Title: Refining our Upper Mississippi River's ecosystem states framework

PREVIOUS LTRM PROJECTS:
The proposal builds off key recommendations for future research as expressed through the Resilience Assessment [1–3] and Habitat Needs Assessment-II [4]

PRINCIPAL INVESTIGATOR:
Dr. Danelle Larson, U.S. Geological Survey, UMESC
Phone: 608-781-6350; Email: dmlarson@usgs.gov
Danelle will be responsible for: project management (budgeting, contracts, data management plan, progress and completion reports); leading response-driver analyses and state-and-transitional modeling; writing at least 2 manuscripts and 1 technical report; and publishing online data products. She has expertise in aquatic vegetation and management, as well as ecological state theory and applications.

COLLABORATORS:
Ms. Alicia Carhart, WI DNR, UMESC
Phone: 608-781-6378; Email: Alicia.carhart@wisconsin.gov
Alicia will help with the conceptualization and study design of Objectives 1 and 2; assist with dataset compilation; assist with data interpretation and publications.

Dr. Wako Bungula, University of Wisconsin- La Crosse, Mathematics Department
Phone: 608-785-6608; Email: wbungula@uwlax.edu
Wako will mentor an undergraduate student using topological data analysis to address Objective 1 and 2; write manuscript and present on topological data analysis results.

Mr. Jason Rohweder, U.S. Geological Survey, UMESC
Phone: 608-781-6228; Email: jrohweder@usgs.gov
Jason will help conceptualize the study design for Objectives 1 and 2; gather and integrate the datasets for Objectives 1 and 2; conduct spatial mapping in Objective 2; assist with data management.

Dr. John Delaney, U.S. Geological Survey, UMESC
Phone: 608-783-6451; Email: jdelaney@usgs.gov
John will lead Objective 3-vulnerability assessments and the associated products listed below. John is currently leading a climate change vulnerability assessment for the Upper Mississippi River Watershed.

INTRODUCTION/BACKGROUND:

What's the issue? What do we already know? How will this work improve our understanding of the UMRS?

A Programmatic goal is to ensure all desired ecosystem states are preserved and functioning across the riverscape and that restoration supports a resilient ecosystem. [5] The UMRS' *ecosystem states* (i.e. the set of biological and physiochemical characteristics, processes, and interactions) are not well quantified or mapped, but necessary [6]. An ecosystem states approach has been employed for over a century in many types of ecosystems under various names such as phytosociology, alternative community states, and ecological regimes and regime shifts. Restoration practitioners and river managers need an ecosystem state-and-transition modeling (STM) framework to promote multiple species, habitats, and vegetation diversity and redundancy[2,4–6].

Two distinct ecological states for the UMRS have been conceptualized and broadly demonstrated using a state-and-transition model [1,7–9]: the "clear water state" and the "turbid state." [10] The upper pools have experienced large-scale shifts from turbid to clear water in the 2000's, but it's unclear whether this change happened systemically by a principal driver, or, whether there remain eutrophic areas at smaller scales to focus our restoration and management. We also need more information about how to transition turbid reaches (pools 10 and below) to a clear-water state. The scientific and management communities plea for applying an ecosystem states framework in rivers worldwide, while acknowledging most rivers do not have sufficient data to properly evaluate [2,11,12].This proposal will use the wealth of UMRS data to identify the criteria to classify all ecosystem states and their drivers of change at multiple spatial and temporal scales.

State and transition models (STM) are effective tools for organizing and communicating ecosystem states, state transitions, and employing adaptive restoration and management.[13,14] Vegetation (abundance or species composition) and chlorophyll *a* are the primary state variables. The STM incorporates expert knowledge, stakeholder feedback, historical references, and data into a synthetic framework for shared understanding and restoration guidance. The STM first describes the vegetation that can occur at a site, and then identifies causes of state stability and transitions (including succession, disturbance, or management). An ecosystem state can display "*transient dynamics/transitions,*" [15] which are significant but temporary changes in vegetation that is reversible or naturally in flux. "*State transitions*" (also called "regime shifts") are dramatic changes in ecosystem state that are irreversible, have unacceptably long recovery times, or require significant restoration action and resources. *Drivers* are variables that cause change, and identifying the drivers is key to preventing or inducing state changes (e.g., preventing "clear-water to turbid" state shifts, or, expanding wild celery beds). Identifying driver-response relationships (Fig. 1) will inform how a state is *resistant* to changing environmental conditions, how *resilient* a state may be after a severe disturbance, and, assess *vulnerability* of state transitions. The STM will integrate information on the states, transitions (both transient and long-term), drivers, and remaining uncertainties. The STM can be an excellent framework for implementing structured decision making[14] because restoration decisions are guided by science and become more transparent when the model is used as a communication tool. Further, the STM can lead to a framework for adaptive monitoring and management[16,17]. The STM model allows "learning by doing" restorations because the model can be updated with new information, and this information can alter restoration decisions and techniques based upon the STM.

