Title: Response of a Man-Made Forest to the Catastrophic Wildfires of 2022: Recovery of the Sandhills Halsey Nebraska National Forest

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Statement of Issues & Justification

Climate variability and change, and land use and landcover change continue to impact fire regimes and subsequent forest-grasslands ecosystem dynamics, functioning, and resilience, including the plant-soil-water nexus immediately post-fire. Monitoring post-fire effects on vegetation structure and composition, soil health, water availability, and their interactions is important for understanding ecosystems' regime shifts and resilience, as well as developing and implementing locally and regionally relevant adaptive management practices post-fire. At 50,000 km^2, the semi-arid grasslands of the Nebraska Sandhills are the largest stabilized fragile sand-dunes in the western hemisphere and reside over an important water resource, the Ogallala Aquifer. The Sandhills offer many ecosystem services, including grazing on 95% of the area in support of the livestock industry, the largest agricultural sector in Nebraska with 12 billion dollars added to the state's economy each year (equivalent to nearly half of the agriculture receipts of the state).

A major threat to the Sandhills is encroachment of woody eastern redcedar (*Juniperus virginiana*) and the localized expansion of ponderosa pine (*Pinus ponderosa*). Eastern redcedar now constitutes over 22% of forested lands in Nebraska (encroachment rate into grasslands and forests was ~ 25,000 acres yr^{-1} between 2010 and 2015). Several drivers have been posited to explain woody species invasion into grasslands, including fire regime shifts, increases in atmospheric CO_2, nitrogen deposition, recruitment of grassland mycorrhizal networks and intensive livestock grazing (Archer 1994, Liang et al. 2017; Harr et al. 2014, Archer et al. 2017, García Criado et al. 2020). Consequently, areas impacted by woody species invasion tend to experience shifts in ecosystems and the services they provide, including declines in species richness and diversity (Ratajczak et al. 2012, Sala and Maestre 2014, Mazis et al. 2021); reductions in net primary productivity and forage availability with subsequent impacts on livestock rearing communities (Twidwell et al. 2013); ecohydrological alterations leading to reduced soil water (Awada et al. 2012; Kishawi et al., 2022); shift in microbial communities (Liang et al. 2017; Fowler 2021) and biogeochemical cycles (Hibbard et al. 2001); shift in fire regimes (Twidwell et al. 2013) and the emergence of respiratory problems in humans in response to pollen (Leis et al. 2017).

The encroachment of woody species into the grasslands has increased the risk of catastrophic wildfires with serious ecological, human, and economic losses. The recent Bovee Fire at the Nebraska National Forest (NNF) at Halsey is a prime example of this, where over 19,000 acres of grasslands and forests were burned (Oct. 2022). NNF is the largest man-made forest in the USA. It was established on the semi-arid grasslands of the sandhills in 1903 and includes 25,000 acres of hand-planted conifers (with eastern redcedar and ponderosa pine being the two main species). Some of the most concerning impacts of the current wildfires in this mature forested area are on vegetation structure and composition, as well as soil functional integrity, and resilience post-fire. Our long term (15 years) research at NNF (McIntire Stennis #1017953 NEB-38-114; #1000916 NEB-38-098 and 212707 NEB-38-060) has demonstrated the impact of eastern redcedar and ponderosa pine on vegetation diversity, soil microbial composition, carbon (decline with depth relative to adjacent grasslands), and soil water recharge (drier soils under forested lands impacting soil water recharge). The combined effects of above and below-ground tree architecture and litter, together with declines in soil organic matter and carbon have led to soil erosion in several of these forests, which we anticipate becoming exacerbated with the combustion of vegetation. *Given the history of the NNF and the age of plantations, we have a unique opportunity to be proactive and quantify the impact of wildfire on the recovery of these unique mature forests (of the oldest in NE and the region) and implement ecosystem management strategies to avoid undesirable changes that sooner or later will impact the 22% of tree-invaded areas in the Sandhills.* Additionally, this fire represents an ideal opportunity to assess recovery dynamics in alternative stable states in grasslands, analyze the transition dynamics between woody and grassy states in this complex system, and explore the degree of hysteresis present in the woody state: ***Does the system recover to grassland or woodland and what interventions may mediate those transitions?***

The effects of the Bovee wildfire in the NNF is of concern not only to ranchers and the Forest Service, but also to the public who use the forest for recreational activities and have deep cultural connection to the ecosystem. Our efforts will emphasize engagement with our stakeholders, providing outreach and experiential learning opportunities to diverse students in rural communities, and demonstrating the real time trajectory of recovery using phenocams (to be hosted by the Center for Resilience in Agricultural Working Landscapes [CRAWL] at the University of Nebraska–Lincoln).

