BIRS Workshop on Rate-induced transitions in networked systems

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Motivated by ecological systems as prototypical examples of complex adaptive systems (CAS), this workshop discussed frontiers in the multidisciplinary understanding of tipping points in adaptive structures. We set rate-induced critical transitions(RIT) as the focal point of phase changes between different states. Taking biological examples, we found novel technological and social systems models that exhibited analogous properties. We also focused on the role of interconnectivity in maintaining adaptive capacity and aimed to identify a collection of problems under rapidly changing exogenous forcing in order to build interdisciplinary knowledge.

We had participants that were versed in critical transitions across many fields and challenged them to think of the adaptive capacity of their systems, the rate of change in exogeneous drivers, and the impacts of their interaction. By collating multidisciplinary problems liable to rate-induced transitions, we have (i) created updated definitions of resilience within this context, (ii) identified a gap of existing databases in a variety of fields that can inform early-warning signals under RIT, (iii) created a management framework for complex adaptive systems, and (iv) proposed the creation of a standardized set of guidelines for the future collection of data across fields.

1 Overview of the Field

Many of the world's processes are increasing their pace: the development and deployment of technology accelerates with economic growth [1], information flows increase with the automation of data analysis [2], data-driven models of world-markets lead to near-instantaneous transactions [3]. In the natural world, increasing emissions of CO_2 drive ecological change at all scales [4]. Socially, internet access expands and also disrupts ways of communicating and living [5]. Fortunately, all of these systems have a range of mechanisms to respond and adapt to change, generating resilience [6]. Schools now teach students the perils of the online world, and there is a growing effort to highlight and prevent the spread of false information [7]. Financial systems develop capital buffers and additional regulation and deregulation practices to prevent economic bubbles and market crashes [8]. Species adapt and migrate as temperatures and resource availability change [9]. Given that their elements are heterogeneous, interconnected and responsive, we label examples such as these as "complex adaptive systems". However, we do not expect unbounded adaptability from these systems. Indeed, we acknowledge and even exploit those limits, such as by treating bacterial infections through administering a large amount of antibiotics as opposed to a gradually increasing dosage.

The current theory of tipping points includes the study of transitions that occurs through bifurcation, noise, or external rates of change [13]. The climate system is a prototypical example exhibiting critical phenomena. E.g., when looking at the weather as a fast-process (stochasticity) and climate as a slow process, it can lead to Noise-induced tipping. But depending on which parameters of the system one varies, systems can exhibit different types of transitions [13]. Thompson & Sieber [17] distinguished between safe bifurcations (where an attracting state loses stability but is replaced by another "nearby" attractor), explosive bifurcations (where the attractor dynamics explore more of the phase space but still returns to the vicinity of the old attractor) and dangerous bifurcations (where the attractor dynamics after bifurcation are unrelated to its previous path). Identifying tipping points in these systems using time series requires the separation of time scales in the change in parameters, and between the slowest and faster decaying modes of the system.

Well-known bifurcation forms and noise-induced critical transitions hinge on the idea of escaping from attractors. However, adaptability challenges concepts of stability in such systems. Changing a control parameter is typically visualized as a shifting position on a static attractor, but in an adaptive system, there is a reshaping of the attractor itself such that it may revert to its original form. Rate-induced transitions occur when there is a critical value on the rate of change of a control parameter beyond which the system can no longer maintain the shape of the attractor, causing the system to tip into a different state. This type of transition is often related to a separation of time scales [15]. Early warning signals for the different types of transitions have also been studied [16, 14].

Applications of bifurcation theory and noise-induced transitions have permeated through many fields, but rate-induced transitions seems to be less well-known and have found fewer applications. A remarkable exception is the field of ecology. Rateinduced critical transitions have been applied to ecological models [11] and early warning signals for these transitions have been identified in salt marshes [12]. Salt marshes adapt to sea level rise by increasing sedimentation. The physical process of sedimentation, however, has a maximum rate and requires the presence of marshes. Finally, Siteur et al. [11] argue that the current resilience concept relies too much on bifurcation-type concepts and may not be sufficient to prevent system collapse.

In this workshop we aimed at extending and unifying the study of rate-induced critical transitions to a broad range of disciplines, with a focus on networked systems. Our goal was to frame rate-induced transitions in social and socio-technical, socio-ecological, and ecological systems as an intrinsic property of complex adaptive systems and further the study of critical transitions and their early-warning signals. As illustrated, the theory of rate-induced critical transitions plays a role in many different disciplines, such as physics, chemistry, engineering, ecology, epidemiology and the social sciences. We take as cornerstones examples originating from ecology, the field of prototypical complex adaptive systems and use it to extend the current concept of resilience and develop a new framework for systems management.

Field activity

While there have been a few recent workshops on the general topic of critical transitions and/or tipping points, these events are typically focused on either (i) presenting general analytical or numerical methods to identify early-warning signals or (ii) highlighting specific examples in fields such as ecology, medicine, and engineering. Overall, research relating to rate-induced transitions are typically not included, and if there is some discussion, it is a notably small fraction of talks. For example,the *"Predicting Transitions in Complex Systems"* Workshop at the Max Planck Institute for the Physics of Complex Systems (Dresden, Germany; April 2018 [1]) and the *"Anticipation of Critical Transitions in Complex Systems"* Workshop at the University of Muenster (Muenster, Denmark; Aug 2017 [2]) did not feature talks on rate-induced transitions. In the very recent *"Workshop on Critical Transitions in Complex Systems 2020"* (online workshop, July 2020 [3]), there were only two talks out of 31 total that discussed research on rate-induced transitions.