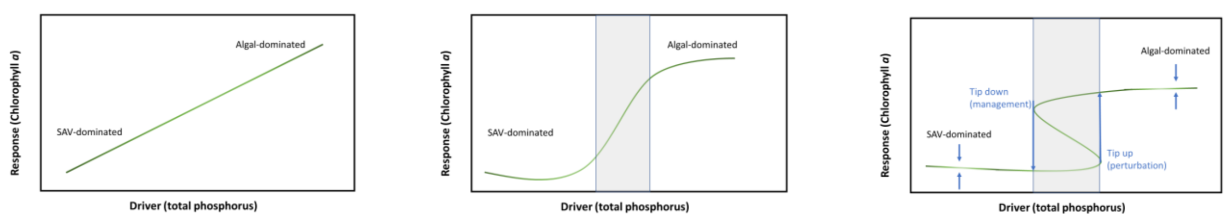

Fig. 1: Three examples of driver-response relationships. The ecosystem states are algal-dominated (high chlorophyll a) and SAV-dominated (high vegetation prevalence). The state variable is chlorophyll *a* (or conversely, SAV), and the driver is total P concentration. Each curve shows different responses to nutrient loading and provides management guidance. Panel (a) is a linear response and implies that management simply needs to reduce any amount of total P to see a decrease in chlorophyll *a*. Alternative states can exist with linear relationships, but different states and endpoints falls along a gradient. Panel (b) is a non-linear and threshold response and informs managers they must cross a threshold concentration of total P to reduce chlorophyll *a* and enter a SAV-dominated state. Panel (c) is a hysteresis-type response that suggests complexity for management intervention because alternative stable states exist. Recent hypotheses state panel (c) may occur in the UMRS [2], although panels (a) and (b) are also feasible. To best manage and restore ecosystem states, it is imperative we understand driver-response relationships and constraints.

We will build off the UMRS' current STM, but our new STM will be refined with further information and explicitly consider vegetation species composition[18] to align with our restoration goals, like increasing wild celery or vegetation diversity[4,5]. When using a community composition approach with state theory[18], ecosystems can have 2–5+ states. Previous HREP evaluations suggest that we can restore aquatic vegetation communities [19,20], but predictable outcomes will require advanced knowledge. The UMRS' vegetation communities change at various scales in space and time [2,19,21–23]; however, we generally don't understand the conditions that define, create, maintain, or transition these states [7,8,24,25]. We also do not recognize which vegetation community changes are transient dynamics versus state transitions, but desire this distinction for restoration[6].

Upper Mississippi River Restoration (UMRR) Science in Support of Restoration and Management Proposal for FY2021: Ecosystem States Framework

The goal of this proposal is to build off the UMRS' existing STM of the "clear water" state and "turbid state." Our advanced STM will identify all the UMRS' ecosystem states that considers vegetation community composition, within-state transient dynamics, and potential causes for transitions. We will analyze LTRM and other riverine datasets using multiple techniques, as well as obtain expert knowledge from the scientific literature and during a UMRS workshop. We will synthesize all these sources of information into a STM, which will greatly improve our understanding of ecosystem states, restoration, management, and knowledge gaps.

What are the objectives, hypotheses, and associated focal areas (FA)?

The overarching goal of this proposal is to: **Create a state-and-transition model that synthesizes information about all the UMRS' states, causes of transitions, and management implications.** These four objectives will be the foundation of the STM:

(1) What are the various ecosystem states [including vegetation communities]? (FA 2.3 and FA 2.5)

(2) Where are the states in the UMRS and how do they vary with spatial scale (e.g., aquatic area, strata, pool, and reach)? (FA 2.1, 2.3, 2.5)?

(3) How often do the states change? What are the main drivers of transitions? What is the evidence for transient dynamics versus major regime shifts, and at what scales should those be defined? (FA 2.1, 2.3, 2.5)?

(4) Are some river reaches and backwaters more vulnerable to state transitions, or, "low-hanging fruit" for management? For example, where would a small, low cost reduction in water level maintain or expand submersed aquatic vegetation and prevent a turbid state?

