Regime Shifts in the Anthropocene

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Para Lucila quien siempre me recordó que resiliencia es la capacidad de salir fortalecido de las adversidades

To Lucila who always reminded me that resilience is the capacity to persist and learn in the face of adversity

“Podrán cortar todas las flores, pero no podrán detener la primavera”
Pablo Neruda
List of Papers

Paper I:

Paper II:
Rocha, J.C.; Peterson, G; & Biggs, R. Regime Shifts in the Anthropocene: Drivers, Risk and Resilience. [Submitted to Nature]

Paper III:

Paper IV:

Other publications by the author not included in the thesis:

Book chapter:

Contributions to the Regime Shift Database:


Other online resources:


Working papers:


Rocha, J.C., Castillo, D. Misperception of feedbacks: another source of vulnerability in social-ecological systems.
Abstract

Abrupt and persistent reconfiguration of ecosystem’s structure and function has been observed on a wide variety of ecosystems worldwide. While scientist believe that such phenomena could become more common and severe in the near future, little is known about the patterns of regime shifts’ causes and consequences for human well-being. This thesis aims to assess global patterns of regime shifts in social-ecological systems. A framework for comparing regime shifts has been developed as well as a public forum for discussing knowledge about regime shifts, namely the regime shift database. The most common drivers and expected impacts on ecosystem services have been identified by studying the qualitative topology of causal networks as well as the statistical properties that explain their emergent patterns. Given that long time series data for ecosystems monitoring is rather sparse, and experimenting with ecosystems at the scales required to understand their feedback dynamics is rarely an option; we also proposed an indirect computationally based method for monitoring changes in ecosystem services. I hope the results here presented offer useful guidance for managers and policy makers on how to prioritize drivers or impacts of regime shifts; one take home message is that well-understood variables are not necessary the ones where most managerial efforts need to be taken. I also hope the scientific community rigorously criticize our results, but also acknowledge that when doing theoretical or empirical work, our methods tend to ignore the multi-causal nature of regime shifts. By bringing back multi-causality to the scientific debate, I hope our results offer new avenues for hypothesis exploration and theory development on the human endeavour of understanding Nature.

Resumen

Transiciones críticas o cambios de régimen en ecosistemas se definen como reconfiguraciones abruptas de su estructura y función. Estos cambios, en ocasiones inesperados, se han documentado en una gran variedad de ecosistemas en todo el planeta. Algunos científicos proponen que en el futuro cercano dichos fenómenos pueden volverse más frecuentes y severos. Sin embargo, sabemos muy poco sobre las causas y consecuencias potenciales para el bienestar humano. El objetivo de esta tesis es evaluar patrones globales de cambios de régimen en sistemas socio-ecológicos. Un marco conceptual para comparar cambios de régimen y un foro público de discusión sobre el estado del arte en su conocimiento fue desarrollado en la base de datos virtual www.regimeshifts.org. Las causas más comunes y los impactos en servicios ecosistémicos más esperados han sido identificados estudiando las propiedades topológicas de redes causales, así como las propiedades estadísticas que explican sus propiedades emergentes. Dado que experimentar con ecosistemas a la escala adecuada para capturar sus mecanismos causales generalmente no es una opción, y dado que la disponibilidad de datos de largo plazo necesarios para monitorear cambios de régimen son la excepción y no la regla, proponemos un método indirecto computacional para monitorear cambios en servicios ecosistémicos. Espero que los resultados sean de utilidad para actores encargados del diseño de políticas o del manejo de ecosistemas, especialmente espero que ofrezcan una guía sobre cómo priorizar causas y consecuencias de estos cambios de régimen: una lección clave es que las variables que mejor entendemos o las que más monitoreamos no son necesariamente aquellas en las que debemos enfocar las estrategias de manejo. También espero que la comunidad científica critique con rigor nuestros resultados, pero a su vez reconozca que tanto el trabajo empírico y teórico como los métodos que comúnmente se utilizan para estudiar cambios de régimen tienden a ignorar su naturaleza multi-causal. Al enfatizar la diversidad de sus causas, espero que los resultados ofrezcan nuevas posibilidades para la exploración de hipótesis y el desarrollo de teorías para entender mejor la Naturaleza.
**Sammanfattning**

