FINAL REPORT

Ecosystem Change in the Blue Mountains Ecoregion: Exotic Invaders, Shifts in Fuel Structure, and Management Implications

JFSP PROJECT ID: 16-1-01-21

December 2021

Becky Kerns, PI
USFS Pacific Northwest Research Station

Meg Krawchuk, Co-PI
Oregon State University

John Kim, Co-PI
USFS Pacific Northwest Research Station

Temesgen Hailemariam, Co-PI
Oregon State University

Nicole Vaillant, Co-PI
USFS Rocky Mountain Research Station

Bridgett Naylor, Co-PI
USFS Pacific Northwest Research Station

Ty Nietupski, graduate student
Oregon State University

Lesley Morris, Co-PI
Oregon State University

Claire Tortorelli, graduate student
Oregon State University

Rebecca Lemons, postdoc
Oregon State University

JOINT FIRE SCIENCE PROGRAM
FIRESCIENCE.GOV
Research Supporting Sound Decisions

Table of Contents

List of Figures

List of Abbreviations of Acronyms

BME, Blue Mountains Ecoregion

BRT, Boosted Regression Tree

dNBR, Normalized Burn Ratios

ERC, Energy Release Component

FSIM, large-Fire SIMulation system

GCM, General Climate Models

NDVI, Normalized Difference Vegetation Index

PNB, Pacific Northwest Bunchgrass

PNW, Pacific Northwest

PRISM, Parameter-elevation Regression on Independent Slopes Model

RAWS, Remote Automatic Weather Stations

RCP, Representative Concentration Pathway

RdNBR, Relative Differenced Normalized Burn Ratio

RF, Random Forest

SEF, Starkey Experimental Forest

ZPP, ZUMWALT Prairie Preserve

Keywords

Annual grass, Blue Mountain Ecoregion, climate change, fire effects, fire modeling, fire regimes, FSim, fuels, grazing, habitat suitability, heterogeneous, invasion, landscape pattern, land surface phenology, mapping, post-fire, prescribed fire, scablands, spatial pattern, species distribution modeling, vegetation structure, *Ventenata dubia*

Acknowledgements

As with any project of this size, there are numerous people we wish to thank. First and foremost, we acknowledge the many land managers in the northwestern US shaped our approach, understanding, and work, particularly the vegetation, weed, ecology, range, botany and fire and fuels specialists from the national forests, Bureau of Land Management, and The Nature Conservancy (Zumwalt Prairie Preserve) in the Blue Mountain Ecoregion, as well as program leads in the USFS R6 office. Special thanks to Jill Welborn for study design and sampling advice. Field and lab assistants included: K. H. Coe, B. K. Johnson, D. A. Clark, C. L. Brown, M. Young, D. Gannon, A. Gallo, M. Domingues. Richard Halse at Oregon State University confirmed identification of our plant vouchers and Ariel Muldoon and Bruce McCune provided statistical guidance.

Lastly, we acknowledge key collaborators that made this work possible, including: Michelle Day and Karen Riley from RMRS, Alex Dye, Robert Kennedy, Ana Barros from Oregon State University, and Kevin Vogler at Pyrologix. Jeff Hollenbeck (PNW ORISE fellow) assisted with developing the species distribution model used in Objective 2.

Abstract

Ventenata (*Ventenata dubia*) is an invasive annual grass species recently introduced to the Pacific Northwest. With continued expansion and ability to thrive at higher elevations than other well-known invasive annual grasses, many public and private land managers and others are concerned about the impact of ventenata on the ecosystems within Blue Mountains Ecoregion (BME). To understand the current and future ecological and wildfire impacts ventenata may have on this ecoregion, our project focused on the following four interdependent objectives: 1) documenting the state of the invasion in the BME, how it has changed through time, and what environmental and disturbance factors exacerbate populations, 2) determining how climate change may alter the invasion, 3) examining and describing invasion dynamics in dwarf-shrublands (scablands) and open areas, and 4) estimating potential shifts in fuels and fire regimes. We implemented a series of interrelated studies to address our four objectives. Methods ranged from more traditional field-based studies to ecoregion wide novel landscape scale mapping, species distribution modeling to wildfire simulations using climate change scenarios. Key findings include: 1) Ventenata has expanded the overall invasive grass footprint in the ecoregion and will likely continue expansion into vacant suitable habitat in the BME and likely throughout the western US, 2) Fire and grazing disturbance are not necessary precursors for invasion but may exacerbate ventenata populations and associated impacts to native plant communities, 3) Ventenata invasion can create novel landscape conditions and alter fire behavior, and 4) Scenarios for the future suggest invasion and associated fire impacts may shift northward and up in elevation by the end of the century, although results vary considerably depending on future climate. Climate alone may also drive increased fire activity in the ecoregion even if the invasion does not expand. Our results have been disseminated in numerous presentations, field visits, workshops with managers, direct communications with users, three student theses, four manuscripts in print, and five manuscripts in preparation. Since the covid pandemic disrupted traditional and more hands-on science exchange efforts, a deep dive concluding webinar is scheduled for 2022.

Objectives

This project responded to the 2015 JFSP FON Task Statement 1: Implications of changing Ecosystems – selected regions (Pacific Northwest). *Ventenata dubia* (ventenata) is an invasive annual grass that has been rapidly expanding throughout the Pacific Northwest (PNW). Since its discovery in Washington in 1952, the species has spread into seven western states (CA, ID, MT, OR, UT, WA, WY) (Wallace et al. 2015). With continued expansion and ability to thrive at higher elevations, many public and private land managers and others are concerned about the impact of ventenata on the ecosystems within Blue Mountains Ecoregion (BME). To understand the current and future ecological and wildfire impacts ventenata may have on this ecoregion, our project focused on the following four interdependent objectives:

1. Determine the current state of the invasion, how the invasion has changed through time and what environmental and disturbance (fire and grazing) factors influence populations. We report from two studies that addressed this objective:
    a. Spatial and temporal invasion patterns in the BME and relationships to fire.

    b. Grazing, prescribed fire, and ventenata at the Zumwalt prairie.
2. Explore how future climate change may alter the habitat suitability and potential distribution of ventenata.
3. Examine and describe ventenata invasion dynamics in dwarf-shrublands, also known as scablands, and non-forested areas within the broader overall ecosystem.
4. Estimate potential shifts in fuels and fire regimes by developing scenarios to examine how the ventenata invasion might change fuels, fire behavior, burn probabilities, fire size, and fire effects across large landscapes now and into the future. We report on three interrelated studies that addressed this objective:
    a. Invasive grasses: A new perfect storm for forested ecosystems?
    b. Feeding the fire: annual grass invasion and fire behavior across a forest-mosaic landscape.
    c. Wildfire, plant invasion, and future climate change scenarios.

Background

Exotic plant invasions are a growing challenge to the management of native biodiversity, ecosystem functioning, and fuels and fire management. The effects of exotic invaders are particularly dramatic when they alter disturbance regimes beyond the range of variation to which native species are adapted, resulting in community shifts and ecosystem transformations (D'Antonio and Vitousek 1992; Mack and D'Antonio 1998). Exotic annual grasses that alter fire regimes are recognized as some of the most important ecosystem-altering species on the planet (Brooks et al. 2004). Grasses such as *Bromus tectorum* (cheatgrass) and *Taeniatherum caput-medusae* (medusahead) are negatively impacting millions of hectares across the Great Basin by fundamentally altering the ecosystems in which they invade (DiTomaso 2000). A similar threat is developing in the forestlands, shrublands, and grasslands of the interior PNW region with a relatively new invasive annual grass, *Ventenata dubia* (ventenata, North Africa grass, wiregrass). Ventenata thrives at higher elevations than does cheatgrass, where it threatens native forest biodiversity and is creating ecosystem-level changes. Our engagements with managers at the time this proposal was written revealed that ventenata is a primary species of concern in many areas of the Blue Mountains Ecoregion (BME) of the Pacific Northwest (Figure 1).

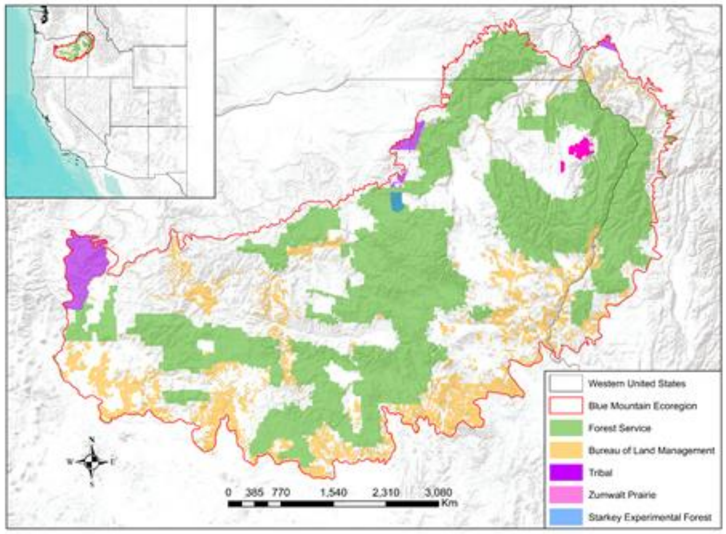


Figure 1. The Blue Mountains Ecoregion (BME) (Omernik 1987, US EPA 2013) is located within the Pacific Northwest of the US, largely located in Oregon but spans portions of Washington and Idaho and includes five national forests and other land ownerships. The western US inset map depicts the study area used for Objective 2.

Of particular concern is ventenata's ability to create novel landscape conditions and alter fire behavior. Forestland managers noted in 2015 and 2016 that ventenata was a "game-changer" largely because of the species' ecosystem-level transformation potential. Several large wildfires in 2015 burned over 300,000 acres of forests and rangelands in the BME. Fire and fuel resource managers working these fires expressed concern regarding novel fire behavior, particularly in open meadows and dwarf-shrublands (locally as referred to as scablands) interspersed within the forest matrix. These open areas harbor rare species and occur throughout the BME. They are also tactically used as wildland fire breaks and firefighter safety zones because fire does not traditionally carry through them well due to the presence of small-statured plant species and interspaces of shallow, gravelly/rocky soils (Johnson and Swanson 2005), resulting in low fuel connectivity in these low productivity environments. The spatial arrangement of fuels across the landscape is a major driver of wildland fire behavior, and ventenata invasion could potentially change these areas, creating flashy fuel beds prone to a fast-moving fire. In the 2015 fires, firefighters witnessed rapid fire spread fueled by this dry grass (Hallmark and Romero 2015). The exotic annual grass-fire cycle is recognized for cheatgrass in the Great Basin (DOI 2015) and ventenata poses a similar but poorly understood threat to the wildlands of the BME.

Materials and Methods

Study Area

The study area is the 71,000 km² Blue Mountain Ecoregion (BME) located in the northwestern US (Figure 1). Elevation ranges from 235 m at the Snake River along the Washington-Idaho border to 2,997 m at Sacajawea Peak in the Wallowa Mountains. Vegetation within the ecoregion represents a transition between the flora of the Cascade Mountains to the west and Rocky Mountains to the east. Geology, soils, and topography drive local community composition. Grasslands, including remnants of the Pacific Northwest Bunchgrass and Palouse Prairies are mostly present in the northern portion of the ecoregion. Shrublands largely dominated by sagebrush (*Artemisia* spp.) and western juniper (*Juniperus occidentalis*) woodlands are more common in the south. Ponderosa pine (*Pinus ponderosa*) forests dominate the forested parts of the region, but dry and moist mixed conifer and subalpine forests are also found.

The largely continental climate varies widely across the ecoregion. Precipitation ranging from 20 to 195 cm annually is primarily snow and rain during the winter and spring (PRISM Climate Group, 2012). Mean annual temperatures range from -1 to 13° C (PRISM Climate Group, 2012). Portions of the northern ecoregion are influenced by milder and wetter maritime conditions owing to moisture penetrating the interior along the Columbia River. Soil moisture regimes include xeric or aridic in lower elevations and udic in higher elevations. A low to high soil productivity gradient generally exists along the elevational gradient partially because of the change in erosion rate and partially from more volcanic ash in the region's higher elevations (Clarke and Bryce, 1997).