Workshops that focus specifically on integrating biology and complex system science show a similar pattern. Though there were a few recent workshops that mentioned the importance of understanding the rate of transition and feedback processes underlying these transitions, none have specifically studied the rate-induced aspect of these changes. A series of recent workshops at NIMBIOS focused on "long transients" in biological systems [4], investigating how long-term transient dynamics emerge and how theory can be used to predict timing of sudden regime shifts [5]. However, it remains a challenge to understand how rate-changing feedbacks could affect the timescale of persistence of these transient states, inhibiting progress towards greater predictability. Another workshop was aimed at extending sustainability theory, emphasizing that "feedback" is often left out in forecasts despite its importance [6]. The limitations in these former workshops suggest the importance of our proposed work.

2 Motivation

Traditionally, tipping points in ecological systems are based on the idea of steady-state analysis. The flexibility to adapt to different conditions for living organisms can be attributed to behaviour, niche expansion, phenotypic plasticity, evolution, and most likely, a combination of these and other processes. Importantly, each of those mechanisms operates on its own timescale, generating typical and maximum rates for the adaptive response. Usually, the conditions of ecological systems change at a slower pace than adaptive capacity, allowing for a decoupling of parameter changes and ecological dynamics. However, the current anthropogenic disturbances are, on the one hand, eroding or destroying some of the mechanisms that support adaptive capacity and, on the other hand, increasing the rate at which the environment changes. Therefore, while time scale separation of external forces and adaptation has been possible so far, as the rates of external change increases, so does the importance of studying the systems' ability to cope with change. We need to focus more of our research efforts on the study of rate-induced tipping points and in distinguishing and identifying early-warning signals associated with these transitions.

3 Approach

In our workshop, we took a range of ecological processes, from coral reefs – the fastest-changing large-scale ecosystem on the planet – to tundra plant-root mutualisms – characterized by slow underlying processes – and collate the processes that contribute to the adaptability of these systems under changing environments. In parallel, we identified systems from different disciplines that exhibit analogous rates of change and adaptive properties, as well as the solutions and tools that have resulted from the study of these systems in transition.

To do so, our participants actively work in areas that included technology diffusion, the energy transition (green technology revolution), transitions to sustainable food systems, social networks, tipping-points in social norms, and prosocial computing in human-robot hybrid systems, all of which contain the key ingredients for rate-induced transitions. We invited participants versed in critical transitions and challenge them to think of the adaptive capacity of their systems, the rate of change in exogenous drivers, and the impacts of the interaction between both within their study systems.

We looked to emphasize the role of interconnectivity-based (network) properties on the elements of these systems. For example, diffusion networks across different marine communities can serve to distribute genes that have adapted to different environments; these connections are affected by changing ocean currents. Social capital, drivers of organizational success and livelihood adaptation are defined by the connections among individuals of a certain group. For example, online social networks enhance the number and interchangeability of those connections but weaken their strength. Large-scale coordination problems among humans, where tipping points are desired, can be slowed down by growing conflict but can also be influenced by interactions with artificial agents, which can divert information flows or simply create empathetic relations with humans. These examples illustrate the multiple, entangled disciplines that are relevant to our topic. Our interdisciplinary perspective piece (*In prep.*) will be framed around the goal of defining resilience in the context of rapid change and identifying early-warning signals that precede these transitions.

In preparation, we asked our participants to reflect on the key properties of their system that lead to rate-induced tipping. Namely, they filled out the form in the following subsection. This form was filled in for various subsystems and will serve as the cornerstone expert-based data to demonstrate the existence of rate-induced transitions in multiple fields and the important role of networks in those systems. The results of this form can be found in the "Presentation Highlights" section below.

To stimulate initial discussions and get our interdisciplinary scholars on the same page, we provided a set of references. These initial readings were divided into basic readings, followed by advanced and applied ones. The list illustrating the organization is in the section "Form: Initial literature" below. The literature was discussed by the groups, focusing on understanding of the differences between the different types of tipping points. The "Overview of the Field" section above presents the main points discussed by the group. Below, we provide the list sent to our participants:

Finally, we used the theoretical framing of rate-induced transitions to identify potential databases that can be used to identify early-warning signals across different systems. In doing so, we aimed to develop a standard set of guidelines for the future collection of data that will facilitate the analysis and identification of rate-induced transitions and their early-warning signals across disciplines.

By compiling this information and discussing it, we hope to raise awareness of the RIT field and find various novel applications of critical transition theory.

Initial goals

Given the current increasing pace of globally relevant processes across different fields, this workshop aimed to:

- take the examples of ecological processes studied under the context of rate-induced transitions and characterize the common properties of multidisciplinary problems that are expected to have rate-induced transitions,
- identify non-ecological models/examples that exhibit the same mathematical properties,
- identify multi-disciplinary examples of rate-induced critical transitions with a focus on networked systems,
- propose a definition for resilience based on the pace of adaptation and disturbance in a given system, and
- locate different databases in each field that could detect early-warning signals for rate-induced transitions, develop a standard set of guidelines for the collection of data in that context, and, ideally, propose the creation of specific equivalent datasets across fields to facilitate comparative studies.

Form: Systems with Rate-induced Transitions

The following is the list of questions we posed about each participant's system to understand whether it may exhibit rate-induced transitions and what elements contribute to the transition.