***Hypotheses*:**

We expect that distinct ecological states that can be defined by aquatic vegetation communities that are associated with specific sets of environmental covariates. There may be at least 6 distinct ecosystem states in the UMRS: (1) "clear-water" and SAV-dominated (SAV prevalence but species not considered); (2) "turbid" and algal dominated (water quality conditions prevent SAV); (3) "brown" state, where sediments hinder both SAV and chlorophyll *a*; (4) lotic-SAV dominated (wild celery); (5) lentic-SAV dominated (coontail); and (6) high vegetation diversity. We acknowledge there may be other unique states not yet known (e.g. like SAV and emergent mixed stands) and will allow the data analyses to reveal those. We suspect these states will be found throughout the UMRR, but the upper pools will exhibit a greater number and diversity of states.

State transitions can occur and be detected through LTRM at three major spatial scales: the aquatic areas scale (i.e., large, individual backwaters), strata, and pool. The states that are fluctuating frequently with seasonal water levels are transient dynamics (e.g. SAV→turbid→SAV). The states that change but do not reverse after the triggering event is likely a regime shift (e.g. SAV→turbid). We suspect that Pools 4, 8, and 13 all experienced a state transition (submergent plants <50% frequency of occurrence → submergent plants >50-95% occurrence) around year 2004 and the vegetated state is now stable (except Pool 13 may be questionable). Additionally, we hypothesize that Upper Pool 4 experienced a state transition from low vegetation species richness to high species richness around years 2008-2010. We expect that pools 13-19 are the most vulnerable to aquatic vegetation loss and state transition (pers. Comm. with partners), but it also may have the most restoration potential, as well. We provide additional testable hypothesizes in figures here:

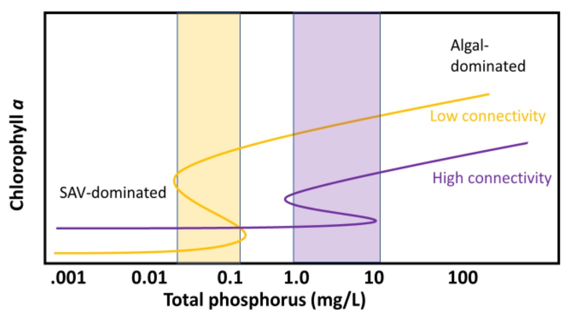

Fig. 2: We predict that the thresholds (yellow or violet bands) for state change depends on the interaction of nutrients and connectivity (measured as the "%_channel" metric[26]). Specifically, less connected backwaters are more susceptible to increased total P that causes an algal-dominated state transition. At higher total phosphorus concentrations and connectivity, algae cannot overtake established SAV due to flushing with connectivity to the mainstem.

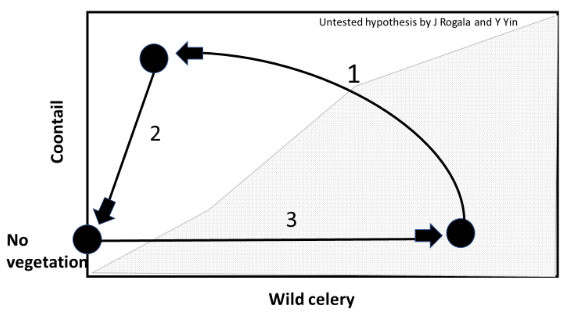

Fig. 3: Recently three ecological communities were suggested in the UMRS (black nodes: coontail, wild celery, or no vegetation[21]). Are these state transitions (long-term changes) or simple transient dynamics, and how does that influence restoration decisions? These states may transition by way of hypothesized drivers (arrows 1, 2, and 3; transitions remain untested). If wild celery dominates, transition 1 suggests that low flows can allow filamentous algae, duckweeds, and eventually coontail to displace celery, and the celery population crashes. In the coontail state, arrow 2 suggests flood scours quickly transition to an unvegetated state. In the no vegetation state, transition 3 would occur when normal to higher flows allow wild celery to recolonize, but celery establishment can take more than *8-10 years*. We will evaluate if these state transitions occur, how often and where, and estimate the thresholds to expect change (e.g., quantitatively define "low and high flows" and thresholds for scouring of vegetation). This information can help managers anticipate state transition with hydrological predictions, intervene with water level manipulation, or manage transition pathway 3 to reduce the number of years to reestablish desirable wild celery.