Methods

Methods are covered briefly in this section owing to the large scope of the project, particularly if the study is published or available elsewhere.

We addressed Objective 1a by using machine learning modeling (random forest or RF algorithm) and remote sensing image fusion methods to determine the current (2017) and past (2006) distribution of ventenata across all lands of the BME. We assessed regional-level change between 2006 and 2017 in terms of invasion extent, ventenata's biophysical associations, spatial patterns of spread and persistence, and relationships to large wildfires. To investigate the role of large wildfires in impacting ventenata populations, we examined how ventenata probability differed between areas within and outside of wildfire boundaries. In addition, we assessed the association between changes in ventenata probability and burn severity (RdNBR) within fires that occurred between mapping years (2006 and 2017). Detailed methods can be found in Nietupski 2021a and Nietupski et al. 2021b.

We examined how cattle grazing and prescribed fire affect the abundance (standing crop, cover, frequency, and density) of ventenata and other plant groups on the Pacific Northwest Bunchgrass (PNB) Prairie over time by remeasuring two separate long-term field studies established in 2004 (Objective 1b) from the Zumwalt Prairie Preserve (ZPP), owned and managed by The Nature Conservancy (Figure 1). In 2018 we resampled a series of plots that were originally part of a larger multidisciplinary study. Detailed methods about the two studies are provided in Ridder 2019 and Ridder et al. 2022.

To explore how different future climate change scenarios may alter the habitat suitability and the potential distribution of ventenata (Objective 2), we developed a climate-based habitat suitability model for the western US using boosted regression trees (Kerns et al. 2020). Predictors included bioclimatic variables calculated from the PRISM spatial climate model data for the US (Daly et al. 2008) using a water year definition (October to September). Future climatic habitat suitability was predicted by applying the BRT-derived model to climate projections generated by 30 GCMs under the RCP 8.5 climate change scenario for the end of century (2070-2099).

We addressed Objective 3 using a field study and sampled burned and unburned plant communities from seven recently burned fire perimeters within the ecoregion (from 2014 to

2017). Following a modified version of Herrick et al. 2017 methodology, we collected foliar cover for each plant species as well as soil and disturbance data at each plot. Burn severity was estimated in the field and calculated using difference Normalized Burn Ratios (dNBR) from 30m Landsat TM+ pre and post fire imagery. Detailed methods are provided in Tortorelli et al. 2020.

To set the stage for our Objective 4 work, we first synthesized information and developed a conceptual framework to delve into the intersection of several processes with the potential to drive major ecosystem change in forested ecosystems such as the BME: grass invasion, climate change, wildfire and overstory management. We dubbed the interplay of these processes a potential “perfect storm” (Kerns et al. 2020). In a separate study, we used the Large Fire Simulator (Finney et al. 2011) to simulate the present-day occurrence and spread of large fires across the BME according to weather, topography, and vegetation inputs, testing its sensitivity to shifts in fuels associated with the ventenata invasion. We used our 2017 ventenata invasion map developed in Objective 1 and understanding of fuel conditions and invasion dynamics from studies in Objectives 1 and 3 to develop two custom fuelscapes for our simulations: present day invaded and uninvaded. Both fuelscapes were based on modifications of the LANDFIRE fuel model grid (LANDFIRE 2019a). FSim was calibrated using the invaded fuelscape, and historical fire and weather data from 2000-2017 (using Allison RAWS weather station) as described in Tortorelli et al. (in prep).

We used an ensemble of future estimates of Energy Release Component (ERC) and FSim to explore how the ventenata invasion may change fire behavior under future climate scenarios and to address our last research objective (4). Methods build on results from our prior remote sensing, mapping, modeling, and simulation studies outlined in Objectives 1-4a. Following Riley and Loehman (2016), we calculated monthly projected changes (“deltas”) in temperature and precipitation for the mid- and end-of century using NASA NEX-DCP30 downscaled climate data (Thrasher et al. 2013) relative to our benchmark weather station data (Allison RAWS). We generated future ERC streams for 28 GCMs and the representative concentration pathway (RCP) 8.5. We ran FSim 1,000 times (Monte Carlo-style) for the mid- and end-of century time periods using a solid performing GCM for the Pacific Northwest (Rupp et al. 2014). Other inputs into FSim were based on our invaded calibration run described above. Additional ERC streams from other GCMs will be used to complete more FSim runs, but that work is beyond the scope of our current project and funding.

Results and Discussion

Objective 1a: Spatial and temporal invasion patterns in the BME and fire
A hybrid model including land surface phenology, climatic, and topo-edaphic predictors performed the best at classifying the presence of the ventenata in the BME (mean cross-validated AUC of 0.89). Abundant ventenata populations (>20% cover) were commonly predicted in ecotones between forested and non-forested areas of the region and in shrub-grass openings of the forest matrix. Our models indicate that 7.7% (5,454 km2) of the BME may have contained robust populations of ventenata in 2017 (Figure 2). We note that species with similar phenology, like cheatgrass, may have led to some misclassification within the environmental space in which

these two species overlap. Comparison of our hybrid model to a bioclimatic only model revealed that parts of the region with high environmental suitability have not yet been invaded.

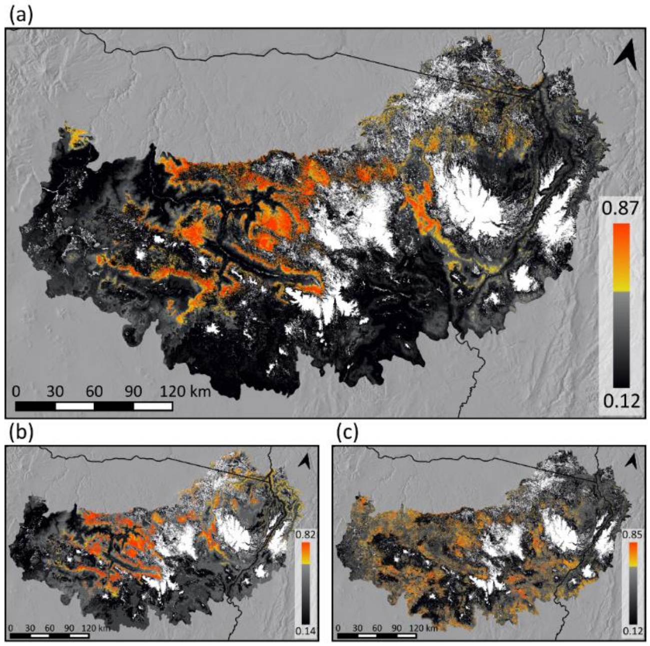


Figure 2. Distribution estimates for ventenata (> 20% cover) for the three models developed for this study: (a) hybrid, (b) bioclimatic, and (c) phenology (Nietupski 2021a).

Applying the hybrid model to map the historical invasion extent in 2006 revealed that, over 11 years, the total area occupied by ventenata increased by more than 40% (378,000 ha to 545,000 ha) (Figure 3). From 2006 to 2017, the total number of patches decreased and mean patch size increased, indicating that radial spread was more common than discontinuous expansion. Most of the expansion occurred at higher elevations (> 1,300 m) and within forested and ecotonal environments.

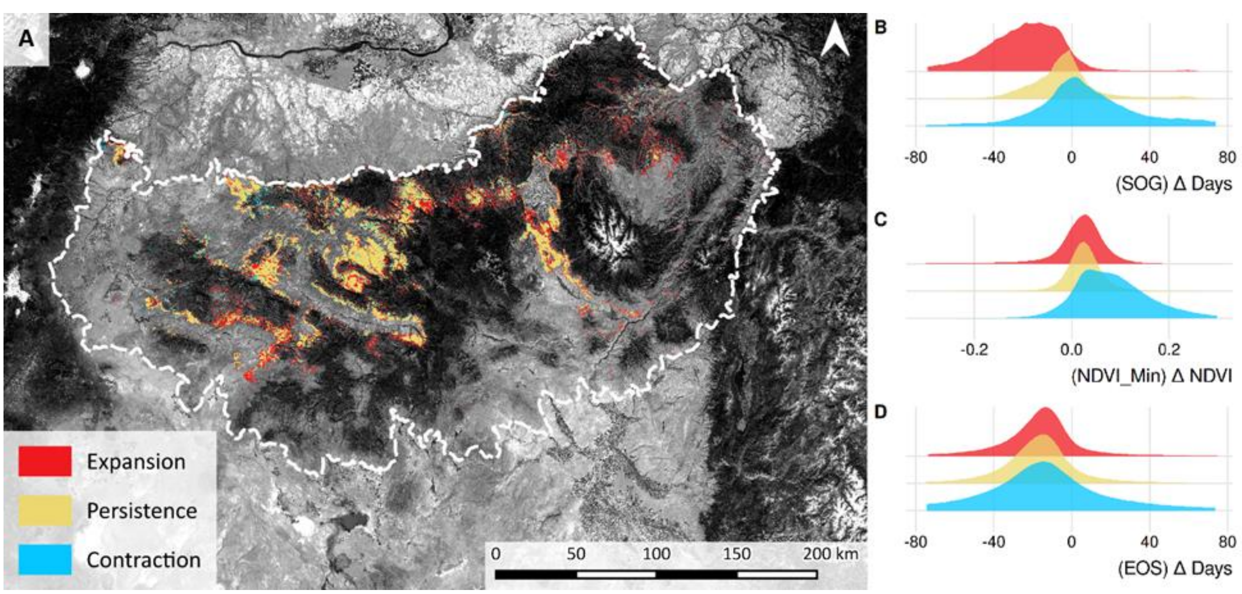


Figure 3. Expansion, persistence, and contraction of ventenata populations from 2006 to 2017 throughout the BME. In A, the categorical change in ventenata's distribution is mapped across the region. In B-D, the distribution of change in phenometrics for areas of expansion, persistence, and contraction between 2006 and 2017 is shown for the start-of-greenup (B), minimum-NDVI (C), and end-of-season (D), where change is calculated as 2017 value – 2006 value. The density plots in B-D are scaled to show equal area for visibility. Positive values indicate that: vegetation greening was later in 2017 (B), minimum-NDVI was higher in 2017 (C), end-of-season was later in 2017 (D). From Nietupski 2021a.

Large wildfires within dry-forest and highly mixed forest/non-forest experienced a greater increase in ventenata probability than similar areas that did not experience large wildfires (Figure 4). High burn severity (RdNBR) was also associated with an increase in ventenata probability in some parts of the region. These findings provide insight into the spatio-temporal patterns of the ventenata invasion in this region over recent past and suggest that there may be an association between wildfire and this invasion, likely related to the opening of canopy cover in burned areas. However, ventenata also expanded in much of the region in the absence of wildfire, a result that we also documented with our other studies in the ecoregion (Ridder et al. 2022, Tortorelli et al. 2020).

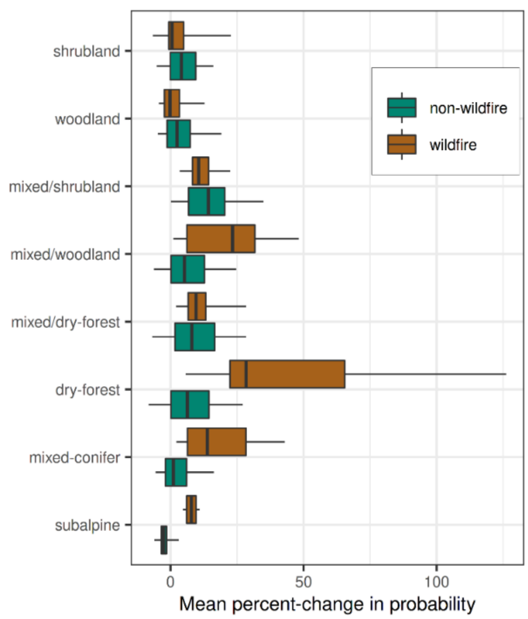


Figure 4. Summaries by vegetation groups for the mean percent-change in the probability of ventenata within wildfires and non-wildfire areas. Boxplot summaries include the median (middle line segment), the 25th and 75th percentile (the upper and lower hinges), and the 5th and 95th percentile (the whiskers). From Nietupski 2021a.

