**Anticipating Abrupt Ecological Change in the 21st Century**

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## 3. PROJECT DESCRIPTION
## Anticipating Abrupt Ecological Change in the 21st Century

**Abstract**. Science currently lacks a framework for predicting when, where, why, and how surprisingly abrupt and fundamental changes are likely to occur in ecosystems and other complex systems. Rates of environmental change are accelerating, and understanding the consequences of these 21st-Century changes for natural resources and human wellbeing is among the biggest challenges in contemporary ecology. We will develop and apply new theoretical and mathematical approaches to detect and predict abrupt ecological changes, creating a new *UW-Madison Center for Study of Abrupt Change in Ecological Systems (ACES)*. We will develop mathematical and statistical models that describe system dynamics without forcing *a priori* assumptions about ecosystem processes. The challenges associated with anticipating abrupt changes arise in all ecosystems, so solutions require the close integration of novel theoretical and modeling approaches with high-quality empirical data drawn from a diverse array of managed and unmanaged ecosystems. We will focus on a diverse set of four real-world 'model ecosystems', each characterized by complex spatial dynamics and time lags that can mask impending abrupt change, and each tied to critical resources important to Wisconsin and US economies that are vulnerable to sudden change. Three postdoctoral researchers with complementary, cutting-edge skills will produce critical synergies and the focused effort required for rapid progress. Outcomes include a graduate seminar taught jointly by the PIs; at least six manuscripts; a proposal development workshop; and at least one major grant application (e.g. NSF programs in Macrosystems, Innovation in Food/Water/Energy Systems (INFEWS), or Risk and Resilience). This new collaborative research will fuel the growth and integration of theoretical and empirical expertise at UW-Madison needed to produce critical breakthroughs and shape ecological research for the coming two or three decades.

### Aims and Questions

*Science currently lacks a framework for predicting when, where, why, and how surprisingly abrupt and fundamental changes are likely to occur in ecosystems and other complex systems*. Rates of environmental change are accelerating, and understanding the consequences of these 21st-Century changes for natural resources and human wellbeing is among the biggest challenges in contemporary ecology. We aim to answer several fundamental research questions. How much disturbance can living resources absorb before they change qualitatively? Where are the tipping points in ecosystems, and what forces can push ecosystems past those tipping points? When and where do we expect significant changes in our landscapes and waters? What natural resources are likely to change radically in the coming decades? The potential for large and sudden ecosystem change is clear, yet these questions have proven difficult to address. Ecosystems respond to multiple, interacting disturbances; thresholds are difficult to identify before they have been passed; ecosystems include built-in time lags due to long-lived organisms and slowly changing processes; and feedbacks and spatial variation can dampen or amplify ecosystem changes. These challenges arise in all ecosystems, so solutions require the close integration of novel theoretical and modeling approaches with high-quality empirical data drawn from a diverse array of managed and unmanaged ecosystems. The 2015 report on re-envisioning environmental research and education at NSF states, "*Preparing for and responding to future rapid environmental change, including extreme events, requires a different perspective and skillset than planning and designing for common or average conditions. An emerging suite of new resources, approaches, tools, and data streams are available that have the potential for a transformative reach*" (Advisory Committee for Environmental Research and Education 2015). With UW2020 support, we will identify common mechanisms of abrupt change that are general across systems and operationalize concepts of change and resilience in diverse ecological systems. We will develop new capacities to anticipate and understand ecological changes that are applicable in a wide array of systems and will position UW-Madison to expand its leadership role in next-generation ecological research.

## Approach

*With UW2020 funding, we propose to overcome a major challenge to understanding abrupt ecological shifts—namely, the disparity between existing theory and what is testable and measurable in the real world*. We will develop and apply new theoretical and mathematical approaches to detect and predict abrupt ecological changes, creating a new *UW-Madison Center for Study of Abrupt Change in Ecological Systems (ACES)* that includes the PIs, three new postdocs, an information manager, and current graduate students and postdocs. UW-Madison has a roster of ecologists internationally recognized for their work on complex systems, resilience theory, early warning signals of abrupt change, novel ecosystems, disturbance ecology, spatial ecology, and climate change. This project represents a new collaboration among PIs who are leaders and have complementary expertise in theoretical and applied ecology; a range of terrestrial, aquatic, and agricultural systems; and scales that extend deep in time and from local to global extent. We will recruit a cluster of three postdoctoral researchers with complementary, cutting-edge skills to produce the critical synergies and level of full-time effort required for rapid progress. The postdocs will be experienced collaborators with flexible ecological modeling skills covering three general areas: (1) ecosystem modeling, (2) spatial modeling, and (3) linking models with big data. Our research will focus on a diverse set of real-world 'model ecosystems,' each characterized by complex spatial dynamics and time lags that can mask impending abrupt changes. Each model ecosystem is tied directly to critical resources—forests, fisheries, and food production—that are important to the economies of Wisconsin and the US and vulnerable to abrupt, fundamental change.

