeconomic variables [13, 136]. Whilst poaching generally takes place in rural areas, ex-situ consumption occurs in urban settings, which coincides with the experiences of other countries where IWT develops from disadvantaged to wealthier areas [102, 189]. Colombian rurality is characterised by high rates of material deprivation, unemployment, food insecurity, land tenure inequity, lacking access to basic needs, and other types of inequalities [236]. These inequities are tied to more than a half-century of internal conflict that has produced over 8 million victims, including over 23,000 deaths.[2]

4.2.1 Data collection

Following the characterisation of the spatial structure of IWT in Colombia made by Bonilla et al. [38] and Arroyave et al. [13, 10], we strategically selected 8 departments where poaching and ex-situ consumption of wildlife is more prevalent (see Supplementary Figure 1). In each department we first contacted the authorities charged with the control of IWT, and then identified other relevant actors using a snowball sampling based on the information provided by the authorities. Actors are described in the next section. Overall, our study includes actors from 7 regional environmental authorities, 7 environmental police units, 2 rural communities where poaching is carried out and 3 supporting organizations. We acknowledge that smugglers, captive-breeding companies, non-local consumers and other actors are also important, but they were beyond the methodological capabilities of this study.

The interviews with the identified actors were inspired by the fieldwork done in the project *'Implementation of the plan for sustainable use of the hicotea turtle in Colombia'* (2012) funded by the ministry of environment and development and the Universidad Nacional of Colombia. Two interviews developed during the mentioned project are included here. Further details regarding sample representativity, the questionnaire used, ethical approach, procedures during the interview, and other aspects can be found in the Supplementary Materials (SM). It's important to note, our sample is representative of the environmental and police authorities, and likely of supporting organizations. Our study initially included 2 academics that were removed because they are not representative of their community. However, results including the academics are shown in SM as we think that including the attitudes of academics is relevant -even if they are not representative- since it might help us picture potential convergences (and divergences) in the attitudes of coexisting actors.

The lead author of this study developed open-ended interviews that varied from 25 minutes to 150 minutes, approximately. Interviews usually lasted at least 60 minutes and were led by the interviewee. A questionnaire was used to guide the interview and the questions were asked, merged or removed according to the rhythm of the interview. The purpose of the interviews was to capture the individuals' perceptions, thoughts and preferences (i.e. their attitudes). The information was collected by notetaking, and the interviews focused on five domains of the problem: *a*) recognition of the issue, *b*) identification of causes, *c*) identification of consequences, *d*) characterisation of alternatives and *e*) relations with other actors. The interviews also sought details about the interviewees' specific activities and practices. Some of the interviews involved more than one interviewee; these interviewees nonetheless expressed similar thoughts (see SM).

4.2.2 Characterisation of actor types

The four actors' types included are: individuals from rural communities -where poaching is frequent-, environmental authorities, control authorities (i.e. environmental police forces) and supporting organisations. In what follows we briefly describe them and introduce their interactions with the IWT operation.

Rural communities

The rural communities addressed here, like with others in Colombia, are composed of peasants and fishermen who do not own land – or are small landholders, at best. They exist in high or extreme multidimensional poverty. These communities share a mestizo ancestry (i.e. indigenous and/or afro) that is demonstrated in their practices, beliefs and myths [287, 112]. Wildlife consumption is an important part of their economy and cultural heritage [38, 39]; indeed, selling wildlife and its derivatives represents a temporary, albeit necessary, income for many families. Colombian jurisprudence states that subsistence wildlife consumption is a legal and legitimate custom, though it only provides a narrow definition of subsistence.[3] Only direct and immediate consumption is permitted, despite the fact that selling wildlife surpluses or possessing organisms for later consumption might be essential for household economy. Therefore, any attempt to sell or harbour wildlife products could be considered as illegal trade, and thereby encoded into law by the judiciary as an environmental offense.

Environmental authorities (*'Corporaciones autonomas regionales'*)

These authorities[4] are regional administrative units -commonly one per department- that have been legally mandated to manage, control and survey natural resources and conduct administrative and sanctioning processes. Controlling IWT encompasses reactive law enforcement and preventive actions, and control is frequently reduced wildlife confiscation, after which the organisms must be rehabilitated (when possible). Environmental authorities also provide technical assistance to the prosecution authority ('*Fiscalia*') and the law administration system when punitive actions are pursued. Legal mandates allow environmental authorities to confer part of their responsibilities to other authorities.

Control authorities

These authorities include police and armed forces that support environmental authorities by implementing control. In Colombia, police are divided into separate functional branches (e.g. criminal investigation, highway patrol), though any branch works to ensure law compliance. Of importance to this study, the environmental and ecological policy branch focuses on environmental law compliance, including felonies such as animal cruelty. This branch may actively seek and conduct confiscation of wildlife products and support environmental authorities in other activities such as education. Although police officers can act with autonomy, they must inform and coordinate with the local environmental authority to perform confiscations.

Table 4.1: **Propositions used for evaluating attitudes**. Propositions are grouped into domains that describe the goal pursued.

Domain	Proposition
(a) Recognising the issue	(a1) IWT is a recurrent problem in the territory.
	(a2) IWT is operated by criminal organisations.
	(a3) The market for wildlife is structured and can be described.
(b) Identifying consequences	(b1) Ecosystems or species are severely affected by IWT.
	(b2) Human communities and practices are affected by IWT.
(c) Identifying causes	(c1) Illegal uses of wildlife are important for cultural heritage.
	(c2) Wildlife constitutes an important good for local gastronomy.
	(c3) IWT is driven, to a great extent, by cultural factors.
	(c4) Poverty is a significant cause of IWT.
(d) Characterising Alternatives	(d1) Alternative uses (e.g. ranching) are feasible.
	(d2) Law enforcement is needed to reduce IWT.
	(d3) Education is needed to reduce IWT.
	(d4) Government should support communities to prevent IWT.
(e) Describing their relationship with others	(e1) The organisation is interested in cooperation.
	(e2) The organisation is currently cooperating with others.
	(e3) The relationship with your closest authority* is good.
	(e4) Authorities that control and prevent IWT are doing a good job.
	(e5) IWT is a concerning issue within the organisation.

**Closest authority refers to the one with whom the actor interacts the most – this frequently means 'environmental authorities'. In case of Environmental authorities, it corresponds to police authorities.*

Supporting organisations

These organisations provide the necessary facilities, staff and experience for treating organisms illegally traded, which environmental authorities usually lack. In this study, we include zoos and zoo-like organisations that vary in nature (NGOs, civil organisations) and purpose (exhibition, ex-situ conservation). Supporting organisations provide triage and first aid to confiscated animals and take custody of those that are unable to be returned to their habitats, which are used for education.

4.2.3 Analytical approach

For analytical purposes, we summarised the questionnaire into 19 propositions (Table 4.1). Based on the notes taken, we inductively establish the actor's attitudes regarding the propositions (see SM) using a scale that includes agree (+), disagree (-), and undecided or not answered (0). Then, the attitudes were tabulated in a matrix that was used to implement a correspondence analysis (CA), in which the dimensionality of the matrix is reduced by producing few synthetic dimensions [176]. In the CA, actors with similar attitudes are closely located within the dimensions, whereas diverging attitudes tended to localise farther apart.[5] Finally, we identified clusters (groups) of actors who held similar attitudes by using a hierarchical clustering analysis (HCA) based on the actors' locations in the CA [176].

4.3 Results

The attitudes of the interviewees were diverse and provided enriching information. We first summarise the attitudes by detailing the most relevant elements captured during the interviews, and the commonalities and divergences on attitudes for each actor type. Whilst describing the results, we also refer to literature that further supports or expands on the points made. The purpose of describing the attitudes is to expose how each type of actor frames IWT and foresees solutions to it. Finally, we contrast the different attitudes by using the Hierarchical Cluster Analysis (HCA), where we reveal the overarching attitudes and governance preferences.

4.3.1 Summary of actors' attitudes

Rural communities

Wildlife is an important part of the livelihoods and customs of the rural communities, including cuisine tied to religious rituals,[6] gift giving or traditional medicine [38, 39, 287]. These communities do recognise, however, that wild populations are declining because of human intervention. One community attributed the decline to overharvesting, while another connected it to mining-related pollution of upstream water sources. Species decline was deeply concerning for these communities, as it represents the extinction of cultural practices and food insecurity. Notably, these communities focused their consumption on a limited number of species that are (or used to be) abundant

[331].

Wildlife constitutes an important part (if not the only source) of protein intake during the poaching season [10, 39, 38]. Fishing is the main source of employment for these communities. The catch is often sold in nearby markets; it is rarely consumed in the household because the income is required for purchasing products such as rice or oil. Selling wildlife species within the community, along highways, in urban markets and to intermediaries also occurs frequently [39, 331]. Although communities acknowledge other uses of species, such as for the production of leather and musical instruments or as pets, they claim that such uses are infrequent.

These communities are aware that selling or possessing wildlife is illegal, but for several reasons, they continue to use wildlife despite the legal consequences. First, communities are deprived of other production means and use wildlife to meet their needs and to acquire essential goods. Second, government apparatus is seen as corruptible. In fact, a participant in one collective interview stated that he sells crocodile skins to an environmental authority staff member who then resells the skins to a captive-breeding skins producer. The environmental authority staff member responded by saying that 'communities like to make jokes'.[7] A member from another community indicated that if someone gets caught by the police, they only must *'pay the fee'*. He also stated that big smugglers of wildlife have contracts with police officers that allow them to pass through control points. Third, the national government is mostly absent except during electoral times or to enforce law, and therefore has become non-credible to community residents. Law enforcement mainly occurs when IWT is recurrent (e.g. during Easter) and with high community resistance. Fourth, the government is not considered to be reliable. For example, one community tried repeatedly to implement legal exploitations of wildlife, but a lack of governmental support (technical, legal and financial) impeded the community's success. The communities regarded enclosed exploitation as mechanisms for local development and species conservation, but they were easily frustrated when their expectations differed from the outcomes. For example, a community member dug a pond in which he raised tortoise and alligator hatchlings (which is considered IWT) with the expectation that he would complete the breeding cycle in a couple of years; in reality, the breeding cycle is much longer than that [38].

Environmental authorities

Attitudes of environmental authorities are diverse and are partially drawn from their roles. Some environmental authorities in poaching regions argue that wildlife constitute an important aspect of local customs (e.g. gastronomy), whereas the authorities closest to the cities claim that the species are used as pets or souvenirs (e.g. decorative skins) for reconnecting with nature. These authorities demonstrate a good understanding of the IWT operation,[8] and they frequently highlight the economic incentives behind IWT or the relevance of particular species for community's subsistence and beliefs.[9]

Environmental authorities face bottlenecks when implementing control and enforcing laws, which promotes the continuity of IWT with impunity. For example, only a limited number of staff members (mainly contractors without employment benefits and stability) are responsible for curbing IWT (among other activities) across vast areas; these members often lack training and equipment. Although IWT is a concern for them, it is only one of many issues they are responsible for. These authorities argue that prosecution entities lack commitment,[10] which results in impunity, even for big smugglers of wildlife. This weakness in the justice system is enhanced by the failure of environmental authorities to make their cases in court. Impunity is also exacerbated by leaks; authorities have been known to alert smugglers to raids. Although many environmental authorities feel unsupported by other government entities, some do argue that after years of relationship building, they have forged effective pathways for collaboration.[11]

According to their experiences and the successful experiments, environmental authorities propose education and law enforcement as the main mechanisms for diminishing IWT. For instance, one interviewee asserted that creating sensitivity around animal welfare and cross-species ethics was effective for reducing the demand. Other interviewees expressed that propaganda regarding legal and ecological consequences of IWT discourages this practice. The interviewees also acknowledged that education must transcend communities and include prosecution institutions and law administrators to increase their awareness and commitment. Interestingly, environmental authorities framed academics as disconnected actors who do not provide pertinent and timely knowledge because they are motivated by different objectives and the need for funds.

Control authorities

Police officers usually have an urban background; therefore, they are often disconnected from the culture and heritage where poaching takes place. They do, however, identify the routes and means that are used by wildlife smugglers. The police officers interviewed argued that poaching is driven by revenue, whereas consumption reflects a 'narco' culture[12] that is tied to the boom of drug cartels in the 1980s. One officer indicated that IWT is driven by superstition and witchcraft. Other officers acknowledged the value of particular species for communities' livelihoods. Given its profitability, however, IWT has become co-opted by some organised groups, including armed ones.[13] Organised groups are sometimes family structures that develop portfolios of wildlife and engage in by-demand IWT to reduce smuggling and storage risks. The officers expressed concern about the ecological consequences of IWT as it has generated rewilded populations of potentially invasive species.

Multiple limitations hampered the effectiveness of anti-IWT activities. Manpower is commonly lacking; for example, IWT control for an entire city is responsibility of only one police officer. Infrastructure, logistics and budget are typically scarce; for instance, in one city officers only have a motorcycle for patrol and transportation of confiscated animals (e.g. sloths and ocelots). In contrast, in one exceptional example, in another (equivalent) city there are as many fully equipped vehicles as officers.[14] Another limitation is that environmental authorities are not always available to accompany officers to control points or receive confiscated organisms, especially at night or on weekends. Such unavailability forces officers to keep custody of confiscated wildlife without (most of the time) having received appropriate training or resources. Indeed, the interviewees pointed out their own lack of pertinent knowledge in identifying, handling and caring for confiscated wildlife. They highlighted that prosecution and law administration entities are also unsupportive. The officers also emphasised that high levels of turnover between workplaces and branches[15] resulted in a deep erosion of processes and collaboration forged with other organisations.

The police officers stated that while law enforcement is a necessary strategy for curbing IWT and related gangs, education should be the primary goal when developing prevention activities. Furthermore, they claimed that more well-trained, suitable and committed officers are needed and that their labour must be better appreciated within the organisation.

Supporting organisations

These actors perceive wildlife consumption as an extended practice that is becoming less common due to changes in consumer preferences and nutritional alternatives. However, they asserted that the use of wildlife as pets is frequent and likely increasing. Wildlife use has been associated with elders, who are the most reticent to change their behaviours. Consequently, demand-reduction programmes should focus on children, who are more receptive and will echo the message in their households. Most of the staff in the supporting organisations are veterinary doctors who emphasise the medical consequences of IWT, including high mortality rates, undernourishment, malformations, mutilations and infections, as well as endocrine, nervous and behavioural disorders [225]. Given that many of the confiscated animals (mammals and adult animals in particular) cannot be released back into nature, they often end up being used for exhibition or education. Supporting organisations are frequently overloaded and lack the technical and financial capabilities to diagnose and maintain the confiscated wildlife that come into their care.

Education is generally included in the mission of supporting organisations, and this is seen as a primary tool for curtailing IWT. These organisations argued that education is effective, especially when communities have the will to change. Notwithstanding this, a portion of the community tends to resist change, openly recognising that if given the chance, they will continue to consume wildlife. Furthermore, supporting organisations indicated that economic alternatives are necessary for highly disadvantaged communities that supply wildlife smugglers. Such alternatives are expensive and governmental funds are often insufficient and inconstant, which affects the effective engagement of local communities.

4.3.2 Mapping attitudes

The statistical analysis of the attitudes revealed three groups or clusters of neighbouring actors mapped in the Correspondence Analysis (CA) that share similar attitudes (Fig. 4.1). The clusters identified by the Hierarchical Clustering Analysis (HCA) reflect commonalities regarding the framing of IWT, possible solutions and management preferences. We refer to those commonalities as the frame of reference, or the particular set of assumptions and attitudes used to filter the perceptions of a phenomenon to create meaning [329]. In what follows we present the main results of the CA, the composition of the clusters identified and their corresponding frame of reference.

The CA explained more than 60% of the total variance in the first three dimensions and the main results do not vary when the academics interviewed are included (SM). The first CA dimension is mostly composed of propositions e5, c2, d2, and c4 (Table 4.1), or of the inclination (or lack thereof) to acknowledge that IWT is important for communities, is boosted by poverty and requires more law enforcement. The second dimension is largely composed of propositions e4 and a2, which indicates the inclination to defend authorities and criminalise IWT. Propositions c3 and c4 composed the third dimension, in which poverty and culture are recognised as drivers of IWT (Fig.4.1).

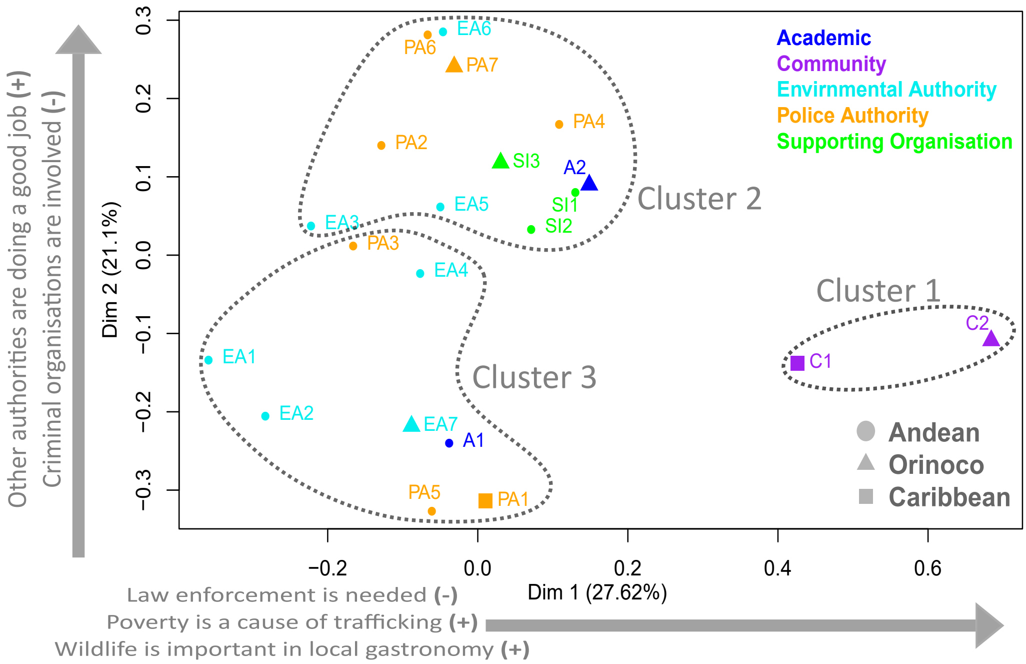

Figure 4.1: **Evaluation of attitudes of actors regarding illegal wildlife trade using CA.** The first two dimensions are shown and the corresponding variance is explained. Actors are clustered according to their positions in the CA. The colours identify the different types of actors and the shapes represent the geographical regions in which they are located (see SF.1). For each dimension, it is indicated which variables (Table 4.1) contribute the most and whether they increase (+) or decrease (-) with the arrow.

The first cluster is composed of the local communities, who regarded poverty as the cause of IWT. Therefore, law enforcement was not seen as a direct solution; instead, it was seen as a source of conflict with authorities. This group advocated for species management based on local sovereignty rather than in the more common top-down approach, as their management experiments suggest. Several experiences have shown the viability of such a governance model [79, 78, 283], which nonetheless requires a long-lasting commitment of both the communities and the government, as well as subsidies, incentives and other neoliberal strategies of governance – a situation that is not always affordable or able to meet the expectations of all of the parties.

The second cluster contained environmental authorities, police authorities and supporting organisations. This group is predominated by the concept of IWT as a sociocultural problem that has severe implications for communities. This group hesitated to recognise the existence of criminal groups and perceived other actors as committed and willing to cooperate. This group emphasised a governance based on discipline in which education serves as a central mechanism for reducing IWT by promoting demand reduction, a controlled offer and a better in situ use of species (biopower). Although some actors in this group also saw neoliberal incentives as mechanisms to reduce IWT, such mechanisms remained unclear.

The third cluster, composed by police and environmental authorities, stressed that IWT is operated by criminal organisations, but they were not inclined to recognise its social effects whilst posing poverty as a main cause. Notably, this cluster argued that the problem is not taken as seriously as it should be and perceived law enforcement as an important mechanism for the control of IWT, despite their mostly negative perception regarding their peers and other actors. Contradictorily, this group also advocated for a top-down sovereignty approach whilst expressing a lack of confidence in the entities that enforce the law. In addition, this group indicated that neoliberal strategies that foster conservation, alleviate poverty and reduce IWT are rarely feasible.

Importantly, a salient aspect from the analysis of attitudes and the emerging frames of reference is the differences between actors of the same type. For example, environmental authorities were divided (roughly by half) between those who were more inclined to criminalise IWT and communities (Cluster 3), and those who were not (Cluster 2). One might think that such a difference would correspond to the phase of IWT (poaching, smuggling, consumption) faced by the actors, nevertheless there was no association between actors from the same regions (Fig. 4.1), therefore the segment of the market (i.e. offer, demand) existing in their jurisdictions. Similar results can be found for police authorities. Altogether, our results suggest that the frames of reference likely revealed individual experiences, biases and preferred modes of governance, rather than the functional, institutional or geographical contexts of the actors.

4.4 Discussion

Illegal wildlife trade (IWT) presents a harmful problem that must be addressed. However, the wicked (ill-defined) nature of the problem [14, 359], evidenced in ongoing debates in academia and society at large [71, 106], resists any *'silver bullet'* type of solution [61, 92]. Multiple perceptions of and approaches to understanding and addressing (i.e. attitudes) the problem exist, and it is necessary that these be acknowledged for the management of IWT and the inclusion and engagement of the government and society.