Objective 1b: Grazing, fire and ventenata at the Zumwalt Prairie

We documented a 30% increase in ventenata cover and 55% increase in frequency on the ZPP over the past fifteen years, including areas that were not recently disturbed by fire or cattle grazing since 2006 (Figure 5). We found some weak evidence that cattle grazing increased ventenata standing crop when compared to cattle excluded paddocks. There was no evidence that prescribed burning impacted the response of ventenata on its own. However, we found some evidence of interactions between cattle grazing and prescribed fire that suggests prescribed burning could help reduce the abundance of ventenata in areas grazed by livestock. These studies reinforce the important differences between ventenata and other invasive winter annuals in grasslands and clarify a need for research that focuses primarily on the dynamics between this relatively new exotic species in grasslands and the many ecosystems it now inhabits.

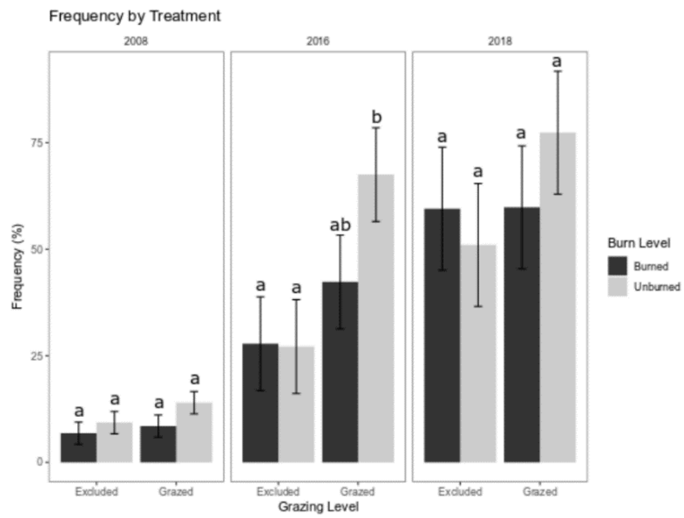
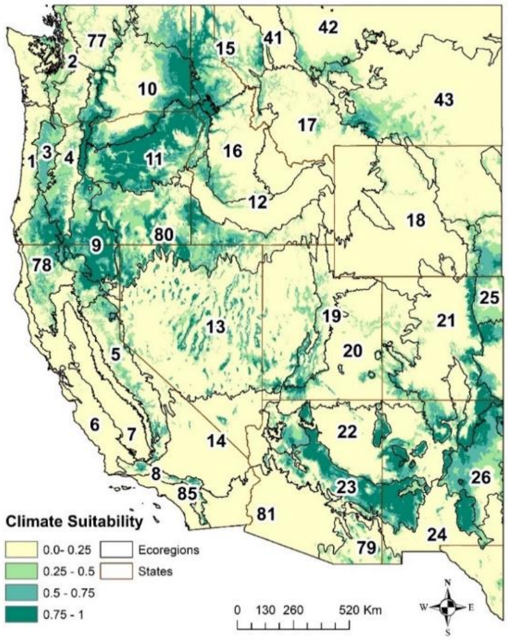


Figure 5. Ventenata frequency(±SE) in response to grazing and prescribed fires (2006 and 2016), (Ridder 2019, 2022).

Objective 2: Future climate change and ventenata habitat suitability

Results from a BRT model based on bioclimatic variables for the present day suggest that many areas of the western US contain climatically suitable habitat for ventenata and may be at risk for invasion given adequate propagule pressure and other abiotic conditions (Figure 6) (light, nutrients, soil moisture). Notably, we found a high habitat suitability (>0.75) in the southwestern mountainous regions including the Arizona and New Mexico mountains where ventenata has yet to be reported. Additionally, mountainous regions in northern California appear to have high suitability and are not currently reported to be heavily invaded. Only scattered climate suitability extended into the Central Basin and Range, overlapping some but not all of the range of cheatgrass. The Snake River Plain was mostly unsuitable to ventenata, a region known for heavy cheatgrass invasion. We also found low suitability throughout much of the Californian foothills and valleys, Northern Rockies, and Northwestern Plains with some scattered hot spots of high suitability.

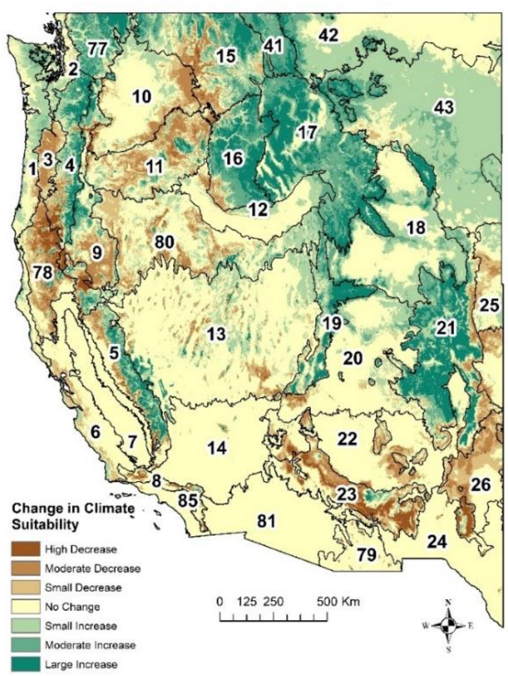
These results show that much of the uninvaded western US presently has climatically suitable habitat. Mountainous areas and areas with high tree canopy cover that also have high ventenata climate suitability may be at risk for invasion with canopy removal via fire or management actions (Kerns et al. 2020). Early detection and eradication of populations may help to prevent widespread invasion in areas less amenable to control.



Code	Ecoregions Name
1	Coast Range
2	Puget Lowland
3	Willamette Valley
4	Cascades
5	Sierra Nevada
6	Central California Foothills and Coastal Mountains
7	Central California Valley
8	Southern California Mountains
9	Eastern Cascades Slopes and Foothills
10	Columbia Plateau
11	Blue Mountains
12	Snake River Plain
13	Central Basin and Range
14	Mojave Basin and Range
15	Northern Rockies
16	Idaho Batholith
17	Middle Rockies
18	Wyoming Basin
19	Wasatch and Uinta Mountains
20	Colorado Plateaus
21	Southern Rockies
22	Arizona/New Mexico Plateau
23	Arizona/New Mexico Mountains
24	Chihuahuan Deserts
25	High Plains
26	Southwestern Tablelands
41	Canadian Rockies
42	Northwestern Glaciated Plains
43	Northwestern Great Plains
77	North Cascades
78	Klamath Mountains/California High North Coast Range
79	Madrean Archipelago
80	Northern Basin and Range
81	Sonoran Basin and Range
85	Southern California/Northern Baja Coast

Figure 6. Present day climate suitability for ventenata in the western US (left). This map was generated using a BRT model and climate predictors from PRISM at 30-arc sec resolution.

By the end of the century, results from this model suggest that climate suitability for ventenata may shift northward and up in elevation (Figure 7). Areas with low climate suitability broaden geographically, while highly suitable areas contract. The predicted change between the current and future climate suitability reveals that the largest increases in suitability may occur within the Rockies and the Idaho Batholith ecoregions (Figure 7). Open areas within these ecoregions may be vulnerable to invasion and canopy removal via fire or management may catalyze invasion if propagules are available (Kerns et al. 2020).



Code	Ecoregions Name
1	Coast Range
2	Puget Lowland
3	Willamette Valley
4	Cascades
5	Sierra Nevada
6	Central California Foothills and Coastal Mountains
7	Central California Valley
8	Southern California Mountains
9	Eastern Cascades Slopes and Foothills
10	Columbia Plateau
11	Blue Mountains
12	Snake River Plain
13	Central Basin and Range
14	Mojave Basin and Range
15	Northern Rockies
16	Idaho Batholith
17	Middle Rockies
18	Wyoming Basin
19	Wasatch and Uinta Mountains
20	Colorado Plateaus
21	Southern Rockies
22	Arizona/New Mexico Plateau
23	Arizona/New Mexico Mountains
24	Chihuahuan Deserts
25	High Plains
26	Southwestern Tablelands
41	Canadian Rockies
42	Northwestern Glaciated Plains
43	Northwestern Great Plains
77	North Cascades
78	Klamath Mountains/California High North Coast Range
79	Madrean Archipelago
80	Northern Basin and Range
81	Sonoran Basin and Range
85	Southern California/Northern Baja Coast

Figure 7. Change between historical and future climate suitability for ventenata is based on comparing current (1983-2013) to future (2070-2099) suitability using GCM derived climate predictors and an ensemble-average from 30 global climate models.

Objective 3: Invasion and fire dynamics in scablands

Plant communities that were the most heavily invaded by ventenata were largely uninvaded by other non-native annual grasses. Ventenata differed from *Bromus tectorum* and *Taeniatherum caput-medusae* by heavily invading both burned and unburned dry forest, woodland, and forest scablands ranging from 1,250 to 1,665 m throughout the Blue Mountains Ecoregion (Tortorelli et al. 2020). Ventenata's tolerance for the frigid basalt-derived lithosols characteristic of forest scablands further separated its realized niche from *B. tectorum* and *T. caput-medusae* (Figure 8).

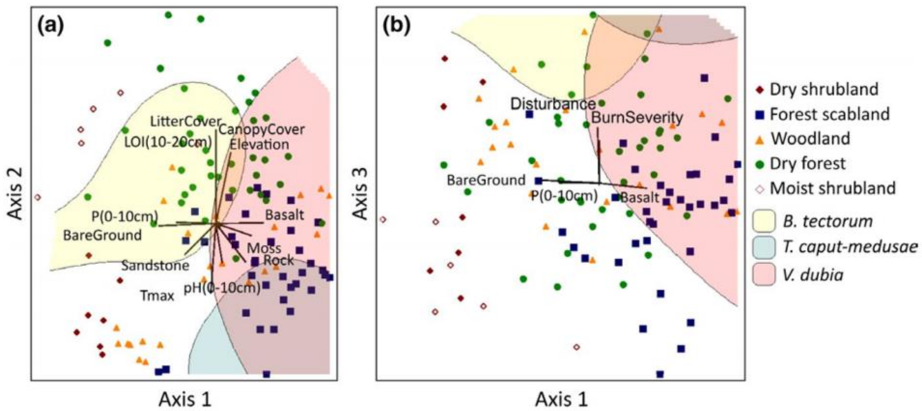


Figure 8. Comparison of invasive annual grass species *(Bromus tectorum, Taeniatherum caput-medusae, and Ventenata dubia*) and their environmental characteristics across sample plots in the Blue Mountains Ecoregion (Tortorelli et. al 2020).

Ventenata invaded plots across a wide range of understory and canopy cover. The most heavily invaded plots (ventenata cover >75%) were burned plots with <50% understory cover and <20% canopy cover. Mean ventenata cover decreased with increasing resident species cover for all functional groups in burned plots, but only with perennial forbs in unburned plots (Figure 9). Burning intensified negative relationships between ventenata cover and native species richness, annual forb cover, annual grass cover, and non-native species cover. This finding may suggest that, while not heavily competing with species in unburned areas, ventenata may more efficiently allocate post-fire resources, potentially excluding species from burned areas while filling in gaps around existing species in unburned areas. Cheatgrass has been shown to have the ability to allocate and deplete soil resources after a fire thereby suppressing the recovery of native species (Melgoza and Nowak, 1991; Monaco et al., 2003). Ventenata has may have a similar mechanism that allows it to better allocate post-fire resources to outcompete native vegetation in burned areas.