Abrupt och ihållande omkonfigurering av ekosystems struktur och funktion har observerats i en mängd olika ekosystem världen över. Forskning visar på att dessa fenomen antas bli vanligare och allvarligare inom vår närmsta framtid. Kunskapen kring dessa s.k. regimskiften är dock bristfällig, framförallt kring dess konsekvenser för mänskligt välbefinnande. Denna avhandling syftar till att bedöma globala mönster av regimskiften. Ett ramverk för att jämföra regimskiften, samt ett offentligt forum, ”the regime shifts database”, för att främja diskussion och spreda kunskap om regimskiften, har utvecklats. De mest förekommande drivkrafter och effekter på ekosystemtjänster har identifierats genom att studera kvalitativa topologiska och kausala nätverk, samt de statistiska egenskaperna som förklarar deras framväxande mönster. Då långvariga tidsserier av ekosystemövervakning är få, och då de experiment som krävs för att förstå regimskiftens återkopplingsdynamik sällan är möjliga, föreslås också en indirekt beräkningsmetod för övervakning av förändringar i ekosystemtjänster. Resultaten från denna avhandling ämnar ger värdefull vägledning för beslutsfattare om prioriteringsordningen mellan olika typer av drivkrafter och effekter av regimskiften. En viktig slutsats är att gedigen kunskap om en viss variabel inte nödvändigtvis ger området där insatser bör tillsättas. Vidare, genom att föra tillbaka multi-kausalitet till den vetenskapliga debatten, erbjuder avhandlingen nya vägar för hypotesprövning och teoriutveckling inom vår gemensamma strävan att förstå Naturen.
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Introduction

Since the industrial revolution the world’s economy has grown by a factor of 50, energy consumption by a factor of 40; and since my parents were born (1950s) human population doubled, all together causing an unprecedented rate of change in world’s ecosystems. The ‘Anthropocene’ has been proposed as a new geological epoch where humans as a collective have the ability to shape planetary scale processes. Under current trends of environmental forcing, scholars suspect that ecosystems will undergo more frequent and severe critical transitions or regime shifts. Regime shifts are abrupt reorganization of a system’s structure and function, where a regime corresponds to a characteristic behavior of the system maintained by mutually reinforcing processes or feedbacks. The shift occurs when the strength of such feedbacks change, usually driven by cumulative change in slow variables, external disturbance or stochastic shocks.

Regime shifts present a challenge for ecological management and governance, because they are difficult to predict and reverse, while having substantial impacts on the availability of ecosystems services. Examples of regime shifts include i) well-established cases such as freshwater eutrophication, where lakes turn from clear water to murky water leading to reduced fishing productivity and toxic algae blooms; ii) controversial cases such as dryland degradation when dry forest and savanna shift to deserts and bare soils, significantly reducing ecosystem services such as agricultural production and water cycling; and iii) speculative regime shifts such as the melting of the Greenland ice sheet where the frequency and intensity of warm events will shift the ice sheet from permanent to occasional, reducing services such as coastline protection and climate regulation.

Although we have a fairly good theoretical understanding of regime shifts in ecosystems, little is know about the overall patterns of regime shifts causation and their impacts on human well being. We do not know how common they are, what could be their long lasting consequences, where are they most likely to happen, what are their main drivers, what can we do to avoid them, what are the potential cascading effects or who will be the most affected groups in society. These questions have inspired most of my work during the last 6 years. First I will introduce the concepts behind regime shifts theory, then the answers to my research questions followed by some methodological reflections. The thesis concludes by revisiting the questions that reminds unanswered, hopefully providing a plan for future research.

Theory

Regime shifts are large, abrupt, persistence changes in the function and structure of systems. They have been documented in a wide range of systems including financial markets, climate, the brain, social networks and ecosystems. Regime shifts are also known as critical transitions, phase transitions or phase shifts in other disciplines; but I use the terms interchangeably. Regime shifts in ecosystems are policy relevant because they can effect the flow of ecosystem services that societies rely upon, they are very difficult to predict and often hard to impossible to reverse.