This study evaluated the multiple attitudes regarding IWT as an initial step towards designing more effective, inclusive and just management strategies for the curtailment of IWT. Our case study results reveal a diversity of attitudes that can be expressed in three general frames of reference, which are informative for management and policy making purposes. Notably, the frames of reference are associated to how IWT is understood, solutions to it are framed and the underlying models of governance (governmentality). Communities advocated for an in situ sustainable management approach in which they can actively participate and benefit (bottom-up sovereignty), whereas authorities and other organisations posited controlled and restrictive use as mechanisms of conservation, suggesting relying on either education/propaganda (discipline) and economic alternatives (neoliberal environmentality) or law enforcement (top-down sovereignty). Similar to other studies [338, 160], our results suggest that this differentiation in attitudes is driven by competing uses of resources (consumption/commerce vs. conservation).

Contrary to theories that posit social interactions and contextual factors as drivers of agreement between actors [36, 91, 77], our results did not indicate a clear association at the social (interact with whom), organisational (actor type) or functional (which segment of the market is addressed) levels. Besides preferred species use, the frames of reference seemed to be influenced by narratives (e.g. criminalise poachers) and individual biases, even in the case of academics. The results suggest a lack of institutionalisation of narratives [113] and a dearth of communication and knowledge circulation [317, 14] evidenced by the tension and the differences in attitudes of equivalent and interacting actors (i.e. actors of the same type and same region).

Like other complex problems, the management of IWT requires, at a minimum, agreement between the different actors involved [92] and that organisational barriers and weaknesses, such as those discussed above, be overcome. Importantly, reductionist and short-sighted strategies that ignore the nuances of the problem are likely to be ineffective [47, 136, 181, 92, 225]. We therefore argue that management strategies to reduce and control IWT will not succeed without inclusive agreements regarding the characteristics, nuances and complexities of IWT, the best ways of curbing the problem (i.e. alignment of attitudes) and the participation of most of the actors involved in IWT (for and against) at regional scales.

We acknowledge that this study has some limitations and can't be generalized to all types of actor or geographies. First, our sample is relatively small, biased towards particular regions and only representative of authorities. Second, due to security concerns, the interviews we conducted were restricted to local communities in which IWT is common but is not the main activity. Third, our sample unintendedly contained more males than females.[16] Fourth, we focused on the actors' perception and opinions rather than official organisational stance, which would require further analysis. Finally, not all of the actors involved in IWT were included in this study; despite this fact, our case study does include a large diversity of actors.

In light of our results and this study's limitations, we argue that management strategies must advance towards 1) recognising the value of wildlife for local communities, thereby better defining the boundaries between legitimate and illegal use of wildlife [47, 102, 136, 333]. We acknowledge that while, for example, selling wild species as pets is despicable, selling and exchanging these species for consumptive purposes within closed communities might be acceptable if it is properly managed. 2) Reducing tension and mistrust between local communities and governmental entities, and between collaborating organisations. Efforts championed by an organisation cannot succeed without the help of those who complement and support them [61, 92]. 3) Increasing integration between actors, enhanced cohesion, knowledge circulation, cross-fertilisation, trust and nurturing. All of them are the basis for strengthening organisations [338, 225] and therefore, reducing impunity. Further communication and knowledge circulation between the parties might favour consensus formation, experiences interchange, experimentation testbeds and the generation of collaboration pathways. 4) Optimising control; although findings indicate the existence of criminal organisations that apparently include governmental officers and private corporations, as has been previously reported [15, 360], such structures have not been properly addressed by law enforcement, as the findings of Arroyave et al. [10] indicate.[17] 5) Reframing and institutionalising the governmental approach to environmental problems. Although there have been successful experiences of community–government partnerships,[18] the current military/repressive approach[19] may hamper future partnerships, and ultimately, conservation goals [101, 168]. Finally, 6) partnership with academics, prosecutors and law administrators should increase and overcome the perceived lack of commitment or conflicting goals. Such a partnership has the potential to improve the efficiency of curbing strategies as well as to foster synergies and the development of new management strategies, as well as further consensus among academics regarding IWT complexity.

4.5 Conclusions

Environmental problems as complex systems involve multiple views, understandings, perceptions and preferences between actors, and this has important consequences for their management. This study reveals how actors' attitudes are shaped by perspectives regarding how illegal wildlife trade should be governed. Contrary to the findings of previous studies [77], attitudes are not largely affected by contextual factors, but rather by individual biases related to the purposes served by wildlife and therefore, biases regarding approaches for curtailing IWT. Notably, fundamental elements for effective management (e.g. agreements, shared visions and trust) were widely absent in our case study, while a lack of institutionalised narratives indicates limited communication within organisational structures and between complementary parties and therefore, narrow circulation of knowledge. We argue that in addition to institutional weaknesses, the notable differences in the participants' attitudes related to the duality of consumption and conservation might lead to further marginalisation of local communities and species vulnerability.

Supplementary Material

Supplementary materials are available at https://zenodo.org/record/7636770 and include: **Supplementary Figure 1**: Geographical coverage and context of the interviews developed. **Supplementary Note 1**: Characterization of the sample sites. **Supplementary Note 2**: Sampling method. **Supplementary Note 3**: Ethical guidelines. **Supplementary Note 4**: Interviews development, trust and rapport. **Supplementary Note 4**: Establishing attitudes regarding the propositions. **Supplementary Note 5**: Analysis of results including Academics.

Notes

[1]Including overharvesting, habitat deterioration, expansion of agro-industrial fields, among others.

[2]Colombian population is about 44 million people, thus near the 20% of the population is victim of the conflict. More official information about the armed conflict and the victims can be found in the National Centre for Historic Memory available here.

[3]See articles 30 and 31 of the National Statute of Environmental Protection (Law 84 of 1989, Colombia)

[4]More details and examples of the 'Corporaciones Autonomas Regionales' can be found here

[5]Similar approaches using attitudes regarding environmental issue have been implemented. See, for instance, Jenkins [160], Jenkins and Jenkins [163], Sundström et al [320]

[6]Catholicism (the dominant religion in Colombia) mandates the consumption of 'white meats' during Easter. Fish and chicken are used in urban contexts, while tortoises and iguanas are the equivalents in rural settings. Rueda [287] posit that the Catholic church defined some wildlife as white meat to ease the adoption of Christianity within indigenous-descent communities.

[7]In this case the environmental authority staff was who introduced the interviewer into the community. The staff member did not take part in the interview and the situation described happened while the community was informed of the purpose of the interview.

[8]One authority claimed that academics are the major traffickers or 'biodiversity predators' because they collect specimens without legal permits or exceeding established quotas.

[9]Communities are superstitious, and some species of turtles are kept in even numbers for good luck. Other species are used as aphrodisiacs.

[10]In Colombia, pressing issues like narcotraffic, manslaughter, and insurrection overload the law administration system causing a generalized impunity.

[11]For instance, the air force has facilitated the transportation of rehabilitated organisms to national parks. Such collaboration is restricted to some environmental authorities and only happens after 'years of trying'.

[12]This refers to the collection of exotic possessions (including wildlife) as a way of showing social status and wealth.

[13]Many officers confirmed that organised armed groups operate IWT. Some officers posit that such groups are also drug smugglers (see Arroyo-Quiroz & Wyatt [15]), whereas other indicate that such groups become organized in a mafia-like business and then got armed.

[14]The Interviewee argued that such equipment was possible thanks to the political will of the city major.

[15]As a non-written police doctrine, officers are reassigned every 2 years (approximately) to distant geographical points that differ in socio-cultural features, and sometimes it means turning environmental police officers into another specialty (e.g., tourism, vigilance) or vice versa.

[16]Although the interviews with communities involved women, the discussion centred on men (household leaders). For the other actors, at least one actor of each type was a woman.

[17]This study reported that in Colombia 90% of the control activities only represent the 3% of all reptiles confiscated (i.e., many small confiscations and few large-volume ones). Therefore, much of the effort is focalized towards small smugglers.

[18]For example, ASOCAIMAN is a representative case in which a cooperative association of poachers/fishers began the process of creating a legal exploitation in a captive-breeding model of Caymans (more details here and see Roe and Booker [283])

[19]After the peace agreement between Colombian government and the FARC guerrilla, deforestation associated to narco-crops and cattle-ranching has increase in national parks. The government deployed a multi-agency military operation called 'Artemisa operation' (2019) in which small farmers (not related with coca) were presumably disposed from their (illegally occupied for decades) lands after being blamed for the ongoing deforestation. More information about the case can be found here, here, and here

Chapter 5

Network Embedding for Understanding the National Park System Through the Lenses of News Media, Scientific Communication and Biogeography

The U.S. national parks encompass a variety of biophysical and historical resources important for national cultural heritage. Yet how these resources are socially constructed often depends upon the beholder. Parks tend to be conceptualized according to their (fixed) geographic context, so our understanding of this system of systems is dominated by this geographic lens. To expose the systemic structure that exists beyond their geographic embedding, we analyze three representations of the national park system using park-park similarity networks according to their co-occurrence in: (a) 423,000 news media articles; (b) 11,000 research publications; and (c) 60,000 species inhabiting parks. We quantify structural variation between network representations leveraging similarity measures at different scales: park-level (park-park correlations) and system-level (network communities' consistency). Because parks are governed and experienced at multiple scales, cross-network comparison informs how management should account for the varying objectives and constraints that dominate at each scale. Our results identify an interesting paradox: whereas park-level correlations depend strongly on the representative lens, the network communities are remarkably robust and consistent with the underlying geographic embedding. Overall, our data-driven methodology is generalizable to other geographically embedded systems and supports the holistic analysis of systems-level structure that may elude other approaches.

5.1 Introduction

The U.S. national parks (NPs) are representative pieces of North American natural and cultural heritage, where managers, visitors and many other stakeholders can experience NPs wonders and contribute to their conservation. Ecological complexity and its geographical embedding are frequently seen as keystone elements of NPs management, whereas social complexity is overlooked despite it is a significant challenge for NPs managers, especially at light of the NPs' dual mandate to preserve nature and facilitate visitation [299, 105, 161]. Addressing social complexity involves considering the multiplicity of attitudes of diverse stakeholders [203, 235]. For example, decision-making in NPs should consider the 'best available science' and social concerns [144, 162, 204], even when they contradict each other. Whilst studies have addressed attitudes' multiplicity regarding NPs by evaluating how NPs are framed in social media [203, 205, 304], they seldom evaluate systemically how framings and representations vary across stakeholders; a valuable resource to inform NP policy and communication. This study leverages network analysis to explore the interrelation of three different NP representations (i.e., biodiversity, scientific research, and mass media) and their implications for NP management.

Historically, NPs management has been challenged by different societal sectors given that NPs dual mandate rarely implies satisfactory outcomes for everyone [182]. The diversity of management preferences regarding NPs might promote disagreement and controversy, which could explain long divides existing between NPs management, science and the public [122, 14, 299]. For instance, some NPs policies (e.g., predator control) might satisfy public interests while being scientifically unsound, whilst others (e.g., prescribed fire) might adhere to the best available science and nevertheless cause social discomfort [299]. We argue that such divergence in preferences undelays how different stakeholders frame NPs.

How phenomena such as NPs are framed depends upon internal (e.g., preconceptions, experiences, interests) and external conditions (e.g., funding, institutional agendas, bureaucratic barriers). Such conditions steer how NPs are experienced, known and felt [53, 179, 247, 304, 327]. For instance, a framing about NPs from a particular academic lens is influenced by existing knowledge, physical and financial capabilities, scientific hierarchies and agendas [14]. Although experiencing NPs, as a primary way of knowing and framing NPs, was restricted to a portion of the population [299, 304], communication systems have opened NPs up to the broader public. Communication systems, such as online social networks, mass media, and scientific communication, enable the emergence of new frames and geographies where NPs can be experienced and re-imagined [53, 205, 304, 315]. For instance, scientific publications and mass media are rich sources of information and intertwined communication channels for catalyzing action, however, there is a disconnection between priorities and prominence of discourses between both forms of communication as they might differ on how a phenomenon is framed [54, 255]. Studies have largely focused on how NPs are framed in online social networks [203, 205, 235, 327], yet such consumer-oriented approach do not inform about frames used by other stakeholders or bring insights regarding the NPs system structure looked through the lenses of multiple audiences.

Emerging frames and geographies are socially constructed by different stakeholders (e.g., scientists, journalist, media editors) based upon existing imaginaries, value systems and mental shortcuts that facilitate making sense of the problem [54, 232] and developing representations of the system and their interdependences. In this study, we develop a method that quantifies the systems' representation by analyzing the similarity between NP-NP pairs. When aggregated, the entire set of NP-NP relationships render a systematic representation of the NP system structure. Moreover, to assess how representations depend on the lens used, we construct three different NP networks based upon biodiversity, scientific research, and mass media data specific to each NP. We then apply network comparison methods to assess the similarities between the representations themselves. The advantage of embedding the system of NP within a network is to facilitate the evaluation of structural properties from the local (NP unit) to global (system) scales [227, 40] and to inform management about differences in NPs framing between stakeholders.

In what follows, we first introduce the dataset built to evaluate the different representations of the U.S. NPs system and the networks methods used for analyzing the interrelation between representations at different scales. We then analyze a paradox of scales, namely a weak local consistency in the NP-NP relationships, that nevertheless translates into robust system-level structure largely corresponding to the system's geographical embedding. We conclude by discussing how local versus global information contained in the network embedding informs management.

5.2 Methods

This study evaluates three different representations of the U.S. NPs system by identifying relational configurations between NPs as they appear in two types of public communication: scientific publications (research) and mass media (media). Research and media representations are indicative of how scientific and public stakeholders frame the system. Additionally, a third representation accounting for biogeographical features of NPs (biodiversity) is included as benchmark for comparison. In what follows we introduce the data used to reconstruct the NPs representations, and then we describe how network representations are analyzed.

5.2.1 Data

We collect data specifically designed to address each dimension. First, the biodiversity dimension is evaluated through the species inhabiting each NPs as reported in the Integrated Resource Management Applications (IRMA). Such species lists including animals, plants, fungi, and bacteria, contain 153,534 entries referring to 59,588 species. It is expected that NPs with similar biogeographical characteristics share a significant number of species. Hence, the NP system representation based on co-occurring species reflects the most traditional representation of the system according to its intrinsic geographic embedding.

Second, the information regarding scholarly research was collected through Web of Science (WoS), a longstanding and widely-used index of scientific research published in established peer-reviewed journals [186]. By searching the publications containing "National Park" and limiting the search to the U.S. and the years 2010-2020, we gather information from nearly 11,000 research publications. Records for each publication comprise information regarding authors, title, abstract and keywords. We then identify 8,941 publications mentioning one or more specific NPs by string matching NP names with the content of publication (i.e., title, abstract, keywords).

Third, we recover media articles mentioning NPs by way of the MediaCloud project, which is a system that indexes and curates information derived from articles published in newspapers and magazines, blogs and other (print and online) sources. A keyword-based query of the MediaCloud returns a list of articles featuring that specific entity, which facilitates analyzing a wide-ranging set of voices, including scientists, journalist, politicians, and the general public [255]. Over the same period 2010-2020, we identify 423,002 media articles that specifically mention at least one NP by its official name. The articles were disambiguated as some of them could be the same article but with small variations at their URLs or title [255]. Also note that we can only evaluate the temporal dynamics of research publications and media articles, as species list do not account for time-related variations.

The distribution $P(n)$ that quantifies the relative frequency of exactly n NP co-occurring within the same dimension (research or media) indicates that most communications only mention a single NP unit, yet a non-negligible fraction of each corpora mention various NPs simultaneously (Fig.5.1). Interestingly, the distribution $P(n)$ calculated for both research and media follow a remarkably similar statistical regularity, evidenced by the inverse-linear decay when the frequency distributions are plotted on logarithmic axes; these distributions are also invariant when evaluated across non-overlapping time windows. Such statistical regularities are distinctive of complex systems and describes the atypical and disproportionate importance of rare elements in the system [227, 326]. In our case, the distribution is indicative of the inherent limitation of mentioning several NPs simultaneously given, for example, human communicative restrictions and optimizations deriving from bounded context [18].

5.2.2 Data analysis

Network representations are formed from the aggregate composition of dyadic NP_i-NP_j interrelations, that quantify the NP-NP similarity based on their co-occurrence in scientific publications and media articles, or the species featured by them. Networks are composed of nodes (NP units) and links connecting each pair of nodes if, for example, there is at least one media article mentioning both (see Fig.5.2). For each NP-NP link, we quantify the degree of similarity using the Jaccard similarity index, defined as

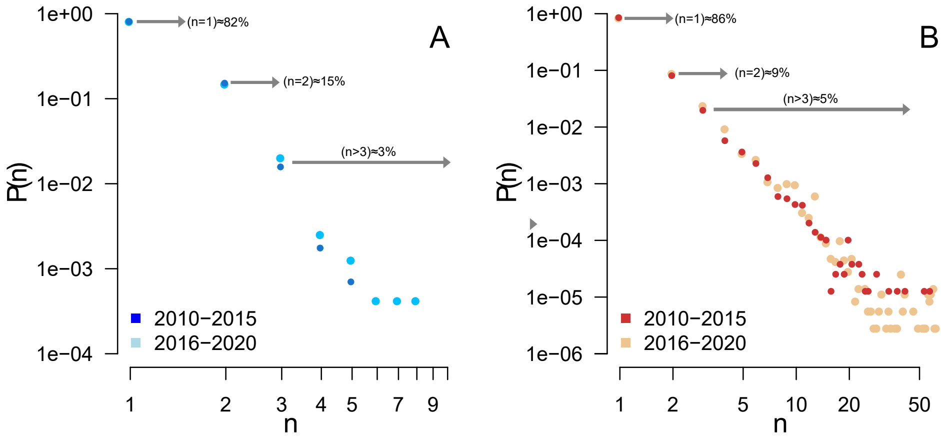

Figure 5.1: **Frequency distribution of the number of NPs mentioned per research publication (A) and media article (B).** The extremely skewed distributions indicate that the vast majority of communications feature just a single park. However, there is a statistical regularity exhibited, where infrequent but non-spurious occurrence of communications that feature two or more parks is indicative of the system-level structure that extends well beyond the geographic embedding.

$J_{ij} = (R_i \cap R_j)/(R_i \cup R_j)$. This index evaluates the fraction of shared elements (i.e., species, research publications or media articles) between two NPs ($R_i \cap R_j$), with respect of the whole set of elements associated with both ($R_i \cup R_j$). The Jaccard Index varies from 0 (no shared elements) to 1 (complete overlapping of elements) and appropriately accounts for differences in the respective sample sizes.

We are interested in evaluating the similarities across network representations at two different scales: microscopic (node level) and mesoscopic (network structure level). At the mesoscopic scale we infer similarity based upon a direct comparison of each network's community structure obtained using the Louvain's algorithm [32]. At the node-level, various methods for comparing networks have been developed [206, 294, 323, 355]. Given the networks' characteristics, a suitable method must consider: (1) networks being compared contain the same set of nodes; (2) the links are weighted; and (3) network can be fragmented. Unfortunately, according to Tantardini et al. [323], only distance-based methods satisfy these three conditions. To address this methodological gap, we develop a 'nodal correlation' as a distance-based metric to evaluate the differences between networks at the microscopic (node-level) scale. One advantage of this method is it can identify those nodes that contribute the most to the similarity between the two networks.

Nodal correlation is based upon comparing the ego-network of a given node i between the two networks a and b being compared, while considering the set of link weights for a node $\{J_{ij}\}_a$ (resp., $\{J_{ij}\}_b$). The nodal correlation for node i is defined as the Pearson's correlation R_{ab} between the pairs. As such, R_{ab} values approaching +1 indicate reinforcing similarity across the two dimensions; negative R_{ab} values approaching -1 indicate opposing similarity, such that if a link is strong in one network then it is weak in the other; and R_{ab} values close to 0 indicate no similarity for node i across the two networks.

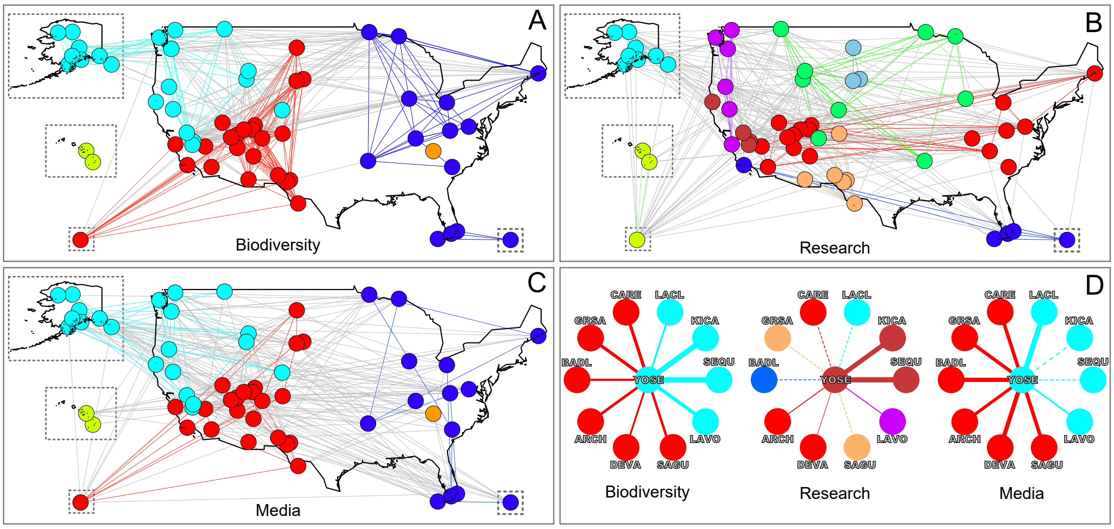

Figure 5.2: **Network representation of the U.S. national parks** according to their biological similarity (A), their co-occurrence in research publications (B) and in media articles (C). Nodes are colored according to the communities using the Louvain algorithm. Biodiversity and media networks are clustered and visualized using only a portion of the strongest links. Boxes in dashed lines are re-located and the box corresponding to Alaska is downsized to a 25%. (D) Example ego-networks of Yosemite NP (YOSE). Line thickness is proportional to NP-NP similarity and dashed lines correspond to values close or equal to zero.