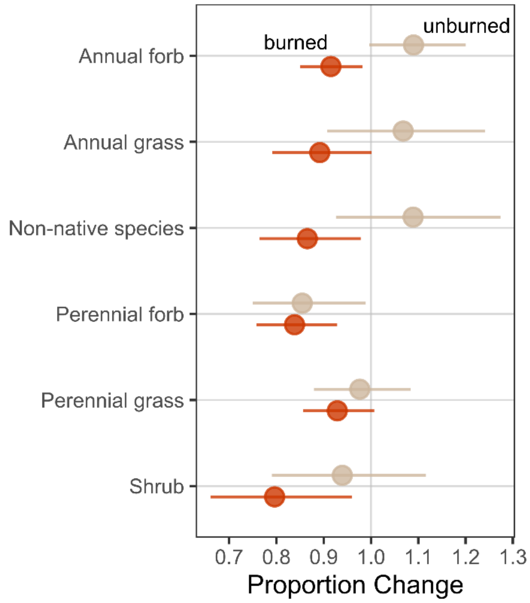


Figure 9. Estimates of the change in functional group cover for a 10% increase in ventenata cover in burned and unburned plots with 95% confidence intervals. Values above 1.0 indicate an increase and below 1.0 indicate a decrease.

Shannon diversity decreased with increasing ventenata cover, and this relationship was stronger in burned plots than in unburned plots (Tortorelli et al. 2020). Native species richness also declined with increasing ventenata cover in burned plots, but not in unburned plots. Unlike native species richness, non-native species richness was only weakly related to ventenata cover regardless of the burn status of the plot. This finding indicates that ventenata may more negatively impact native species than non-native species after fire, potentially exacerbating fire-induced shifts in species composition to non-native dominating plant communities.

Overall, our results indicate that ventenata is expanding the annual grass invasion footprint and potential impacts by heavily invading previously uninvaded vegetation types. While ventenata can invade areas both with and without burning, invasion in burned areas may lead to larger losses in functional diversity, species richness, and vegetation structure. Fire and annual grass induced state shifts in these historically shrub and tree dominated vegetation types may result in decreased wildlife habitat and altered nutrient and hydrologic cycling. These findings support previous studies that found disturbances, especially fire, to exacerbate the impacts of annual grass invasions (Corbin and D'Antonio, 2004; Kerns and Day, 2017). See Tortorelli et al. 2020 for detailed results and more figures and data from this study.

Our findings inspired a separately funded field experiment investigating how plant community invasion resistance is influenced by above and below-ground plant traits and biomass across three vegetation types. We found that above-ground biomass and communities with species that had more similar traits to ventenata were more resistant to invasion, but only in wet meadows where relative biomass was high. In less productive scab-flats and low sage-steppe plots, relationships between plant community traits and invasion resistance were weak. These findings demonstrate that the biotic factors driving invasion resistance are context dependent. More details from this study can be found in Tortorelli et al. (in revision).

Objective 4a: Invasive grasses: A new perfect storm for forested ecosystems?

Forest may be surprisingly more vulnerable to grass invasion than conventional wisdom might suggest, and climate change and wildfire may increase invasion risk for forests (Figure 10). However, knowledge is only now emerging about the extent to which these species could catalyze rapid and novel change and reduce resilience in forested ecosystems worldwide. Increasing evidence suggests that drier forests and woodlands may be vulnerable to climate and wildfire driven state changes and vegetation type conversion due to inherently unstable states between grass and tree dominated ecosystems. The effects of both climate change and a century of fire suppression and uncharacteristic fuel loads have ushered in an era of megafires with the potential to create large highly invadable early seral patches that may exacerbate ecosystem state changes. There is considerable risk that these state changes may be persistent due to exotic grass invasion, particularly if a destabilizing grass-fire cycle develops.

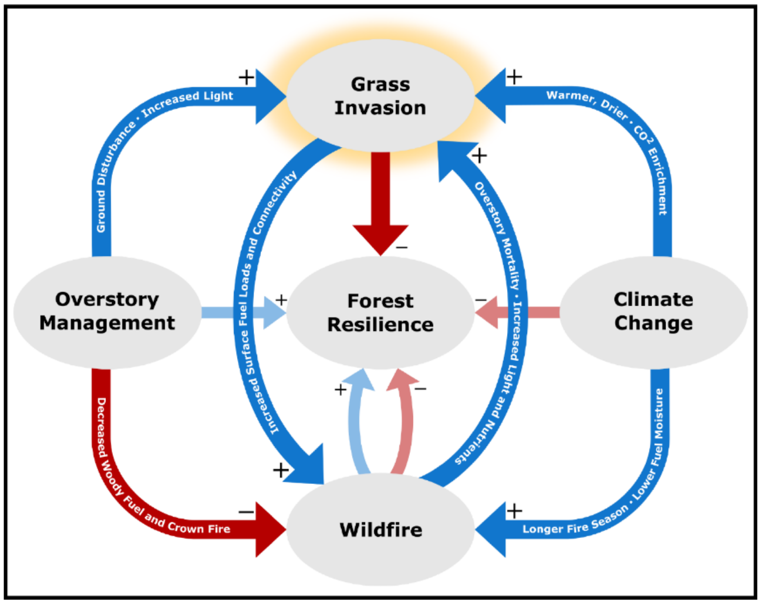


Figure 10. Grass invasion (presumed exotic) in forested landscapes can strongly influence woody and other native plant establishment and reduce forest resilience. Grass invasion combined and interacting with climate change, wildfire, and overstory management may be a perfect storm that threatens forest resilience. Bold blue "+" arrows indicate positive interactions while bold red "–" arrows indicate negative interactions (Kerns et al. 2020).

The interactions between grass invasion, climate change, and wildfire and the increasing potential for grass-fire cycles are sufficient cause for concern for forest managers, but overstory management may represent a fourth critical factor in this potential perfect storm. Forest management actions designed to manipulate forest structure or alleviate threats related to wildfires almost exclusively focus on trees and woody fuel targets and treatments. However, these treatments can exacerbate invasive grass populations, increase invasion risk, and then substitute highly flammable and easily ignitable fine fuels for less ignitable woody fuels. The evidence, examples, and models presented we discuss in Kerns et al. 2020 not be relevant for all forest systems, particularly wetter and colder forests with reduced fire risk, or in less common circumstances where grass invasion increases fuel moisture and reduces fire spread.

Objective 4b: Feeding the fire: annual grass invasion and fire behavior across a forest-mosaic landscape.

The ventenata invasion altered simulated fire behavior within invaded patches and the surrounding forest (Tortorelli et a. in prep). Across the ecoregion, mean burn probability was 0.0003 (2.8%) higher, mean intensity was 11.4 kW/m (1.4%) higher, and integrated hazard was 0.25 (2.6%) higher in the invaded scenario than in the uninvaded scenario. Throughout the study area, over 158,000 ha that burned at low mean fireline intensity (< 350 kW/m) in the uninvaded scenario increased to moderate mean intensity (350-1700 kW/m) in the invaded scenario (Figure 11).

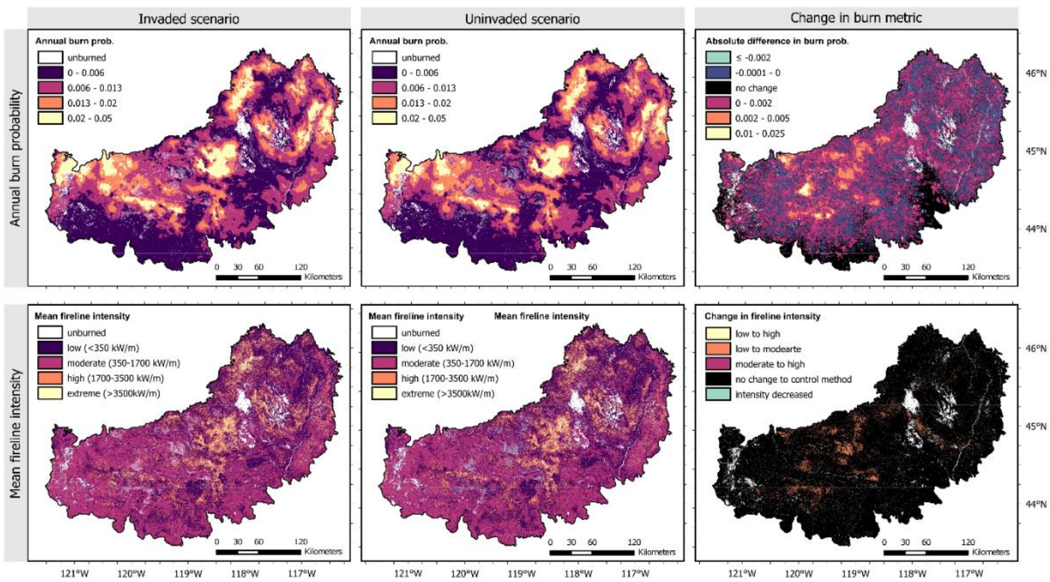


Figure 11. Annual burn probability, mean fireline intensity, and the difference in burn metrics for the uninvaded and uninvaded scenarios.

Differences in fire behavior between the two simulations varied by vegetation type. The greatest difference in fire behavior between the invaded and uninvaded scenarios was in the dwarf-shrublands (scablands) where mean burn probability was 0.001 (15%) higher, mean intensity was 61.2 (12.1%) higher, and mean integrated hazard was 0.87 (30.1%) higher in the invaded scenario (Figure 12). We saw substantial differences in mean fireline intensity in dwarf-shrublands and open tree canopy where over 75,000 and 20,000 ha converted from low to moderate mean intensity in the invaded scenario, respectively.

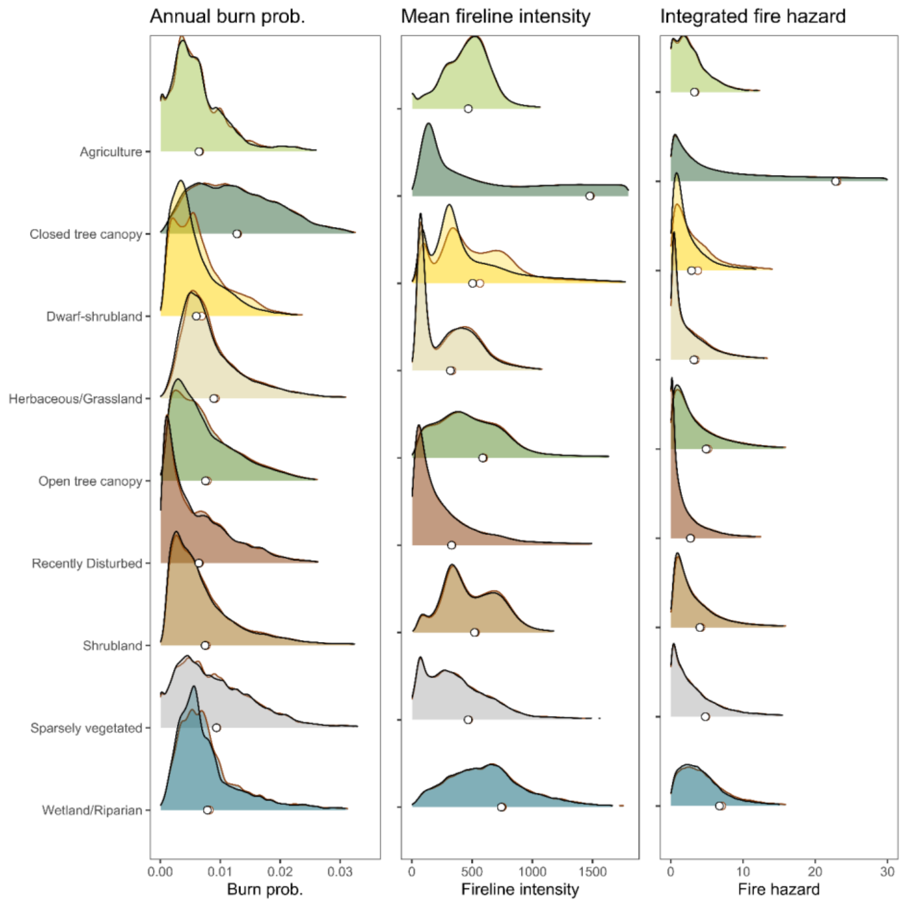


Figure 12. Density of (a) annual burn probability, (b) mean fireline intensity (kW/m), and (c) integrated hazard for the uninvaded (black line) and invaded (red line) scenarios for each vegetation type. Dots represent the mean values for the uninvaded and invaded scenarios.