The aim of this project is to establish new long-term research and demonstration plots in newly burned eastern redcedar and ponderosa pine stands, as well as burned grasslands at the Nebraska National Forest at Halsey and continue the data collection on existing established non-burned long-term sites. We also propose to develop state-of-the-art spatial monitoring and modeling tools using an in-situ phenocams network, and airborne and spaceborne remote sensing technologies with corresponding data analytics that are validated and complemented with ground measurements (i.e., productivity, biodiversity, soil, and water). With these, we will immediately implement post-burn studies to screen for signals of: 1) vegetation recovery; 2) invasive species; 3) desertification; 4) soil health (carbon accounting, nutrients, and microbial communities); 5) hydrology; and 6) hysteresis within this system. Meanwhile, through our engagement with our diverse group of stakeholders, we will not only communicate scientific findings but also gather input and together co-develop solutions and management practices that are impactful at local to regional scales.

Specifically, we will compare areas that have escaped wildfire (plots established early 2000s with continuous data collection) with burned grasslands and forests of eastern redcedar and ponderosa pine at NNF. We will use advanced and appropriate statistical tools, process-based models, machine learning, and computer vision to answer the immediate post-fire questions: 1) what are the most significant indicators of ecological recovery and regime shifts? 2) what system will most likely re-emerge, grassland or woodland, and how will climate variability and change affect the recovery of the vegetation? 3) can we use advanced machine learning to detect the signals for recovery or regime shifts? 4) how can we best work with managers and landowners to co-develop adaptive management plans? 5) how can we best provide our diverse students with experiential learning experiences related to fire ecology and recovery of land? and 6) how can we best engage with the public?

Related Current and Previous Work:

During the previous research at the NNF (funded in part by the McIntire Stennis), the PIs established 17 permanent long-term sites that range from open grasslands to dense canopy forests of ponderosa pine, eastern redcedar or mix of the two for research on the ecology of trees and grasses, dendroecology (tree rings), ecophysiology and ecohydrology, soils health, and diversity and composition of soil microbial communities. As part of this proposed project, we conducted a search in NIFA's Research, Education, and Economics Information System (REEIS) on November 8, 2022. We used the search term "eastern redcedar fire", which resulted in 50 projects. Projects covered a wide range of topics including forage production, nitrogen application, hydrology, plant ecology, invasion, fungal abundance, animal – plant interactions, and grazing efficiency, but none on the recovery of vegetation post-fire in the Sandhills of Nebraska.

Goal and Objectives:

The overarching goal of this proposed research is to investigate post-fire indicators of ecological recovery and regime shifts in grasslands and planted forests of eastern redcedar and ponderosa pine at the Nebraska National Forest, Halsey. Specifically, we will:

1) Determine the system that will re-emerge post fire –grassland or woodland.

2) Assess environmental drivers (e.g., climate, soil health and water availability) that determine the type of vegetation and regime shifts post-fire.
3) Implement advanced data analysis tools to detect signals of recovery or regime shifts.
4) Engage with diverse managers and landowners to co-develop adaptive management plans and provide our diverse students with experiential learning experience related to fire ecology and recovery of land.

Methods

The study will be conducted at the Nebraska National Forest (NNF) Halsey. A 25,000 acres experimental forest that was hand-planted with coniferous species, including ponderosa pine and eastern redcedar. The documented history, site characteristics and uniformity of plantations, age, and soils make this location uniquely suited to address our objectives. Seventeen sites were established in the early 2000s at NNF ranging from grasslands to dense forests of eastern redcedar or ponderosa pine. Data on stand structure, tree age and growth, nutrient availability (down to three meters depth), root biomass, leaf area index, soil water, and microclimate have been collected on all plots. These established non-burned sites will remain and will serve as controls. For this study, we will select three controls from our existing representative sites (grasslands, dense eastern redcedar, and dense ponderosa pine). We will also establish nine new sites of three recently burned grassland (control) and six severely burned forested sites (three eastern redcedar and three ponderosa pine).