By way of example, Fig. 5.2D shows a portion of the ego-network for Yosemite NP (YOSE) for the three dimensions. Note that there is a positive correlation in corresponding link weights of biodiversity and research networks, largely attributable to the co-occurrence of YOSE with its geographic neighbors KICA and SEQU. However, comparing biodiversity and media, we observe asymmetric link weights, which contributes to a more negative nodal correlation values than in the previous case.

5.3 Results

Networks representations of the U.S. NP system offer several insights regarding how the systems is structured around its biodiversity, how it is researched, and how it is imagined (Fig.5.2A-C). Networks representations include 62 NPs (JEFF was excluded since species are not reported for this NP). All networks are completely connected when aggregating observation data over 2010-2020, however at the annual level the networks are fragmented to varying degrees. Interestingly, the networks are dense and have high abundance of weak links. In what follows, we present the results of nodal correlations (microscopic analysis) and then the results of communities' structure (mesoscopic analysis).

5.3.1 Microscopic analysis

The ego network illustrated in Fig.5.2D shows the local network that is representative of a NP-specific management perspective. This microscopic perspective is contrasted with a mesoscopic (i.e., community-level addressed in the next session) and even system-level perspective (associated with the global connectivity of all nodes). Qualitatively, the nodal correlation measures to what degree a given NP is framed in similar ($R_{ab} \approx 1$), unrelated ($R_{ab} \approx 0$) or opposing ($R_{ab} \approx -1$) ways by different stakeholders. The later may be source of conflicting imaginaries, governance priorities, and a host of other challenges.

We first consider how the distribution of R_{ab} values calculated for each NP vary over time. Figure 5.3A-C show the average R_{ab} value, along with an error bar indicating the 10-90th percentile range of R_{ab}. Considering first Figure 5.3A which shows the relation between research and media representations, we observe two distinct periods. Between 2010-2012, R_{ab} values are mostly negative, and from 2013-2020 they are distributed around 0. In other words, in the first period NPs frequently researched together rarely coincide simultaneously in media communication, and vice versa. And from 2013 onwards, this antipodal relationship diminishes to the point that there is little relationship between the two frames. Moving next to Fig. 5.3B comparing research and biodiversity dimensions, R_{ab} values are mostly positive with no significant changes in the characteristic level over time, indicating that NPs similar in their biological composition tend to also be researched together. However, the magnitude of R_{ab} values is relatively low, suggesting that the biodiversity dimension captures only a fraction of the

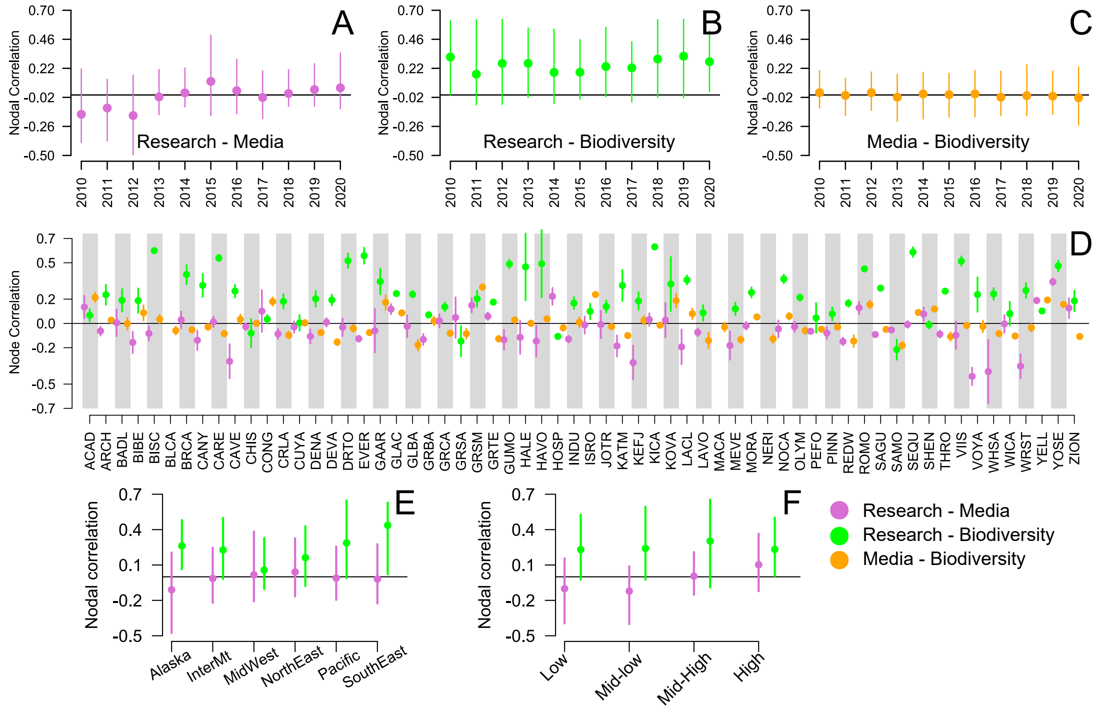

Figure 5.3: **Nodal correlation across multiple layers or representations of the U.S. national park system.** Top panels (A-C) show the temporal variation in nodal correlation (R_{ab}) (using Pearson‘s correlation) between the representations of research, media, and biological networks of the U.S. national parks. Panel (D) shows the variation of R_{ab} for each NP and bottom panels show the difference in R_{ab} clustered in regional (E) and popularity (F) groups, using the same color scheme as the top panel. Circles indicate the mean R_{ab} value and lines indicate error bars showing the 10-90 percentile interval.

connectivity in the research dimension. Finally, comparison of the media and biodiversity networks in Fig.5.3C indicates little relation between these two dimensions, with relatively small variation within year and across time.

Figure 5.3D shows the characteristic value and range of Rab for each NP. Results indicate that trends in Fig.5.3A-C are consistent at the individual NP level. Downscaling to NP units facilitates identifying those NPs with particularly large R_{ab} values. For instance, in the research-media network comparison three NPs with significant negative R_{ab} values are Wrangler-St. Elias (WRST), White Sand Dunes (WHSA), and Voyageurs (VOYA). Interestingly, these three parks simultaneously feature significant positive R_{ab} values for the research-biodiversity comparison, and $R_{ab} \approx 0$ values for the media-biodiversity comparison. Together, this information suggests that the connectivity of these NPs in the media dimension are not driven by research or geographic contexts, and are thus likely related to other important park-system frames such as governance and travel.

To further understand the variation in R_{ab} values, we tested how the distributions relate to NP characteristics associated with administrative region and visitation. Region is defined according to the spatial and administrative division defined by the NPs system, while popularity is defined as quartile groups of NPs according to their 2010-2020 mean number of recreational visits reported in IRMA. We apply ANOVA to test for differences in the mean R_{ab} values calculated for the research-media and the research-biodiversity comparisons, separately. Results (Fig.5.3E) identify statistical difference in the research-media dimensions ($F-value = 2.283$, $p-value = 0.046$) for NPs belonging to the Alaska region. And for the research-biodiversity comparison we identify the Midwest region as being statistically distinct ($F-value = 27.043$, $p-value < 0.001$).

Figure 5.3F shows the analog analysis grouping instead by visitation intensity, which captures both popularity and proximity to large cities. For the research-media comparison, the most and least visited NPs feature statistically significant deviation from the population average ($F-value = 13.515$, $p-value < 0.001$). For the research-biodiversity comparison, none of the visitation groups are statistically distinct, and so the variation in R_{ab} values for this comparison can be attributed to NP-level idiosyncratic factors exhibited in Fig.5.3D that are not related to visitation intensity.

5.3.2 Mesoscopic analysis

Results from the microscopic analysis suggest that network representations of NPs in research and biodiversity dimensions conserve some degree of similarity, while the media dimension seems to be the most distinct of the three. However, mesoscopic analysis shows a contrasting pattern.

First, the biodiversity representation shows a distinction between NPs in the East, Midwest and Northwest (Fig.5.2A). Such distinction is based on the communities identified by the (unsupervised) Louvain algorithm [32], which identifies clusters of nodes by maximizing the connectivity (i.e. links) within clusters while minimizing the connectivity between clusters. Although there are several strong links connecting the clusters internally, there are also several links connecting NPs located in the northern regions, indicating that biological composition follows both latitudinal and longitudinal gradients. Second, research network is structured in several communities that to a large extent are associated with a geographical partitioning (Fig.5.2B). For instance, there is a community distributed in the pacific coast (purple); one encompassing the Alaska region (cyan); one containing the pacific islands (light green). There are some communities (e.g., red) that do not follow a strict geographical pattern. Importantly, a large number of NPs (75%) are found together in the same community in the research and the biodiversity networks. As such, research communities are to a large extent subcomponents of communities that highly correlate with common biodiversity. These results indicate that research addressing multiple NPs tend to be developed in proximal NPs with ecological similarities, which might be associated with the fact that most of the research developed in NPs is related to conservation and biodiversity, as opposed to tourism management for example, and therefore is centered around species ranges or ecosystems. Thirdly, the network representation based on media co-occurrence (Fig.5.2C) shows an identical partitioning in communities of what is shown by the biodiversity representation. Nevertheless, there is little correspondence between the dominant links in the biodiversity and media networks. For instance, looking at the blue community located in the East it is notable that the number of strong links within the community in the media network is smaller than the number of links within the same community in the biodiversity network.

Overall, our systemic, cross-scale and cross-dimension analysis indicates the existence of common mesoscopic characteristics of the NPs network representations in the biodiversity, research, and media dimensions, despite such characteristics are mostly absent at the microscopic level. In other words, regional clustering is an emergent property of the NPs that is recognizable in multiple dimensions and can't be fully explained by the properties of it composing NPs. As such, while local or NP-based framings in scientific research and mass media largely differ, even involving opposing relationships ($R_{ab} < 0$), upscaling to collective perspectives indicates a large degree of agreement in NP system framing, owing to its principal biogeographical embedding.

5.4 Discussion

Managing national parks requires addressing both ecological and social complexity by harmonizing nature protection and public's enjoyment [299, 161, 144]. However, the multiplicity of stakeholders and their perspectives around NPs lead to conflicts between NPs managers and different societal sectors such as the public or academics

[299, 162, 14]. Although NPs management strategies have evolved towards more inclusive and adaptive forms of governance [203, 122], reconciling managerial preferences of multiple stakeholders remains fundamentally problematic. Understanding how stakeholders frame the system is therefore informative for NPs policy and communication design [302].

Our analysis of network representations of NPs in biodiversity, research and media dimensions shows an interesting paradox regarding collective forms of organization: while the NP-NP similarities appear to be highly dependent upon the lens used to construct the representation, meso-level network structure nevertheless are robust and converge towards a geographically localized perspective – independent of the communication channel or the interests of those producing the message (e.g., ecological issues, outdoor recreation). In other words, while NP-NP similarities are indicative of lacking coordination between dimensions, meso-level community structure suggest that research and media frame NPs in a similar way resembling the biogeographical structure of the system defined by their species composition and geographical embedding. Such paradox might be originated by 1) differences in constraining factors affecting science (e.g., funding, experimental design) and media (imagination), and 2) the importance of inter-medium NP-NP similarities and similarities with second neighbors. Such mechanisms are beyond the scope of our analysis and require further investigation. Similarly, further exploration of the mechanisms causing R_{ab} differences at regional and popularity grouping of NPs could bring insights regarding how common mesoscale properties of NPs emerge, and how they can be most effectively and efficiently managed.

In particular, and owing to the expansion of digital communication, the nexus between science and media has become an active area for studying various social processes. However, most of the studies have focused on what information is distributed and how [203, 232, 235, 327], thereby overlooking other cognitive processes such as collective understandings of the problems at hand [53, 179, 352] that originate from bottom-up and top-down significations. We argue that further investigation is needed regarding how stakeholders leverage communication channels at system-levels and how their framing resonates with specific audiences creating a sense of place and meaning [205].

The identification of structural properties at mesoscale in networks is not new [227, 40, 32], nevertheless it brings insights for geography studies and protected areas management. First, the identification of physical spaces that are mimicked by emergent geographies (research and media) at the intersection of systems that transcend digital and material space is notable by itself and highlights the need of system-level approaches for characterizing complex social phenomena. Second, our results suggests that policy and communication strategies emphasizing focal entities (e.g., NP units) might be less effective than strategies based on upper-level forms of organization because local spaces could bring further room for disagreement [182]. Moreover, system-level approaches could facilitate cross-scale coordination, knowledge circulation, and scientific literacy [232, 247, 284, 296] as they leverage global similarity for fostering consensus [14]. In this way, our results shed new light on the nuanced systemic structure that exists beyond the traditional geographic embedding of the US national park system.

Chapter 6

Underappreciated Science Convergence in National Park Systems of the Americas: Parks-Centered Research Reinforces Transdisciplinary Science

Environmental systems are a suite of wicked complex problems that call for holistic approaches and knowledge necessary for making informed decisions and guide actions towards sustainable management regimes. Part of such approaches is the inclusion of the voices, preferences, interests, and experiences of the multiple stakeholders that might contribute to the sustainable management regimes. For example, national parks management needs to address the concerns and contributions of academia, policy and society, which otherwise might promote social tension and discomfort. Indeed, coalitions of multiple stakeholders producing (transdisciplinary) science have been proposed as mechanism for strengthening governance and foster informed and science-based management. Furthermore, the integration of knowledge users in the research process promises to facilitate knowledge diffusion. However, little is known regarding to what extent knowledge users and other stakeholders have participated in research, and how they are integrated in the research systems. In this study, we evaluate the dynamics of transdisciplinary science in the research of the national park systems of eight countries in the Americas. Our quantitative approach assesses the impact of including knowledge users as researchers on the publications' prestige and on downstream research. Our results indicate that little progress have been made towards increasing the participation of transdisciplinary (cross-stakeholder) teams as teams form by the same type of stakeholder show an excess of abundance respect to a random sorting. Furthermore, a panel analysis indicate that cross-stakeholder research is usually more prestigious (up to 18% citation premium) and can derive into more transdisciplinary research, however, publications authored by national parks lack visibility for academic audiences. We argue that more transdisciplinary research in national parks will be beneficial to all parties, and mechanisms for fostering such a research include strategic alliances with governmental actors, which here were identified as brokers at the science-practice interface.

6.1 Introduction

Planetary problems such as climate change or biodiversity loss call for cross-scale initiatives intended to accelerate solutions' development and bring progress towards addressing systemic risks [356, 152, 125]. Global accords to cope with these planetary problems, such as the Sustainable Development Goals (SDG), the AICHI targets, or the 30x30 strategy, have made of protected areas, and national parks (NP) in particular, a cornerstone strategy for protecting species, ecosystems and the services that they provide [264, 341]. These accords have been materialized (at least in paper) on increases in the number, size, and status upgrade of protected areas. However, with the expansion of protected areas different problems arise in social, political, ecological, and managerial domains [351, 236, 76, 348].

Protected areas are complex environmental systems at the nexus of social and ecological dynamics comprising a wicked suite of multiple interconnected problems [143, 286] resisting 'one-fits-all' solutions [92, 14, 4]. Decision-making around protected areas such as NP has high stakes and must consider their dual mandate (i.e. protect biodiversity while allowing public enjoyment), needs and perceptions of the public that cherish NP, law compliance, and importantly, high uncertainty scenarios owing to incomplete knowledge [11, 29, 104, 143, 217]. NP management therefore needs vast amounts of multidisciplinary knowledge regarding the problem at hand while considering the concerns and expertise of multiple stakeholders (Fig.6.1a). By way of example, wildfire management requires considering variability and uncertainty of climate regimes, weather conditions, biophysical aspects of the terrain, human demography, potential systemic risks, among others; In addition to accounting for agency mission goals, public and politic perception, neighbors and visitors' safety and enjoyment. It is worth mentioning that science-informed management has different levels of idiosyncrasy [14, 286] such that learnings and experiences could be transplanted within NP systems, but less frequently between systems. We argue that science convergence is necessary for addressing the challenges, complexity and particularities of NP systems management.

Science convergence as "the coming together of insights and approaches from originally distinct fields" [82] implies blending multiple disciplines (interdisciplinarity) and stakeholders (transdisciplinarity) for enabling the development of coherent frameworks that address technical and conceptual challenges of real-word problems [249, 29, 46, 156, 305]. In other words, science convergence is characterized by intrepid combinations in conceptual (i.e. disciplinary) and social (i.e. actors, institutions) domains [248, 249, 11, 254], necessary to address the complexity of hard problems such as NP management (Fig.6.1a). Studies have shown that conceptual and social convergence have become characteristic of boundary-spanning domains such as grand challenges [343, 284, 248, 249] or environmental problems [24, 11, 29, 46, 156, 365]. Yet, it is unknown to what extent science convergence have integrated relevant stakeholders, such as knowledge user, to participate in the co-creation of knowledge and to produce impact.

Science convergence, as a transdisciplinary form of research, is a necessary element for strengthening science-policy-practice interfaces and developing inclusive and effective management strategies for systems such as the NP. Indeed, transdisciplinary research in NP systems is a necessary step towards closing gaps in information access and knowledge usability [46, 156, 286, 305], and help knowledge users to navigate the systems' complexity. Convergent science in NP could be expected to deliver robust baseline information for understanding phenomena, reconciles existing differences between perceptions, goals and expectations across stakeholders, and fosters development of the much needed in-house capabilities for research [143, 305, 365, 299]. Overcoming the frequently described divide between research and practice in NP systems -owing to differences in background, values, expectations, training and experience- might contribute to orchestrate critical efforts and capabilities at the science-practice-policy interface for developing actionable knowledge that guide and inform decision-making [187, 252, 29, 46, 185, 286].

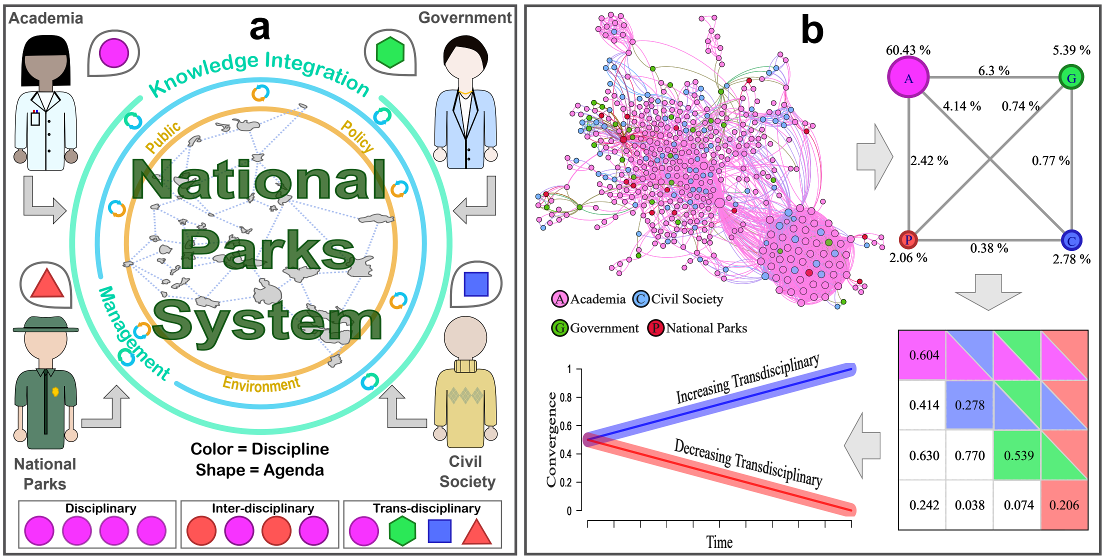

Figure 6.1: **Conceptualization and measurement of transdisciplinary convergence in national parks.** (a) Different types of knowledge producers, each one having particular disciplinary and organizational backgrounds. While management must address environmental, public and political concerns, a management informed by multiple stakeholder could be impactful. (b) Measurement of transdisciplinarity convergence. First, the network of collaboration between in institution is simplified in a network showing the interactions between stakeholders. Then, the network is represented in an association matrix, from which is calculated the convergence index.

Overall, we argue that science convergence is fundamental for informed decision-making as well as for an inclusive management of complex phenomena such as those occurring within NP. Science convergence could thereby promote more actionable knowledge as knowledge users' interests and expertise could be accounted and acknowledged. However, it is unknown to what extent science convergence has indeed integrated knowledge users and what it might imply. As such, this study addresses the following research questions. **RQ1:** To what extent has science convergence taken place in NP systems? **RQ2:** Does research about NP acknowledge the relevance of transdisciplinary convergence? **RQ3:** What is the downstream impact of including knowledge users in research?

To answer these questions, we analyzed the scientific publications related to NP systems from eight countries in the Americas (Argentina: ARG, Chile: CHI, Colombia: Col, Costa Rica: CRI, Ecuador: ECU, Peru: Per, the United States of America: USA), each one defining a unique system characterized by their size, ecological complexity, management mandates and preferences, and bureaucratic independence; in addition to organizational culture and capabilities of country-specific Science, Technology, and Innovation (ST&I) systems, where NP systems are embedded. Although, it is tempting to think that the U.S. NP system has served as model for Latin America, it has been argued that Latin American NP systems have their own identity due to political, historical, and economical reason [236, 180, 345].