**Mathematical approaches: Goldilocks model complexity for prediction and management**. The literature on mathematical techniques to understand abrupt nonlinear changes in ecological systems is growing, because mathematics are needed both to disentangle the possible causes of changes in existing data sets (Carpenter 2003) and to predict possible abrupt changes before they occur (Dakos 2012). These mathematical techniques can be divided into two camps: (i) simple numerical descriptions of system dynamics (metrics) that give insights into changing dynamics (e.g., the autocorrelation that measures the dependence of changes in a system on the past) (Carpenter 2011), and (ii) complex models built from biological first principles that attempt to explain the system dynamics from known causes and effects (Ives 2008). Each of these approaches has limitations. Simple metrics describing dynamics often do not have very much statistical power to identify abrupt changes before they occur, and they cannot be used to make future predictions of ecosystem dynamics. Complex system-specific models often require more information about an ecosystem than is known, and their complexity presents a significant challenge when attempting to fit them to data. We will focus on models for analyzing and predicting abrupt changes that lie at the Goldilocks "just right" position between simple metrics and system-specific models. Our goal is to develop simple models that describe system dynamics without forcing *a priori* assumptions about ecosystem processes. These methods will have greater statistical power and predictive abilities than existing metrics, and will allow easier, broader, and more robust applications than system-specific models, thereby increasing our ability to generalize among multiple systems. Because these methods are both predictive and broadly applicable, they provide natural tools for managers both to anticipate abrupt changes and to plan for possible mitigations in advance.

Approach: Our initial Goldilocks models will be multivariate time-varying autoregressive models and their statistical relatives (Ives 2012), although we will quickly expand to explore other approaches. We will also pursue simple metric and system-specific modeling approaches for each of the four case studies, including process-based dynamic vegetation models designed for use in forested and agroecosystems. Competing these different approaches is the only way to discover which approach works best, where "best" has to be assessed in multiple dimensions including statistical power to predict change, information provided by the models that inform managers, and ease and generality of application. Our initial work will focus on four cases outlined below. These cases provide an excellent suite of challenges, as they involve retrospective analyses (harmful algal blooms and tree population collapses) and management where predictions are needed (ecosystem conversion, and food system vulnerability).

**Harmful algal blooms**. Harmful algae blooms (HABs) are outbreaks of toxic microorganisms in water bodies polluted by excess nutrients. In freshwater, HABs are usually cyanobacteria or 'blue-green algae', species of photosynthetic bacteria that produce potent hepato- and neurotoxins. As nutrient pollution has expanded and analytical methods have improved, toxic HABs in lakes and reservoirs are being discovered more frequently. HABs in lakes and reservoirs are associated with high inputs of phosphorus. However phosphorus explains only a fraction of the variability observed among lakes on the landscape (Filstrup et al. 2014). Thus other characteristics of landscapes related to topography, hydrology and soils are also important (Soranno et al. 2015). Cyanobacteria have increased in abundance in northern hemisphere temperate and subarctic lakes over the past 200 years, according to contemporary records and sediment cores (Taranu et al. 2015). Nonetheless, cyanobacteria concentrations vary enormously from day to day, or year to year, in a given lake. This variability is related to weather, grazing, cycles of other nutrients (iron, nitrogen) and other factors. A great diversity of models has been used to understand and predict the biomass of cyanobacteria in lakes. However, no models (to our knowledge) address broad spatial extents (large landscapes with many lakes) and within-lake temporal dynamics together with sufficient precision to anticipate abrupt changes and to meet the needs of lake managers.

Questions and data sources: How variable is cyanobacteria biomass among lakes, and how is this variability related to watershed characteristics? How variable is cyanobacteria biomass over time, and how is this variability related to climate, nutrients, grazers and other factors? Do we see regime shifts (discontinuities in abundance or cycles) of cyanobacteria across landscapes; across time, since the beginnings of European agriculture, or the intensification of agriculture in the 1950s; or among or within years in individual lakes? If such regime shifts are evident, what factors are associated with the regime shifts? We will aggregate databases from the Western Great Lakes region (Iowa, Michigan, Minnesota, Ontario, Wisconsin) for analysis, and develop models for predictions of cyanobacteria blooms. We will assess gaps in databases and models to set priorities for proposals to NSF or other agencies.