- System / System property:
- Sources of stress

  Statistically invariant/historical Sources of stress:

  Sources of stress/external element changing (at increasing rates):
- Adaptive/acclimation abilities to cope with changing elements

  What sources of variability of the environment contribute to adaptation:

  Adaptive ability to cope with changing elements deriving from networks:
- Is there evidence that your system has multiple stable equilibria? I.e., does the system change irreversibly after a large disturbance?

Form: Initial literature

Basic readings:

- Siteur, K., Eppinga, M. B., Doelman, A., Siero, E., & Rietkerk, M. (2016). Ecosystems off track: rateinduced critical transitions in ecological models. Oikos, 125(12), 1689-1699.
- Neijnens, F. K., Siteur, K., van de Koppel, J., & Rietkerk, M. (2021). Early warning signals for rate-induced critical transitions in salt marsh ecosystems. Ecosystems, 24(8), 1825-1836.
- Ashwin, P., Wieczorek, S., Vitolo, R., & Cox, P. (2012). Tipping points in open systems: bifurcation, noise-induced and rate-dependent examples in the climate system. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 370(1962), 1166-1184.

Theory:

- Ashwin, P., Wieczorek, S., Vitolo, R., & Cox, P. (2012). Tipping points in open systems: bifurcation, noise-induced and rate-dependent examples in the climate system. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 370(1962), 1166-1184.
- Siteur, K., Eppinga, M. B., Doelman, A., Siero, E., & Rietkerk, M. (2016). Ecosystems off track: rateinduced critical transitions in ecological models. Oikos, 125(12), 1689-1699.
- Ritchie, P., & Sieber, J. (2016). Early-warning indicators for rate-induced tipping. Chaos: An Interdisciplinary Journal of Nonlinear Science, 26(9), 093116.
- Ashwin, P., Perryman, C., & Wieczorek, S. (2017). Parameter shifts for nonautonomous systems in low dimension: bifurcation-and rate-induced tipping. Nonlinearity, 30(6), 2185.
- Hahn J. Hopf bifurcations in fast/slow systems with rate-dependent tipping. arXiv preprint arXiv:1610.09418. 2016 Oct 28.

Applications:

- Neijnens, F. K., Siteur, K., van de Koppel, J., & Rietkerk, M. (2021). Early warning signals for rate-induced critical transitions in salt marsh ecosystems. Ecosystems, 24(8), 1825-1836.

Tipping-points/critical transitions:

- Suz, L. M., Bidartondo, M. I., van der Linde, S., & Kuyper, T. W. (2021). Ectomycorrhizas and tipping points in forest ecosystems. New Phytologist, 231(5), 1700-1707.
- Vasseur, D. A., DeLong, J. P., Gilbert, B., Greig, H. S., Harley, C. D., McCann, K. S., & O'Connor, M. I. (2014). Increased temperature variation poses a greater risk to species than climate warming. Proceedings of the Royal Society B: Biological Sciences, 281(1779), 20132612.
- Vanselow, A., Wieczorek, S., & Feudel, U. (2019). When very slow is too fast-collapse of a predator-prey system. Journal of theoretical biology, 479, 64-72.
- Scheffer, M., Van Nes, E. H., Holmgren, M., & Hughes, T. (2008). Pulse-driven loss of top-down control: the critical-rate hypothesis. Ecosystems, 11(2), 226-237.

Adaptability mechanisms:

- Valdovinos, F. S., Moisset de Espans, P., Flores, J. D., & RamosJiliberto, R. (2013). Adaptive foraging allows the maintenance of biodiversity of pollination networks. Oikos, 122(6), 907-917.

Environmental change:

- Pinek, L., Mansour, I., Lakovic, M., Ryo, M., & Rillig, M. C. (2020). Rate of environmental change across scales in ecology. Biological Reviews, 95(6), 1798-1811.

Networks for resilience:

- McManus, L. C., Vasconcelos, V. V., Levin, S. A., Thompson, D. M., Kleypas, J. A., Castruccio, F. S., & Watson, J. R. (2020). Extreme temperature events will drive coral decline in the Coral Triangle. Global Change Biology, 26(4), 2120-2133.
- McManus, L. C., Tekwa, E. W., Schindler, D. E., Walsworth, T. E., Colton, M. A., Webster, M. M., & Pinsky, M. L. (2021). Evolution reverses the effect of network structure on metapopulation persistence. Ecology, 102(7), e03381.

4 Presentation Highlights

We had a total of 19 talks that spanned multiple disciplines across three broad groups: ecological systems (e.g., forests and phytoplankton), social-ecological systems (e.g., infectious disease and agricultural systems) and social systems (e.g., manufacturing systems and political ideologies) - see Figure 1 for summaries. A common thread was the CAS perspective that was highlighted across all talks. The CAS characteristics that were particularly relevant included (1) the ability of each focal system to adapt in response to changing external conditions and (2) the existence of feedback loops and non-linearities.

Most participants presented work on a single system or a set of related systems that have the potential to exhibit rate-induced transitions (a handful of participants presented broad overviews of rate-induced transitions or a related topic). In general, participants working in ecological and social-ecological systems cited environmental seasonality (e.g., temperature, rainfall, fire) as the statistically invariant or historical stressor. For these systems, the sources of stress were largely related to climate change which affected the frequency, magnitude and overall ranges of cyclical environmental dynamics. Participants working in social systems cited general socio-economic disturbances or pulses as the major source of stress. Disturbances to social networks that modified the strength of edges/links between or within communities or removed nodes from the network was another major stressor. Even though few participants were actively working on rate-induced transitions before the workshop, it was evident that all participants were working on at least one system that had the potential to exhibit rate-induced transitions, even if participants had not yet formally addressed this question in their own work. The presentations served as the basis for both formal and informal discussions (in terms of addressing generalities and differences among systems), and was also the source for the initial material and ideas for the direction of the perspectives paper.