These critical transitions have been documented on a broad range of marine, terrestrial and polar ecosystems. Two well studied examples include the eutrophication of lakes, when they turn from clear to murky water affecting fishing productivity and on extreme cases human health; or the transition of coral reefs from coral dominated to macro-algae dominated reefs, loosing the provision of services related to tourism, coastal protection and food. Controversial examples include dryland degradation or the shift from forest to savannas, where we know they can happen but we do not fully understand their mechanisms and there are disagreements about their drivers. Proposed examples of regime shifts includes the weakening of the Indian Monsoon or the weakening of the Thermohaline circulation in the ocean. We know both can happen from paleological records, but to what extent they are likely under present conditions is less understood.
What these phenomena have in common, regardless of scale or system type, is that their scientific understanding relies on the same mathematical theory of dynamic systems. The behavior of a system can be described by a set of equations that define all possible values of their variables, for instance coral cover or fish abundance. These systems tend to fluctuate around regions of the parameter space that are called equilibrium, basins or domains of attraction. Systems prone to regime shifts have more than one domain of attraction; this means that roughly under the same parameter values they can suddenly shift from one domain to another when critical thresholds are crossed. Note in Figure 1 that these domains of attraction or regimes are not punctuated equilibriums, they are dynamic, they fluctuate within the boundaries of the basin of attraction. Thus for example, a forest is never the same forest twice: the species composition, their abundance and distribution is always changing as the forest endures fires, hard winters, storms or pests outbreaks. Yet its identity can always be characterized as a forest. The same can be said of any regime.

**Figure 1.** A minimal model of vegetation shifts. The left panel shows a representation of the bifurcation manifold, this is the parameter space where the system tends to an equilibrium characterized by forest or dominated by grasslands. Depending of the parameters of the system it can respond to disturbances in a quasi-linear fashion (back), a threshold-like response (middle) or present hysteresis (front). On the right panel the hysteresis case is further elaborated. The system shifts from being dominated by dense vegetation when the harvesting rate reach values close to 9; however, one has to reduce the harvesting rate down to 3 for the system to flip back. The probability distribution for the model behaviour (lower panel) shows a representation of the basins of attraction. Another way or representing basins of attraction is by plotting the potential function of the system. The equation that determines the dynamics of this toy model is composed by two terms. The vegetation dynamics over time is the logistic growth determined by the growth rate \( r \) and the carrying capacity \( K \) minus a saturation harvesting term determined by the maximum harvesting capacity \( h_{\text{max}} \) and the harvest \( h \).
However, a regime shift does not imply any change of an ecosystem, it has to affect the feedback structure of the system that maintain its stability and emergent properties; this is, a change that effects its identity (e.g., Forest, coral reef, mangrove). Scientist when they refer to regime shifts often emphasize that they are abrupt and persistent changes. It worth noticing that the abruptness and persistence are relative to the dynamics defining the system’s identity. Back to the forest example, one generation of trees can last hundreds of years, then a change over the time span of a decade is abrupt from the forest perspective.

History of the concept and evidence
First notions of systems that can have multiple attractors date back to 1885 when Henri Poincaré first described bifurcations. However, only until late 1960s these mathematical developments were introduced to ecology when leading scientist debated about stability in ecosystems, which lead to the first theoretical developments, often models, of potential regime shifts in fisheries, disease outbreaks, and grazing – harvesting systems. These early developments were criticized by the lack of empirical evidence in the 1980s, but by early 2000s enough evidence have accumulated on systems such as coral reefs and lakes, validating the existence of regime shifts and igniting further research on their detection and management.

Nowadays there are still some differences on how the concept is used across disciplinary fields, especially between community and population ecologist. For example, while oceanographers consider a regime shift a phenomenon on the scales of decades that has to be driven by climate, marine biologist focus on the time span of key species life cycles. Another source of confusion is disciplinary jargon. See for example the contradictory use of ‘phase shifts’ in coral reefs in refs and , which is not necessary supported by theory.

Evidence of regime shifts has accrued in the last two decades. It comprises empirical evidence when experimentation is possible, observational evidence from long-term time series data, paleological records from sediments and ice cores, as well as mathematical models that explore the possible mechanisms explaining such observations. Yet, criticism persist based on the lack of empirical support, ambiguous system boundaries definitions, or inconsistent disciplinarily jargon.

Why are regime shifts hard to detect and costly to reverse?
Empirical and theoretical developments have shown that regime shifts are hard to detect and sometimes hard or impossible to reverse. Change in slow variables (e.g., temperature in coral reefs, nutrients accumulation in lakes) often shrinks the basin of attraction, making the system more susceptible to shifting when exposed to shock events (e.g., hurricanes, storms) or the action of external drivers. When the shift occur the strength of feedbacks change and some times new feedbacks mechanism come to place, making difficult to restore the original system state. This difficulty is often termed ‘hysteresis’; this mean that the critical tipping point at which the system flip from one regime to another is not the same at which the system is expected to flip back.