6.2 Methods

In order to evaluate the science convergence in the research developed in and around the NP systems of the eight countries studied, we studied transdisciplinary associations (cross-stakeholder) of authors participating in scientific publications related to the NP systems. With this, we quantify the degree of science convergence in each system and evaluate the implications of such transdisciplinary research in terms of visibility and downstream convergence. In what follows, we detail the data and methods used.

6.2.1 Data

To identify the scientific publications related to the national park systems we, first, downloaded the worldwide records of publications in Web of Science (WoS) that matched with the words "National Park" and "Sanctuary" or their variations in Spanish (see Supplementary Index 1). In addition to WoS core collection, we included records from SciELO citation Index. Both, WoS and SciELO are Databases curated by Thomson Reuters. The mix of these similarly curated dataset aims to include international (WoS), regional and domestic (SciELO) journals. SciELO journals are particularly important as they have provided visibility of Latin American research while improving spillovers, research quality and reducing language barriers [339]. Second, from the combined records (Wos and SciELO), we identified the publications studying protected areas of the national park systems of Argentina (ARG), Chile (CHI), Colombia (COL), Costa Rica (CRI), Ecuador (ECU), Mexico (MEX), Peru (PER), and the United States (USA). Publications studying the target NP systems were identified by string matching the names of the national parks of each system (see SI.2) with publications' title, keywords and abstract. As such, each publication was labeled according to their mentions of NP units. Our labeling method yielded 13,433 unique publications mentioning one or more NP.

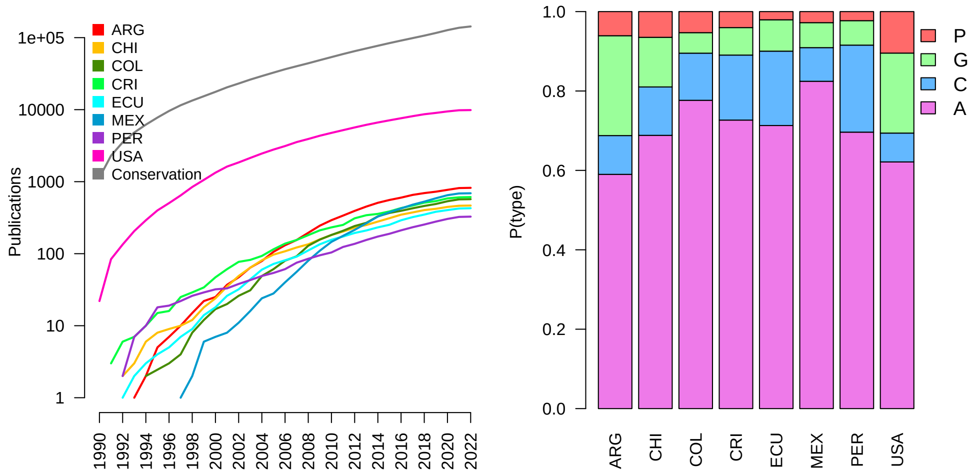

Figure 6.2: **Characteristics of publications about national park systems.** (Left) Cumulated number of publications per national park systems (named after their country). As comparison, it is included the trend in publications of WoS category 'Biodiversity and Conservation'. (Right) Differences between countries on the probability of finding a given type of stakeholder in a publication.

To evaluate the robustness of the labeling method, we identify the possible fraction of publications misidentified by manually assessing the labels assigned to publications. To be specific, over a sample including the 5% of the publications per country, we measure the proportion of publications in which a NP name was identified but the publication is not directly related to that NP. Our evaluation shows that the proportion of publications misidentified is negligible ($< 5\%$) (SI.3). Additionally, we assess possible sources of biases in our dataset. First, the growing trend in the number of publications per country is comparable in all the cases and consistent with the growth of related fields such as 'Conservation' WoS discipline (Fig.6.2a). Second, the number of NP units per system does not correlate with the number of publications found ($R^2 = 0.408$, $p.value = 0.363$), and there is not a relationship between the size of NP units and the number of publications (SI.4). We therefore argue that the eight systems are comparable in terms of the publications dynamics, not their abundance, and the dataset is not biased by artifacts of the data processing or other idiosyncratic factors.

In order to assess the interactions between different types of authors, or the formation of cross-stakeholder teams, we extracted the affiliations of authors, which were manually standardized and classified in four categories of stakeholders: Academics (A), including any education and research-oriented organization such as universities, colleges, science academies, among others. Civil organizations (C), encompassing civil groups, tribal organizations, companies, NGOs, among others. Government (G), referring to agencies, offices, departments, and any other administrative division of local or national governments. National parks (NP), comprising national park units or offices, directive units of the national park systems, among others. In the NP category we also include other protected areas such as preserves and monuments; this inclusion do not affect the NP category as they represent only 2% of all NP entries. Supplementary Index 5 bring further details of the classification and examples of each stakeholder. Overall, we extracted 5009 unique affiliations of which $< 2.5\%$ could not be classified. As expected, most of the affiliations correspond to academics (A), while the other stakeholders vary in their prominence across countries (Fig.6.2b) likely owing to national characteristics of the Science, technology and innovation (STI) systems and research capabilities of each NP system.

6.2.2 Measuring transdisciplinary convergence

Based on the standardized affiliations, we constructed the collaboration networks at organizational level for each system (SI.6) where nodes represent organizations (e.g. 'University X', 'Governmental agency Y') and edges between them indicate that they have coauthored scientific publications (Fig.6.1b). Such networks were summarized in smaller networks (M), and the corresponding weighted adjacency matrix, that indicate the occurrence probability of configurational pairs of stakeholders (Fig.6.1b). Following Petersen et al. [254], we evaluate the science convergence index (C_i) between stakeholders as $C_i = {}^{1-T}/_{||M||}$, or the complement ratio between mono-stakeholder configurations (T) and all the non-equivalent elements (mono- and cross-) of the stakeholders' network ($||M||$). In the C_i variation range [0,1], values close to 0 (close to 1) are indicative of abundance of mono-stakeholder (resp., cross-stakeholder) configurations. Additionally, we calculate the Shannon entropy (S) on all the non-equivalent elements of M as a complementary metric of transdisciplinary convergence, for which values close to 0 are indicative of dominance of one single configuration while values >0 show a more homogeneous distribution of configurations' frequencies. Since M is a size-constant (10 possible configurations), there is not sample-size dependency in the Shannon entropy calculation and comparison. Note that C_i is indicative of the fraction of cross-stakeholder interactions [254], while S shows the parity in the occurrence between all mono- and cross-stakeholder interactions. The analysis of these metrics contributes to answering **RQ1**.

To evaluate to what extent empirical transdisciplinary convergence values yield are the result of the underlaying frequency distribution of stakeholders, we developed a null model for estimating the expected transdisciplinary convergence under random conditions. Specifically, the null model consists of 10000 iterations, where each iteration takes the collaboration network between organizations for a given year and country, and randomizes the identity (i.e. stakeholder class) of the nodes while preserving the relative frequencies of stakeholders and the structure of collaboration between organizations. As such, the null model estimates transdisciplinary convergence accounting for several permutation of association between stakeholders. We express the results of the null model as the relative difference of the convergence indices $C_i^* - C_i/C_i^*$ between the estimated values from the null model (C_i^*) and the empirical value (C_i), where values close to 0 indicate no difference between the two, negative values are indicative of C_i larger than the random expectation and therefore strategic cross-stakeholder associations, and positive values indicate excess of mono-stakeholder associations (see SI.7).

6.2.3 Evaluating the impact of transdisciplinary science

To assess the impact and prestige of cross-stakeholder publications, we reconstructed the citation network between the 13433 publications leveraging the DOIs reported in their reference list. The citation network comprises 7,433 publications and 36476 citations. We argue that this subset of publications corresponds to parks-centered research characterized by recognizing part the existing literature about NP in the region and contributing to the cumulative process of building up knowledge about them (e.g. 'Impact of a century of climate change on small-mammal communities in Yosemite national park, USA' [223]). The complementary subset (5,999 publications) corresponds to research developed inside parks but without being immersed in the NP literature. We argue that these publications are problem-focused research as they might emphasize characteristics of the phenomenon at hand rather than circumscribing the research in NP systems context (e.g. 'What drives elevational patterns of diversity? a test of geometric constraints, climate and species pool effects for pteridophytes on an elevational gradient in Costa Rica' [173]). We argue that these subsets differ in terms of the target audience (one interested in NP and the other in the phenomenon). Further to this, they differ in their disciplinary composition (i.e., problem-focused subset integrates a larger share of social sciences) and the cognitive basis they use to frame the problems (see S.I.8 for details). However, there are not important differences on the distribution of stakeholders (S.I.8). We argue that differences in the transdisciplinary dynamics of these subsets could be cause by their epistemological differences (i.e. how the problem is assessed and to whom) and the associated social dynamics, rather than by the stakeholders' composition and abundance.

For each subset of data (parks-centered, problem-focused), we evaluate models addressing the effect that cross-stakeholder teams have on citations received, whilst additional models for the parks-centered subset evaluate the degree of transdisciplinarity of the teams citing and receiving the citations, as we describe in what follows. The models contribute to answer **RQ2** and **RQ3** by establishing the relationship between transdisciplinary research, its prestige (measured via citations), and the production of downstream convergence.

In order to evaluate prestige, we leverage citation counts (Z) as a proxy. Considering the time-dependency of citations, we ensure stationarity of Z by normalizing it as $Z_{ct} = {}^{log(Z_t+1)-\mu_t}/_{\sigma_t}$, where μ_t is the mean of $log(Z_t + 1)$ in time t, and σ_t is the standard deviation of $log(Zt + 1)$ [249]. Z_c values were estimated for the 13433 publications, but only used for analyzing problem-focused research. Furthermore, we use the in-degree count (K) in the citation network (i.e. citations received from other publications in the network) for the parks-centered subset as an additional proxy of prestige. Note that K is also susceptible to time-dependency, so its normalized version (K_c) was also calculated. While K_c represents a measure of prestige of a publication within the specific audience of NP, Z_c is indicative of prestige in the broader scientific audience.

To quantify the effect of transdisciplinary, research we design two sets of generalized lineal models following the same structure $y = \alpha + \beta x + \delta_i + \epsilon$, where the dependent variable (y) is analyzed at light of a set of covariates (x) and variables used as fixed effects (δ). β correspond to the estimated effect of x on y, and ϵ is the error of the model. For both sets of models, we independently assessed i) the effect of each stakeholder by "knocking them out", or evaluating how Y changes when a given stakeholder is present/absent as coauthor of the publication; ii) the effect of transdisciplinarity by identifying how Y changes as the number of stakeholders coauthoring the publication increases (2, 3 or 4 compared to mono-stakeholder). Note that i and ii are dummy covariables that were evaluated independently to reduce potential collinearity. Additionally, we also include as covariates the management orientation and the scope of publications. Management-oriented publications correspond to those classified as "Management" WoS discipline. The scope of the publication is defined by the number of NP mentioned in the publication (single-NP, Multi-NP). As fixed effects for both set of models, we include NP system (ARG, CHI, COL, CRI, ECU, MEX, PER, USA, Multi-Country), year (1990-2022), discipline (Natural, Social, interdisciplinary), journal prominence (define as the quintile class based on the average citations per journal), type of publication (article, conference proceedings, series, book), and number of coauthors (1, 2, 3, 4, 5, 5+). Fixed effects account for confounding factors by including any idiosyncratic source of variation (e.g. capabilities of national NP and ST&I systems), additional time-dependencies, and known sources of variations (discipline, team's size, journal prominence).

The two sets of models differ on what variable is considered as dependent variable. The first set of models evaluate the effect of transdisciplinary convergence (i.e. identity and number of coauthoring stakeholders) on publications' prestige by using Z_c as dependent variable for problem-focused publications and K_c for parks-centered publications. The second set of models evaluate the downstream impact of transdisciplinary research on the cross-stakeholder nature of the citations received. To this end, the second set of models consider two dependent variables. On the one hand, models include the fraction of citations received (f_{in}) that come from cross-stakeholder teams; while on the other hand, models use an indicator of how diverse the stakeholders' configurations (e.g., A, ACG, AGP) citing the publication are. Such diversity is calculated as the Evenness index (S_{in}) or the standardized Shannon entropy [211] of the citing configurations. Both f_{in} and S_{in} are also normalized to reduce time-dependency. Note that all the dependent variables included in our study are *log*-transformed variables, therefore, the relationship between y and x must be understood as $\Delta y\% = 100 * e^{(\beta-1)}$ [318]. All the OLS models were fitted and then tested for normality, collinearity and homoscedasticity (SI.9-10) using R 3.6. [324].

6.3 Results

Science convergence as "the coming together of insights and approaches" implies intrepid mixings of stakeholders to produce knowledge by blending concepts, perceptions, and interests. While increasing science convergence has been characterized in various research domains [14, 24, 248, 254], examples rarely evaluate variations of transdisciplinary convergence across geographies or regional systems. Our study addressing this issue in NP systems shows that, as expected, a great part of the publications is concentrated in the U.S. NP system whilst Latin American ones comprise only a fraction of all publications (Fig.6.2a) likely owing to differences in capabilities and science practice between countries [339]. Although there is a numerical difference in publications between systems, the growth trend for all the systems is similar and follows the same pattern shown by related fields such as 'Biodiversity and Conservation' (Fig.6.2a). We argue that differences in the science convergence in NP systems is product of the cross-stakeholder dynamics rather than an effect of publications abundance (Fig.6.2b) as differences in the structure of co-authorship networks between NP systems also suggest (SI.6).

6.3.1 Changes in convergence

To evaluate science convergence we calculate two metrics, C_i and S. Results indicate that the two metrics and thereby transdisciplinary convergence have increased in all the systems (Fig.6.3). NP systems with small transdisciplinary convergence (e.g. COL, MEX, PER) are characterized by low prominence of NP and government (G) stakeholders (Fig.6.3b, SI.6), suggesting that transdisciplinary convergence might be caused by stakeholders abundance. We test this hypothesis by implementing a null model that estimates C_i^* and S^* in random assemblages of stakeholders (see methods for further details). Null model estimations indicate that the observed growth in transdisciplinary convergence seems to be the product of stakeholders' abundances rather than to their collaboration patterns (see SI.7). Actually, C_i (S) values yield are lower than the C_i^* (S^*) estimated, indicating that NP systems patterns of collaboration are suboptimal as potential cross-stakeholder interactions are not fully developed. We argue that the observed suboptimal cross-stakeholder collaboration is rooted in the homophilic association between them, or the tendency of preferring mono-stakeholder collaborations. An interesting counterexample is ARG, where there is a burst in $4 < C_i >$ during the period 2006-2020, which is more convergent than the expectations of the null model. Such a burst is nonetheless less accentuated when measured as $< S >$, indicating that the burst is largely the product of the markedly increase in the frequency of a particular cross-stakeholder combination. Closer inspection indicates that the strategic combination Academia-Government (AG) is responsible for the burst as it counterbalances the prominence of the research authored by mono-stakeholder (AA or GG) teams.

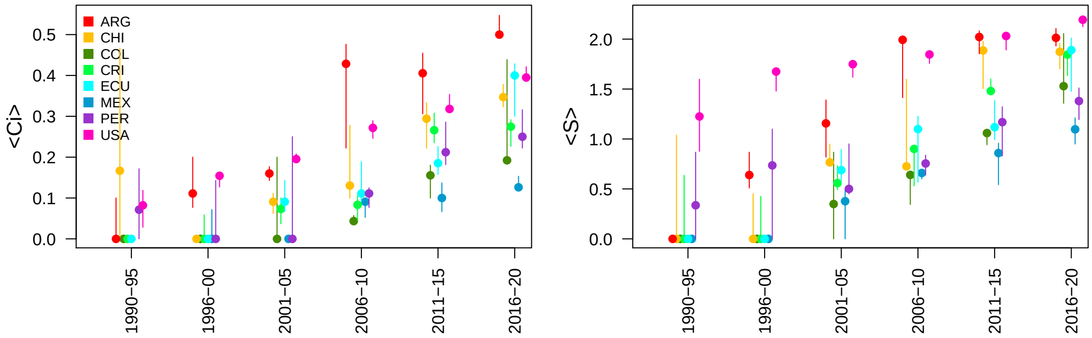

Figure 6.3: **Dynamics of transdisciplinary convergence research about national park systems in the Americas.** Left panel correspond to transdisciplinary convergence measured as the Convergence Index ($< Ci >$) proposed by Petersen et al.[254] calculated as $C_i = {}^{1-T}/_{||M||}$, where T correspond to the mono-stakeholder interactions and $||M||$ refers to all the interactions between stakeholders. Right panel correspond to the evaluation of transdisciplinary convergence measured as the Shannon information entropy ($< S >$) of all the non-equivalent elements contained in the stakeholders' interaction matrix. Year-based measurements are shown in 5-years intervals and indicating the median value (circle) and the 25 and 75 percentiles (vertical line). Location of the points are slightly displaced in the x-axis to avoid overlapping.

6.3.2 Explaining the effect and importance of transdisciplinary convergence

As mentioned, government (G) and NP seem to be key actors to unlock transdisciplinary convergence of the science in the NP system. To assess the downstream effect of cross-stakeholders' teams on research, and therefore addressing **RQ2** and **RQ3**, we leveraged two sets of linear models. One set of models evaluating citations quantity, and another evaluating the characteristic transdisciplinary of citations received. We use OLS estimation of the coefficients for the two sets of linear models, which are specifically designed to *i*) evaluate the effect of each stakeholder by "knocking them out", *ii*) assess the different levels of cross-stakeholders' collaboration, and *iii*) control for confounding and idiosyncratic factors (see methods and SI.9-10 for further details).

Our first set of models considers two types of publications. On the one hand, 7434 publications connected via citations, named as parks-centered publications, which are contextualized in NP literature and therefore interested in NP. On the other hand, the remaining 5999, named as problem-focused publications, that we argue are interested in phenomena happening inside NP, rather than the NP themselves. These models evaluate two forms of citations: one accounting the normalized citations received in the citation network (K_c) comprising parks-centered publications, and the other considering the normalized citation reported by WoS and SciELO repositories (Z_c) and comprising problem-focused publications. K citations are indicative of the impact or prestige of a publication for NP audience, whereas Z indicates the prestige for an external audience.

Results indicate that K_c and Z_c have mostly dissimilar behaviors (Table 6.1, SI.9). First, problem-focused publications featuring Academics (A) or Government (G) receive a significant citation (Zc) premium of 11.9% and 7.5%, respectively. In other words, problem-focused publications authored by A or G receive more citations in average than publications that were not authored by them. Other stakeholders have only marginal or no effect on Z_c. In contrast, parks-centered publications authored by NP show a 18.3% citation (K_c) premium, whilst publications authored by civil society (C) receive 12% less citations that those not featuring this stakeholder. A and G authorship have no effect on K_c. Second, the degree of teams' transdisciplinarity (i.e. number of stakeholders) does not affect the Z_c citations received by problem-focused publications, whilst for parks-centered publications authored by three types of stakeholders are 9.5% more cited than mono-stakeholder publications. However, parks-centered publications featuring all four types of stakeholders are 21.7% less cited than mono-stakeholder publications likely owing to the negative effect produced by including C. Finally, problem-focused publications addressing management issues have a citation premium of 4.9%, whilst parks-centered publications studying multiple NP receive 35.6% more citations than those focused only on a single NP. Complete models description and estimates can be found in SI.9.

Our second set of models focuses on parks-centered publications (Table 6.2) and evaluate two response variables: one showing the fraction (f_{in}) of citations received from cross-stakeholder teams, and the other indicates the stakeholder configurational diversity (S_{in}) of citing teams. At differences with the first set of models, this set does not focus on the citation count but on the nature of the citing sources. fin therefore indicates whether citations come from cross-stakeholder teams as opposed to mono-stakeholder groups, whereas S_{in} shows if the citations received are less concentrated in types of (mono- or cross-) stakeholder configuration. Results indicate that the fraction of cross-stakeholder citations (f_{in}) received by parks-centered publications authored by

Table 6.1: **Results of linear models evaluating citations.** Models evaluate the inclusion of each type of stakeholder (A= academia, C= civil society, G=government, P=National parks) as coauthor in relation to when they are not included, the degree of transdisciplinary (i.e. Number of stakeholders), the generality of the studies' scope (mono-NP vs. Multi NP), and the inclusion of management elements in the study(Mgmt). System (i.e. country), year, discipline (Nat, Soc, Multi), journal prominence (i.e. quintile class based on their average citation count), the number of coauthors (1, 2, 3, 4, 5+) and type of publication (journal article, book, conference paper, series) are considered as fixed effects. Models evaluate two types of citations. i) The normalized citations count originated from other publications in the parks-centered subset of publications. In other words, a normalized in-degree in the citation network *(K_c)*. ii) The normalized citation count reported by WoS *(Z_c)* for publications in the problem-focused subset, or in other words, excluding from the model publications connected in the citation network.