4.1 Advocating for JEDI as an Early Career Scholar Workshop

In this workshop, we focused on providing examples of strategies for early career scholars in promoting Justice, Equity, Diversity, and Inclusion (JEDI) in academic workspaces. The workshop began with definitions of JEDI and a review of the academic literature regarding common inequities in academic spaces towards particular identities (race, ethnicity, gender) and their various drivers (systemic bias, implicit bias, stereotype threat). As early career scholars, workshop participants are at critical points in their careers, where they are both the subject of significant academic JEDI barriers to success and also have new opportunities to enact change as they advance in their careers and take on more leadership roles and responsibilities.

Though always historically important and pressing, JEDI has become an increasingly dominant issue for triage in academic spaces as our workspaces become diverse and power structures shift in accordance. Today's early career scholars will be leaders in ushering in new policies to create more just, equitable, diverse and inclusive communities. The workshop provided examples from the literature of methods that new PIs can implement as they recruit and support students and staff. These include code of conducts, course design and departmental changes including the development of JEDI programs. The workshop organizer, Prof. Theresa Ong, provided an example of JEDI programming, the EEES Scholars Program at Dartmouth College. This program provides guidance for applicants of minoritized groups in the graduate school application process including CV building, formal and informal mentorship, and mock interviews. In our BIRS workshop, Prof. Ong talked through the challenges and opportunities in designing, advocating and supporting the successful implementation of these important bridge programs and how institutional structures impact advocacy strategies.

The workshop was specifically planned for Wednesday morning to allow for interpersonal connection and community building in the afternoon during our scheduled half day off. During the afternoon, many informal discussions were had across workshop attendees regarding specific institutional, programmatic, departmental barriers to JEDI and many impromptu brainstorming sessions emerged for co-developing strategies to implement change.

We found that the workshop brought together participants in mutual support of one another and the JEDI mission, as well as did a lot to build camaraderie and direct Early Career Scholars in obtaining information and strategies for implementing JEDI programming at their own institutions. Feedback from participants and BIRS staff was positive, with many expressing a desire to carry out outlined best practices at their own

Presenter	System or System Property	Statistically invariant/historical stressor	Source of stress/changing external element	Sources of environmental variability	Adaptive ability derived from networks	Evidence of multiple stable equilibria?
Jude Kong [Eco]	Phytoplankton light intensity	Seasonal light variation	Increasing light			No
Wenying Liao [Eco]	Forest ecosystems	Seasonal variation	Increasing temperature, precipitation	Rapid evolution, phenotypic plasticity	Dispersal, root network for the redistribution of water/nutrients	Theoretically yes, but little empirical evidence
Mingzhen Lu [Eco]	Fynbos-forest system; savanna system; Tropical monodominant forest; Southern temperate forest	Fire (depletes nutrients), rainfall, herbivory, fungal associations	Climate change			Yes
Benton Taylor [Eco]	Forest regeneration	Hurricane/cyclone frequency; return interval of land clearing; rate of patch clearing; fire frequency	Climate change and increasing anthropogenic stressors			Yes
Senay Yitbarek [Eco]	Duckweed/rapid evolution/spatial structure/species interactions/trait distribution	Nutrient pollution; increasing floating plant biomass	Temperature, decreasing plant species richness	Variation in light, temperature and nutrients can contribute to rapid evolution	Genetic variation - short generation times and small size; plant-microbiome interactions - rapid evolution and host fitness	Yes
Victoria Junquera [SES]	Agricultural systems, rural regions	Weather, pests, regulations	Changing markets, changing land regulations (insecurity), income variability	Land use and/or livelihood changes	Social networks facilitate livelihood changes; networks as preconditions to crop booms	Yes
Juan Rocha [SES]	Ecological regime shifts; linked ecosystems		Climate, fires, erosion, agriculture, urbanization			Yes
Andrew Tilman [SES]	Livestock grazing pressure (Mongolian nomadic pastoralists)	Seasonal temperature, occasional droughts	Climate change, more extreme seasonality; increasing frequency of drought	Seasonal temperature and rainfall	Mongolians can move their herds to different locations or can move to the city	Yes
Luojun Yang [SES]	Infectious diseases, immunological and behavioral responses to infections	Pathogen evolution, demographic dynamics	Seasonality due to climate change, vaccination, policy intervention	Variability in immune responses and contact networks	Coupling and decoupling between disease transmission and information networks; clustering of susceptible individuals	Yes
Elisabeth Krueger [Soc]	Cities; Urban socio-technological development		Sea level rise and land subsidence; urban growth and infrastructure development	Seasonal water scarcity		
Flávio Pinheiro [Soc]	Countries, Regions, Organizations	“Market competition,” technological shifts	Extreme socio-economic events, climate change	Technological and policy heterogeneity, changes in value chains		S-shaped curve of development suggests 2 basins of attraction
Fernando Santos [Soc]	Opinion consensus/polarization in social networks	Removing links between communities	Recommendation algorithms, strengthening links within communities/weakening between communities			Depending on network structure, polarization and consensus states can be equilibria
Peter Sloot [Soc]	Illegal cannabis production chain (Netherlands)		Law enforcement targeting certain links in the chain		Information dissipation (out-of-equilibrium dynamics) peaks at nodes with intermediate number of connections	

Figure 1: Summary of ecological systems (Eco), social-ecological systems (SES) and social systems (Soc).

institutions.