**Tree population collapses: Climate variability and tipping points in eastern mesic forests**: Hydrological variability is expected to increase this century as temperatures rise, due to an intensified hydrological cycle, with stronger precipitation extreme events and more severe and long-lasting droughts (Cook et al. 2008). Tree mortality rates are increasing globally in response to these changes in hydroclimatic variability (Allen et al. 2010), and mesic deciduous forests of eastern North America are at risk of experiencing abrupt tree mortality. However, this risk is not widely appreciated, and the underlying processes are poorly understood. Key evidence comes from long (>10,000 yr) records of forest composition based upon fossil pollen assemblages extracted from lake and mire sediment cores (Booth et al. 2012, Wang et al. in press). Several mesic tree species experienced repeated abrupt collapses in population abundances. For example, eastern hemlock (*Tsuga canadensis*) experienced a range-wide mortality event and population collapse roughly 5,300 years ago (Bennett and Fuller 2002); at some sites the collapse occurred in <10 years. American beech (*Fagus grandifolia*) experienced at 4-6 abrupt population collapses over the last 7,000 years (Wang et al. in press). The causes of these abrupt collapses remain uncertain, with hypotheses including direct responses to drought or cross-scale interactions between high-frequency events (e.g. pest outbreaks) and decadal- to centennial-scale climate trends (Booth et al. 2012).

Questions and data sources: Which species, forest ecosystems, geographic regions, and time periods were most susceptible to abrupt changes in population abundances, over timescales of decades to millennia? Are past abrupt mortality events synchronous or asynchronous across regions? Are past abrupt mortality events linked to external forcing climatic events, (e.g., drought), high-frequency events (e.g., pest outbreaks), or internal stochastic processes? We will extract long time series from the Neotoma

Paleoecology Database and develop statistical models to identify species, ecosystems, regions, and time periods characterized by high variance and high likelihood of abrupt change; analyze the CCSM3 SynTrace and CMIP5 simulations (decadal-scale resolution) to identify times and regions characterized by high hydroclimatic variability; run Dynamic Vegetation Models using climatic forcing scenarios from CCSM3 and CMIP5 and sensitivity experiments based on alternative paleoclimatic scenarios to identify the sensitivity of selected species to abrupt hydroclimatic thresholds and identify mortality thresholds.

**Ecosystem conversion: Climate change, fire, and tipping points in western forests.** Western North America is experiencing warmer temperatures and larger, more severe wildfires than at anytime in recorded history. Current analyses predict novel fire regimes during the 21st century, with profound consequences for landscape resilience (the ability of a system to tolerate disturbance without shifting to a qualitatively different state controlled by different processes; e.g., Westerling et al. 2011, Millar and Stephenson 2015). Biological communities are often well adapted to particular disturbances occurring in a given climate space, but novel disturbance regimes and climates may abruptly change ecosystem structure and function. Determining whether and how climate-disturbance interactions will push regional vegetation into alternative states is difficult for long-lived organisms like trees; few studies have explored forest transitions at local and regional scales or elucidated mechanisms underpinning such shifts. Although resilience theory is well developed, how to operationalize the theory in real landscapes is unclear, especially in a no-analog future (Thrush et al. 2009, Reyer et al. 2015). Changes to climate and disturbance pattern will substantively influence forest landscapes, potentially disrupting feedbacks that confer resilience and triggering conversion of forest ecosystems to grasslands or shrublands.

Questions and data sources: How and why might warming climate and changing fire regimes (altered fire frequency, size, severity) push forest stands over a tipping point (i.e., such that tree regeneration fails)? Where and when might projected changes in climate and fire activity erode local, landscape and regional forest resilience? How do stand and landscape indicators of resilience scale to the region, and what geographical areas are most likely to be vulnerable to changing drivers? We will develop and calibrate stand-to-region process-based models, exploring combinations of climate, fire, forest type, and spatial context using downscaled historical and projected climate data; test predictions against our field data (e.g., Turner et al. in press, Harvey et al. in review) and large regional databases (e.g., USFS FIA data); and evaluate metrics of resilience with process models and data.