	Dependent variable:			
	$<Z_c>$		$<K_c>$	
	(1)	(2)	(3)	(4)
Include A (Y)	0.112***		−0.042	
	(0.031)		(0.048)	
Include C (Y)	0.043*		−0.128***	
	(0.026)		(0.035)	
Include G (Y)	0.072***		0.002	
	(0.023)		(0.027)	
Include P (Y)	−0.030		0.168***	
	(0.028)		(0.033)	
Stakeholders(2)		0.039*		0.008
		(0.021)		(0.026)
Stakeholders(3)		0.062		0.091**
		(0.044)		(0.046)
Stakeholders(4)		0.155		−0.244**
		(0.135)		(0.121)
Mgmt	0.052**	0.044**	−0.016	−0.0001
	(0.022)	(0.022)	(0.028)	(0.028)
Multi-NP	0.022	0.021	0.305***	0.304***
	(0.026)	(0.026)	(0.028)	(0.028)
Observations	5,999	5,999	7,433	7,433
R^2	0.580	0.579	0.116	0.112
Adjusted R^2	0.576	0.575	0.109	0.105
Note:				*p<0.1; **p<0.05; ***p<0.01

C, G, and NP is respectively 42.3%, 59.5%, 108.5% greater than in publications not authored by them. Similarly, an increasing number of coauthoring stakeholders (2, 3, 4) is associated with greater f_{in} values (72.1%, 170.7%, 238.4%) respect to mono-stakeholder publications. Finally, while management-oriented publications have 32.4% larger f_{in}, publications addressing multiple NP are cited by a fraction of cross-stakeholder teams 15% smaller than single-NP publications. Teams' diversity (S_{in}) shows a similar pattern that f_{in}. Complete models description and estimates can be found in SI.10.

Overall, our study yields four salient messages about transdisciplinary convergence in different NP systems of the Americas. First, there is an illusory increase in the prominence cross-stakeholder combinations, measured as C_i and S, owing to the increase in productivity of non-academic stakeholder rather than to an increase in cross-stakeholder combinations. Transdisciplinary convergence is negatively influenced by homophylic attachment that causes an exacerbated prominence of mono-stakeholder combinations and therefore a missed opportunity for strategic cross-stakeholder research. Second, NP authorship boost the prestige of publications (i.e. citations) in the parks-centered audience, nevertheless NP authorship is underappreciated by the problem-focused audience. Third, while the parks-centered community have high appreciation for publications addressing multiple NP units, and likely having a systemic view of NP, such multi-NP view is not associated to further transdisciplinary research downstream. Fourth, transdisciplinary teams, especially those involving NP and government, are associated with more subsequent cross-stakeholder research. In other words, transdisciplinary research in the parks-centered niche is self-reinforced as the more transdisciplinary a team is, the more transdisciplinary the citations received are.

6.4 Discussion

National parks (NP) are a cornerstone strategy for addressing several global challenges and are characterized by high uncertainty at the nexus of social and ecological dynamics [143, 286]. Diverse, inclusive and science-based management of NP therefore requires vast multidisciplinary knowledge and to consider and acknowledge the interests, values and organizational culture of various stakeholders, including government and the public [29, 46, 156, 305, 365]. Transdisciplinary convergence has the potential to foster such a management by closing the gap between science and practice [14, 187, 252, 286], which nevertheless is a poorly explored dimension of science convergence. We address

Table 6.2: **Evaluation of the downstream influence of transdisciplinary research in the production of more transdisciplinary research.** It is evaluated what proportion of citations received by a publication come from transdisciplinary (stakeholders>1) teams (f_{in}), and the parity between the citing species (S_{in}). Citing species correspond to the combinations of citing mono- or cross-stakeholder teams (e.g. ACGP, AGP, A). Parity is measure as the standardized Shannon entropy, or the Evenness entropy. Both f_{in} and S_{in} are normalized. As covariates are evaluated the inclusion of each type of stakeholder (A= academia, C= civil society, G=government, P=National parks) as coauthor in relation to when they are not included, the degree of transdisciplinary (i.e. Number of stakeholders), the generality of the studies' scope (mono-NP vs. Multi NP), and the inclusion of management elements in the study(Mgmt). System (i.e. country), year, discipline (Nat, Soc, Multi), journal prominence (i.e. quintile class based on their average citation count), the number of coauthors (1, 2, 3, 4, 5+) and type of publication (journal article, book, conference paper, series) are considered as fixed effects.

	Dependent variable:			
	$<f_{in}>$		$<S_{in}>$	
	(1)	(2)	(3)	(4)
Include A (Y)	−0.129**		−0.177***	
	(0.061)		(0.066)	
Include C (Y)	0.353***		0.232***	
	(0.050)		(0.055)	
Include G (Y)	0.467***		0.250***	
	(0.035)		(0.038)	
Include P (Y)	0.735***		0.283***	
	(0.044)		(0.047)	
Stakeholders(2)		0.543***		0.271***
		(0.035)		(0.038)
Stakeholders(3)		0.966***		0.427***
		(0.062)		(0.066)
Stakeholders(4)		1.219***		0.728***
		(0.183)		(0.188)
Mgmt	0.273***	0.315***	0.210***	0.224***
	(0.038)	(0.038)	(0.042)	(0.042)
Multi-NP	−0.157***	−0.168***	−0.315***	−0.321***
	(0.035)	(0.036)	(0.039)	(0.039)
Observations	3,810	3,810	3,153	3,153
R^2	0.242	0.211	0.213	0.201
Adjusted R^2	0.230	0.199	0.198	0.186
Note:			*p<0.1; **p<0.05; ***p<0.01	

this issue and some of its consequences by studying how different stakeholders "come together of insights and approaches" by producing scientific knowledge around the NP systems of eight countries.

Our evaluation of transdisciplinary convergence suggests that strategic cross-stakeholder collaborations in the research about NP systems are suboptimal as there is a homophylic tendency of producing mono-stakeholder publications. Such homophylic interactions might be caused by inherent challenges of multidisciplinary research, including coordination cost for addressing and prioritizing recombinant knowledge forms, institutional and financial barriers, differences in communication style, interest, and organizational culture between stakeholders [82, 249], which ultimately could affect the alignment and actionability of science. Additionally, lacking engagement of NP in publications and cross-stakeholder collaborations might be caused by the chronic underfunding and understaffing of NP systems, and by the crisis-driven managerial style of many NP [143, 299].

Transdisciplinary convergence, as an advantageous mode of science, leverages synergies yielding breakthrough successes [185, 248, 305] that are typically prestigious within the scientific community [249, 254]. However, as previous studies have questioned [46], our study demonstrates that not all audiences acknowledge science convergence given that the involvement of direct knowledge users (i.e. NP) is only appreciated (i.e. 18% citation premium) within the parks-centered community. Scientists' community therefore suffers myopia regarding the value of research done by knowledge users and therefore further enhance the diversity paradox [155], where contributions of underrepresented groups of stakeholders could be neglected. Notwithstanding, there is positive feedback between transdisciplinary research such that cross-stakeholder research is highly valuated by subsequent cross-stakeholder teams, especially when a systemic perspective is embraced. Notably, government entities seem to be enablers of visibility (i.e. citations premium), downstream transdisciplinary convergence and in few cases (i.e. ARG), and are potential enables for strategic cross-stakeholder research, probably due to some of them (e.g. USGS, NOAA, CONICET) are by design central pieces at the science-practice-policy interface.

Our results suggest that the transformative potential of NP research for bridging science and practice is confined to a research niche where is developed a communication between similar stakeholder. Additionally, transdisciplinary convergence might be further limited to accessible non-peer reviewed literature [46], that is important to evaluate but nonetheless beyond the scope of our study. The research niche of NP science might favor knowledge integration in appropriate formats [184, 305], limit topics to a common set of interests probably oriented towards problem-solving rather than deep understanding the phenomenon at hand, while allowing knowledge exchange, mutual learning and reduce power inequities [29, 365]. While the niche might bring room for experimentation, co-creation, cross-sectorial fertilization and broad shifts in science and society toward greater complexity and accelerating social and environmental change [284, 297, 296], it has risk of exacerbating the differences in interest and perception between academics and NP managers [143, 184] and therefore impairing the potential benefits of science convergence.

6.4.1 Conclusions and policy lessons

Bridging science and practice is a problem that spans different domains, including NP systems [184, 252, 286]. While cross-sectorial benefits of science convergence include promoting innovation and fostering robust science-based management strategies [46, 82, 305, 365], such benefits could be fully harnessed if the barriers for transdisciplinary integration are overcome. This implies not only the participation of knowledge users in the research process, but also facilitating the inclusion of their interests, organizational culture and ontological frameworks [29, 92, 156, 249]. For the case of NP systems, transdisciplinary convergence also includes developing trust and communication channels between academia and management to overcome their historical mutual disconnection [143, 299]. NP systems management, as mission-oriented problems, could be potentiated by strategic alliances between stakeholders that bring experience, new ideas and help to develop a systemic understanding of NP. Government organizations seem to be key actors for gluing cross-sectorial collaborations as many of them have mastered the scientific rigor and the technicalities of policing, so they can enable communication and reconcile interests between science and practice. Finally, there are opportunities for developing and shielding the NP research niche and the embedded transdisciplinary feedback, so further cross-sectorial fertilization and nourishment can be achieved [284, 296, 297].

Supplementary materials

Supplementary materials are available at https://zenodo.org/record/7636880 and include: **Supplementary Index 1**: Search equations for identifying publications related to national parks research. **Supplementary Index 2**: List of national parks. **Supplementary Index 3**: Evaluation of false-positive rates in publications tagged. **Supplementary Index 4**: Evaluation of the relationship between publications abundance and national park systems' characteristics. **Supplementary Index 5**: Description of manual classification of stakeholder and examples of each class. **Supplementary Index 6**: System-based co-authorship networks and stakeholders' networks. **Supplementary Index 7**: Comparison of empirical science convergence results and estimations produced by the null model. **Supplementary Index 8**: Evaluation and comparison of the two subsets (parks-centered and problem-focused). **Supplementary Index 9**: Linear model evaluating citations count (Zc, Kc), and models' assumptions evaluation. **Supplementary Index 10**: Linear models evaluating fraction and diversity of transdisciplinary citations received, and models' assumptions evaluation.

Chapter 7

Research Alignment in the U.S. National Park Service: Impact of Transformative Science Policy on the Supply of Scientific Knowledge for Protected Area Management

The US national park system includes 63 national parks encompassing diverse environmental and tourism management regimes, together governed by the 1916 Organic Act and its dual mandate of conservation and provision of public enjoyment. However, with the introduction of transformative science policy mandates concentrated around the year 2000 (e.g., National Parks Omnibus Management Act; Natural Resources Challenge), the mission scope has since expanded to promote overarching science-based objectives, thereby fostering knowledge generation critical to park management, as well as promoting the "pristine" territory for "wild science" – as protected areas represent valuable counterfactuals to anthropogenic biomes. To this end, individual US national parks formally explicate itemized "need statements" representing targeted calls for science-based problem solving. Yet despite the paradigm shift instituting "science for parks,

parks for science", there is scant research exploring the impact of science policy on research alignment (i.e., supply-demand) in national parks. We address this gap by leveraging the clearly delineated and well-ordered attributes of the US national parks to develop a spatiotemporal framework for evaluating knowledge alignment, here operationalized via quantifiable measures of supply and demand for scientific knowledge. More specifically, we apply a machine learning algorithm (Latent Dirichlet analysis) to a comprehensive park-specific text corpus (combining official needs statements and scientific research metadata) in order to define a joint topic space, which thereby facilitates quantifying the direction and degree of knowledge alignment at both the parks and systems levels. Additionally, we grouped topics into two categories — normative (overarching) and non-normative (idiosyncratic) — to facilitate assessing their differential response to the transformative science policy characterized as addressing normative issues such as air quality and wilderness. Results indicate an overall robust degree of knowledge alignment, with misaligned topics tending to be over-researched (as opposed to over-demanded), which may be favorable to many parks, but is inefficient from the park system perspective. Results further indicate that the transformative science policy exacerbated the over-supply of research in normative knowledge domains, manifesting in higher levels of misalignment. In light of these results, we argue for improved decision support mechanisms to achieve more timely alignment of research efforts towards distinctive park needs, thereby fostering convergent knowledge co-production and leveraging the full value of national parks as living laboratories.

7.1 Introduction

Scientific knowledge constitutes an important input for management of coupled human environmental systems, where a deep understanding of complex processes, interdependencies, path dependencies, sensitivity, robustness and risk are crucial [152, 6]. However, the demand for such knowledge often derives from distinct sectors (society, academia, industry, non-profit organizations, government), and so the supply of knowledge may be misaligned or otherwise inadequate from the perspective of the stakeholders charged with addressing the overarching social, environmental, and/or technological challenges [74, 14, 249, 70, 93, 266, 298, 311, 249].

Recent efforts to evaluate knowledge alignment in various problem domains such as public health, food security and nutrition, and climate science [70, 74, 291] illustrate the mismatch between the supply and demand for scientific knowledge, and highlight the utility of alignment measures to inform science policy and evaluation. However, despite the importance of configuring efficient streams of knowledge production for timely and prioritized action on present global challenges, little is known about how different factors, such as the alignment of science policy, or drivers, such as policy change, might affect the degree of knowledge alignment. We contribute to this literature stream by developing a framework for measuring and assessing knowledge alignment in the US National Park Service as it relates to management of scientific activities in the US national parks – designated public areas belonging to the International Union for Conservation of Nature (IUCN) Category II protected areas, featuring very high levels of protection and regulation.

The US national parks (hereafter referred to as parks for brevity) and the scientific community are involved in a mutually beneficial relationship that has integrated over time since the first established park in 1872 (Yellowstone national park). Parks are valuable treasures representing both natural and cultural heritage, thereby embodying valuable potential to deliver insights and lessons about global change to both scientists and society at large, in particular by establishing spatiotemporal regimes corresponding to low levels of anthropogenic influence useful as counterfactual baselines [113, 95, 281]. In this way, parks are valuable living laboratories that facilitate the large-scale analysis of anthropogenic phenomena such as air, water and land pollution, invasive species and climate change – in addition to protecting unique geomorphological sites and providing multiple ecosystem services, such as biodiversity refugia [169, 200, 351].

The US national park system is managed by the US National Park Service (a federal agency within the US Department of the Interior), and is a longstanding, well-ordered and clearly delimited set of protected areas, collectively encompassing 344,000 km2 (an area nearly the terrestrial size of Germany); of this total area, roughly 62% belongs to 63 national parks, with the remainder belonging to national monuments, wildlife preserves and other protected areas. Given its size, diversity and human-environmental mission, the integrity and the social and ecological value of the parks system substantially depends upon assertive managerial decisions and practices, which require the consideration of multiple factors incorporating environmental, behavioral, and financial uncertainty [113, 165, 175, 200, 243, 299]. Because this administrative agency is located within the Department of the Interior, it is less reliant on traditional sources of national funding for scientific knowledge production than other knowledge-intensive domains (academia, industry). Indeed, because the parks mission centers around natural resource preservation and public visitation, the integration between parks and other agencies configured around scientific knowledge production has traditionally been neither explicit nor implicit. However, there was a paradigm shift in science policy governing the system concentrating around the year 2000, effectively introducing an additional dimension to the parks' mandate by bridging traditional park management with scientific endeavors. This extension benefits internal and external stakeholders, as conducting science on and in parks is beneficial to the scientific community and for parks' managers [243, 263, 281, 311]. However, scientific investigations do not always address the most relevant knowledge demands (manifesting in knowledge misalignment), nor the most urgent demands (manifesting in temporal misalignment, i.e. detrimental time lags in the sequence of legislative development, approval and policy implementation) [50, 200, 212, 228, 311].

In this work we address the issue of knowledge (mis)alignment, defined as the degree to which park-oriented knowledge is under- or over-supplied. To operationalize evaluating the dynamics of knowledge alignment over time, we first identified a set of 40 core park-management topics by applying a standard unsupervised text-mining method (latent Dirichlet allocation, or LDA) to a comprehensive parks management-science corpus. We constructed this corpus by combining official park "needs statements" with publication metadata (title, keyword, and abstracts) for research associated with specific parks. Projecting stated research needs and published scientific research against a common set of topics thereby facilitates quantifying the direction and degree of knowledge alignment at both the parks and systems levels.

Hence, our analysis provides relevant insights into the management of national parks, and protected areas more generally, in two ways. First, by developing a framework for evaluating to what extent upstream knowledge producers (specifically, academics and national park scientists) meet the demands of downstream knowledge consumers (specifically, national park managers and scientists). And second, by evaluating how this alignment changed in response to transformative shifts in science policy instituting parks as living laboratories – thereby extending the scope of the 1916 National Park Service Organic Act, whose original intent purpose was "to conserve the scenery and the natural and historic objects and the wild life therein and to provide for the enjoyment of the same in such manner and by such means as will leave them unimpaired for the enjoyment of future generations" (Organic Act, 1916). In summary, we develop and apply a systematic text-mining framework to evaluate how transformative shifts in national park science policy concentrated around the 2000 have impacted knowledge alignment – at both the parks and system levels.

The structure of this study is as follows. First, in Section 7.1.1 we motivate our study against the theoretical background of knowledge alignment. In Section 7.1.2 we expand on the historic relationship between science and parks, in particular the evolution of US science policy of national parks (denoted hereafter by SPNP). We then describe our data and methodological approach for evaluating knowledge alignment in Section 7.2. We summarize our findings by describing the areas in which alignments are found using a system-level analysis in Section 7.3.1, and then downscale our analysis at the park level in Sections 7.3.2 and 7.3.3. Finally, in Section 7.4, we discuss our results and the policy implications of our findings.

7.1.1 Evaluating knowledge alignments

In what follows, we introduce some elements required to understand how knowledge alignment between science and society (or organizations) proceed. We begin by presenting determinants for the supply of scientific knowledge —or how research priorities are defined— and then define the societal demand for knowledge —or research needs— and how they can be assessed. Finally, the concept of knowledge alignment as an economic supply-demand analogy is introduced, and we provide a method for the quantitative evaluation of alignment between research priorities and research needs. In our conceptualization, we provide case examples from particular parks that also serve to illustrate particularities of the system as a whole.

Supplying target problems by identifying research priorities

It is often thought that science is intended to support advances extrinsic to itself. Thus science is expected to satisfy knowledge needs at organizational and societal scales [74, 114, 291], however, this is not guaranteed because many factors affect the dynamics of science[1] influencing what is researched and how frequently, two factors that shape the ultimate stock or portfolio of available knowledge [74, 70, 118, 133, 166, 198, 266, 268, 291, 346].

Although science is plural and inclusive, encompassing a variety of disciplines, not all disciplines are equally prominent [186, 70]. For instance, natural sciences dominate mainstream journals [130] and science repositories [70, 153]. One of the reasons why social sciences seem to be less abundant than disciplines such as physics is the difference in practices [178, 118, 153] and historical differences in baseline funding [314]. Various studies [74, 70, 346] suggest that science cartographies are adequate, albeit not perfect, indicators of what research domains have been prioritized.

The identification of research priorities is a first step towards connecting science and final users. Detailed cartographies, indicative of research priorities, enable managers to navigate the ever-growing scientific literature [114, 278] and promise to be informative for science policy and better governance in specific areas [74, 133, 198, 240, 268, 346]. Although final users, such as park scientists or managers, might face some barriers (e.g., non-open access publications, technical language), knowledge inventories would allow them to better use literature and identify knowledge gaps.

Defining normative and expressed research needs

It is crucial to determine what research must be conducted to satisfy the knowledge required for managing complex socio-environmental systems, as represented by parks. However, this process depends upon the ability of managers to define their needs of knowledge. Describing what affects social and/or organizational needs and what constitute them is challenging because needs can be manifested in many ways and vary across physical, social, and organizational contexts [74, 70, 107, 114, 278]. Drawing on the taxonomy of needs developed by Bradshaw [45], we focus on both normative and expressed needs. Normative needs are desirable standards (defined by, for example, experts) that should be met (e.g., minimum daily caloric intake), whereas expressed needs are those that an agent "feels" and takes action to satisfy. For parks, normative research needs represent the (top-down) mandatory (e.g., congressional mandates) knowledge required for adequate administration of resources, whereas expressed research needs are those that parks actively pursue (bottom-up) by conducting research or promoting third parties to do so. Note that normative and expressed needs might intersect each other, as Bradshaw [45] clarifies, and both needs might be partial [45, 93].

Both normative and expressed needs can differ depending upon the ability of agents (internal or external) to identify needs, as well as their interests and context.

For instance, air and water resource quality, endangered species, and wilderness could be considered as normative research needs because congressional mandates enforce their study, whereas research on wildfires can be expressed research needs since their study is promoted by parks initiatives. Interestingly, expressed research needs may be mediated by the idiosyncrasies of parks, the expertise and experience of parks managers, and the comprehension that they have about the knowledge that has or has not been properly fulfilled [93, 239, 291].

Analyzing alignments between research priorities and needs

Research priorities and research needs interact and might even coevolve according to common selection mechanisms. The development of new knowledge typically involves the production of new questions and future research. To some extent, the same could be expected for research needs; as such needs are defined, they could illuminate the path for identifying the next layer of needs. Moreover, it is likely that research needs trigger changes in research priorities as scientists devote efforts to meet such needs, while scientific discovery could highlight knowledge gaps and societal unknowns that later become research needs. As a result of such iterative processes, it could be expected that research priorities and research needs change and eventually become more aligned [114, 291].

Parks have developed mechanisms to interact with the scientific community in the collaborative production of knowledge, with the overall objective to better align capacities, a consideration further elaborated in Section 7.1.2. Scientists develop products (e.g., articles, reports, reviews, books) that could satisfy the knowledge that parks require, and parks inform scientists by multiple means (e.g., conferences, personal communications, calls for projects, advertising) about the current research needs (Fig.7.1a). The expected outcome is an increased alignment. However, such a process is not always effective because scientists may be unresponsive or uninterested, whereas historically, communication channels between parks and the scientific community have been inefficient.