4.1.1 Demographic information

At the close of our BIRS workshop participants, we distributed an anonymous demographic survey. We felt strongly that participants should self-identify themselves. Out of 30 total workshop participants, including 11 in-person attendees, 19 responded. Our participants were gender balanced with 57.9% identifying as men, 36.98% women, and 5.35% non-binary. Out of all survey respondents, 39% identified as White, Caucasian or European-American, while 66.6% identified as Asian, Asian-American, Black, Afro-American, Dutch, Hapa, and Latin American (participants could include more than one identity). Our participants are citizens in 10 different countries and were born in 13 different countries (see Fig. 2).

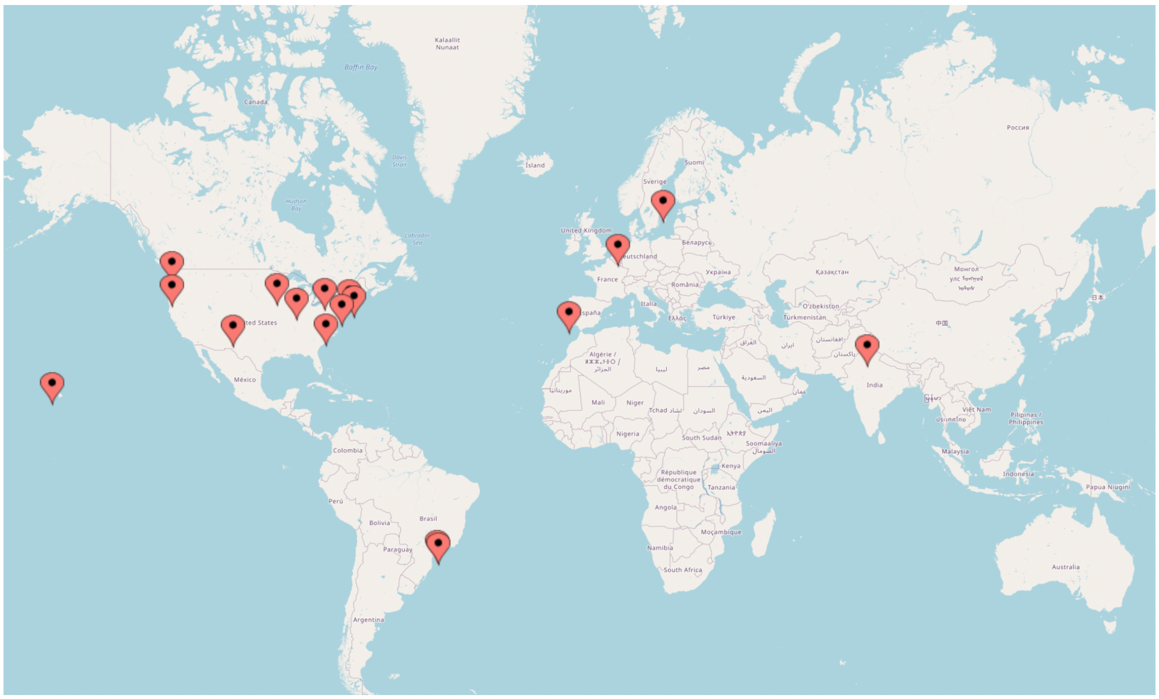

Figure 2: Map of workshop participant home institutions.

Regarding educational background, 15.8% of participants reported that the highest educational achievement of their parents/guardians was high school or similar secondary education or below (no formal schooling). An additional 26.3% had parents with a Bachelors but no graduate-level education. Overall, we feel that our BIRS workshop achieved high levels of demographic, background and career-stage diversity. We can see that there was an even distribution of faculty to graduate students, with a skew towards early career researchers (Fig. 3). Still, we acknowledge the continued need to strive for greater representation in coming years.

5 Scientific Progress Made

During the workshop, organizers and invited participants discussed the readings, which were distributed prior to the meeting. The RIT literature has a strong connection with the tipping points literature. During the first day of the workshop, we discussed the three main types of tipping points that are already mathematically formalized: bifurcation (B), noise-induced (N) and rate-dependent (R) and their importance for complex adaptive systems. In the second phase of the workshop, the group explored and discussed the formalization of how these three types of tipping points are entangled. In the third phase, the group discussed how networked stage distribution.pdf

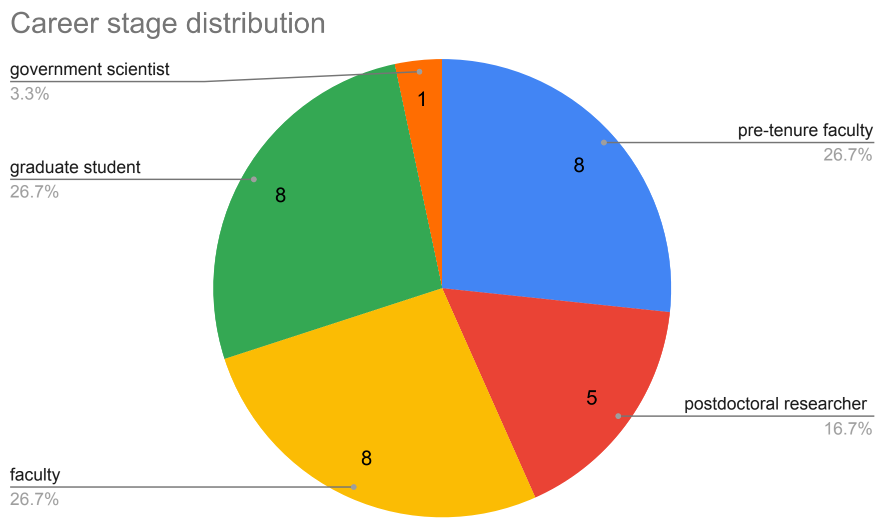

Figure 3: Career stage distribution of workshop participants.