In forested areas, fire behavior was influenced by the amount of invaded area in the surrounding neighborhood. Predicted absolute difference in burn probability, mean intensity, and integrated hazard in forested cells increased as the amount of invaded area within a 116 ha (1,080 m x 1080 m) neighborhood surrounding the forested cell increased (Fig. 13). As the proportion of invaded area increased from 0.25 to 0.75, predicted difference in burn probability doubled and difference in fireline intensity nearly tripled.

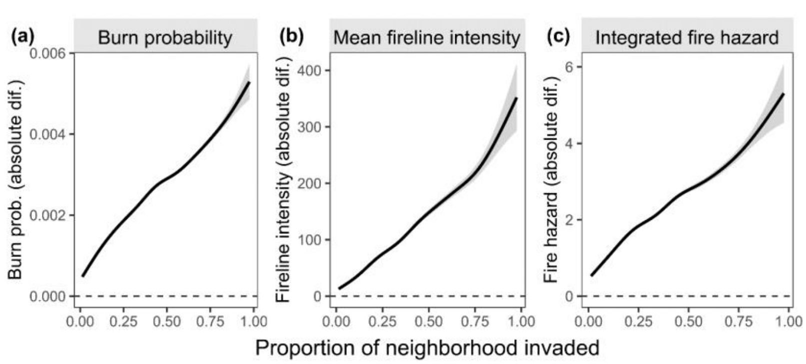


Figure 13. Forested cell absolute difference in burn probability, mean fireline intensity (kW/m), and integrated hazard response to the proportion of invaded neighborhood surrounding forested focal cells. Neighborhood area is 116.6 hectares.

Fire transmission between vegetation types differed between the invaded and uninvaded scenarios (Figure 14). On average, large fires ignited in dwarf-shrublands transitioned into and burned 14.6% (328 ha/yr) more of the study area in the invaded scenario. Collectively, these fires burned 14.9% (44 ha/yr) and 16.1% (76 ha/yr) more closed and open canopy forest and between 5 and 12% more of the remaining non-forested vegetation types. Simulated fires ignited in all vegetation types transitioned into and burned more dwarf-shrubland in the invaded scenario (Figure 8). On average, fires ignited in closed and open canopy forests transitioned into and burned 16.5% (78 ha/yr) and 20.2% (134 ha/yr) more dwarf-shrubland in the invaded scenario, respectively.

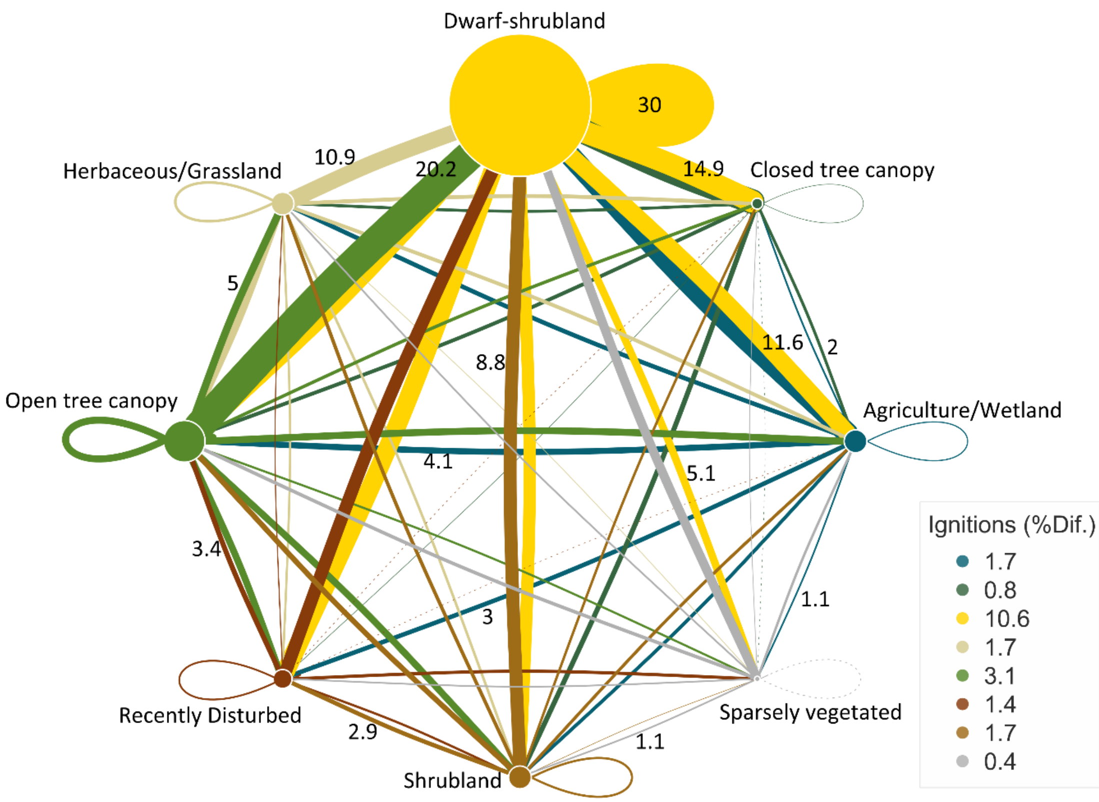


Figure 14. Percentage difference between the invaded and uninvaded scenarios in fire transmission pathways between vegetation types (nodes). The size of the nodes is proportional to the percentage increase in the number of ignitions that grew to fires ≥100 ha for each vegetation type. Paths between nodes represent fire spread between ignition and affected (burned) vegetation types and are colored by the source of fire (ignition vegetation type). The width of the path is scaled by the percentage increase (solid lines) or decrease (dashed lines) in the average number of hectares burned/yr in the connecting vegetation type. Percentages for some transmissions are presented for reference.

Overall, our findings suggest that invasion will result in dramatic increases in burn probability and fireline intensity in invaded areas, including historically fuel limited dwarf-shrublands, and surrounding uninvaded areas. Increased burning in dwarf-shrublands may lead to the loss of fire sensitive species (as shown in Tortorelli et al. 2020), and associated losses to ecological function. Additionally, increased fuel loading in invaded areas can lead to increased fire transmission into adjacent vegetation types (especially forests), resulting in higher burn probabilities and fireline intensities in forests with high proportions of invasion in their surrounding neighborhood.

Increased fire transmission through historically fuel limited dwarf-shrublands has important management implications by restricting fire access points, limiting fire fighter safety zones, and reducing the effectiveness of woody fuel reduction treatments (Hallmark and Romero 2015).

Objective 4c: Wildfire, plant invasion, and future climate change scenarios

Monthly averages of energy release component (ERC) for the middle and end of the century are shown for the 28 GCMs used (RCP 8.5) in Figure 15. The majority of GCMs show increases in ERC throughout the spring, summer, and fall relative to the Allison RAWS benchmark, and most of these models are also well ranked in skill for simulating present day climate of the Pacific Northwest (Rupp et al. 2013). The dominant pattern of increased ERC during the spring, summer and fall suggests that the BME will likely have more ignitions and fire spread, resulting in generally increased burn probabilities across the landscape. However, a few GCMs show small decreases in ERC especially for the mid-century, although this pattern is not as common by the end of the century.

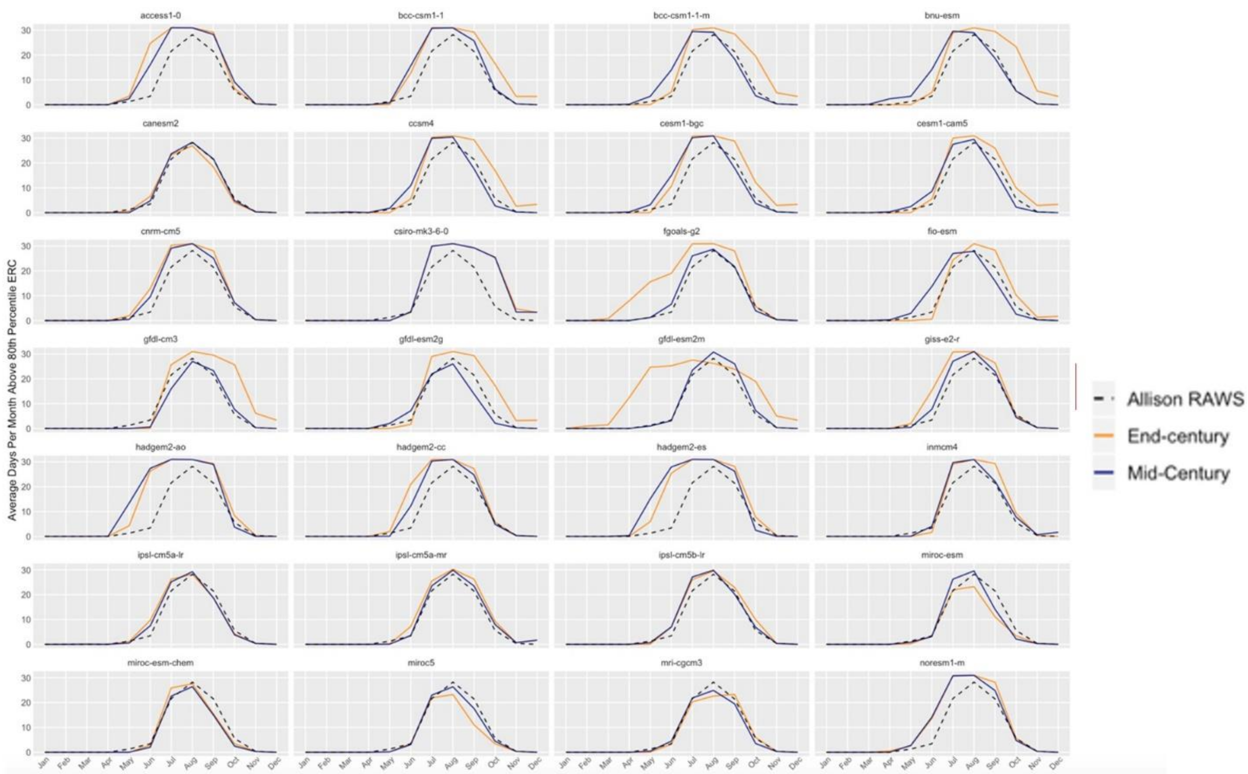


Figure 15. Monthly averages of energy release component (ERC) for Allison RAWS (observed), and mid- and end-century (2035-2064 and 2070-2099 respectively) projections based on 28 global climate models (GCMs).

Projected increase in fire activity may be partly mitigated by projected increases in precipitation during the fire season (Figure 16), which likely explain why some GCMs show small decreases in ERC. ERC is keenly sensitive to precipitation, where even a small amount of precipitation can wet fuels and lower ERC. Exactly how any increase in precipitation would suppress ERC values and therefore simulated fire activity depends on whether the increase in precipitation translates to increases in intensity or duration, with the latter having a larger effect.