Understanding whether research priorities respond to research needs has recently gained relevance in the study of science and innovation policy. Many works have addressed this through urgent issues such as medicine and public health, pharm-industries, agriculture, and climate change [74, 70, 239, 252, 266, 268, 278, 291, 346]. In

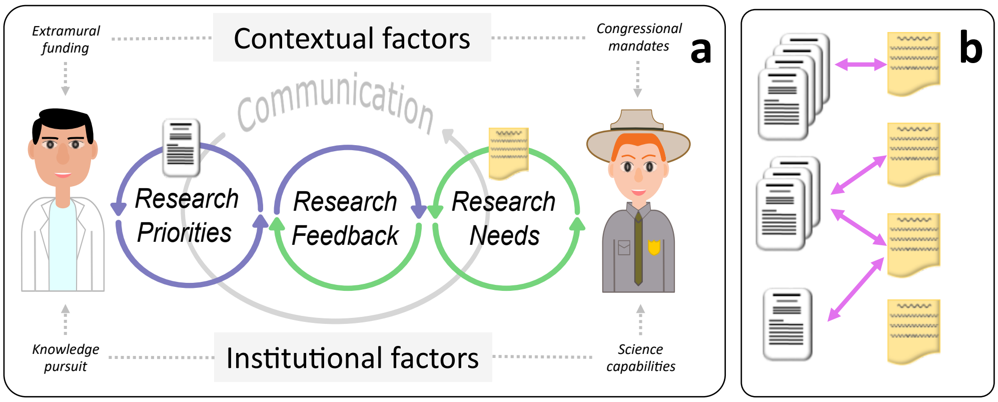

Figure 7.1: **Schematic of the research feedback in the U.S. national parks.** a) Scientists produce codified knowledge (research priorities) in research publications that are relevant for managing parks. Parks identify their research needs and (re)codify them in multiple ways to inform scientists what knowledge is the most needed. New scientific knowledge also promotes the identification of new needs while needs induce the production of new knowledge ("research feedback"). Note that research priorities and research needs are affected by multiple contextual and institutional factors. b) Research priorities (publications) and needs (official national park needs statements) alignment is visualized as a bipartite network comprised of these two sets of nodes – priorities and needs – connected by common topics (magenta links). Whereas some needs are exhausted by the scientific literature, others may be neglected. As such, this approach accounts for several ways that scientific knowledge could be relevant to one or more research needs, and vice versa.

such studies, the concept of alignment introduced by Sarewitz & Pielke [291] has been useful for assessing the coupling between research priorities and research needs. Alignment, or the lack of (misalignment), is defined as the relationship between the knowledge, information, and societal outcomes provided by the scientific community and the knowledge required to achieve specific societal goals. Alignment can be understood from an economic perspective as the supply and demand for knowledge [291]. Although analysis of knowledge alignment is promissory and informative [74, 70, 166], there is scant literature developing these concepts further within a science policy framing.

The analogy of supply and demand for knowledge is a straightforward framework to connect research priorities and needs. However, one underexplored dimension is how the research is allocated along multiple needs (Fig.7.1b) in so far as research priorities and needs are not homogeneously distributed across knowledge domains. We argue that the balance between the intensity in which a particular knowledge is supplied and the intensity in which it is demanded would inform the degree of alignment of such knowledge. Specifically, a knowledge domain could be perfectly aligned if supplies match the levels of demand; on the contrary, misaligned research could be produced by different degrees of oversupply or overdemand, representing a scenario of "missing opportunity" proposed by Sarewitz & Pielke [291]. Thereby, (mis)alignments can be understood by both the direction and magnitude of the supply-demand imbalance.

Science in parks differs significantly from other development areas (e.g., industry, health care) because research is not directly associated with commercialization. Hence, such science is likely to be less influenced by confounding factors such as extramural funding prioritization [94, 198, 268, 298, 346]. As such, science in parks is a well-defined and well-delimited domain, corresponding to what Kitcher [172] defines as a well-ordered science that is mostly driven by societal needs and research interests and, therefore, a problem for which most of the areas should be expected to be highly aligned.

7.1.2 Science and science policy in the US National Parks

The perceived benefits of parks as living laboratories are tied to the dynamics of science. In contrast to much basic research, science in parks has been proposed as mission-oriented research [243] important for managerial purposes[2] [299, 55, 263]. Although the current science commitment of parks seems natural, this has not been the case for substantial part of the system history. While a complete historical review of the science in parks is beyond the scope of this work[3], we nonetheless provide the essential details and factors regarding the most relevant events associated with the history of science in parks in Fig.2 and Supplementary Table 1 (ST.1).

Science was largely neglected throughout much of the history of parks and fully appreciated only recently in the late 1990s [175, 243, 299], after the policy change aimed at bringing scientific problems into focus, as opposed to management issues historically centered on visitation. Such a policy change represents a paradigm shift because it altered how parks management and the role of science are envisioned. Although early attempts to include science into parks management were fostered (e.g., George Wright in the 1930s and Stalker Leopold in the 1960s), science did not consolidate into formal policy until around the year 2000 (Fig. 2). In fact, the momentum gained by science in the past century was undermined by regressive policies[4].

A foundational event of the modern structure of science commitment in parks is difficult to identify. Instead, we find that the science policy of national parks (SPNP) was achieved by way of a paradigm shift in the framing of parks as living laboratories, which established a fundamental role for science by way of a burst of interrelated policies and political initiatives emerging in the late 1990's and persisting thereafter (Fig.7.2). Three interacting components shaped the SPNP: academic and societal pressure, legal mandates to conduct science, and parks' realization of the importance of scientific knowledge. First, parks received much criticism from inside and outside the system [5, 28, 58, 81, 84, 122, 233, 234, 275, 288, 299] that highlighted harmful policies, the lack of scientific programs, and deterioration of resources, among other issues [344, 262, 301].

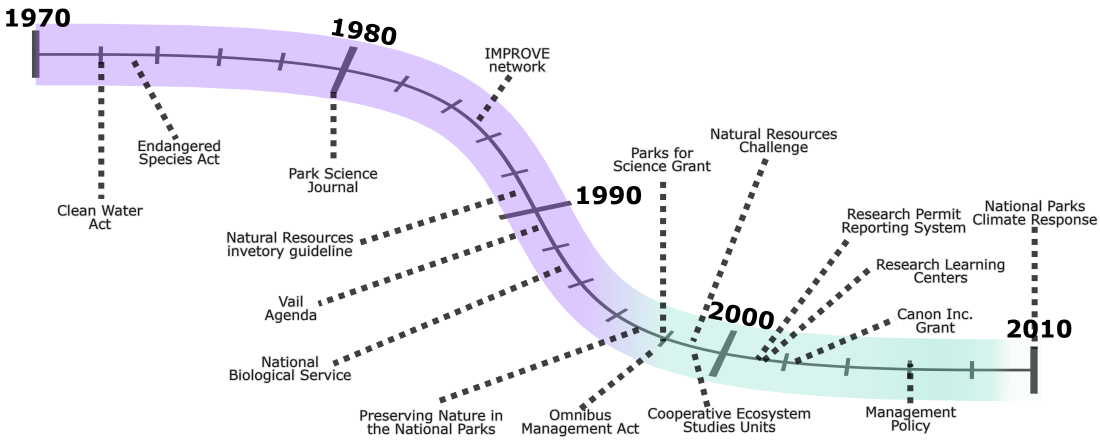

Figure 7.2: **Timeline of relevant events that contributed to shaping modern commitment to science in the U.S. national parks**, in particular the paradigm shift occurring around the year 2000. Colors represent the transition between the "old" and the "new" model of science-based management. Details about the events can be found in Supplementary Table 1.

Second, congressional bills[5] have implicitly or explicitly mandated federal agencies, parks included, to survey, establish long-term monitoring programs, and intervene to protect natural and historical resources using the best available science [113, 144, 197]. Importantly, the National parks Omnibus Management Act (1998) gave parks the legal authority to conduct scientific studies for management purposes.

Third, in response to and in recognition of the pervasive effects of former parks policies centered on visitation and development [50, 58, 299, 311], parks opted to promote the scientific programs needed to better protect resources. Such programs were initially framed in the Vail agenda (1991) and later consolidated in the Natural Resources Challenge (1999). The latter seems to respond to the Omnibus Management Act, and is one of the first internal policies that institutionalized science [113].

The Omnibus Management Act and the Natural Resources Challenge, as well as subsequent science policies[6] (see ST. 1 and Fig. 7.2), are the constituents of the SPNP. In general, the SPNP policies are framed from the quote "*Parks for Science, Science for Parks*" first introduced by Council [81], aimed at bridging scientific knowledge and parks management. The rationale behind the quote is to increase the scientific knowledge available for management by incentivizing universities and third parties to conduct research in parks [200, 204, 228, 243, 281, 310, 311]. Notably, the SPNP does not seek a self-sufficient production of scientific knowledge but relies on external capabilities. Therefore, pertinent and timely knowledge is not necessarily ensured.

The "*Parks for science, science for parks*" idea and the SPNP were manifested through millions of dollars granted for collaborative research and the adequacy of facilities for conducting science [144, 299, 310]. For example, initiatives such as the Cooperative Ecosystem Study Units (CESU)[7] were supported by funds of the Omnibus Management Act. External funds also leverage that idea by funding Ph.D. students[8]. Parks initiatives, including Sabbatical-in-the-parks, Research Learning Centers, National parks ecological research fellowship program, and the internet-based Research Permit and Reporting System (RPRS) reflect the modern openness of parks administration and their willingness to incentivize research in parks [243, 310]. However, it is largely unknown whether science has met the knowledge that managers require for the stewardship of parks and if the SPNP has indeed bridged the historical gap between the academic community and parks.

Accordingly, in this work we assess to what extent scientific publications (*"research priorities"*) and the knowledge demanded by parks' administration (*"research needs"*) are aligned? And what has been the impact of the SPNP on that alignment? This study therefore evaluates the science-parks relationship by describing the dynamics of knowledge (mis)alignment. Consequently, this study contributes by identifying some implications of the current SPNP and contributes new insights to the discussion regarding science's organizational value.

7.2 Methods

The evaluation of knowledge alignment has taken place through multiple methodologies, for which the characterization of research priorities commonly relies on cartographies of knowledge based on scientific publications [74, 70, 266, 346]. Although various methods for mapping scientific knowledge exist [241, 140, 303, 41, 72], not all them have been used for assessing knowledge alignment. On the other hand, research demands have been addressed by using basic need indices [74], disease burden [266], interviews and stakeholder opinions [346, 198], and policy documents [70], among other sources. Research needs vary by the nature of investigation, their content, and how they are codified, all of which constitute an important challenge.

Matching and interpreting the relationship between research priorities and needs is not without its shortcomings. Frequently, knowledge alignment has been evaluated qualitatively, indicating what is perceived as (mis)alignment [291, 93, 298]. Other cases have accounted for the degree of alignment using statistical models [74, 252, 70]. Explicitly or implicitly, the generation of discrete and well-defined categories underlies the analysis of knowledge alignments. We therefore propose making explicit such categories and use them as units of analysis for estimating the balance between the supply and demand for knowledge. In what follows we describe the sources of information used for measuring knowledge alignment in the US national park system and then describe a conceptual model designed to match-up research priorities and needs to evaluate the degree of alignment between them.

7.2.1 Data

To evaluate alignments between research priorities and needs in parks, we use two data sources specifically related to each side. We evaluate research priorities by analyzing scientific publications (i.e., articles, reviews, books, and conference papers) indexed in Web of Science (WoS). WoS is highly structured and one of the largest repositories of science, frequently used for evaluating scientific outcomes [186]. Although WoS does not include all scientific publications, it is a reliable source of systematically indexed and annotated scientific knowledge.

The publications contained in WoS were retrieved using two queries[9] resulting in 17,326 research articles published between 1921 and 2020. Each one includes the affiliations of authors, title, year, keywords, and enhanced keywords (WoS standardized keywords). We limited our analyses to publications that met at least one of two criteria: one or more authors were affiliated with a US national park; or, one or more US national parks are mentioned in the title, keywords or abstract. We applied these criteria by performing string matching across the standardized metadata associated with each publication. As a result, we identified 8,088 publications developed in, or by parks.

In this study we leverage information regarding research needs from the RPRS available at the Integrated Resource Management Applications (IRMA)[10], which is the official system for requesting research permits to parks administration. In RPRS each park enumerates their research needs (termed 'research preferences') to inform researchers about the most urgent issues and the knowledge that parks consider require further investigation. IRMA therefore provides a direct measurement (and therefore draws a realistic picture) of the park's research needs, which conceptually correspond to expressed research needs.

We inspected IRMA webpages for all national parks[11], nonetheless some parks did not state their research needs, or the webpages were not accessible due to broken web links. As such, we gathered the information for 36 out of 60 national parks (with three parks recently added, now totaling 63). Throughout this study we use the simplified acronyms that IRMA utilized to designate parks, listed in ST.2. We divided the research needs into individual need statements when they were stated in prose, without including major changes in syntax or content. In total we count 1,035 individual need statements, with noticeable variation across parks, varying from 2 statements at Everglades NP (EVER) to 155 for Sequoia and Kings Canyon NPs (SEKI). On average, there are 29 need statements per park.

7.2.2 Analytical approach

In Section 7.1.1 we introduced some of the common theoretical approaches and conceptual challenges for evaluating knowledge alignments. Another challenge addressed in this study arises from the two different research priority and research needs text sources, which differ in both origin and intended purpose. Hence, we first aim to establish a common set of topical intermediary categories based upon these two text sources (see Fig. 3). There are various dimensional reduction methods for identifying topical categories (i.e., clusters of related scientific knowledge), and these methods can generally be divided into two types: knowledge maps and topic modeling. The former method is more common within studies of knowledge alignment than the latter method. Notably, both methodological approaches lead to similar outputs [336].

Knowledge mapping approaches commonly leverage existing keywords ontologies or other article-level descriptors, useful as heuristics for defining categories of scientific knowledge [72, 96, 118, 130, 140, 284, 361, 364]. On the other hand, topic modeling is a more appropriate approach in the absence of ontology metadata.

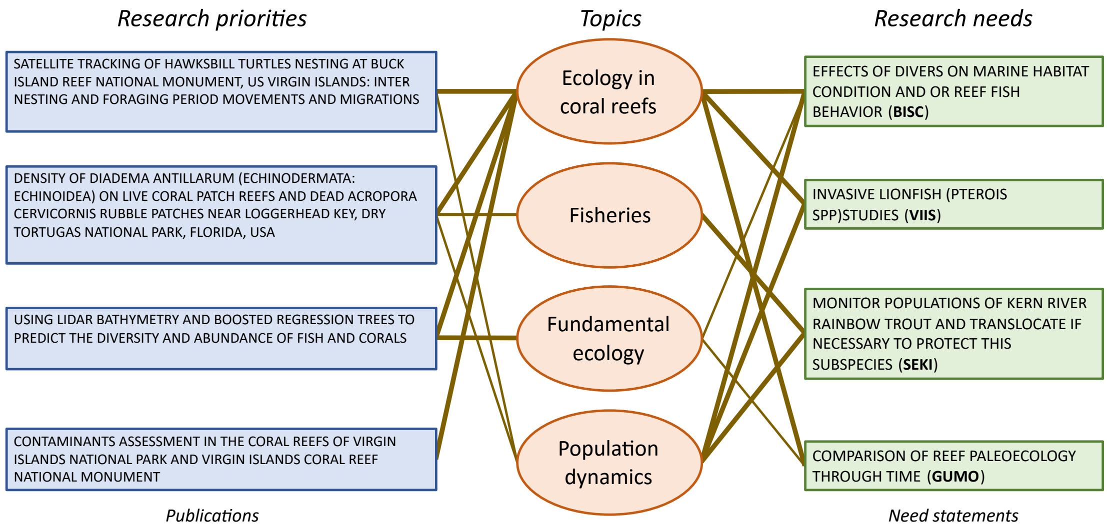

Figure 7.3: **Conceptual model for evaluating alignment between research priorities and research needs through topical categories.** Research priorities correspond to publications, and research needs are official park-specific "need statements" (specific source NP indicated in bold). Research priorities and needs are associated with LDA topics with different strengths, as indicated by the variable thickness of the brown lines. The information used in the schematic correspond to real data.

Since there is no established ontology for national park concepts and entities, we apply Latent Dirichlet Allocation (LDA) topic modeling to the text sources in union [12]. We chose this method because it is a relatively general, well-understood, and replicable machine learning algorithm designed to identify a certain number of topic categories based on semantic associations [303, 186, 44, 141, 306]. As illustrated in Fig. 7.3, topics identified by LDA are connected to publications and need statements that refer to similar issues and consequently relate to each other. With this approach, the relative (dis)parity in the composition of topics in terms of publications and need statements indicates the degree of (mis)alignment.

Figure 7.3 illustrates the implementation of the topic-modeling approach, using empirical examples taken from our data sample. Several characteristics of our natural-language machine learning approach are worth mentioning: (*i*) publications and need statements are written in different styles; (*ii*) both publications and need statements can be associated with multiple topics and the intensity or weight of such association might vary; (*iii*) while some topics in the example are well represented in both publications and needs statements (e.g., 'Ecology in coral reefs'), others are disproportionately weighted on one side (e.g., 'Population dynamics'). Indeed, this (dis)parity is the basis for the quantitative evaluation of knowledge alignment that follows. For instance, 'Ecology in coral reefs' is well aligned because the supply/demand balance based upon connectivity from each domain is close to a 1:1 ratio, whereas 'Population dynamics' is misaligned, in this case representing an over-demanded research topic.

Table 7.1: **List of 40 LDA topics used for assessing knowledge alignment in the US national parks.**. Topics (T) were identified using the Latent Dirichlet Allocation (LDA) algorithm applied to scientific publication metadata and parks' need statements. We manually assigned a title to each T listed below based upon the 20 most prominent words associated with each topic. Topics denoted with ** are here associated with normative needs since they relate with congressional policies that mandate their study (see ST.4).

T-1	Ecology in coral reefs	T-21	Sustainability**
T-2	Ecology of amphibians	T-22	Biodiversity in the Rocky Mountains
T-3	Geology and paleontology**	T-23	Habitat use in deserts
T-4	Wetlands and restoration	T-24	Control of invasive ants
T-5	Marine ecology	T-25	Sierra studies
T-6	Fire ecology	T-26	Human impacts**
T-7	Vulcanology	T-27	Fundamental ecology
T-8	Paleoclime and paleoecology	T-28	Visitation and recreation**
T-9	Bio and social studies in caves**	T-29	Ecosystems management**
T-10	Management and modelling**	T-30	Mammalogy
T-11	Air quality**	T-31	Species distribution**
T-12	Ecology in hot springs	T-32	Clime and climate change
T-13	Forest**	T-33	Ungulate studies
T-14	Ecological monitoring**	T-34	Population dynamics ecology
T-15	Floristics in mid-west	T-35	Forest and alpine ecosystems
T-16	Limnology	T-36	Pollution**
T-17	Fisheries and freshwaters	T-37	Nutrient cycles
T-18	Invasive plants	T-38	Environmental modelling
T-19	Invasive animals	T-39	Trophic interactions ecology
T-20	Bears' ecology	T-40	Landscape studies

Acknowledging the differences in written style, text format, abundance, and length between publications and need statements, we explored different combinations of publication metadata (i.e., title, abstract, keywords)[13] as illustrated in Appendix A. Our systematic investigation indicated that the LDA topic model produced from text input comprised of full need statements and the title and keywords of publications are appropriate for the scope of our study. As such, we found that 40 topics are adequate to capture the aggregated corpus. Table 1 lists the identified topics; Supplementary Table 3 further lists the 20 most relevant words defining each topic. All LDA analyses were conducted in R [324] using the package topic models [157].

Furthermore, we classified the topics themselves into two categories: normative and non-normative, as indicated by the asterisks in Table 1. We used relevant congressional mandates[14] to differentiate normative (representing those following official US government standards) from non-normative topics. In this way, normative needs correspond to those initiatives advocated by law (see Supplementary Table 4).

7.3 Results

Topics found with our analysis illustrate a set of important knowledge domains for science and the National Park Service. Although the identified topics might suggest a bias towards natural sciences, many capture inter- or multi-disciplinary topic domains, and others reflect social and management sciences, as well as the human dimensions of the environment (Table 1). For example, topics capture anthropogenic impacts (e.g., T-4 'Wetlands and restoration'), ecosystem management (e.g., T-21 'Sustainability') and tourism (e.g., T-28 'Visitation and recreation'). Because parks are socio-ecological systems, it is not surprising that the 40 topics span the management, social, engineering and natural sciences, as well as convergent knowledge domains at their intersections [249].

To what extent parks' research needs are addressed by scientific research can be evaluated across two dimensions of park generality and specificity. In the first case regarding park generality, one can assume that broadly reaching scientific knowledge is beneficial to all parks indistinctively. For instance, findings regarding water or air pollution may be informative to all parks in the system. However, in the second case when considering how specific are the results of scientific research to a specific park, research is further contextualized by park-specific idiosyncrasies and history. While characterizing the range of applicability of each publication to each particular park is beyond the scope of this study, we nonetheless acknowledge that applicability of research findings are likely to vary between parks, just as research needs also vary across parks.

Consequently, in the following section, we first present the analysis based on a system-level investigation assuming that research findings are informative to all parks.