**Food system vulnerability: Warming climate, water availability, and abrupt shifts in crop yields.** Climate change threatens US food security and economies, and may put increasing pressure on water resources where irrigation is currently necessary to maintain high productivity. Climate change may cause an increase in irrigation where it occurs today, or irrigation may become necessary in other regions to sustain high levels of productivity. Globally, 75% of freshwater withdrawals go to supporting agriculture. In the US, we identify three at-risk regions where irrigation is a mainstay: the Central Valley of California, the Great Plains, and the Central Sands region of Wisconsin. Research has already demonstrated that the frequency of extreme heat (Lobell et al. 2013) and warming in general (Hatfield et al. 2011), which increases crop water use/loss through evapotranspiration (ET), can be detrimental to production. Yield trends have stagnated in some regions, suggesting that agriculture will not be able to keep pace with a rapidly growing global population (Ray et al. 2013). With concerns already surrounding unsustainable water management practices to produce food, climate change could exacerbate water use problems, and could force new policies that impact agricultural production. What is lacking are analyses of how crop demand for water (often referred to as potential ET, or PET) has changed (with previous climate change) and will continue to change. This will help quantify how groundwater use and surface water diversions may need to keep pace, and whether this is sustainable.

Questions and data sources: Do irrigated and non-irrigated maize and soybeans in the US Corn Belt exhibit different trends and responses to weather variability? How has water demand for fruit and vegetable crops responded previously to changing climate? Where and for what crops might the demand for water be escalating, and are there tipping points at which production might be significantly effected? How will crop demand for water change with projected future changes in climate, and will we see regime shifts that are dependent on region and/or crop type? Has yield growth stagnated in some regions due to climate change, or will it likely stagnate due to limited water resources? We will assemble USDA databases on annual agricultural productivity for corn, soybean, wheat, fruit, vegetable, and nut crops from central California, the Great Plains, and central Wisconsin; combine historical gridded daily weather data and downscaled climate model (GCM) data with agroecosystem models to document changes in crop water use (ET) and PET; analyze how ET:PET trends have changed and will continue to change in the future; compare model output with available data on irrigation water use to understand producer response to previous climate change and project future water withdrawals necessary to maintain production.

## Innovation, Impact and Significance

*The work we propose will fuel the growth and integration of expertise at UW-Madison needed to produce critical breakthroughs and shape ecological research for the coming decades.* The spatial scope and rapid pace of global change is increasingly pushing ecology toward large collaborative efforts that span multiple ecosystems and cover broad geographic regions. The advances we propose are broadly recognized, conceptually related, and critically important for understanding and anticipating the future of natural resources and the economies that depend on them during the $21^{st}$ century. Each PI is experienced in the effective team science required for such efforts to succeed. Over time, we will grow the new Center to include more faculty and bring in new approaches and systems to the common challenge of modeling the drivers and precursors of abrupt changes in complex systems.

## Timeline and Expected Outcomes

*We will establish the research team, theoretical background, and proof of principle needed to compete successfully for large-scale external funding.* Expected tangible outcomes are in bold.

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| Spring 2016 | Recruit cluster of three postdoctoral associates |
| Fall 2016 | PIs jointly teach a **graduate seminar in Abrupt Ecological Change** during fall semester. Graduate seminars are extremely effective for making rapid progress in emerging research topics and will engage a broader spectrum of the UW community. |
| Fall 2017 | ACES hosts **proposal development workshop**, including additional UW-Madison faculty and potential external collaborators. |
| Spring 2018 | Proposal development; manuscript development, leading to **at least six publications**, including a high-impact conceptual synthesis. |
| Summer 2018 | Submission of **at least one major external grant proposal**. |

## Plans for External Grant Submissions

*We will submit at least one major grant application during the UW2020 award.* Development of new quantitative analyses and model-data integration and the application of these methods to distinct real-world case studies will provide the proof of concept needed for extramural funding applications to be highly competitive. We will evaluate several options, none of which are mutually exclusive. We will consider a new NSF Science and Technology Center, for which the next call for proposals is in 2017, along with other NSF programs including Macrosystems; Innovation in Food/Water/Energy Systems (INFEWS); Risk and Resilience; Science, Engineering, and Education for Sustainability; and National Ecological Observatory Network (NEON), a distributed nationwide observatory planned for a 30-yr lifespan. In addition, we will explore possibilities for private funding requests (e.g., Google Foundation, Microsoft Research's program in Computational Ecology and Environmental Science).

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