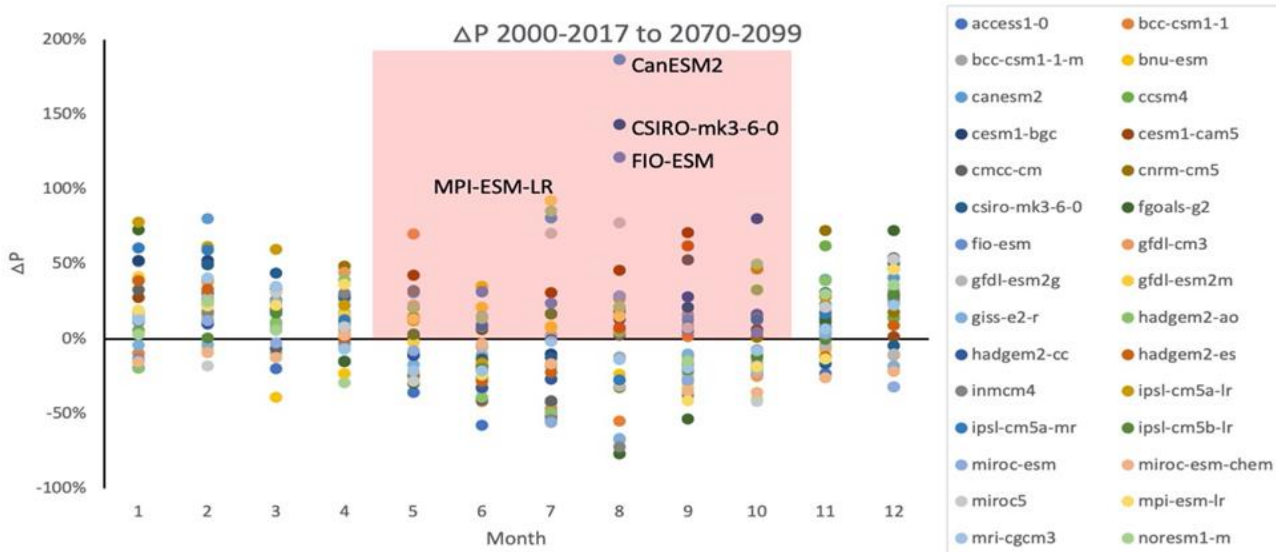


Figure 16. Projected change in precipitation by end-century (2070-2099) relative to observed (2000-2017). Pink box identifies data points representing projected increases in precipitation during the fire season (May-Oct).

Results from an FSim simulation for mid-century climate with the HadGEM2-CC GCM and present-day invaded fuelscape is shown in Figure 17. We compared the simulated mid-century burn probability grid to that based on historical climate and obtained the difference between the two grids. Annual burn probability increases in some places and decreases in others, with increases occurring more in mid-elevation forests. This is consistent with ERC curves for HadGEM2-CC (Figure 17), where significant increases in ERC is projected for early- and mid-summer by mid-century.

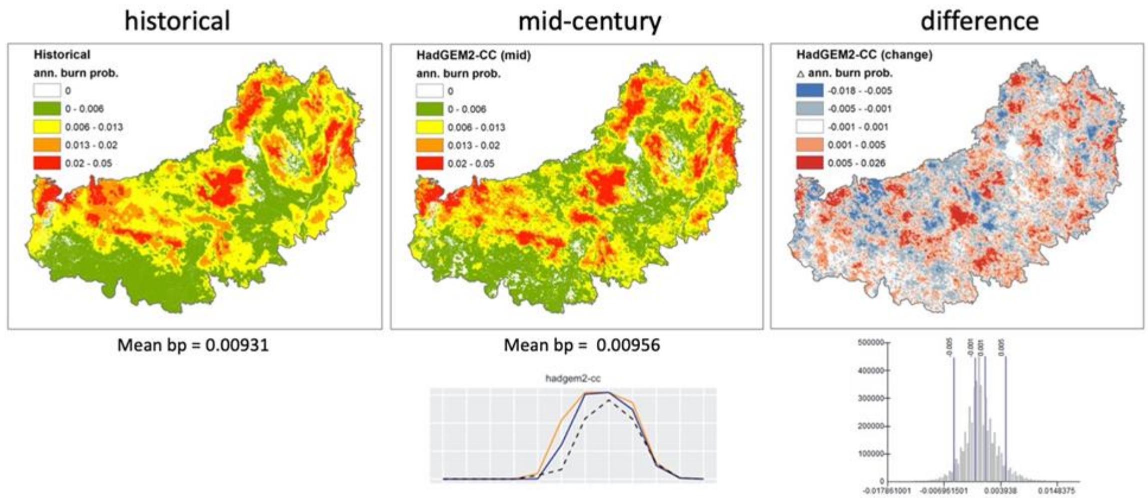


Figure 17. Historical and projected mid-century (2035-2064) burn probabilities based on HadGEM2-CC GCM, and the difference between the two. Line graph at center-bottom is from Figure 15 (above). Histogram on bottom right shows the distribution of the difference values. Note that this FSim run only included 1,000 fire years and results should be interpreted cautiously.

Science Delivery Activities

Throughout this project, we actively pursued a variety of different science engagement and delivery activities. We first established a website through the Northwest Fire Science Consortium webpage that described our project, including tools that local managers could use to help collect and share ventenata occurrence data (https://www.nwfirescience.org/ventenata) using a customized app (Survey 123). We held training webinars on using the app and ventenata identification, as the species was being easily confused in the field. How to guides are also available on the website, as well as a ventenata bibliography that we updated several times. We are now in the process of retooling this website to reflect findings and project completion.

Science delivery included 4 scientific publications in press, 9 presentations at conferences, 9 posters, 1 doctoral dissertation (an additional one is planned for spring 2022), 1 graduate thesis, and 6 public presentations, including a keynote address and two posters at an international conference in Europe focused on the Ecology and Management of Invasive Species (EMAPi). Science delivery also included 8 direct communications/workshops/field trips with users where we were able to reach out and establish connections with managers, stakeholders, agency and university scientists, and students. In addition, we plan to produce two more manuscripts from Objective 1 (based on Nietupski et al. 2021), one from Objective 2, and two more manuscripts from Objective 4. Our work also stimulated a field trip with USDA-ARS in Europe in conjunction with the EMAPi conference and colleagues working on biocontrol measures for ventenata. During this three-day trip Kerns, Tortorelli and Nietupski examined the local native habitat of ventenata. This work also inspired a National Science Foundation Graduate Research Fellowships Program grant (led by Tortorelli) that will result in two additional manuscripts, a dissertation, and associated presentations.

Conclusions

The goal of our work was to increase understanding of the current and future impacts that the ventenata invasion will have on the ecosystems, fuels, and fire regimes of the Blue Mountain Ecoregion, as well as the implications of these changes for fuel and fire management. Our key findings are summarized here.

Ventenata has expanded the overall invasive grass footprint in the ecoregion and will likely continue expansion into vacant suitable habitat in the BME and likely throughout the western US. The extensive ventenata invasion (8% of the ecoregion in 2017) is primarily occurring in ecotones between forested and non-forested areas, in shrub and grass openings of the forest matrix, and in non-forested areas of the Pacific Northwest Bunchgrass Prairie. Ventenata has a unique niche that allows it to invade habitats that other invasive annual grasses (e.g. cheatgrass and medusahead) cannot colonize. Between 2006 and 2017, the total area occupied by ventenata in the BME increased by more than 40% and mean patch size increased. Most expansion occurred at higher elevations (> 1,300 m) and within forested and ecotonal environments. On the Pacific Northwest Bunchgrass Prairie, ventenata cover increased 30% and frequency increased 55% over the past 15 years.

Results using output from our boosted regression tree (BRT) species distribution model indicate that many areas of the western US presently contain climatically suitable habitat for ventenata and may be at risk for invasion given adequate propagule pressure and abiotic conditions (light, nutrients, soil moisture).

Fire and grazing disturbance are not necessary precursors for invasion but may exacerbate ventenata populations and associated impacts to native plant communities. The ability of ventenata to invade in the absence of disturbance (wildfire, prescribed fire, cattle grazing) was demonstrated in several of our studies across a variety of habitats. However, areas within dry-forests and highly mixed forest/non-forests that experienced large wildfires were more likely to experience invasion, and high burn severity (RdNBR) was associated with an estimated increase in ventenata probability in some parts of the region. Wildfire may also exacerbate invasion impacts to native species richness and functional diversity. Cattle grazing was not strongly associated with increases or decreases in ventenata cover or frequency, but we found weak evidence that prescribed fire may help reduce ventenata abundance in areas grazed by livestock in prairie habitats.

Ventenata invasion can create novel landscape conditions and alter fire behavior. Ventenata invasion into low productivity areas and associated changes in fuels increased simulated mean fire size, burn probability, fireline intensity, integrated hazard, and fire transmission throughout the ecoregion. The largest differences in simulated fire behavior were observed within invaded patches (primarily dwarf-shrublands or scablands) and in nearby uninvaded areas, including open and closed canopy forests.

Scenarios for the future suggest invasion and associated fire impacts may shift northward and up in elevation by the end of the century, although results vary considerably depending on future climate. Climate alone may also drive increased fire activity in the ecoregion even if the

invasion does not expand. Results suggest that by the end of the century, climate suitability for ventenata may decrease in the BME and shift northward and up in elevation into other regions of the western US. The largest increases in suitability may occur within the Rockies and the Idaho Batholith ecoregions. It is likely that invasion in these areas could potentially create similar novel landscape conditions and alter fire behavior, particular in ecosystems that do not typically support fuels that lead to frequent surface fires. Within the BME, changes in climate and ERC will likely cause more ignitions and increases in burn probabilities across the landscape. FSim output driven with a larger ensemble of GCMs may yield a more complex and/or robust set of results. Increased fire in the ecoregion may open up more invadable habitat and substantially increase burn probability and potentially create grass-fire cycles that will be challenging to manage in the future.

Implications for management/policy and future research

Our work suggests that substantial portions of the BME and the western US are at risk for invasion, and invasion risk may shift northward and up in elevation throughout the 21st century (Nietupski et al 2021, in prep). This information is critical for managers as these areas can be flagged for early detection and rapid response measures that are more successful than eradication and control efforts at the later stages of invasion.

Our work also clearly demonstrates that ventenata invades and can spread in the absence of wildfire, although the influence of fire is tied to changes and mortality of native species, particularly woody species and trees (Tortorelli et al. 2020, Ridder et al. 2022, Nietupski et al. 2021). This may explain why prescribed fire had little impact on invasion in our bunchgrass study but fire mattered and exacerbated invasion in more forested areas. This nuanced context around fire and ventenata invasion can assist land managers as they implement fuel treatment and prescribed fire programs and across different plant communities.

Similar to other invasive annual grasses, ventenata has the ability to alter fuels and fire regimes and invasion could further lead to changes within ecosystem states across large regions (Kerns et al. 2020). Mitigation and understanding large-scale ecological impacts of the invasive grasses is critical for effective planning and management (Cheney et al. 2018; Jetz et al. 2019; Funk et al. 2020, Harvey and Mazzotti, 2014). Throughout the BME, ventenata invasion primarily altered simulated fire behavior in invaded patches. However, invasion had landscape-scale effects as it enhanced fuel continuity and fire spread between invaded and nearby fuel-rich forests (Tortorelli et al. in prep). Our study provides valuable insights into how annual grass invasion may influence fire behavior and spatial patterns of fire in a forest-mosaic landscape. Annual grass invasion can influence fire behavior in forests despite primarily invading non-forested areas, and highlights invasion as an important management issue in a forest-mosaic ecosystem.

Future research could focus on several key themes.

Mapping annual grasses through time and space: Our mapping methods for ventenata could be refined and expanded to more areas. Greater spatial and temporal resolution in relation to species distribution map data may be helpful in developing better understanding of rates of spread. Some management decisions might benefit from updated information on a frequent basis (e.g. annually). Ventenata is problematic in many other ecoregions of the interior northwest. Additional work also needs to be done in teasing out the phenological differences between ventenata and other annual grasses. It may be possible to better differentiate species based on phenology alone, but better data would be needed (i.e., repeated surface observations by means that are not as hindered by early season cloud cover). Testing the use of fine scale classification to predict abundance at landscape scales could also be explored (i.e., use of drones).