An illustrative iconic example is eutrophication, the shift from clear to murky waters in lakes. The most common driver of eutrophication is the accumulation of nutrients such as nitrogen and phosphorous, although it has been reported that it can also be caused by climate change alone. Excess of nutrients in the water often come from the use of fertilizers when growing food. Nutrients are naturally present in the soil and in combination with other indirect drivers such as deforestation, nutrient inputs both natural and anthropogenic can accelerate when rain comes and wash the soils. Nutrients accumulate on lake sediments and are kept by rooted plants. But when a threshold of nutrients on the water is transpassed, microalgae growth explodes creating algae booms. These booms reduce light penetration to the bottom of the lake, which reduces the ability of rooted plants to survive. With less rooted plants the nutrients accumulated on sediments are resuspended on the water column, reinforcing the original cause of the algae blooms. This is a new reinforcing feedback in place that makes the regime shift hard to reverse. Figure 2 shows the structure of the system.
by summarizing the key feedbacks that maintain the clear water regime or the eutrophic state respectively.

Detecting regime shifts is a challenging task. First one needs to clearly define the boundaries of the system and select focus variables that serve as indicators of the system state. Data requirements will depend directly on the spatial and temporal scales at which the underlying feedback mechanisms operate. Sometimes regime shifts are identifiable from historical data by looking at jumps on the time series; however statistical techniques are required to test whether it was a real regime shift. Amongst the most common test used are the principal component analysis, which compresses several time series of related variables into few uncorrelated ones; chronological clustering, and sequential t-tests. Recent efforts on improving prediction rather than detection from past events have been focusing on the development of early warning signals. They are based on the statistical signature of a system approaching a regime shift called critical slowing down which can be observed on the increased autocorrelation (temporal or spatial) and skewness while decrease in variance.

Figure 2. An illustrative example of freshwater eutrophication. The causal loop diagram summarizes the potential feedback loops (coloured) underlying the dynamics. In black are the direct and indirect drivers of eutrophication. P stands for phosphorous and DO is dissolved oxygen.

Research on regime shifts has adopted either an empirical, modelling or early warning indicator approach, which requires deep knowledge of the causal structure of the system or high quality spatial-temporal data respectively. These requirements have largely confined regime shift research to the analysis of individual regime shifts rather than their comparison, with a handful of exceptions for climate, agriculture, and hydrology related regime shifts. But what do we do when we do not have the luxury of long term monitoring programs or incomplete understanding of underlying mechanisms? How do we inform managers about the risk of critical transitions with impacts to society? Can we overlay knowledge from one system to another to better understand patterns of causation and potential impacts on human well-being?
Summary of Results

This thesis attempts to fill these gaps by assessing global patterns of regime shifts. We have developed an analytical framework to study and compare regime shifts across different systems and scales (Paper I). The Regime Shifts Database [www.regimeshifts.org](http://www.regimeshifts.org) is an effort to systematically collect, synthesize and communicate current knowledge about regime shifts. Our initial focus is regime shifts that matter to people, that have potential impacts on ecosystem services and human well-being. Our database inherits the focus on non-linear dynamics from its predecessor, the thresholds database developed by the Resilience Alliance and Santa Fe Institute. Our database, however, advances the conceptual framework to enhance comparability across cases by stressing the role of feedback mechanisms, distinguishing drivers from processes and highlighting impacts on ecosystem services as well as management options. Thanks to the collaboration of over 60 contributors (researchers and grad students), the database offers today synthesis of >800 scientific papers, summarizing more than 200 cases and about 30 generic types of regime shifts across the globe.

*What are the main drivers of regime shifts?*

Drivers are defined as any natural or human-induced factor that directly or indirectly causes a change in an ecosystem. Of course, that depends on the imaginary boundaries that we pose on reality when delimiting the ‘system’ of analysis. While those boundaries change from observer to observer and from one scientific discipline to another; understanding the relative importance of drivers requires embracing their diversity.

Inspired by recent applications of complex systems science to the network of human diseases, we have applied similar methods to disentangle the main drivers of regime shifts and their impacts on ecosystem services in settings where very limited information regarding field data is available (time series or spatial data), or when evidence about the causal relationships underlying their mechanisms is contested (Papers II & III).