RELEVANCE OF RESEARCH TO UMRR:

How does this work inform river restoration and management? How will the proposed work contribute tothe selection or design of HREPs?

We need to identify the ecosystem states within the UMRR to help set realistic restoration goals (See Fig. 4, step 1), recognize the constraints to overcome (step 2) and use this information to prioritize constraints and HREPs (step 3). <u>Collectively, our STM will address steps 1-3</u>***.*** Then, our continued LTRM vegetation monitoring and future research can evaluate actions that produce or inhibit state transitions (step 5). Our STM, in conjunction with long-term monitoring and/or adaptive management, will provide feedback to guide managers to maintain the desired state (step 6) or redefine feasible restoration goals (step 1).

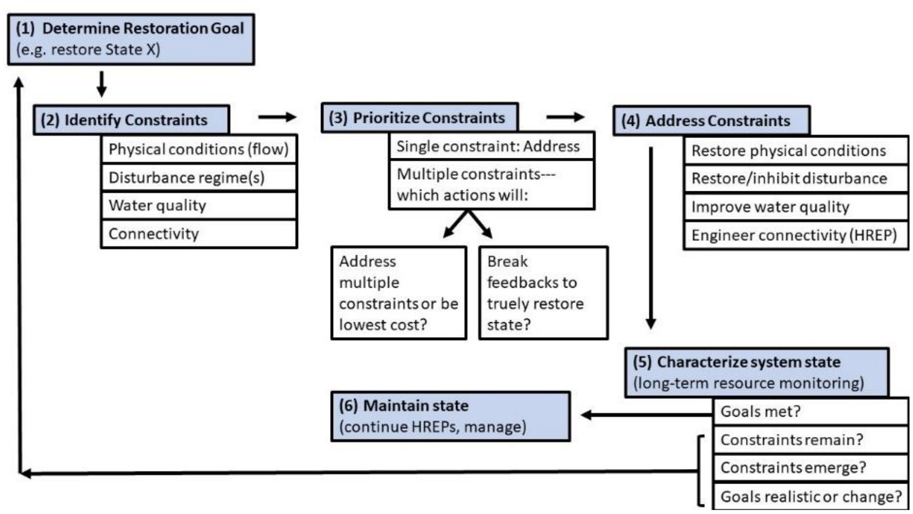

Fig. 4. Our STM will help to identify and prioritze constraints to reach restoration goals (steps 1-3). The STM will connect directly to HREP selection and adaptive management (steps 4-6) [27].

Describe how the research addresses one or more of the 2020 Focal Areas: This work encompasses three focal areas (2.1, 2.3, and 2.5). Our proposal will effectively cover >50% of the research questions outlined in FA 2.3.

If work involves an HREP, name it: The Lower Pool 13 HREP; Peterson Lake in Pool 4 (see details in Methods).

METHODS:

To achieve the 4 objectives and create an advanced STM, we will propose several different techniques that provides unique information.

(1) *Define the major states* and vegetation communities using non-metric multidimensional scaling (NMDS).
(2) *Map the states and changes* using the NMDS scores and a curve-fit approach[21,28] on the LTRM time series. We will map states at several spatial and temporal scales. This will delineate where community changes occur along the river continuum and how frequently (e.g., annual vs. decadal time steps) to help differentiate transient dynamics and state transitions. State maps can help prioritize HREP's.
(3) *Reveal distinct criteria for classifying the states* by conducting Topological Data Analysis (TDA; Fig 5).
(4) *Detect state transitions at the pool-scale* using TDA on our LTRM time series. TDA will test hypotheses that vegetation diversity abruptly arose in certain pools and time periods.
(5) *Seek drivers of transition* by graphing driver-response curves (examples in Fig. 1 and 2).
(6) *Obtain expert opinion* regarding states, transitions, and vulnerabilities during a UMRR Workshop.
(7) *Create vulnerability maps* that assess where and when ecosystem states are vulnerable to undesirable changes (e.g., vegetation "crash" or loss of plant diversity).
(8) *Synthesize information in methods 1-7 into a STM graphic and narrative.* The STM will include the states, transient dynamics, drivers of state transitions, and remaining uncertainties. The STM is a framework for communication, prioritizing restoration, future experiments, and adaptive management.
(9) *Solicit stakeholder feedback* on the STM and improve as needed before releasing publicly.

Detailed methodology for each step is provided below.