We then downscale to park-specific analysis, where we leverage the implicit connection between the research publications associated with a given park (based upon string matching of title, abstract and keywords) and the needs statements of the same park. It is at the park level that we evaluate the impact of SPNP policy change on topical alignment.

7.3.1 National Park system-level results

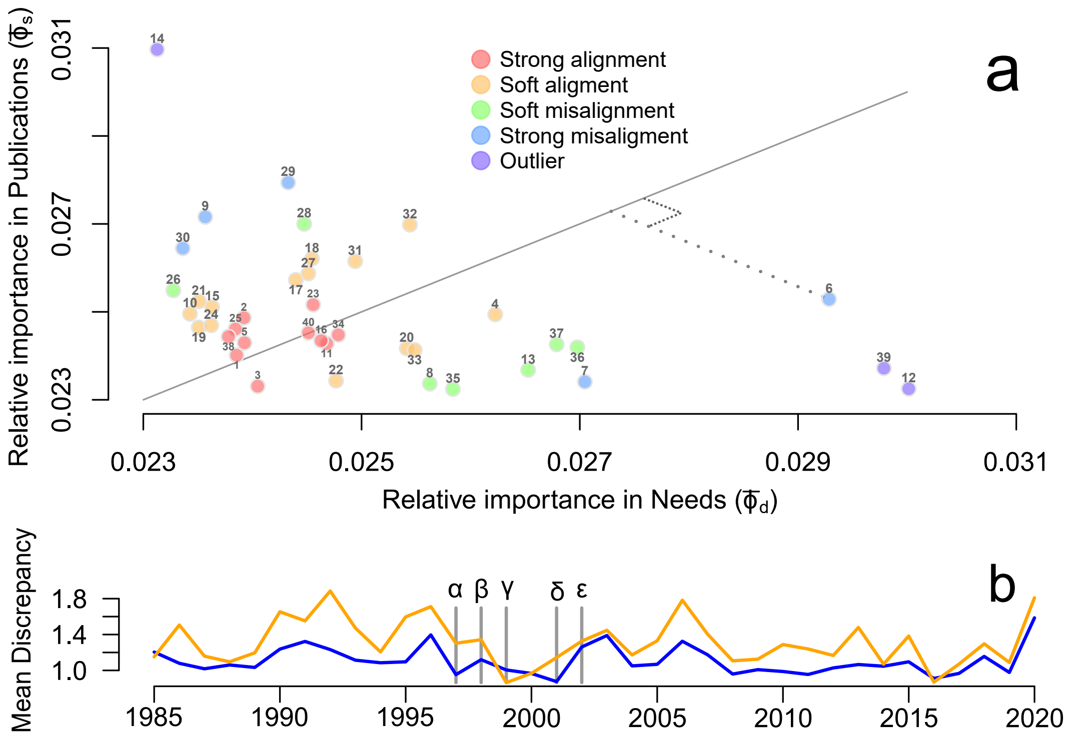

Figure 7.4: **Alignments between research priorities and research needs based upon data aggregated across all US national parks with available data (N=36).** (a) Topics identified with the LDA model are plotted in terms of their relative importance in publications ($\overline{\phi}_s$) and need statements ($\overline{\phi}_s$), and colored using quintile class according to their discrepancy. For example, the dashed line represents the discrepancy for Topic 6. (b) The change in the annual mean discrepancy across the 40 topics (blue) and for the normative topics (orange). Vertical lines represent important events as follows: (α) Preserving Nature in NPs (Sellar, 1997), (β) Omnibus Management Act, (γ) Natural Resources Challenge / Cooperative Ecosystem Studies Units (CESUs), (δ) Research Learning Centers, (ε) Canon Inc. Scholar grants.

Figure 7.4a shows the relative prominence of each LDA topic, quantifying research supply as the mean likelihood ($\overline{\phi}_s$) calculated across all publications; and quantifying research demand as the mean likelihood ($\overline{\phi}_d$) calculated across all need statements. Perfect alignment corresponds to the 1:1 ratio between the two relative measures, corresponding to the diagonal in Fig.7.4a. Deviations from the parity line indicate misalignment. We quantify the misalignment as the length of the bisect segment that connects a topic with the diagonal line, which we term discrepancy (see for example the dashed line in Fig.7.4a).

We classify the topics into quintile categories based upon the distribution of discrepancy measures. Topics close to the diagonal characterized by small discrepancy values are denoted as "Strong alignment"; whereas topics with large discrepancy values are classified as "Strong misalignment". Intermediate levels of (mis)alignment are classified as "soft"; conversely, outlier discrepancies are identified as extreme cases of misalignment, corresponding to topics: 'Trophic interactions ecology' (T-39), 'Ecology in hot springs' (T12) and 'Ecological monitoring' (T14). In addition to the degree of (mis)alignment, we differentiate the direction of misalignment, where topics above the diagonal are considered to be over-researched, while those below are over-demanded.

Our results indicate that nearly 63% of topics are either softly or strongly aligned. Of those that are misaligned (23%), most of these topics are over-demanded or below the diagonal line. In addition, 7 out of 12 topics associated with normative needs were misaligned, of which only T-13 ('Forest') and T-36 ('Pollution') corresponded to over-demanded topics. Overall, Fig. 3a shows that topics tend to be relatively close to the diagonal, and thus well-aligned; and misalignments were commonly over-demanded topics, except for the normative topics which were mostly over-researched.

Over-researched topics located above the diagonal mostly correspond to monitoring (e.g., T-9 'Bio and social studies in caves', T-14 'Ecological monitoring', T-30 'Mammalogy') and parks management (e.g., T-26 'Human impacts', T-28 'Visitation and recreation', T-29 'Ecosystems management'). Over-demanded topics located below the diagonal correspond to highly specific ecosystems (e.g., T-12 'Ecology in hot springs' T-13 'Forest and alpine ecosystems', T-35 'Forest') or labor-intensive and long-term studies (e.g., T8- 'Paleoclime and paleoecology', T-36 'Pollution', T-37 'Nutrient cycles', T-39 'Trophic ecology'). Strong alignments were represented by topics that are highly disciplinary (e.g., T-3 'Geology and paleontology', T-34 'Population dynamics ecology'). To test whether these patterns are spurious, we developed a null model consisting of documents with various degrees of randomness based upon shuffling a certain amount of the text words (Appendix B). The results of such a null model did not reproduce the mentioned pattern of topical alignment, and so it is unlikely that the observed patterns arose simply by chance [15].

When analyzing how the knowledge alignment has changed over time, we found that the absolute value of discrepancies (i.e., disregarding whether the data point is above or below the diagonal) has not systematically changed over time. Notably, topics associated with normative needs tend to be slightly less aligned (i.e., larger mean discrepancy) than the average calculated over the 40 topics (Fig.7.4b). The temporal trend of the mean discrepancy shows that the topics were mostly aligned and fairly close to zero discrepancy.

In general, our system-level results suggest an optimistic scenario in which research priorities are aligned with research needs across many topics, and with no notable differences between expressed (all topics) and normative needs. Thus, we do not find clear evidence of systematic changes in the mean degree of alignment over time, with no clear indication of the SPNP policy change on aggregate-level alignment (Fig. 7.4b). Interestingly, although just a few topics strictly related to human aspects, many topics address cross-domain problems, which suggests that our results are not necessarily biased by the disciplinary disparities in publications. In particular, those topics related to social sciences are not under-researched as one might expect, but rather they appear to be intensively researched (e.g., T-21 “Sustainability” and T-28 “Visitation and recreation”).

7.3.2 Individual park-level results

To evaluate changes in knowledge alignment and its characteristics at the individual-park level we address discrepancies in two ways. First, we evaluate the distribution of discrepancies considering their sign to differentiate over-researched and over-demanded topics. Second, we assess the overall degree of (mis)alignment calculated as the total discrepancy (the sum of the absolute distances) as an indicator of the magnitude of (mis)alignment.

Figure 7.5a shows the park-specific distributions of discrepancies, which tend to be centered around positive values representing over-supply, indicating that the topics are well-aligned or slightly over-researched on average. Yet there is considerable variation in the interquartile and total range of topic discrepancies, within and across parks. For instance, CARE (Capitol Reef NP) is a park in which few topics are extremely over-demanded, whereas VOYA (Voyageurs NP) represents a case in which topics are evenly distributed above and below the diagonal, as shown by the median located near zero, although the distribution is rather wide. SEKI (Sequoia and Kings Canyon NPs) had the most need statements, and its distribution is quite narrow and right skewed, indicating that most of the topics were fairly well aligned or slightly over-researched. We explored factor analysis of parks' characteristics (e.g. size, budget, visitors) but no observed significant relationship with the overall degree of alignment.

The total (absolute) discrepancy captures the overall degree of (mis)alignment. We evaluate how this metric varies over time for each park (Fig.7.5b; see Appendix C for all the parks), identifying some differences in the trend that each park follows. While some parks are rather stable (e.g., YELL, GRSM), others feature a significant increase (e.g., KATM) or decrease (e.g., ARCH) over time. Consistent with the results found at the system level (Fig.7.4b), we did not identify a dominant increasing or decreasing park-level trend (see Appendix C).

Notably, we did not measure any significant Pearson's correlation between the mean, median or total discrepancy with the number of publications found in each park ($R^2 = 0.003$; $R^2 = -0.305$; $R^2 = -0.230$, respectively) nor the number of need statements declared ($R^2 = -0.327$; $R^2 = -0.153$; $R^2 = -0.217$). Hence, it is unlikely that these park level results arise from variation in the sample size of publications or need statements.

7.3.3 Policy evaluation and parks-science alignment

Finally, we apply ANOVA to assess the relationship between supply-demand alignment and the documented paradigm shift in science policy of national parks (SPNP) around the year 2000. In particular, we test for differential impact of SPNP on the (mis)alignment of non-normative versus normative topics. To be specific, we test for shifts in characteristic discrepancies, calculated by grouping park-topic-year discrepancy values into 4 non-overlapping subsets separating normative and non-normative topics measured before and after 2000. To account for park-specific variation (as indicated by Fig.7.5), we normalized discrepancy values such that d_i are defined as the annual discrepancies d_{kjt} for each topic (k) and park (j) divided by the typical standard deviation of each topic (σ_i).

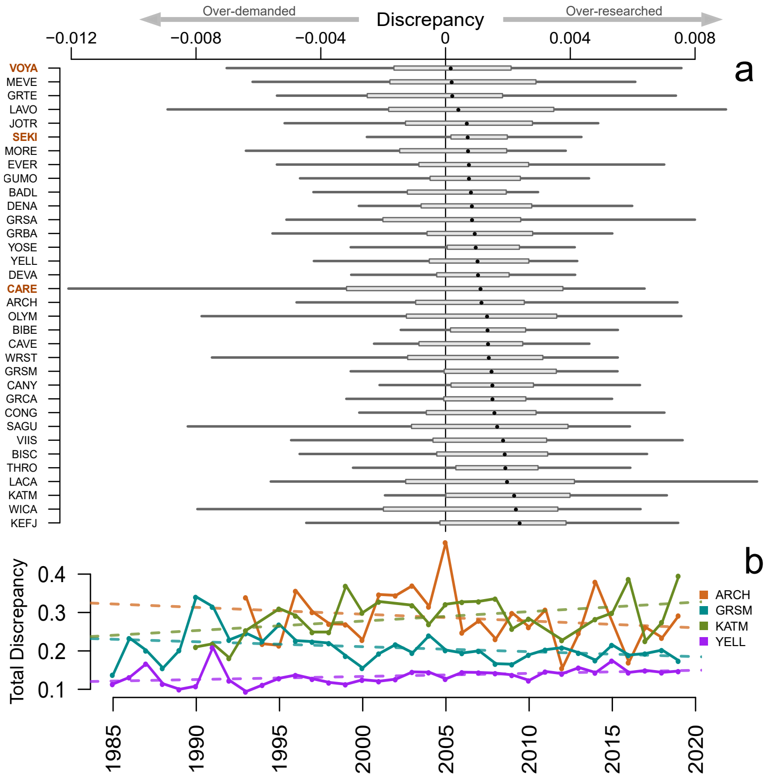

Figure 7.5: **Spatial and temporal variation in the degree of alignment between research priorities and research needs across US national parks.** (a) Spatial alignment evaluated as the distribution of discrepancies for each park. Parks are labeled according to their official acronyms; those mentioned in the text are colored in brown. Distribution of discrepancies are represented as boxplots for which dots indicate the median discrepancy. (b) The temporal variation of alignment is measured as the total discrepancy and shown for 4 parks. For illustrative purposes, the linear trend (dashed line) for each park is included, estimated by ordinal least squares (OLS). Temporal variation for all the parks can be found in Appendix C.

We first tested for a statistically significant shift in the mean d_i value associated with the introduction of the SPNP by comparing values calculated before versus after 2000. Results indicate no relation between the introduction of the SPNP and the overall topical alignment (t value$= 0.545$; $p - value = 0.586$). However, comparing the mean d_i value conditional on the topic being normative versus non-normative, we found non-normative topics to be statistically more aligned than normative ones (t value$= 8.876$; $p - value < 0.001$).

Based upon these two results, we calculated the Difference in Difference (DiD) between normative and non-normative topics, calculated before and after 2000. Such a

DiD measures the shift in mean non-normative discrepancy, relative to the normative baseline, associated with the introduction of SPNP. Figure 7.6 summarizes the results of the ANOVA, which indicate that SPNP exacerbated the difference between normative and non-normative topics (t value= -2.139; $p - value$= 0.033). Hence, while SPNP did not appear to directly affect topical alignment, its introduction does correlate with a divergence of alignment between these two distinct topics classes. These results are consistent with the implications of SPNP, which served to mandate the overarching normative topics, resulting in an over-reaching effect of over-stimulating normative research and, consequently, leading to a higher degree of misalignment.

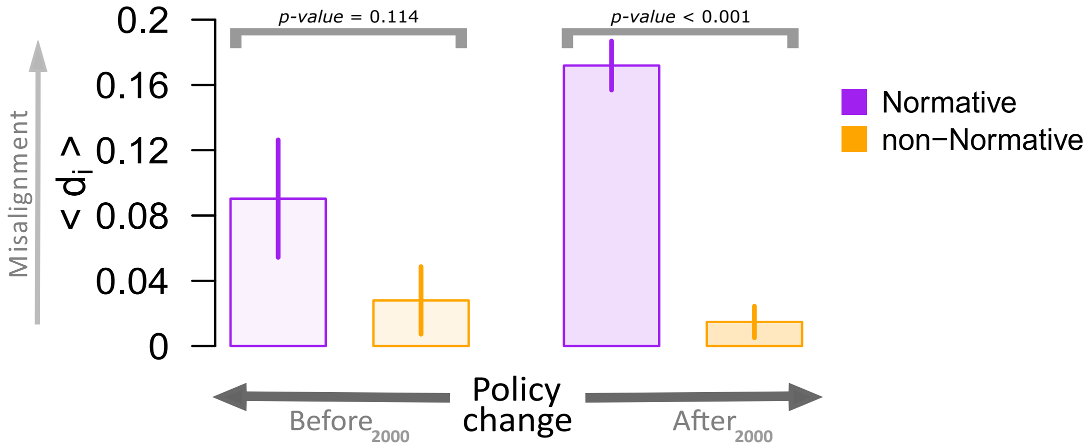

Figure 7.6: **Evaluation of how shifts in science policy of the US national parks (SPNP) correlate with shifts in park-level misalignment, assessed by way of mean topical discrepancies.** Each bar shows the mean topical discrepancy $\langle d_i \rangle$ (calculated for park-level observations that are appropriately standardized to account for characteristic park-level variation levels) and the corresponding standard error of the sample mean (indicated by the vertical line). Note that divergence from 0 correspond to greater misalignment. Park-year-topic discrepancy values are separated into four groups, corresponding to normative and non-normative topics, and for years before and after 2000 corresponding to the approximate peak of SPNP.

7.4 Discussion

Despite the clear need for science-based research to inform organizational decision-making, what is researched does not always correspond to the most relevant or urgent needs [70, 74, 198, 291, 298]. Understanding how and when such misalignment arises is critical because it may inform policy development [74, 291], and highlight problem domains and their corresponding knowledge regimes that require more attention [14]. To this end, we developed a framework for quantitively evaluating the alignment between scientific knowledge production and the stated needs of individual US national parks by developing a robust method based on pairing research priorities and needs through a comprehensive set of topic categories. As such, this framework enables (1) identifying knowledge areas that are over-researched or under-researched; (2) evaluating spatiotemporal trends in science-parks alignment; and (3) measuring the impact of transformative science-parks policy on knowledge alignment.

Our results indicate an optimistic scenario where most of the research in parks is aligned, and the pool of under-researched topics corresponds to idiosyncratic, complex and generally demanding problems that one might intuitively expect to be misaligned based upon the considerable resources required to address them (e.g. knowledge regarding "Paleoclime and paleoecology"). Although observed levels of knowledge misalignment across parks is variable, topics characterized as aligned and over-researched are typically more common than those that are over-demanded. However, this desirable scenario is attenuated by the fact that normative topics (those addressing overarching system-level themes such as "Air quality" or "Wilderness") tend to be more over-researched than non-normative topics. Importantly, considering the abundance of resource constraints characterizing national parks management, it is likely that over-researched topics may flourish at the expense of other prioritized topics.

The idea of parks as a mission-oriented and well-ordered research system [243, 172] – as illustrated by the transformative "Parks for science, science for parks" narrative [81] – supposes that science in parks should be aligned with managerial needs. Yet, our results suggest that longstanding efforts promoting favorable conditions for parks science have not fostered improved knowledge alignment. In particular, we find that the US science policy of national parks (SPNP) may have exacerbated pre-existing levels of misalignment – i.e., increasing the disparity between normative and non-normative topics. We acknowledge that this result may be the natural outcome of mandates defined around normative needs meeting their initial objectives, as much of the misalignment observed for normative topics is driven by over-research of broad themes such as monitoring (e.g., ecological monitoring and mammalogy) and parks management (human impacts, visitation and recreation, ecosystems management). However, this does not imply that the original policy is meeting current needs associated with over-demanded topics corresponding to pressing challenges (e.g., climate change and forests). We therefore argue that new approaches to co-production and prioritization of research are necessary to address the adaptive management needs of individual protected areas and park systems at large.

Adaptive management regimes implicitly require considering the dynamics of the supply and demand for knowledge, as well as the implications of institutional and contextual factors. First, as we illustrate in Fig.7.1, although the internal dynamics of knowledge producers (i.e., scientists) and the knowledge users (i.e., parks managers) are coupled by the communication between the parties, internal institutional processes can affect the research feedback, and therefore knowledge alignment. By way of comparison with academia, the more centralized governance structure, lower levels of park scientist autonomy and acute preferences of parks managers (i.e., superintendents) can together manifest in activity filters, thereby strongly affecting what research needs are officially declared and prioritized. In particular, this follows from the bureaucratic structure of the parks system such that park managers have significant gatekeeper authority over communication channels, which can directly facilitate or obstruct research activities and feedback. As such, individual parks are embedded in multi-level hierarchical structures – i.e., locally as well as nationally within the purview of the Department of the Interior – which introduces knowledge diffusion bottlenecks that hinder and delay the identification and action upon research needs. Several identifiable mechanisms that contribute to such knowledge production and diffusion inefficiency are the ranking and prioritization of declared need statements; the allocation of scarce resources (financial and human) necessary to produce and capitalize on produced knowledge; and the dissemination of research results, which may become trapped within individual parks, given their geographic dispersion. Whereas hierarchies can foster institutionalization of certain agendas, the same vertical organization may hinder the scaling-up of both local and system-wide efforts.

Second, contextual factors can indirectly affect the research feedback when such factors contribute to the definition of research priorities and needs. For instance, funds that support research in national parks (e.g., via the National Science Foundation) are subject to political inefficiencies due to the implicit misalignment of different federal agencies' missions, mandates, and priorities. Hence, funds prioritized for national parks research must either compete through the traditional academic channels of funding initiatives, or be negotiated at higher bureaucratic levels once certain knowledge domains and research priorities are agreed upon. Another issue that compounds the problem of context is the restrictive nature of mandated research, which can unintentionally alter the orientation, priority and feasibility of stated research needs. By way of example, researchers based in parks must carefully navigate research activities to be compliant with National Environmental Policy Act (NEPA) requirements, lest they run the risk of losing federal funding support. Another dimension of contextual factors is the burdensome lags in science policy development, which can derail both research agendas, and hence both academic and park scientist careers. For example, the "science mandate" of national parks institutionalized in the Omnibus Management Act was congressionally approved almost 8 years after being framed in the Vail agenda [144]. As such, the possible benefits of normative (mandated) research, existing in relative overabundance, are diminished by the glacial speed at which legislation often unfolds. Consequently, these considerations further support the need for more proficient adaptive management of science in parks. Indeed, given the political nature of agency underlying the execution of parks science, attention must focus on identifying configurations of park science governance that coordinate, promote, and expedite knowledge production and communication by improving upon existing science-parks-policy interactions. Investing in such a triple-helix governance model, as traditionally posited for university-industry-government relations [110, 185, 187], could better facilitate the generation of innovative solutions by leveraging the strategic supply-demand-facilitator (triple-helix) configuration [187, 185, 252].