Although most studies focus on few drivers, we show that regime shifts are multi-causal phenomena and the co-occurrence patterns of drivers can inform managerial strategies. For marine ecosystems (Paper II) we found that food production related drivers, coastal development and climate change are the most important drivers. Except by coastal development, this pattern holds when we scale up the analysis to the globe (Paper III). In fact, these drivers are thought to reinforce each other increasing the risk of cross-scale interactions and cascading effects.

*What can we do to avoid regime shifts?*

Not only the diverse scales of key drivers, but also the high co-occurrence of drivers across scales means that managing regime shifts requires coordinating actions, more often than expected at the international scale (Paper III). While marine regime shifts share significantly more drivers suggesting high similarity on their underlying mechanisms, terrestrial regime shifts share fewer drivers making managerial options more context dependent (Papers II & III). Our results show that most management options required to tackle drivers of regime shifts require international coordinated actions, hopefully they offer guidance on the feedbacks that institutions needs to match to avoid the problem of fit.

However, by managing local to regional drivers, managers can build resilience to regime shifts and delay the impact of global ones. Our results suggest that in situations where regime shifts dynamics are poorly understood, managerial options that work in well understood regime shifts can be applied on uncertain data scarce cases if they share similar ecosystem processes, occur in similar ecosystems and whose dynamics occur at similar spatio-temporal scales (Paper III). A deeper analysis on marine regime shifts further forewarn that management for well understood or well monitored variables might not be enough to preclude regime shifts from happening (Paper II). Drivers diversity on one hand, and the different causal pathways they can take to affect feedback mechanism on the other, suggest that management should embrace the multi-causal nature of regime shifts and address more
often indirect drivers even though it is harder to get statistical signature of they causal role on the regime shift, as more intermediate steps between cause and effects take place.

**What are the main impacts on ecosystem services?**

Our network analysis suggests that biodiversity loss, food production (fisheries, primary production, nutrient cycling), disease control and aesthetic values are the ecosystem services most commonly impacted by regime shifts globally (Papers II & III). However, predicting which ecosystem services are likely to be affected by ecological surprises is still one of the greatest challenges of current ecological research. Given that experimenting with large-scale ecosystems is rarely an option, in joint efforts with computer scientists we explore an indirect approach by using machine learning algorithms for topic modeling in the scientific literature (Paper IV). We used the Millennium Ecosystem Assessment as training dataset and a corpus of >800 papers about regime shifts. We found that identifying ecosystem services is possible; the algorithm identifies fairly well provisioning and regulating services but finds more difficulties to correctly identify supporting and cultural ones. We hope our results will open an avenue for using social media as environmental sensors of ecosystem change.

**Summary of methods**

The previous section outlined the main research questions of the thesis as well as the key findings that each paper addressed. For the academic inclined reader, this section will present how questions and findings meet through the application of scientific methods. First I will present a common denominator through my work, something I call the size of the problem or more technically, the parameter space that is to be explored. To better explain it I will use as metaphor the case of cancer to illustrate lessons from biomedical research that can be applied to the problem of regime shifts. Then I justify my methods selection and reflect on their limitations.

Not all regime shifts occur in ecosystems, a regime shift more familiar to the average reader is cancer. Unfortunately everyone knows a relative, colleague or acquaintance that have suffered of cancer. Cancer is in essence a genetic disease. While the human genome is thought of being composed by ~30,000 genes, cancer is know to be caused by ~547 genes, with some of them playing a more important role than others. For some of those gene mutations we know exactly what causal pathway it cascades and what are the potential effects on cellular development; however, for others we only have correlational reports of patients having mutations or atypical concentrations of substances that the gene codify for, but we do not know the mechanisms in place that can related to cancer. In an ideal world where scientist could experiment with humans to explore the problem space of cancer, they will have $2^{547} = 4.6e10^{164}$ experimental combinations –assuming order of mutation does not matter; which plus replicates (or without) rapidly demonstrates that we are not enough humans to run the experiment. Moreover, cancer is an evolutive disease, it can adapt to treatments and such adaptation varies from patient to patient. How do we crack that problem space? How do we advance knowledge without the luxury of rigorous experiments and an uneven understanding of the role of the causal mechanism?