Study area:

We will incorporate information from the entire UMRR (pools 1-26 and the Illinois River) and the LTRM's 22+ years of water quality and aquatic vegetation data. To address the dichotomy of vegetation/clear-water and unvegetated/turbid states, we will use the vegetation presence/absence data collected during summer at all six LTRM water quality stations. We will also supplement with the UMRCC vegetation presence/absence data from the "out-pools" to better understand the pools hypothesized to be in a state of flux and highest potential for rehabilitation (Pools 11-19; pers. comm. with partners). We will use the LTRM aquatic vegetation community data from Pools 4, 8, and 13 to evaluate the states characterized by vegetation assemblages.

Objectives 1, 2, and 3 approaches– identifying the ecosystem states and state transitions:

First, we will integrate all necessary data. The main state variables of interest (aquatic vegetation and chlorophyll *a*) are found across two LTRM datasets. In addition, hypothesized drivers and characteristics of these states are found in at least 5 disparate datasets: LTRM vegetation and water quality, aquatic area metrics, velocity, wind fetch, and discharge. Using ArcGIS, we will summarize the hypothesized drivers (i.e. water clarity, total phosphorus, connectivity, discharge) at the aquatic area scale[26] for each year (total of 22 years).

Next, we will determine the main ecosystem states using LTRM data following the general procedure in Carhart and De Jager 2019 that used NMDS to identify lotic and lentic SAV communities. Here, the NMDS will also include a variety of vegetation life forms (SAV, floating rooted, metaphyton, emergents, and chlorophyll *a*) and hypothesized drivers.

We will map the states and state transitions using the interpolated NMDS scores and a curve-fit[28] from years 1998–2019. Curve fit will be done at multiple time scales (i.e. annual, 5-year, 10+ years) in order to differentiate between transient dynamics and regime shifts. We will use these maps to identify hotspots of specific states and how the patterns vary with scale. We will then quantify and map where the specific states are stable (i.e., high resistance), where they are frequently changing and had reversible change (i.e. high resistance) or have undergone a significant state shift (i.e, low resistance and resilience). In addition, we will examine whether a few previous and ongoing HREP case studies produced desired states by altering water levels or reducing mainstem connectivity through time (e.g., Peterson Lake in Pool 4, Lower Pool 13).

Topological Data Analysis (TDA) will further help visualize ecosystem states and transitions, as well as define the classifying criteria of each state. TDA will include a spatial component to seek differences in strata and pools and sometimes performs better than NMDS. The use of TDA for ecological data is novel and promising (Fig. 5). We will allow the ecological data to determine the distinct criteria that define the states using the TDA Mapper tool. The TDA Mapper is an algorithm that uses dimension reduction [29–31] and makes a network diagram with nodes and connections. The nodes represent sample sites of state similarity and provides information on how the state was defined; for example, a node may be classified as the "clear water state" and contain specific criteria for inclusion such as >60% submersed aquatic vegetation prevalence, <15 mg/L total suspended solids, and <15 ug/L chlorophyll *a*. We will compare the TDA Mapper diagrams to describe commonalities and differences of ecological states and criteria among pools and strata. Another TDA tool called "Persistence Homology" will use the 22-year time series to detect change points and reveal past regime shifts [32] that we hypothesized above.

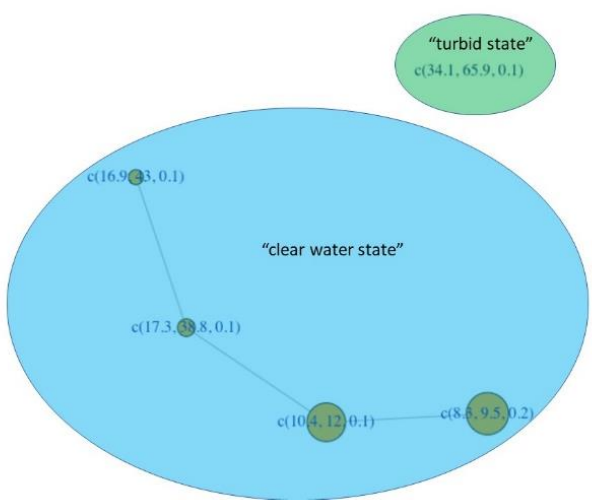

Fig. 5. Example of TDA Mapper output for pool 8 in summer 2011 using LTRM water quality data. TDA Mapper revealed two ecosystem states: a "clear water state" and a "turbid state." Each node is a collection of sampling sites with strong similarity based on the three input variables: total suspended solids, chlorophyll *a*, and total phosphorus. The size of the nodes corresponds to the relative number of sampling sites, and labels on the nodes describe the average values for each variable (sediment, chlorophyll, total phosphorus). Within the "clear water state", the connecting lines between the nodes reveals transient dynamics or expected variability within the state. The states were principally differentiated by two variables: suspended sediments and chlorophyll *a,* but not total phosphorus. The clear water state had low sediment concentrations (8-17 mg/L) and chlorophyll *a* (typically <12 ug/L but ranged 9-43ug/L). In the turbid state, suspended solids were moderately high (34 ug/L), and chlorophyll *a* was high (mean: 66 ug/L). The clear water state dominated in Pool 8, but a few sites were in the turbid state. Future TDA's will include other hypothesized variables to further refine the states, vegetation community composition, and, examine trends across space and time.