systems are affected by rate-induced phenomena, in the context three different (sets of) CAS: ecological, social, and social-ecological systems.

5.1 Combining types of tipping points

Complex adaptive systems are characterized by a multitude of positive and negative feedbacks between their elements. These resulting feedback loops can lead to multiple alternative regimes. Each (likely dynamic) regime has a basin of attraction, a set of state values or properties of the system that characterize it; these properties are typically associated with a stable state. External or environmental states affect these feedbacks in different ways, potentially causing different transitions (see Figure 4).

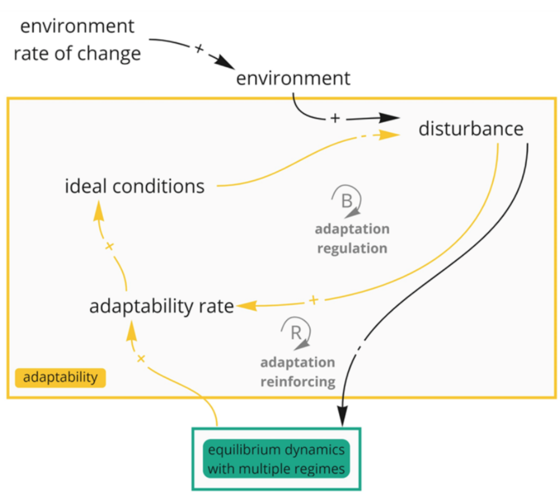

Figure 4: Positive and negative feedbacks affected by external/environmental changes in magnitudes or rates.

Three types of critical transitions are discussed in the literature, depending on how the environment of the system affects it. When environmental change increases the frequency and/or magnitude of perturbations, a critical environmental value can lead to a regime change induced by noise; this is known as a noise-induced transition (t_N). If the environmental state affects the strength of feedbacks, a critical value of the environment can occur, above which one of the feedbacks always dominates, leading to the disappearance of one of the current equilibria; this results in a change-induced transition or bifurcation tipping (t_B). If the changes in the environment move the basins of attraction but not their shape, small environmental changes lead to no regime shift. The system will only exhibit a transition when the movement of the basin of attraction outpaces the ability of the system to remain inside the basin of attraction of a current regime, leading to a rate-induced transition (t_R). Most changes in the external environment of a system will have all the three components (t_{B+R+N}). In Fig. 5, we show an example of how the different types of transitions can be combined in a simple example.

Hypotheses were raised about how the co-occurrence of the three types of bifurcations would anticipate or postpone a critical transition, both in time or parameter range. These hypotheses were formulated geometrically in terms of the shape of the attractor.

This formulation also set the basis for understanding systems' safe operating spaces in terms of the i) internal state change (exogenous, instantaneous shock), ii) external parameter change, and iii) rate of parameter change.

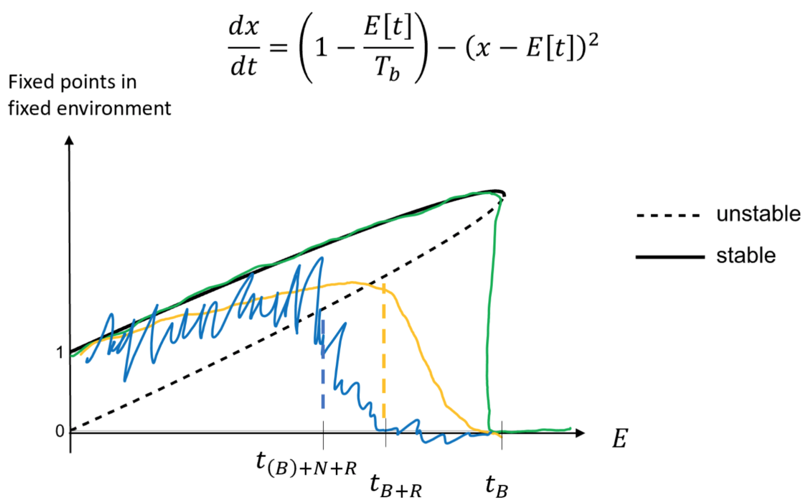

Figure 5: Tipping points and combinations. Bifurcation tipping point (t_B), bifurcation combined with rate induced tipping point (t_{B+R}), and bifurcation, noise and rate induced tipping point ($t_{(B)+N+R}$). Figure adapted from one of the presentations, based on the work of [18].