In social-ecological regime shifts the problem is the same, although the boundaries of the systems are not as clear as with cancer; and the knowledge database is definitely less developed. We have identified ~54 drivers of regime shifts, a list that without doubt is far from complete. As with cancer, for some drivers we know fairly well the mechanism in place although the strength change from place to place (e.g. deforestation), for some other drivers knowledge is contested and evidence inconclusive (e.g. poverty or trade). On an ideal world of free scientific experimentation without ethical concerns, we do need more than one planet to rigorously test for significance. No need to use the ~54 drivers for calculation this time ($2^{54} = 2916$ combinations); the caveat here is the unit of analysis, the system boundary. Take as example the transition from forest to savanna, it has 13 reported drivers ($2^{13} = 8192$ combinations), but we only have few rainforest patches to experiment with moisture recycling feedbacks and the extent of fires (Amazon, Congo basin, Malaysia, Indonesia and
Papua New Guinea). When it comes to regime shifts, long time series data and the possibility of experimentation is the exception rather than the rule.

The first step on the quest of assessing global patterns of regime shifts was creating a platform for comparison (Paper I). As medical doctors have maps of metabolic pathways, we constructed maps about the causation narratives described by scientific papers on the form of causal loop diagrams. Causal loop diagrams (CLDs) are a technique to map out the dynamic structure of a system\textsuperscript{80,81}, they are known to have limitations and obscuring accumulation processes\textsuperscript{82}, yet they are excellent tools for communication and education\textsuperscript{81}. CLDs were key for distinguishing drivers from feedbacks, hypothesize the boundaries of the system in question, and collect knowledge that otherwise is fragmented across academic disciplines. The next step was networks.

Why networks? Network science has proven to be a versatile tool for understanding the structure and functioning of complex systems\textsuperscript{83}, particularly when one needs to understand emergent systemic patterns from localized interactions. The list of applications of network theory to different fields in science is endless, but to keep it short, one of my sources of inspiration was the application of networks to the mapping of human diseases because of the striking similarities of the problem size above described. Networks of genes interactions, proteins, diseases and symptoms are revolutionizing the way we understand medicine today\textsuperscript{69,70,84-87}. Can we say the same about ecosystem management? By studying the statistical properties of the observed networks as oppose to random counterparts we could identify which drivers tend to co-occur more often than expected and which ecosystem services are more impacted by regime shifts. Exponential random graph models\textsuperscript{88-90} were deployed on Paper II to test for how local interactions explained or not the observed global patterns.

Attracted to methods to explore a large parameter space with practical applications, I become interested on latent Dirichlet allocation (LDA). Imagine in how many different ways one can combine words to convey the same meanings, yet if you are talking about a specific topic, say soccer, the frequency distributions of the words selected is probably not random. Paper IV is in itself the exploration of this machine learning technique (LDA) as an indirect method to monitor changes in ecosystem services that in turn could indicate potential regime shifts. Real world applications for decision making in ecosystem management and sustainability science are still an unexplored field.

Table 1. Summary of methods

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The selection of methods for this thesis matched the type of questions asked and the data available at the global scale to answer them. However, all methods have limitations that constraint the extent to which the conclusions stand by themselves. Causal loop diagrams are excellent tools when mapping different plausible explanations of why and how regime shifts happen; they facilitate communication and the use of systems thinking, they force you to be clear on what is consider exogenous, endogenous and the types of causal relationships. However, they are still a subjective conceptual interpretation of what otherwise is a scientific narrative, they are very hard to defend as source of data since replication is context dependent. Latent Dirichlet allocation is a method that has been recently criticized because of reproducibility and accuracy issues\textsuperscript{91}, problems that we did encounter when
searching for ecosystem services. In addition, LDA is a method designed as an explorative tool that we forced into prediction. Nevertheless, that was the purpose of Paper IV: exploring when does it works, when it does not and why. Potential methods that would outperform LDA on topic detection and classification employ community detection algorithms in networks\textsuperscript{91,92}, an avenue still to be explored in our dataset.