Predicting future invasion risks: A more comprehensive modeling approach is needed to understand how climate, dispersal, competition, and disturbance will impact future invasion. Because the ventenata invasion is relatively new, much of the west has not reached equilibrium. It is also unclear how invasion dynamics will change across other plant communities. Continued work around understanding ventenata's niche and environmental tolerance is also needed.

Understanding resistance and resilience and interaction with other disturbances. While our work provides critical information regarding community resistance and resilience to invasion, much more work needs to be done. We also lack understanding around the interactions between tree seedling recruitment and survival in invaded areas after high severity fire. It is possible ventenata is inhibiting or out-competing tree seedling recruitment and contributing to ecological transformations from forest to non-forest.

Likewise, we need additional studies examining the relationship between ventenata and fire, both landscape scale remote sensing assessments as well as long-term field studies. Our studies demonstrate some indication that grazing and fire interact, but more studies are needed regarding the interaction of these drivers. It is unknown if different stocking rates, grazing regimes, and changes in burn schedules will affect ventenata populations.

Wildfire simulations and future scenarios: Incorporating plant invasion into wildfire simulation models is a significant challenge because we lack specific information on the complex role of invasives on fuel loading and fire spread parameters and have limited fuel models that reflect invasive grasses. Additional simulations are also needed to examine landscape sensitivity to different levels of invasion. Such work could be used to examine thresholds around invasion and changes in fire as well as inform how much of the landscape and where invasive plant control treatments could be used to alter fire behavior in invaded ecosystems. In addition, to adequately simulate future wildfire behavior, future fuelscapes need to be developed. Currently future wildfire simulations only alter climate via changes in ERC. However, future vegetation and fuels will also change. Using other models to develop a comprehensive future fuelscape could be used to examine different scenarios about the future that could better prepare society for potential changes to ecosystems and landscapes.

Departure from proposed activities

For Objective 1, the generation of accurate estimates for the current extent of ventenata in the ecoregion and deciphering the species from other annual grasses was more complex and time-consuming than anticipated, and our work started almost a year later owing to several unfortunate events (departure of the original postdoc PI Zald, unexpected death of a major advisor, loss of some key staffing). In addition, FSim inputs related to the invasion required more time to develop than we anticipated and hinged on the completion of Objective 1. Thus, we spent more of our time and resources on Objective 1 and the inputs for the present day FSim runs than we anticipated, which created a squeeze to complete Objective 2 and portions of Objective 4. Therefore, we did not develop as many future scenarios for Objectives 2 and 4 as proposed. In addition, using MC2 to develop future fuelscapes as proposed proved to be beyond the scope of the project given the novel nature of that work and the complexity of other pieces as noted above.

Our work around the invasion, grazing, and fire also shifted. We had planned on using data from the Starkey Experimental Forest (SEF) with its long and detailed records of ungulate grazing, including telemetry locations for cattle, deer, and elk. We spent a significant amount of time trying to use these data; however, it was not a fruitful possibility given the highly complex telemetry and animal density data that needed to be processed. When we became aware of the long-term fire and grazing data available for the Zumwalt Prairie Preserve, we decided to use and remeasure that study. This has been a fruitful departure as this study provided a different plant community type and results provide important implications about fire and invasion that we would have otherwise not been able to elucidate.

While our work in terms of the grant is finished, we are continuing to move forward with this research and future work to eventually implement the complete vision we proposed. For example, we plan to expand on the modeling described in Objective 2, as information garnered from an ensemble of BRT models may improve our ability to estimate climatically suitable habitat and characterize the uncertainty associated with our estimates. Similarly, we were only able to complete one FSim run for the future and that run was limited to 1,000 runs or years rather than the typical 10,000. It is our intent to continue this line of research and create a more comprehensive set of FSim outputs, use MC2 to develop the future fuelscapes, and include more GCMs to address uncertainty.

While we were able to hold many workshops and engage with managers as we planned our work and preliminary results were available in 2017-2019, our planned science delivery field demonstrations and direct in person communications were halted in the spring of 2020 by the COVID-19 pandemic that shut down travel and gatherings. The pandemic continues to impact travel. Presently several project personnel are not permitted to travel unless approved at high organizational levels as mission critical tasks. Science exchange efforts do not fall into this category. We are now planning on a “deep dive” webinar in February 2022, and we will be editing our website to reflect the completed state of the project.

Literature Cited

Cheney, C., Esler, K.J., Foxcroft, L.C., et al. 2018. The impact of data precision on the effectiveness of alien plant control programmes: a case study from a protected area. Biol Invasions 20:3227–3243. https://doi.org/10.1007/s10530-018-1770-8

Brooks, M.L., D'Antonio, C.M., Richardson, D.M., Grace, J.B., Keeley, J.E.. J.M. DiTomaso, R.J. Hobbs, M. Pellant, D. Pyke. 2004. Effects of invasive alien plants on fire regimes. AIBS Bulletin. 54, 677-688

Clarke, S.E. and S. A. Bryce. 1997. Hierarchical subdivisions of Columbia Plateau and Blue Mountains ecoregions, Oregon and Washington. General Technical Report PNW-GTR-395

Corbin, J.D. and D’Antonio, C.M. 2004. Competition between native perennial and exotic annual grasses: implications for an historical invasion. Ecology, 85, 1273–1283

D’Antonio, C.M. and Vitousek, P.M. 1992. Biological invasions by exotic grasses, the grass/fire cycle, and global change. Annual Review of Ecology and Systematics, 23, 63–87. https://doi.org/10.1109/ HIS.2008.71

Daly, C., Halbleib, M., Smith, J. I., Gibson, W. P., Doggett, M. K, Taylor, G. H. 2008. Physiographically-sensitive mapping of climatological temperature and precipitation across the conterminous United States. International Journal of Climatology. Vol 28 (5): 2031-2064.

DiTomaso, J. M. 2000. Invasive weeds in rangelands: Species, impacts, and management. Weed Science 48(2): 255-265.

Funk, J.L., Parker, I.M., Matzek, V., et al. 2020. Keys to enhancing the value of invasion ecology research for management. Biol Invasions 22:2431–2445. https://doi.org/10.1007/s10530-020-02267-9

Finney, M.A., Grenfell, I.C., McHugh, C.W., Seli, R.C., Trethewey, D., Stratton, R.D., and S. Brittain. 2011. A method for ensemble wildland fire simulation. Environmental Modeling and Assessment. 16, 153–167. doi:10.1007/S10666-010-9241-3

Hallmark, B. and Romero, F. 2015. Fuel treatment effectiveness on the Corner Creek Fire, Oregon, USDA Forest Service, Fire and Aviation Management.

Harvey, R.G. and Mazzotti, F.J. 2014. The Invasion Curve: A Tool for Understanding Invasive Species Management in South Florida. Gainesville, FL: IFAS Publication Number WEC347. Available at: http://edis.ifas.ufl.edu/uw392. Accessed January 2019

Herrick, J.E., Van Zee, J.W., Havstad, K.M., Burkett, L.M., Whitford, W.G., Pyke, D.A. et al. 2017. Monitoring Manual for Grassland, Shrubland and Savanna Ecosystems, Volume 1, Las Cruces, New Mexico: USDA ARS Jornada Experimental Range

Jetz, W., McGeoch, M.A., Guralnick, R., et al. 2019. Essential biodiversity variables for mapping and monitoring species populations. Natural Ecology Evolution 3:539–551. https://doi.org/10.1038/s41559-019- 591 0826-1

Johnson, C. G., and Swanson, D. K. 2005. Bunchgrass Plant Communities of the Blue and Ochoco Mountains: A Guide for Managers. General Technical Report PNW-GTR-641. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Kerns, B.K. and Day, M.A. 2017. The importance of disturbance by fire and other abiotic and biotic factors in driving cheatgrass invasion varies based on invasion stage. Biological Invasions, 19, 1853–1862. https://doi.org/10.1007/s10530-017-1395-3

Kerns, B. K., C. Tortorelli, M. A. Day, T. Nietupski, An. M. G. Barros, J. B. Kim, M. Krawchuk. 2020. Invasive Grasses: A new perfect storm for forested ecosystems? Forest Ecology and Management 463, 117985, https://doi.org/10.1016/j.foreco.2020.117985

Mack, M.C. and D'Antonio, C.M. (1998) Impacts of biological invasions on disturbance regimes. Trends in Ecology and Evolution, 13, 195–198. https://doi.org/10.1016/S0169-5347(97)01286-X

Melgoza, G., Nowak, R.S. and Tausch, R.J. 1990. Soil water exploitation after fire: competition between Bromus tectorum (cheatgrass) and two native species. Oecologia, 83, 7–13

Monaco, T.A., Johnson, D.A., Norton, J.M., Jones, T.A., Connors, K.J., Norton, J.B. et al. 2003. Contrasting responses of Intermountain West grasses to soil nitrogen. Journal of Range Management, 56, 282–290

Nietupski, T.C. 2021. Characterizing an annual gras invasion and its link to environmental and disturbance factors using remote sensing: New tools and applications. [dissertation]. Corvallis, OR: Oregon State University. [*in progress*]. https://ir.library.oregonstate.edu/concern/graduate_thesis_or_dissertations/3n2046091

Nietupski, T.C., Kennedy, R.E., Temesgen, H., Kerns, B.K. 2021. Spatiotemporal image fusion in Google Earth Engine for annual estimates of land surface phenology in a heterogenous landscape. International Journal of Applied Earth Observation and Geoinformation. 99, 102323. https://doi.org/10.1016/j.jag.2021.102323

Omernik, J.M. 1987. Annals of the Association of American Geographers. 77: 118–125.

Ridder, L.W., J.M. Perren, L.R. Morris, B.A. Endress, R.V. Taylor, J.P. Averett, and B.J. Naylor (2021) Historical fire and *Ventenata dubia* invasion in a temperate grassland. Rangeland Ecology and Management 75:35-40.

Ridder, L.W., Morris, L.R., Day, M.A. and B. K. Kerns (2022) Ventenata (*Ventenata dubia*) Response to Cattle Grazing and Prescribed Fire on the Pacific Northwest Bunchgrass Prairie. Rangeland Ecology and Management, 80:1-9.

Riley, K.L, and R. A. Loehman. 2016. Mid-21st-century climate changes increase predicted fire occurrence and fire season length, Northern Rocky Mountains, United States. Ecosphere 7, e01543. https://doi.org/10.1002/ecs2.1543

Rupp, D. E., Abatzoglou, J. T., Hegewisch, K. C and P. W. Mote. 2013. Evaluation of CMIP5 20th century climate simulations for the Pacific Northwest USA. Journal Geophysical Research Atmospheres, 118, 10,884–10,906, doi:10.1002/jgrd.50843.

Thrasher, B., Xiong, J. , Wang, W., Melton, F., Michaelis, A., and R. Nemani. 2013. Downscaled climate projections suitable for resource management. Eos, Transactions, American Geophysical Union. 94, 321-323. http://dx.doi.org/10.1002/2013EO370002

Tortorelli C., Krawchuk, M., and Kerns, B. 2020. Expanding the invasion footprint: Ventenata dubia and relationships to wildfire, environment, and plant communities in the Blue Mountains of the Inland Northwest, USA. Applied Vegetation Science. 2020; 00:1–13. https://doi.org/10.1111/avsc.12511

Tortorelli C., Kerns, B. and Krawchuk, M. In review. Community invasion resistance is influenced by interactions between plant traits and site productivity. Ecology.