We will also examine driver-response relationships (e.g., Fig. 1 and 2) to understand drivers and thresholds of transition [13,33]. Although this information seems rudimentary, the river's ecosystem states and drivers are not yet well defined using LTRM's rich datasets. We will fit several competing models to the data to reveal the type and dominate response-driver relationships (Fig. 1, 2, and 3). We will generate many graphics like that in Fig. 2 to explore relationships and then use Akaike's Information Criterion to test which type of response curve fits the data best. The more complex responses like hysteresis will require use of differential equations. Correlation is not always causation, so we will also use good judgement to determine drivers and may recommend future experimental research in the river or UMESC's mesocosms for increased certainty.

Objective 4 approach– vulnerability assessment:

We will produce a comprehensive vulnerability assessment that uses data and expert opinions to understand which backwaters, strata, and pools are stable versus highly susceptible to undesirable state shifts. The undesirable state shifts can include: vegetated → unvegetated, wild celery → coontail, or high vegetation diversity → low diversity. We will host a 2-day workshop to gather expert opinion to develop a robust vulnerability model that is tailored to management needs. The workshop attendees will be selected to provide diverse perspectives and knowledge regarding the river's aquatic vegetation resources, threats, and management objectives. We will list and rank what are the greatest *exposures* to the established aquatic vegetation (i.e. the factors that influence state transitions or vegetation "crash"); list and rank how *sensitive* the aquatic vegetation is to each exposure (using our driver-response data and expert opinion); and list and rank the *adaptive capacity* (resiliency) of the vegetation to such exposures and discuss methods to increase adaptive capacity. Synthesized information based on literature, Mississippi River data, and expert opinion revealed during the workshop will feed a vulnerability model, where: *Vulnerability = (Exposure*sensitivity) – adaptive capacity*[34]

Our vulnerability results will be mapped to identify vulnerability hotspots, prioritize areas for restoration, and develop management strategies.

State-and-Transition Model--- Synthesis of Results:

The highlights from previous UMRR work and discoveries from this proposal will be integrated and synthesized into a classic state-and-transition model.[14] The model will be provided as a visual graphic, like box and arrow diagrams, to show the UMRR's ecological states, transition pathways, and feedbacks. It will contain descriptions of the criteria for each state; differentiate transient dynamics/natural vegetation flux from ecosystem state transitions; describe the triggers, drivers, and response type to drivers (e.g., linear, threshold, or hysteresis) for state transitions; and reveal our remaining knowledge gaps. We will provide basic restoration guidelines for altering ecosystem states, increasing resiliency, and reducing vulnerability.

Beyond this proposal's timeframe, Larson will continually update the model using new data and stakeholder participation for shared understanding and grow the STM's utility for restoration. The STM can become a platform for structured decision making and/or adaptive monitoring and management if the partnership chooses to adopt these approaches.

Data availability: We will create a Data Management Plan that will undergo review before the data collection process, and our data products will go through an additional review before data is released. The Data Management Plan will comply with the USGS' procedures APP045.3 and APP048.0. Our manipulated data files and analyses script will be shared via ScienceBase and the LTRM website for accessibility and repeatability.

SPECIAL NEEDS: None but thank you.

BUDGET: Budget spreadsheet attached.

TIMELINE & EXPECTED MILESTONES: We will begin the project in October 2020, submit all products for internal review by September 2022, and finish a project completion report by September 2022.