Objective 1. Determine the system that will re-emerge post fire –grassland or woodland (Awada, Shi, Uden, Allen, Ameway, Das Choudhury). We have established protocols for existing sites which will be mirrored on newly burned sites. We will annually measure biomass, forest regeneration with spatial soil/plant association, plant biodiversity by species composition and functional group (June and August to capture maximum standing biomass), and ecophysiological responses (monthly) including chlorophyll fluorescence, stomatal conductance (LiCor 6200), and $\delta^{13}C$ isotopes (intrinsic WUE), see Msanne, Awada, et al. (2017) for details. Proximal continuous measurement of understory vegetation will occur through the installation of phenocams on representative control and burned sites (six sites total), these will be complemented by multiscale proximal remote sensing methods that provide unique tools on plants leaf to understory canopy scale that when combined with the other objectives can provide a strong tool for assessment of vegetation health as impacted by the environment. Leaf-level hyperspectral measurements will be performed using Ocean Optic sensors that span from visible to infrared (400-1000 nm) and will be coupled with spectral imagery at 50 cm * 50 cm scale (backpack system, Mazis et al. 2021), and UAV flights (June and August). Data will be validated against traditional measurements (described above) to estimate biophysical vegetation conditions at the plot scale and spatially extrapolate that information across the surrounding landscape. The ground and airborne-based image data will be comparable allowing a series of vegetation indices (VIs) to be calculated to assess various biophysical measures (e.g., chlorophyll, water status, greenness, leaf area).

Objective 2. Assess environmental drivers that determine the type of vegetation and regime shifts post-fire (Khorchani, Drijber, Córdova, Iqbal, Awada). Weather and soil moisture: a total of 6 HOBO U30 USB Weather Station starter kit will be installed on sites for continuous measurement of temperature, relative humidity, solar radiation, wind direction and speed and soil moisture (15 cm). Additionally, we will install three access tubes to 120 cm depth on each site to measure soil moisture profile and nitrate leaching once a month on all plots. Results from this objective will be linked to data from objective 1 to determine the impacts of local weather variability on recovery. Soil health indices: include soil texture and structure, soil pH, soil carbon, nutrient composition (e.g., Nitrogen, Phosphorous, Calcium) and electrical conductivity (EC). Measurements will be taken in years 1 and 4. For soil organic carbon *(OC)*: to assess OC storage and turnover we will sample the topsoil (0-10 cm depth) and subsoil (10-50 cm depth). Carbon isotope ratio ($\delta^{13}C$) will also be determined (Water Lab, UNL) to assess vegetation-derived differences (C3 vs C4) in the composition and turnover of the soil OM (Mellor et al., 2013). Soil microbial biomass and broad taxonomic groups of the microbial community (bacteria, saprophytic fungi and arbuscular mycorrhizal fungi: AMF) will be monitored during recovery using fatty acid profiling (Grigera, Drijber et al. 2006). Because eastern red cedar is adept at tapping into extant grassland AMF communities (Liang, Drijber et al. 2017), is the reverse true during recovery?

Objective 3. Implement advanced data analysis tools to detect the signals for recovery or regime shifts and use ecohydrological process-based models to simulate scenarios of vegetation recovery and climate change (Allen, Uden, Das Choudhury, Khorchani, Shi). For this objective we will use state of the art machine learning tools to integrate continuous and point measurements with features derived from remote sensing and phenocam imagery and computer vision to create data-driven predictive models associated with recovery and resilience. Results and visualizations will be updated on our website on a regular basis. In addition, we will use the regional Ecohydrological Simulation System (RHESSys) model (Tague and Band, 2004) to simulate different trajectories of vegetation recovery and climate. RHESSys is a dynamic process-based model developed to simulate surface and subsurface water fluxes and nutrients under different vegetation and climate conditions. The model has been tested in different environments and has shown high sensitivity to simulate changes to ecohydrological processes related to vegetation disturbance and management (Moran-Tejeda et al., 2015; Khorchani et al., 2020; Bart et al., 2021; Burke et al., 2021). The data that will be obtained from objectives 1 and 2 will be used together with other sources of data (e.g. the U.S. Geological Survey USGS and the World Climate Research Program WCRP among others) to build realistic recovery and management scenarios for NNF. These scenarios will allow a further understanding of the coupled effects of disturbance and climate on vegetation and water dynamics.