Complementary support for more strategic and dynamic science-parks-policy interactions is provided in the knowledge alignment literature, which posits highly aligned sciences as a desirable state, and knowledge misalignments as undesirable outcomes [291, 268, 198, 93, 74, 70]. Against this backdrop, our results raise three important points. First, the complex nature of some research areas might imply large misalignment given the difficulty of producing and leveraging relevant knowledge and does not necessarily imply neglect on the part of the academic community. Second, not all misalignments are equally undesirable. Indeed, in some circumstances over-researched topics might be preferable if urgency to make headway on such issues is required. Third, we acknowledge that normative enforcement of science can facilitate the allocation of the resources necessary to conduct research in urgent issues, although the narrow perspective of organizational management and other top-down science governance strategies might exacerbate misalignments. As such, to increase overall alignment, there is a need for improved adaptive coordination between academics, park managers and park scientists to better align knowledge creation around urgent problem domains. Such democratization of the prioritization of knowledge production can foster better knowledge alignment [133, 240].

We also acknowledge some limitations in our study and potential for improvement. First, the official parks need statements used are aggregated over time; without a temporal component this issue negatively affected our ability to assess the co-evolution of science–parks alignment. Hence, we recommend that this system be updated to include time-stamps and location stamps to facilitate multi-scale analysis and decision support. Second, our assessment of park needs was based upon a set of statements associated with each park, which vary in terms of breadth and depth, and of unclear source generation. Although systematic and uniform, these needs statements lack the broad scope obtained from interviews and other participative methods, which could better identify idiosyncratic needs derived from a pragmatic grass-roots perspective, one that could be decomposed and weighted according to stakeholders' perception and preferences [346, 239, 107, 94, 93, 70, 268]. Third, we were faced with the common trade-off of comprehensive generality versus contextual specificity. As illustrated in Fig. 3, publications and need statements are associated through well-resolved topical categories; however, our model lacks appropriate depth to effectively evaluate whether the knowledge produced in a research publication can indeed be used to address the problem represented by the research need. In addition, it is important to consider that even if publications have a direct and sufficient relation with a particular and highly specific need, this does not always mean that knowledge beneficiaries—parks in our case— will use or operationalize such knowledge. In other words, knowledge could be aligned but not actionable.

In summary, managing national parks, as well as other protected areas governed according to visitation and conservation mandates, is a complex endeavor owing to the canonical challenges of management under uncertainty and finite resources, but also exacerbated by the inherent complexity of intertwined social and ecological systems. More knowledge certainly is beneficial; nevertheless, parks require capabilities for absorbing such knowledge. As historical criticisms have claimed, the autonomous scientific capabilities of parks are always a subject of improvement [311, 299, 113, 144]. Part of this enhancement is the development of adequate systems for informing researchers about current (and updated) parks' needs. Such systems would not only boost the research feedback (Fig. 7.1), but also potentially improve the protection and management of the already-scarce protected lands and their value as living laboratories – thereby serving as valuable counterfactuals for assessing anthropogenic impacts relative to the more abundant anthropogenic biomes. In addition, more strategic science–parks-policy interactions that recognizes the complexity of parks and the interconnected and systemic nature of impacts [152] might strengthen the accomplishment of the parks mandate of keeping resources unimpaired, for the public, forever.

7.4.1 Policy implications and recommendations

Robust research programs that foster knowledge alignment promise to contribute to organizational challenges by providing fundamental knowledge necessary for managing systemic complexity [152]. Yet, what makes a system better aligned is not completely clear. Moreover, a perfectly aligned research system is not necessary a desirable state, particularly when needs become outdated, as is the case when the source problems that originate needs evolve more rapidly than the ability of problem-solvers to identify, coordinate around, and address such problems. We posit that the paradigm shift in SPNP that brought together scientists and organizational actors in the co-production of knowledge could favor alignment, but the results indicate that such science policy may overemphasize certain types of research topics, giving rise to systemic inefficiencies in research allocation (misalignment).

Although the SPNP was not designed to promote knowledge alignment, one might think that this could be an implicit objective. However, our results indicate the opposite. Drawing from the characteristics of the SPNP and its unintended consequences on the overall knowledge alignment, we propose that policies aimed at boosting science–parks interactions should address four considerations.

First, science governance policies should embrace the democratic principles of crowdsourcing by better supporting the inclusion of multiple voices in the negotiation, design, and development of research agendas that improve the research cycle introduced in Fig.7.1. As such, this study takes initial steps towards understanding and ameliorating the science agenda governance problem by developing a relevant knowledge alignment framework for administrators of the National Park Service and other protected areas tasked with prioritization. In particular, we developed this empirical approach for analyzing knowledge alignment by leveraging the valuable system of official "needs statements" implemented across the parks units, which we laud for being made openly available. Yet this valuable reporting system could be improved so that it is more amenable to data-driven analysis, for example by time-stamping the individual needs statements or by making them more uniformly documented.

Second, progressive policy should recognize the adaptive nature of complex systems as well as the multiscale variability of the systems and the unviability of one-size-fits-all solutions. This follows because rigid over-arching policies (e.g., normative needs), as opposed to adaptive ones, may overemphasize outdated organizational demands and capabilities, consequently exacerbating misalignments. Third, such policies should anticipate and support societal challenges. Although we know little about the emergence of societal or organizational needs, it is known that research typically lags demand; hence, ensuring better timing in knowledge production can favor alignment. And fourth, policies should better facilitate knowledge translation. Qualitative alignment requires knowledge transfer, which implies both engaging researchers in delivering accessible knowledge and ensuring a wide range of stakeholders (federal agencies tasked with oversight, parks administrators and scientists designing interventions) with the capabilities to absorb and use the knowledge. Overall, more than ever it is necessary to stimulate a broader involvement of society at large into the production and appreciation of scientific knowledge contributing towards the objective of conservation.

Supplementary Material

Supplementary materials are available at https://zenodo.org/record/7636912 and include: Implementation of the main analytical approach (**Appendix A**), comparisons of the results with the null model designed to test the robustness of the analysis (**Appendix B**), and an analysis of the dynamics of alignment for the different national parks (**Appendix C**). Furthermore, It is provided the list of important historical events that contribute to shaping the science policy of national Parks (**Supplementary table 1**); a list of acronyms of parks (**Supplementary table 2**) and descriptions of the topics produced by the methodological approach (**Supplementary table 3**). Finally, a list of congressional mandates that we define as guiding elements for defining Normative topics is included (**Supplementary table 4**).

Notes

[1]These factors include science policies, extramural sources of funding, investment risk and expected outcomes, researchers' interests, peers' pressure, academic networks, journals influence, researchers' expertise, and other factors.

[2]The Organic Act (1916) that originated the National Park Service (NPS) mandates the agency to conserve the scenery and embedded resources unimpaired, and to maintain the public parks for both present and future enjoyment.

[3]Sellars [299], Parsons [243], Shafer [301], and Harmon [144] are important reviews on the history of the US national parks and its linkage with science.

[4]For instance: National Biological Survey in 1939 and National Biological Service in 1993. Both reforms implied scientific decoupling and administrative reorganization [228, 175, 344]

[5]These include the Clean Air Act (1963), the Wilderness Act (1964), the National Environmental Act (1969), the National Park System General Authorities Act (1970), the Clean Water Act (1972), the Endangered Species Act (1964), the Archeological Resources Protection Act (1979), and the Alaska National Interest Lands Act (1980).

[6]See for instance: Interagency Strategic plan for wilderness [31]; Exotic Plant Management Teams (2000); Rethinking the National Parks for the 21st [122]; Management Policies (NPS, 2006); National Park Service Science in the 21st Century (Earle, 2009); National Park Service Climate Change Response Strategy (NPS, 2010); Business Plan of the NPS Wilderness Stewardship Division (NPS, 2011); Revisiting Leopold: Resource Stewardship in the National Parks (Colwell et al., 2012); Natural Resource Stewardship and Science Framework (NPS, 2016)

[7]Cooperative Ecosystem Study Units are inter-agency research hubs for parks and other federal lands. There, universities, research centers, and park's scientists collaborate through calls for proposals and grant opportunities centered around scientific needs of units or regions. The work conducted at these units could be considered as mission-oriented. More information is available here

[8]This includes the Canon Inc. fellowship. In 1997 the NPS negotiated an agreement with Canon USA Inc., to provide up to 2.5 million dollars to support graduate students to conduct research important to the future of national parks [243]. More information is available here

[9]The queries used to identify the research developed in national parks were "TS=(National Park*)" and "OO=(Natl pk)". Data was downloaded in February 2020.

[10]The RPRS is available here. The system allows one to search what research needs or preferences are declared by each unit in the NPS.

[11]We excluded other NPS denominations such as monuments, battlefields, waterways, among other. We restricted our analysis to national parks as the most emblematic units within the NPS.

[12]LDA considers topics as probabilistic mixtures based on the co-occurrence of semantic structures between and within documents (i.e., documents refer to publications and need statements, indistinctly). LDA was initially introduced by Blei et al. [30], and details of its implementation can be found in Griffiths and Steyvers (2004); we also expound on relevant details in Appendix A. To avoid the subjectivity associated with defining the correct number of topics [70], we followed the approach of Griffiths and Steyvers [141], and Ponweiser [260], which consists of varying the number of topics incrementally until reaching convergence in the likelihood of coefficients. For each resulting topic, we obtained a list of words

that describe its composition and a list of probabilities that denote the association of the topic with each document.

[13]In the model words were stemmed and stop words as well as common and non-informative words (e.g., National-Parks, Parks) were removed.

[14]The National Park Service have made available a list of what they consider the most relevant laws and regulations for parks operation. The list is available here.

[15]To assess the effect of semantic composition of documents, we applied the LDA model to systematically noisy "placebo" corpuses obtained by randomly interchanging words (i.e., substitute all "word 1" with "word 2", and vice versa) across all documents without affecting their statistical properties (i.e., length, word frequencies within and between documents). The model comprises 30,000 independent collections of documents with 1, 2, 5, 10, 20 or 50% of word randomization levels. Each collection of random documents was tested against the LDA model produced by the empirical data. The results indicate that we are unable to recover the same topics when including low levels of semantic noise, thereby providing additional plausibility to the set of 40 topics that we observe in the real data.

Chapter 8

Final Conclusions

Understanding the nature of sustainability knowledge, or the knowledge about environmental problems, is critical to informing management and governance of environmental systems. Specifically, characterizations of sustainability knowledge might enable a better comprehension regarding the knowns and unknows of the problem at hand, and also about social and cognitive processes that steer perceptions and actions [4, 19, 92, 154, 190, 317]. Sustainability knowledge, formal and informal, is a fundamental element that guides decisions and actions (or the lack thereof). Yet, little attention has been paid to the connections between sustainability knowledge – sometimes thought as a homogeneous corpus- and collective action (i.e., governance). It is necessary to acknowledge that knowledge is diverse in its production, use, and content [22, 316, 267], which makes of decision-making and action nuanced processes inasmuch as they are contingent upon what knowledge is leveraged [55, 120, 160, 184]. Because actions could be as diverse as knowledge is, multiple governance regimes could exist but only few could take place [1, 52, 86, 116, 164, 353]. Governing environmental systems is a challenging endeavor as it must reconcile multiple perspectives and interests [36, 75, 183, 209, 242, 245, 317].

Considering, first, the limited understanding of the interconnection between knowledge and governance in environmental systems, and complex systems in general; and second, the relevance of knowledge to inform and guide decision-making towards pathways of action that acknowledge diverse perspectives, preferences, and interests, this dissertation aims to identify how dynamics of sustainability knowledge might influence management and governance of environmental systems.

In this regard, this dissertation evaluates the dynamics of sustainability knowledge in two contrasting environmental problems, namely, 'illegal wildlife trade' (IWT) and 'national park systems management'. These two problems are socio-ecological phenomena characterized by, among other things: the confluence of diverse stakeholders and their corresponding interests and agendas, which sometimes can be conflicting; the use of natural resources, consumptive use in the case of IWT, and non-consumptive in the case of national parks; a mostly top-down governance model intended to ensure sustainable use of resources and to protect the biodiversity involved; in some cases, the exclusion and dispossession of communities who were traditionally users of the resources. For both cases, decision making without a solid knowledge base could profoundly affect the natural resources and the communities that depend upon them for sustaining their livelihoods or for recreation.

The two environmental problems studied differ in various ways. For instance, the illegal nature of IWT implies a collective authoritative mechanism to enforce law comprising several governmental organizations; whereas, such interactions are a defining feature of national parks management. Whilst the users of national parks and their motivations are clearly identifiable, users of wildlife illegally traded are not properly characterized because they operate in dark networks. Similarly, recreational uses and enjoyment of national parks is largely warranted and recognized as legitimate, whereas commercial uses of wildlife in informal markets is typically stigmatized, banned and prosecuted. In this dissertation I argue that analyzing these two contrasting problems is informative as they provide a broad perspective of the knowledge dynamic in environmental systems.

Consequently, this dissertation addresses several aspects of the nature of sustainability knowledge by:

- Analyzing its diverse manifestations in practice, management and policy (Ch.3 and Ch.6).
- Characterizing inter- and trans-disciplinary integration of sustainability knowledge (Ch.3 and Ch.6).
- Evaluating evaluating varying perceptions of diverse stakeholders (Ch.4 and Ch.5).
- Revealing tacit knowledge through the analysis of practices (Ch.2).
- Assessing the alignment of scholarly research and management (Ch.7).

The characterization made of sustainability knowledge brings insight regarding the challenges that management could have, and possible avenues for strengthening inclusive governance in the two cases studied.

The first part of this dissertation evaluates knowledge on illegal trade of wildlife (IWT) and highlights the relevance of this knowledge to actors actively navigating the complexity of the problem. Results indicate that smugglers gather strategic information of the system regarding the structure of the market and routes for shipping species (see Ch.2), whilst stakeholders interested in curbing this practice are unable to consolidate unifying understandings of the problem (see Ch.4) and the lack of consensus among stakeholders hampers the delineation of strategies to effectively tackle IWT (see Ch.5). Additionally, smugglers develop robust networks where IWT can be operated, whereas authorities struggle to control IWT and coordinate actions given the lack of consensus, limited physical and technical capabilities, and high uncertainty regarding the nature of IWT and its drivers, among other factors. As such, governance of species and territories where IWT takes place seems to be weak as multiple interests and preferences are conflicting and impede defining collective strategies of action.

The wicked nature of IWT, seen in its research and its conceptualization on-the-ground, call for knowledge integration and diffusion that enable a reduction in solution uncertainty while favoring inclusive governance. To this end, it is necessary to develop frameworks that facilitate the analysis of causes and consequences of IWT, the institutionalization of knowledge, the integration of multiple stakeholders to evaluate, exchange and integrate their existing knowledge, create consistent agendas, and the definition action plans towards common objectives. Importantly, it is necessary to include the communities that benefit from species into such frameworks and bring them incentives to participate in the governance of species; otherwise, institutional-based management could fail given the differences in capabilities and practical knowledge between communities and authorities [13]. Inclusive governance of IWT, in which local and indigenous communities have a central role, are feasible [27, 79, 78, 283, 340] and under the right circumstances could contribute to mobilize stakeholders, increase capabilities, bring room for social experiments of governance [116, 267, 297], develop strategies to deal with uncertainty, and, ultimately, promote sustainability.

The second part of this dissertation assesses knowledge critical to the management of protected areas, with national parks (NP) being one type that is characterized by a dual mandate of sustainability and public access. This part of the dissertation draws on the importance of multiple knowledge producing actors, and particularly on the inclusion of final users of knowledge in the research process. To be specific, it was identified that academics and other stakeholders share a systemic understanding of NPs, even though there are some differences at finer resolution levels (Ch.5), and that research prioritization responds to the needs for research in NPs (Ch.7). However, the extent to what diverse stakeholders and knowledge users have been included in transdisciplinary research about NPs is limited and suboptimal, but with the potential of creating strategic bridges between science and practice mediated by government agencies (Ch.6). The multiplicity of stakeholders typically implies the confluence of varying interests that could juxtapose. Reconciling such diversity of interests is necessary to advance towards robust governance regimes. Although it is desirable to include knowledge users and other stakeholders in research in order to facilitate consensus, include multiple interests, and bridge knowledge and management [19, 29, 156, 286, 305], the NP systems show that, to some extent, consensus could be reached with a limited bridging between research and management, as it has seen in other systems where consensus could be rapidly achieved in heterogeneous groups [238]. Nevertheless, efforts aimed at further bringing together research and practice (e.g. science policy in the U.S. NP system) have failed in aligning interests (Ch.7).

National parks, as with many other conservation areas, provide valuable resources and services to neighboring communities and the society at large. NPs are also spaces where multiple interests and worldviews converge [75, 122, 143]. Managing NPs is complex because in addition to comprising socioecological dynamics within their boundaries, managers need to account for and satisfy multiple social and political expectations occurring beyond their physical and institutional space.

As shown in this dissertation, decisions within NPs are frequently controversial in the different arenas where NP managers meet with other stakeholders [161, 182, 204, 205, 281, 299], despite widespread agreements on how the NPs are understood as a system (Ch.5) and what type of knowledge is needed for their management (Ch.7). Interestingly, much of the debate tend to occur at local scales. This highlights the challenge that managing NPs at multiple scales is, where each scale contains particular relations between stakeholders and specific problematics. As such, governance requires to be multi-scale, enabling top-down and bottom-up integration by, for example, upscaling agendas and priorities that afterwards could be supported by downscaling policy. Importantly, government agencies are relevant brokers to catalyze joint actions of diverse stakeholders (Ch.6). A multi-scale governance necessitates multiple stakeholders to coalesce, negotiate priorities, exchange knowledge, and find participation mechanisms [19, 46, 61, 91, 92, 143, 252, 284].

8.1 Outlook

Understanding the interface between knowledge and governance of complex systems, such as those studied here, is necessary to adequately characterize the system and to delineate intervention strategies. Although complex systems are highly resistant and resilient to intervention, small interventions can rapidly cascade transforming the system [34, 36, 227, 326], that in environmental systems could produce catastrophic effects on biodiversity and people [23, 307]. In this dissertation it has been argued that it is necessary to consider that simple and 'one-fits-all' solutions are not adequate to environmental systems [4, 92, 190], and therefore it is required to develop tailored strategies of intervention and management that acknowledge the complexity of the system, the diversity of perception and preferences, the confluence of multiple interests, and the importance of including multiple stakeholders. Similarly, decision- and policy-making need to embrace complexity [75, 160, 161, 194, 299] by bridging research, management and society and by enabling the negotiation and debate of strategies at multiple scales.

A governance that merges diverse stakeholders and their interest could contribute to reducing tension and social uncertainty by facilitating integration of stakeholders [151, 150, 126], fostering cohesion to define priorities, coordinating interests to steer actions, and orchestrating efforts to reach common goals [267, 284, 296]. In other words, environmental systems could benefit from inclusive governance regimes where diverse knowledge, interests and preferences can be acknowledged and accounted for; otherwise, problems and difficulties in management are likely to persist.

To conclude, this dissertation contributes to our understanding of sustainability knowledge and its relationship with management and governance, highlighting the relevance of social cohesion at multiple levels and scales to reach consensus regarding pathways of action. Furthermore, it is illustrated that the defining characteristics of the problem at hand could influence to what extent the consolidation of knowledge affects its translation into practice. As such, it is argued that diverse stakeholders are needed to identify robust mechanisms that define collaborative agendas at multiple scales, which can thereby facilitate the delineation of actions towards common goals in order to reduce tension and uncertainty.

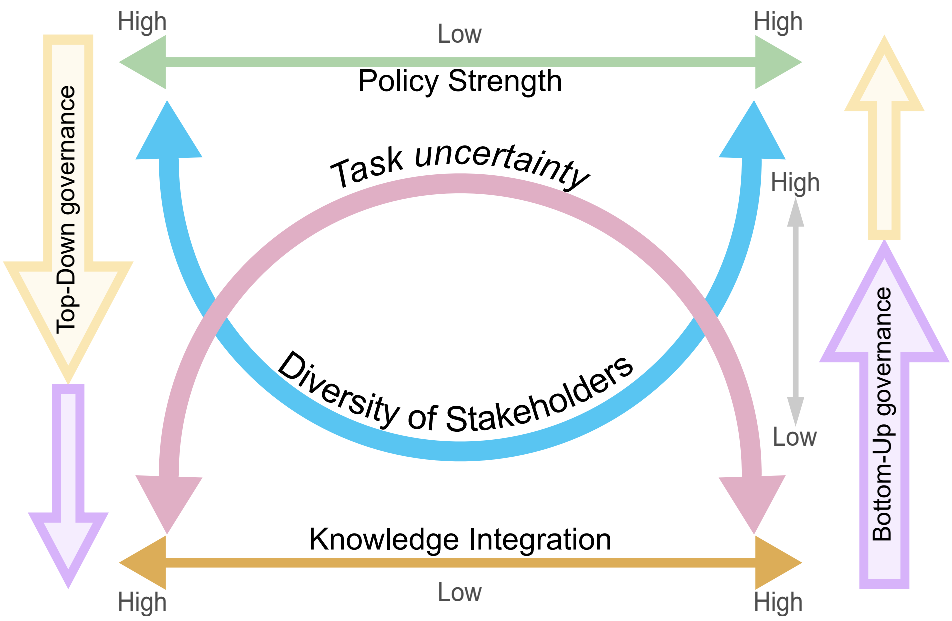

Figure 8.1: **Conceptual model of sustainability knowledge and governance** Robust governance regimes, either top-down or bottom-up, require high knowledge integration in order to foster the inclusion of diverse stakeholders while reducing task uncertainty. Furthermore, strong policy is needed in order to define and enforce rules and mechanisms for promoting integration, debate and the negotiation of common agendas. In the absence of knowledge integration of solid policy, low cognitive and social cohesion might increase controversy that hinders the governance regime.

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