Task	Completion Date	Task Leads
Data integration (gather datasets, integrate)	December 2020	Rohweder (All assist)
Identify states and transitions using NMDS approach	March 2021	Larson, Carhart
Workshop: vulnerability assessment	May 2021	Larson, Delaney
Mentor student intern	August 2021	Bungula, Larson
Annual reporting and data management update	September 2021, 2022	Larson
Vulnerability maps	August 2021	Delaney
Spatial mapping of states and changes	December 2021	Rohweder (Carhart trains)
TDA Mapper, regime shifts	May 2022	Bungula, student, Larson
Draft the STM, share with stakeholders	September 2022	Larson
Completion reportand manuscripts to IDPS for internal review	September 2022	All

PRODUCTS & COMPLETION DATES:
*All our products listed will first be sent to the LTRM Science Director, and then undergo a data and report review following the USGS' IDPS process. All data will be preserved and publicly available through ScienceBase and the LTRM website.

- **Maps** of the ecological states in space and time that vary in scales of interest. Select maps will be posted on the LTRM website to complement the existing "surface maps" that currently highlight places of no vegetation and vegetation. (fulfills Objective 1,2,3; completed December 2021; lead: Rohweder and others)
- **Report** on the topological data analysis outputs. This will be one of the first papers using TDA Mapper in an ecological setting, and the first paper to define multiple ecological states along a river continuum. (fulfills Objective 1,3; completed September 2022; lead: Bungula and Larson)
- **A 2-day workshop** to review existing knowledge and discuss expert opinion on potential impacts, sensitivity, and adaptive capacity of aquatic vegetation communities in the UMRS. This will feed the vulnerability maps and STM. The facilitator will provide a **summary report**. (fulfills Objectives 3 and 4; completed May 2021; Leads: Delaney and Larson)
- **Vulnerability maps** will allow managers to visualize the drivers of change (e.g., connectivity, sediment loads) to help determine and prioritize restoration location and action. (fulfills Objective 4; completed August 2021; lead: Delaney)
- **Publication** of aquatic vegetation vulnerability in the UMRS. This will be the first scientific inquiry into the vulnerability of aquatic vegetation (fulfills Objective 4; completed March 2022; leads: Delaney and Larson)
- **Publication** on the major ecological states and their changes across the UMRR in the past 20 years. State-and-transition modeling will describe the states and transition pathways and identify where the current knowledge gaps remain. (fulfills Objective 1,2,3; draft completed September 2022; lead: Larson)

ACKNOWLEDGMENTS:
We thank the participants at the UMRR2020 Science Meeting for inspiring ideas herein. We are very grateful to J Houser, E Lund, S Winter, KJo Jankowski, and B Gray for providing thoughtful proposal comments.

APPENDIX 1. REFERENCED LITERATURE:

1. Bouska, K. L., Houser, J. N., De Jager, N. R. & Hendrickson, J. Developing a shared understanding of the upper mississippi river: The foundation of an ecological resilience assessment. *Ecol. Soc.* **23**, (2018).
2. Bouska, K. L., Houser, J. N., De Jager, N. R., Van Appledorn, M. & Rogala, J. T. Applying concepts of general resilience to large river ecosystems: A case study from the Upper Mississippi and Illinois rivers. *Ecol. Indic.* **101**, 1094–1110 (2019).
3. Bouska, K. L. *Scientific Framework for Resilience Research on the Upper Mississippi River System*. (2019).
4. McCain, K., Schmueker, S. & De Jager, N. *Habitat Needs Assessment - II : Linking Science to Management Perspectives*. (2018).
5. U.S. Army Corps of Engineers. *A STRATEGIC PLAN FOR THE UPPER MISSISSIPPI RIVER RESTORATION PROGRAM 2015 – 2025*. (2015).
6. Houser, J. *Science Focal Areas for the UMRR 2020 Science Meeting*. (2019).
7. Burdis, R. M., Delain, S. A., Lund, E. M., Moore, M. J. C. & Popp, W. A. *Decadal trends and evidence of an ecological shift in backwater lakes of a large floodplain river: Upper Mississippi River*. (2020).
8. Giblin, S. M. Identifying and quantifying environmental thresholds for ecological shifts in a large semi-regulated river. *J. Freshw. Ecol.* **32**, 433–453 (2017).
9. Sparks, R. E. *et al.* Disturbance and Recovery of Large Floodplain Rivers. *Environ. Manage.* **14**, 699–709 (1990).
10. Scheffer, M. *Ecology of shallow lakes*. (2004).
11. Ibanez, C. Changing nutrients changing rivers. *Science* **365**, 636–637 (2019).
12. Biggs, R., Peterson, G. D. & Rocha, J. C. The regime shifts database: A framework for analyzing regime shifts in social-ecological systems. *Ecol. Soc.* **23**, (2018).
13. Mason, T. J., Keith, D. A. & Letten, A. D. Detecting state changes for ecosystem conservation with long-term monitoring of species composition: *Ecol. Appl.* **27**, 458–468 (2017).
14. Bestelmeyer BT *et al.* State and transition models: theory, applications, and challenges. in *Rangeland Systems: Processes, Management and Challenges* (ed. Briske, D.) 303–345 (Springer, 2017).
15. Larson, D. M. Grassland Fire and Cattle Grazing Regulate Reptile and Amphibian Assembly Among Patches. *Environ. Manage.* **54**, 1434–1444 (2014).
16. Briske, D. D., Bestelmeyer, B. T., Stringham, T. K. & Shaver, P. L. Recommendations for development of resilience-based state-and-transition models. *Rangel. Ecol. Manag.* **61**, 359–367 (2008).
17. Lindenmayer, D. B. & Likens, G. E. Adaptive Monitoring: a new paradigm for long-term research. *Trends Ecol. Evol.* **24**, 482–486 (2009).
18. Kadowaki, K., Nishijima, S., Kéfi, S., Kameda, K. O. & Sasaki, T. Merging community assembly into the regime-shift approach for informing ecological restoration. *Ecological Indicators* **85**, 991–998 (2018).
19. De Jager, N. R. & Rohweder, J. J. Changes in aquatic vegetation and floodplain land cover in the Upper Mississippi and Illinois rivers (1989–2000–2010). *Environ. Monit. Assess.* **189**, (2017).
20. Langrehr, H. A., Gray, B. R. & Janvrin, J. A. Evaluation of aquatic macrophyte community response to island construction in the upper mississippi river. *Lake Reserv. Manag.* **23**, 313–320 (2007).
21. Carhart, A. M. & De Jager, N. R. Spatial and temporal changes in species composition of submersed aquatic vegetation reveal effects of river restoration. *Restor. Ecol.* **27**, 672–682 (2019).
22. Moore, M. *LTRM – 2012A6: Long Term Resource Monitoring Analysis of Spatial and Temporal Dynamics of Submersed Aquatic Vegetation and Metaphyton Communities of Pool 4, Upper Mississippi River (1998-2011)*. (2015).
23. Fischer, J. R. & Claflin, T. O. Declines in aquatic vegetation in navigation pool no. 8, upper Mississippi River between 1975 and 1991. *Regul. Rivers Res. Manag.* **11**, 157–165 (1995).
24. Houser, J. N. *et al.* Nutrient cycling, connectivity and free-floating plant abundance in backwater lakes of the Upper Mississippi River. *River Syst.* **21**, 71–89 (2013).
25. Kenow, K. P. & Lyon, J. E. Composition of the seed bank in drawdown areas of navigation pool 8 of the upper Mississippi river. *River Res. Appl.* **25**, 194–207 (2009).
26. De Jager, N. R. *et al. Indicators of Ecosystem Structure and Function for the Upper Mississippi River System. OFR20181143.* (2018).
27. Suding, K. N., Gross, K. L. & Houseman, G. R. Alternative states and positive feedbacks in restoration ecology. *Trends in Ecology and Evolution* **19**, 46–53 (2004).
28. De Jager, N. R. & Fox, T. J. Curve Fit: A pixel-level raster regression tool for mapping spatial patterns. *Methods Ecol. Evol.* **4**, 789–792 (2013).
29. Singh, G., Mémoli, F. & Carlsson, G. *Topological Methods for the Analysis of High Dimensional Data Sets and 3D Object Recognition*. *Eurographics Symposium on Point-Based Graphics* (2007).
30. Rote, G. & Vegter, G. Computational topology: An introduction. in *Effective Computational Geometry for Curves and Surfaces* (eds. Edelsbrunner, H. & Harer, J.) 277–312 (Springer Berlin Heidelberg, 2006). doi:10.1007/978-3-540-33259-6_7
31. Nielson, J. L. *et al.* Topological data analysis for discovery in preclinical spinal cord injury and traumatic brain injury. *Nat. Commun.* **6**, (2015).
32. Islambekov, U., Yuvaraj, M. & Gel, Y. R. Harnessing the power of topological data analysis to detect change points. *Environmetrics* **31**, (2020).
33. Bestelmeyer, A. B. T. *et al.* Practical Guidance for Developing State-and-Transition Models. *Rangelands* **32**, 23–30 (2010).
34. De Lange, H. J., Sala, S., Vighi, M. & Faber, J. H. Ecological vulnerability in risk assessment - A review and perspectives. *Science of the Total Environment* **408**, 3871–3879 (2010).