Networks are a useful framework to study complex systems, yet they have been criticized by issues of scalability and lack of dynamics\textsuperscript{93}. Thus far, the first critique does not affect any of our datasets since we do not handle millions of nodes. The second, however, does limit the conclusions of my studies since they are all based on structural patterns of a network, not its dynamics. For example, the weighting of links between nodes have been based on co-occurrence. As the writing of this thesis, there is not enough data that allows one to use as weights the relative contribution of a driver to a regime shift at the global scale; moreover, it is expected that spatial heterogeneity\textsuperscript{94} or the ordering of stress events would change the relative weights of drivers. Dynamic modeling across many case studies and empirical studies would be necessary to advance knowledge in that direction. However, our results are a qualitative characterization of potential drivers interactions that offer a fertile ground for generating hypothesis, guide the development of dynamic models and data collection. I believe our conclusions are robust to different choices of categorization (e.g. which drivers to include or not). In other words, it is likely that we have missed regime shifts cases, drivers or impacts on ecosystem services; but it is not likely that including them will substantially change the patterns here reported.

Conclusions

The Anthropocene is pushing humanity outside its comfort zone, an arena where critical transitions in ecosystems are likely to become more frequent and severe. How do we prepare, how do we navigate uncertainty with incomplete knowledge about their dynamics, how do we provide scientific advise when experimenting is rarely an option and waiting for observation might not be socially affordable? This thesis tried to meet the challenge by assessing global patterns of regime shifts: what they have in common, and identifying what we can learn from well-understood cases that can be applicable to more speculative ones.

We have developed a conceptual framework to facilitate comparison and knowledge synthesis of regime shifts. The framework is both a source of data for future analysis and a public discussion forum where other scientist, practitioners and managers can contribute with new knowledge. I hope this open collective effort break the disciplinary silos on which regime shift research most commonly occur. Methodologically, this is probably the first time that tools from network analysis are used to disentangle causal patterns on large-scale phenomena such as regime shifts. Networks have been used in ecology to understand species interactions (e.g. mutualism, food webs) or landscape dynamics (e.g. fragmentation); but to my knowledge, this is the first time that networks are used to study the structure of processes. Topic modeling is also a recently developed technique that is here applied as novel method to explore ecological problems. Both methods have caveats and limitations, but have been essential to push knowledge forwards in ways I did not imagine when started my PhD.

Perhaps the most important lesson learnt is that regime shifts are multi-causal phenomena. Contrary to the text book examples where the authors usually presents you to ‘the’ driver and ‘the’ slow variable; reality seems pervaded by multiple ways in which regime shifts develop, all occurring at the same time. The multidimensionality of these non-linear phenomena does not seems to be appropriated by scholars in many disciplines that insist on getting rid of co-linear variables on the search for clean p-values. That is fine for the statistics in the paper, but in my opinion it misleads the practical application of the science. As George Sugihara would put it, do no use linear methods to study non-linear phenomena, ecosystems are complex systems where variables are often mutually coupled creating feedbacks, in other words, they are not completely independent\textsuperscript{95}. 
At first drivers diversity might sound discouraging, but we demonstrate that they do not co-occur at random highlighting potential managerial strategies. Marine regime shifts share more drivers and processes, by targeting a handful of drivers many of these regime shifts can be prevented. It did not come as a surprise that climate and food production related drivers are core set of regime shift’s causes worldwide, both topics are already hot debates on both the scientific and political realms. Yet, the results show that managing local to regional drivers provide opportunities to delay the effects of global drivers. Surprisingly, the fact that many co-occurring drivers are indirect support the idea of cascading effects: first it suggest that risk of regime shifts can increase in sync; second, it supports the possibility of inconvenient feedbacks through teleconnections. This ideas are further reinforced when looking from the impacts perspective: subcontinental regime shifts consistently impact climate regulation, terrestrial regime shifts commonly impact water cycling, food production, and fresh water, while marine regime shifts typically affect fisheries, water purification, disease control and surprisingly aesthetic values. It is not hard to imagine how the effects of a regime shift can become the causes of another elsewhere.

The quest for better understanding cascading effects is at the frontiers of regime shifts research. Imagine for example how the shift from forest to savanna in substantial parts of the Amazon rainforest will weaken the moisture recycling feedback, reducing rainfall in the Andes and the ocean. How many regime shifts would be interconnected through precipitation? Or imagine the weakening of the albedo feedback related to regime shifts in the Arctic, Greenland and Antarctica ice sheets; which regime shifts would increase the likelihood of occurring down the road by altering climate? I started exploring this question during my master thesis: ‘The domino effect: A network analysis of regime shifts drivers and causal pathways’. However, methodological challenges have left this work unfinished, for now. We are not too far of developing a rigorous framework to explore the variety of hypothetical connections between regime shifts that can inform future theory and empirical developments on the quest of cascading effects.

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