Wallace, J., Pavek, P., and Prather, T. 2015. Ecological Characteristics of Ventenata dubia in the Intermountain Pacific Northwest. Invasive Plant Science and Management, 8(1), 57-71. doi:10.1614/IPSM-D-14-00034.1

Appendix

Appendix A: Contact Information for Key Project Personnel

Becky K. Kerns
Research Ecologist
Fire and Environmental research Applications Team (FERA)
USDA Forest Service-Pacific Northwest Research Station
3200 SW Jefferson Way
Corvallis, OR 97331
Email: becky.kerns@usda.gov

Meg Krawchuk
Associate Professor
Landscape Fire and Conservation Science Research Group
Department of Forest Ecosystems and Society
College of Forestry, Oregon State University
336 Richardson Hall
Corvallis, OR 97331
Email: meg.krawchuk@oregonstate.edu

Claire Tortorelli
Graduate Research Fellow
Department of Forest Ecosystems & Society
College of Forestry
Oregon State University
Corvallis, OR 97331
Email:claire.tortorelli@oregonstate.edu

Ty Nietupski
Postdoctoral Research Fellow (ORISE)
USDA Forest Service-Pacific Northwest Research Station
3200 SW Jefferson Way
Corvallis, OR 97331
Pacific Corvallis, OR 97331
Email: Ty.Nietupski@usda.gov

Rebecca Lemons
Post-Doctoral Research Associate
Department of Forest Ecosystems & Society
College of Forestry
Oregon State University
Corvallis, OR 97331
Email: rebecca.lemons@oregonstate.edu

Appendix B: List of Completed/Planned Scientific/Technical Publications/Science Delivery Products

1. Articles in peer-reviewed journals

In press

Tortorelli, C., Krawchuk, M., Kerns, B. K. (2020) Expanding the invasion footprint: *Ventenata dubia* and relationships to wildfire, environment, and plant communities in the Inland Northwest, USA. Applied Vegetation Science: 23.4: 562-574, https://doi.org/10.1111/avsc.12511

Ridder, L.W., Morris, L.R., Day, M.A. and B. K. Kerns (2022) Ventenata (*Ventenata dubia*) Response to Cattle Grazing and Prescribed Fire on the Pacific Northwest Bunchgrass Prairie. Rangeland Ecology and Management, 80:1-9, https://doi.org/10.1016/j.rama.2021.09.003

Kerns, B. K., C. Tortorelli, M. A. Day, T. Nietupski, An. M. G. Barros, J. B. Kim, M. Krawchuk. 2020. Invasive Grasses: A new perfect storm for forested ecosystems? Forest Ecology and Management 463, 117985, https://doi.org/10.1016/j.foreco.2020.117985

Nietupski, T.C., Kennedy, R.E., Temesgen, H., Kerns, B.K. 2021. Spatiotemporal image fusion in Google Earth Engine for annual estimates of land surface phenology in a heterogenous landscape. International Journal of Applied Earth Observation and Geoinformation. 99, 102323. https://doi.org/10.1016/j.jag.2021.102323

In preparation/planned in the next 1-6 months:

Nietupski, T.C., Temesgen, H., Kerns, B.K. Mapping the invasive annual grass ventenata (*Ventenata dubia*) in the northwestern United States. Biological Invasions.

Nietupski, T.C., Temesgen, H., Kerns, B.K. Spatial dynamics and patterns of recent annual grass in the Inland Northwest and relationships to wildfire. Landscape Ecology.

Tortorelli, Claire, Michelle Day, Alex Dye, Becky Kerns, John Kim, Meg Krawchuk, Rebecca Lemons, Ty Nietupski, Karin Riley, Nicole Vaillant, Kevin Vogler. Feeding the fire: annual grass invasion alters fire behavior across a forest-mosaic landscape. Fire ecology.

In preparation/planned in the next 6-12 months:

Kim, John B., A. W. Dye, Becky K. Kerns, R. Lemons, A. McEvoy Ty Nietupski, Karin Riley, C. Tortorelli, N. Vaillant, Kevin Vogler. Simulating future climate change interactions with ventenata invasion in the Blue Mountains Ecoregion, USA. Ecological Processes or Regional Environmental Change

Nietupski, T.C., J. B. Kim, C. Tortorelli, B. K. Kerns, R. Lemons. *Ventenata dubia* climate suitability in the western US: Invasion potential now and in the future. Biogeosciences.

2. Technical reports

None.

3. Textbooks or book chapters

None.

4. Graduate thesis

Nietupski, T.C. 2021. Characterizing an annual gras invasion and its link to environmental and disturbance factors using remote sensing: New tools and applications. [dissertation]. Corvallis, OR: Oregon State University. https://ir.library.oregonstate.edu/concern/graduate_thesis_or_dissertations/3n2046091

Ridder, L.W. 2019. The response of *Ventenata dubia* to prescribed fire and ungulate grazing on the Pacific Northwest Bunchgrass Prairie. Master's Thesis, Oregon State University.

Chapter in Tortorelli, C. 2022 [expected dissertation]. Corvallis, Oregon: Oregon State University.

5. Conference or symposium proceedings scientifically recognized and referenced.

None

6. Conference or symposium abstracts

Kerns, B. K, John B. Kim, M. A. Day, B. Pitts, R. Drapek. 2017. Improving dynamic global vegetation model (DGVM) simulation of western U.S. rangelands vegetation seasonal phenology and productivity. American Geophysical Union Fall Meeting, New Orleans.

Kerns, B. K., A. Barros, M. Day, C. Tortorelli, M. Krawchuk, T. Nietupski, and J. Kim. 2019. Invasive Grasses: A new perfect storm for forested ecosystems? 6th Fire Behavior and Fuels Conference, Albuquerque, New Mexico.

Kerns Becky K, C. Tortorelli, Ty Nietupski, Michelle Day, Meg Krawchuk, Bridgett Naylor and John B. Kim. 2020. A novel invasive annual grass in North American Interior Ecosystems: Ventenata dubia (North Africa Grass). Weed Science Society of America and Western Society of Weed Science Joint Meeting, Maui, Hawaii.

Kim, John B., A. W. Dye, Becky K. Kerns, R. Lemons, A. McEvoy Ty Nietupski, Karin Riley, C. Tortorelli, N. Vaillant, Kevin Vogler. 2021. Wildfire, plant invasion and future climate change: results from wildfire simulation. 9th International Fire Ecology and Management Congress. E-conference

Lemons, R., Tortorelli, C., Kerns, B., Kim, J., Vogler, K., Dye, A., Riley, K., Valliant, N., Nietupski, T., Krawchuk, M. 2021. Feeding the fire: Invasion in a forest-mosaic landscape. Ecological Society of America 2021 Conference.

Nietupski, T.C. 2021. Annual grass invasion is associated with large wildfires in the interior northwestern US. 9th International Fire Ecology and Management Congress. E-conference.

Ridder, L.W., L.R. Morris and B. Kerns. 2019. Will prescribed fire exacerbate or constrain Ventenata dubia in the Pacific Northwest Bunchgrass Prairie? Society for Range Management Annual Meeting, Minneapolis, MN.

Tortorelli, C., Kerns, B., Krawchuk, M. 2019. A novel niche: The invasive annual grass Ventenata dubia and relationships to wildfire, environment, and community factors in the Inland Northwest. International Fire Ecology and Management conference, Tucson, AZ.

Tortorelli, Claire, Becky Kerns, John Kim, Kevin Vogler, Rebecca Lemons, Alex Dye, Karin Riley, Nicole Vaillant, Ty Nietupski, Meg Krawchuk, 2021. Feeding the fire: modeling annual grass invasion in a forest-mosaic landscape. 9th International Fire Ecology and Management Congress. E-conference.

7. Posters

Kerns Becky K, Harold Zald, Meg Krawchuk, Nicole Vaillant, John B. Kim, and Bridgett Naylor. 2016. Ecosystem change in the Blue Mountain ecoregion: Exotic invaders, shifts in fuel structure, and management implications. Ecological Society of America 2016 Annual Meeting, Ft. Lauderdale, Florida.

Kerns, B. Naylor, and M. Day. 2018. Ventenata Invasion, Fire and Fuels in the Blue Mountain Ecoregion. Oregon Interagency Noxious Weed Symposium, Corvallis, OR.

Kerns Becky K, Meg Krawchuk, Nicole Vaillant, John B. Kim, Ty Nietupski, Harold Zald, and Bridgett Naylor. 2017 Ecosystem change in the Blue Mountains Ecoregion: Exotic invaders, shifts in fuel structure, and management implications. Sagebrush Conservation Strategy Workshop, Reno, Nevada.

Kerns, B., Hollenbeck, J., Nietupski, T., Kim, J. B., Lemons, R., and Tortorelli, C. 2020. The Potential for Ventenata dubia to Intensify the Annual Grass Driven Transformation of the American West Now and in the Future. American Geophysical Union Fall Meeting. E-conference.

Nietupski, T., Kerns B., Temesgen, H., and Kennedy R. 2019. Landscape Phenology for Mapping an Invasive Annual Grass (Ventenata dubia). 15th International Conference on Ecology and Management of Alien Plant Invasions. Prague, CZ.

Nietupski, T., Kerns, B. 2020. Invasive annual Grass Mapping: Leveraging Land Surface Phenology and Bioclimatic Relationships. American Geophysical Union Fall Meeting. E-conference.

Tortorelli, C., Kerns, B., Day, M., Krawchuk, M. 2018. Is a new invasive species, Ventenata dubia, altering fire regimes and native plant communities? Western Forestry Graduate Research Symposium, Corvallis, OR.

Tortorelli, C., Kerns, B., Day, M., Krawchuk, M. 2018. Is a new invasive species, Ventenata dubia, altering fire regimes and native plant communities? International Fire Ecology and Management conference, Missoula, MT.

Tortorelli, C., Kerns, B., Krawchuk, M. 2019. Ventenata dubia: Invasion potential and impact on native communities in North America's Inland Pacific Northwest. Ecology and Management of Alien Plant Invasions (EMAPi) conference, Prague, Czech Republic.

8. Workshop materials and outcome reports

Nietupski, T. 2019. Landscape Phenology for Mapping ventenata. Ventenata Management Workshop for the Blue Mountains Ecoregion. John Day, OR.

Tortorelli, C., Kerns, B., Krawchuk, M. 2019. Impacts and drivers of the invasive annual grass Ventenata dubia in the Inland Northwest. USFS John Day Ranger District invasive species workshop, John Day, OR.

Tortorelli, C., Kerns, B., Krawchuk, M. (2017-2019). Workshop series: Invasive Species Listen and Learn. USFS Naches Ranger District, Naches, WA; USFS Ochoco National Forest Supervisors Office, Prineville, OR; Fremont Winema National Forest, Lakeview, OR.

Kerns, B. K., Ty Nietupski, and C. Tortorelli. Planned late winter 2022. The Ventenata dubia invasion in the Blue Mountain ecoregion and interactions with disturbance and wildfire. Deep Dive Webinar Coordinated through the Northwest Fire Science Consortium.

9. Field demonstration/tour summaries

USFS *Ventenata dubia* and fire field trip, Ochoco National Forest, OR. 2019.

10. Website development
https://www.nwfirescience.org/ventenata

11. Presentations/webinars/other outreach/science delivery materials

Kerns, B.K. 2018. Ventenata dubia and invasive annual grass research at PNW. USFS Region 6 Ecologist Meeting, Medford, Oregon.

Nietupski, T. 2018. Invasive Species and Fire: Monitoring with Satellite Timeseries. Willamette National Forest Meeting. Corvallis, OR.

Nietupski, T. 2019. Invasive Species Mapping with Landscape Phenology. USDS Region 6 Ecology Meeting. Virtual presentation.

Tortorelli, C., Kerns, B., Krawchuk, M. 2018. Ventenata dubia research overview and workshop: Invasion and impacts. USFS Leadership Team Meeting, Bend, OR.

Tortorelli, C. 2021. A new invasive threat to Oregon's native plant communities, Ventenata dubia. Native Plant Society of Oregon monthly chapter meeting, Corvallis, OR

Tortorelli, C. 2020. One-Two Punch to Oregon's Natural Areas: Invasive Plants & Fire. DaVinci Days, Corvallis, OR.