Objective 4. Engage with diverse managers and landowners to co-develop adaptive management plans and provide our diverse students with experiential learning experience related to fire ecology and recovery of land (Ameway, Allen, Smith, Erixon, Córdova, Das Choudhury). Adaptive management is an approach to natural resources management that emphasizes learning-by-management, based on the philosophy that knowledge is incomplete and things we think we know may actually be wrong. Adaptive management has explicit structure, including careful identification of goals, clear identification of management objectives and hypotheses of causation, and procedures for data collection followed by evaluation and reiteration. Collaborative adaptive management (CAM) intentionally integrates stakeholders into the adaptive management process. A key focus of CAM is the collective identification and reduction of uncertainty through management experiments that enhance learning. Engaging stakeholders, implementing change when appropriate, and keeping the public informed are all important for new management approaches. Successful transitions to new management approaches should also be quantifiable and perceived as beneficial by potential managers. Monitoring allows for assessment of the relative success of alternative approaches and allows managers to set new targets and make adjustments to reach those targets as they learn. Hypotheses related to recovery post-fire will be developed with stakeholders, followed by establishing experiments and monitoring protocols. Near real-time Phenocam images and information from weather stations, and annual data analysis of vegetation dynamics will be visualized and hosted on the CRAWL website (Center for Resilience in Agricultural Working Landscapes [CRAWL] at the University of Nebraska–Lincoln) to maintain transparency. Additionally, workshops with stakeholders will be held in years 2 and 4 to co-develop an adaptive management plan. Diverse high school, undergraduate and graduate students will be recruited to work on the project and results will be communicated in classrooms.

Target Audience/Expected Outcomes

This study will establish a foundation that will drive the development of long-term post fire research impact. Our findings will be important in guiding our efforts to mitigate and adapt to climate change (including soil carbon sequestration), extrapolate findings to other areas, develop adaptable management tools, promote recovery of these fragile systems, engage with diverse communities of practices, educate the public, and understand societal costs. Results will provide new information on the role of fire and tree invasion in the resilience of grasslands and wooded areas resilience. As with previous funding/projects, we will continue our collaborations with and seek funding from state (e.g., DNR, Agroforestry, Forest Service, NET – see previous work) and federal agencies (e.g., Sustainable Agroecosystems USDA and Ecosystem Studies NSF). This study will serve as the basis for high school students (PI takes 1-4/yr) and undergraduate/graduate training and junior faculty professional development. We will publish disciplinary and high impact integrated manuscripts, and present findings at professional meetings, state agencies and task forces.

Milestone and timeline

Task / Year	1	2	3	4	5
New sites establishment post fire, including planting, phenocams, and weather stations	x				
Vegetation (Biomass, diversity), soil moisture (15 cm), and weather data collection	x	x	x	x	x
Long term study on soil water to 150 cm depth (monthly throughout the year)		x	x		
Soil sampling for soil physical and chemical characteristics, and soil microbial communities.	x	x		x	
Ecophysiology and proximal sensing (June and August)	x	x	x	x	x
Machine learning, modeling, forecasting		x	x	x	x
Students training	x	x	x	x	x
Communication of findings (papers, presentations, and seminars) and engagement (workshops and web-based near real time data stream)	x	x	x	x	x
Grants submission	x	x	x	x	x

Budget ($75,000 per year for 5 years)

	Year 1	Year 2	Year 3	Year 4	Year 5
Phenocams (6 units at $2000 per unit)	12,000	-	-	-	-
Hobo stations (6 units at $2500 per unit)	15,000	-	-	-	-
Soil analysis	10,000	2,000	2,000	11,000	2,000
Vegetation analysis	6,000	6,000	6,000	6,000	5,000
Workshops/outreach activities	2,000	7,000	7,000	5,000	7,500
UAV and Backpack (CALMIT rental)	5,000	5,000	5,000	5,000	5,000
Access tubes	2,500	-	-	-	-
Travel to site (monthly and stay at Thedford for 2- 3 nights for 2-3 individuals)	8,000	8,000	8,000	8,000	8,000
Undergraduate students (2)	7,000	7,000	7,000	-	7,500
Part time computer, data visualization and web design	7,500	10,000	10,000	10,000	10,000
PhD student	0	28,000	28,000	28,000	28,000
MS Student (student available at no-cost to the project)	0	0	-	-	-
Publications		2,000	2,000	2,000	2,000
Total ($)	**75,000**	**75,000**	**75,000**	**75,000**	**75,000**

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