5.2 RIT in networked systems

The lag between external change and system adaptation can induce critical transitions. Systems of interest in social, ecological, social-ecological, and social-technological domains are often composed of agents organized in complex networks: individuals connected in social media platforms cross-validate information with their peers and counter misinformation, a case in which the system can tip into an undesirable state where fake news become prevalent, or a desirable state where truth prevails; coral reefs connected through current flows can receive species and genetic diversity such that the impact of changing temperature on one reef can be mitigated through re-colonization; urban dwellers receive resources (e.g., water, food, and energy) through infrastructure networks that are also adapted as demands change and grow while urbanization proceeds.

Pathogens of infectious diseases spread via contact networks of hosts, the topology of which affects the rate of transmission, the probability of outbreaks, and the emergence of new strains. From a pathogens perspective, a highly connected contact network of hosts is more likely to withstand the modification of edges/links due to perturbations such as enhanced human intervention strategy, ensuring the continuation of the spread of the disease at larger scales. However, when the removal of the connections happens at a very fast rate, and the whole region is immediately separated into individual isolated patches at the beginning of an infectious disease, the local infections will be more likely to be trapped within the region itself. A similar rate-induced transition can happen in scenarios when the intervention efforts are released at a fast versus at a slow rate. A fast recovery of the topology of contact networks relative to that of the pre-intervention scenario will enable the spread of disease from one local patch to another, the exchange of different dominant strains across patches, and further the reemergence of the disease at a global scale. A slow recovery of the topology of contact networks will result in local endemics. Finally, if the local endemics die out before regional connections are rebuilt, the chance of a global pandemic is less likely.

Questions raised during the workshop concerned the ability of networked system to cope with the challenges imposed by RIT: Can networks rewire fast enough to avoid RITs? Can network topologies reinforce environmental change and induce RITs? Can network properties inform interventions to prevent RITs?

These networked systems have the potential to affect the spread of disturbances that initially occur in different nodes: nodes can mutate or adapt based on neighborhood properties; links might be added, removed, swapped, or rewired; and specific network topologies can amplify or suppress diffusion processes. As a result, networks in the context of complex adaptive systems can strongly impact the change in rates imposed by external stressors and the rate at which systems can potentially adapt. Network structure can therefore determine whether a rate-induced regime shift can occur.

Different network topologies can represent different patterns of interaction, which can in turn affect the speed of environmental perturbations and how the system adapts. It is thereby instrumental to formalize interactions through networks and analyze their structural properties to understand how rates effectively lead to regime shifts. An example is the spread of computer viruses on networks. In random networks, the virus spreads only if the infection rate is above a critical threshold. In scale-free networks, on the other hand, the threshold is zero and viruses always spread. Network science already offers a set of metrics and distributions that can be used to describe interaction patterns and understand how different scales of interaction relate with the probability of regime-shifts:

- **Network connectedness and degree distribution; centrality measures.** Degree distribution is a basic network property. Random graphs are characterized by binomial degree distributions, determined by the probability that two nodes are connected. Scale-free graphs, on the other hand, have power law degree distributions with exponents in the range -3 to -2. Regime shifts in scale-free networks are usually very different from their analogues in random networks. Examples include explosive synchronization of oscillators and the spread of epidemics.

- **Modularity.** Modularity in networks creates potential mismatch between rates within and between groups. Such separation of time scales could trigger regime shifts in the system. The patterns of interaction within CAS are defined by the different possible network topologies representing the system.

- **Network motifs.** Network motifs are patterns of interconnections (or subgraphs) occurring in complex networks at numbers significantly higher than those in randomized networks. These recurrent simple building blocks of the complex network can be a result of evolutionary forces during the dynamical formation of the network. These relatively small groups can play an important role in biological and social networks, such as in financial trade patterns and on predator-prey trophic webs.

- **Percolation properties.** Percolation in networks is related to the formation of a long path in the network, such as in the formation of the giant component, making the network connected. As these long paths form, information can flow through the whole network. The percolation in networks can be increased by adding links with a given probability (bond percolation) or changing the node status with a given probability (site percolation). The percolation in networks is related to its robustness against failure of either nodes or links.

Other network properties and topologies might be important for understanding RITs. We believe that exploring the complexities of adaptive systems through network tools is an important step to understand the adaptive capacity of social, ecological and social-ecological systems to cope with perturbations that are happening faster and faster.

6 Outcome of the Meeting

6.1 Perspectives paper draft

The main outcome of the meeting is a perspectives paper that compiles the group's shared understanding of the necessary progress in the field of RITs in the following different dimensions: extending the range of applications to all CAS, focusing on the role of networks in RITs, and providing a novel management framework that explicitly considers the rate of external change. Below, we share our instructions regarding the future activities relating to the perspectives paper during and after the meeting. We believe that these helped to clarify the tasks at hand and the distribution of responsibilities.

6.1.1 Form: Instruction for perspectives piece

- In this meeting, the small working groups will discuss the proposed idea, as well as the outline and a proposed labor division.
- In a few months after the perspective paper is in good shape, we will call for another joint group meeting where the self-organized smaller working groups can pitch ideas.
- Everyone can then sign up for the different tasks. Next, the organizers (plus a small team) will work on the project to take it over the finish line.

6.2 Facilitated networking

Workshop participants, particularly early career scholars, reported high levels of satisfaction with networking opportunities, especially considering a dearth of conferences available during the COVID-19 pandemic. Our participants engaged with others at many career stages (full faculty, pre-tenure faculty, postdoctoral researchers, research professionals, and graduate students) across 17 institutions (Fig. 1). Graduate students worked in collaboration with faculty in note-taking and drafting our perspectives piece. During breakout writing sessions, graduate students were often paired with early career faculty and postdocs to guide writing on topics of shared interest.

Participants engaged with one another in both formal settings (group and breakout sessions) as well as informal meetings at meals and breaks. In-person participants also benefited from time spent together on hikes and other outdoor opportunities at Banff. Early career scholars also had a dedicated space to workshop advancing JEDI, detailed earlier in this report.

6.3 Inspired products

We are aware of the following products that were inspired by our workshop:

- Review paper on climate-change impacts on agroforestry futures from a RIT perspective submitted by the Ong Lab at Dartmouth College to the Journal of Experimental Biology, Summer 2022.
- Reimagining forest resilience through the lens of rate-induced transition theory Radcliffe Harvard Seminar Series, organized by Wenying Liao and Benton Taylor, March 2022.
- Reimagining forest resilience through the lens of rate-induced transition theory manuscript in preparation by Wenying Liao

6.4 Future collaborations

Many new research collaborations were inspired by the workshop proceedings including, but not limited to, the following:

- Forestry and agroforestry applications, Harvard University and Dartmouth College
- Socio-ecological systems thinking in regards to RIT

6.4.1 Future workshops

Many participants indicated a desire to continue conversations and develop theory in subsequent workshops. Some ideas include:

- Dartmouth College Conference Fund (2024-25) focused on RIT applications to agroforestry systems
- BIRS focused on spatial dimensions of RIT

6.5 Hybrid workshop format

Our workshop included 11 in-person and 29 virtual participants. Considering this distribution, we developed our workshop to maximize hybrid interactions. We fostered hybrid interactions by asking all in-person participants to also log into Zoom during group-wide discussions as well as in smaller breakout sessions. For all of our main talks, we assigned one of the workshop organizers to type a summary during the Q&A sessions in the chat for Zoom participants. Other workshop organizers were responsible for moderating questions from both in-person and for virtual participants.

6.5.1 Successes

When in-person participants also opened Zoom on their individual computers, virtual participants felt like they were one of many attendees rather than participating in isolation. Many virtual participants informed us that that they felt that they could easily contribute to the conversation. We found that we had consistent participation from virtual attendees throughout the workshop.

The chat summaries allowed our full group discussions to be quite effective. During Q&A sessions, we had active participation from both in-person and online participants. Many in-person participants noted that having written summaries of the Q&A helped reify ideas and frame their own contributions to the discussion. Virtual participants noted how the summaries helped clarify information from both speakers and commentators.

The smaller "disciplinary" working group meetings (in-person + online) were productive because all group members, most notably including the graduate students, felt comfortable sharing their ideas. Having a full group meeting soon after these small group meetings allowed people to address any outstanding questions from all perspectives.

6.5.2 Opportunities for improvement

We set up smaller "disciplinary" and "interdisciplinary" working groups, with fewer people split into three different physical and virtual rooms. After these meetings, we organized a final meeting with the whole group in the same room. We found that bringing everyone together for a final discussion, which lasted longer than the smaller groups, was a better use of time than our shorter "interdisciplinary" and split group sessions. For the "interdisicplinary" group sessions, participants took a long time to update their colleagues about discussions from "disicplinary" group sessions, while in the large group meeting, the communication flow was more direct and efficient.

In the future, we would recommend that for "interdisciplinary" group meetings, extra time should be allocated to ensure the group can come to consensus on topics of importance.

We also recommend increasing the number of full group discussions to allow for more streamlined interdisciplinary collaborations to take place.

The hybrid format posed some challenges in terms of timing for breaks and movement in physical space. Though virtual participants could conceptually log on immediately to new rooms, in-person participants had to find new spaces and Zoom links were sometimes confused in the process. We would advise establishing easy to follow links with informative titles such as breakout group IDs to help streamline future hybrid programming.

6.6 Other potential outcomes

During the workshop, we also set up a platform (in a shared live document) for people to devise their own tentative plans for future collaborations in specific related work. The instructions were organized in the following "Action Plan":

- Feel free to propose ideas for future collaborations
- Whoever proposed the idea, please write down a short summary of the project.
- Then, everyone should feel free to sign up (i.e., put your name down on the project) to work on that project after the workshop.
- The person that put down the idea will contact the others and organize the first (sub)group meeting.

Examples from our participants include potential work on:

- An opinion piece on RIT in planetary boundaries among three members;
- An article focusing on "Classical systems through the perspective of RIT: fisheries model", among five members;
- An article focusing on "Changing classical decision making from threshold focus to rate focus", among six participants;
- An article on "Population dynamics of decision making processes based on absolute value vs. a threshold on the rate of change";
- Studying "Discounting as a problem for political movement; the rate at which the risk is perceived changes that discounting parameter and how quickly politicians make decisions";
- "Dimensionality considerations: how many agents need to reach consensus affects the rate of adaptation (in a consensus-driven process); instances where top-down might lead to faster adaptation";
- Set up new projects/a new general discussion to look at "networks and scale" as a generalization of rate-induced transitions in networks, among six participants;
- Analysing how "SES: collective behavior, polycentric behavior, etc. disregard the speed at which you can achieve outcomes - those might be Nash equilibria, but it also depends on the speed of decision-making";
- Apply rate-induced transitions to "economic systems, since they focus on equilibrium dynamics"'
- 'Interplay between homophily and peer influence; polarization vs. non-polarization'
- Explore a 'Harvest model modified to show rate-induced transitions; separation of time scales', among three participants.

We expect that these future projects (and others not registered during the workshop) will generate many new and exciting research avenues.

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