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ORIGINAL PAPER

Climate change and more disturbed land-use types will further the invasion of a non-native annual grass, *Ventenata dubia*

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Abstract Identification of suitable habitat for invasive weeds and their projected infestation extent across different land use cover types under a changing climate is crucial for the broad management goals of prevention, detection, and rapid response. In this study, we adopted an ensemble approach of species distribution models to project potential habitat of the invasive annual grass, *Ventenata dubia*, within the Gallatin County and along its road corridors, in Montana, USA, under current and future climates. The model prediction of *V. dubia* habitat was excellent with an AUC value of > 0.90. The climate predictors with most influence on *V. dubia* occurrence were precipitation, potential evapo-transpiration, relative humidity, vapor pressure deficit, and solar radiation for growing season months. Under current climate, the model projected 243 and 1,371 km^2 coverage of *V. dubia* along road corridors and the entire County, respectively. The projected coverage of *V. dubia* was greatest for road corridors (239% under RCP4.5 and 302% under RCP8.5) compared to that of Gallatin County (127% under RCP4.5 and 241% under RCP8.5). Among the land use cover types, the model projected greatest expansion of *V. dubia* across agriculture land with 425% and 484%, and grasslands with 278% and 442% under RCP4.5 and RCP8.5 respectively. Our modelling approach suggests that the changing climate will facilitate spread and establishment of non-native species in disturbed habitats. We conclude that *V. dubia* with a short history of invasion is expanding at an alarming rate and requires greater investment in detection and monitoring to prevent further expansion.

Keywords Invasive weeds · SDM · Agriculture land · Developed land

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Introduction

Invasive weeds are of global concern and are often spread along transportation networks (Hulme 2009). Seeds attached to vehicles can travel hundreds of kilometers before falling off (Taylor et al. 2012). Consequently, national roads where vehicles are likely driving longer distances and between regions have nearly double the richness and abundance of non-native species than secondary roads (Vakhlamova et al. 2016).

However, the success of such movements depends on the environmental suitability at the new location, and those that establish become the primary source of invasion into adjacent agricultural and wild lands, adversely impacting agriculture production, native biodiversity, and ecological processes (Dostálek et al. 2016; Foster and Ackerman 2021). Understanding the environmental requirements of new invaders can be used to predict where a species is likely to occur now and under global change.

Road corridors provide a more similar environment throughout their length than with adjacent habitats, such that they can be considered a separate habitat (Lugo and Gucinski 2000). Road construction results in homogeneous substrates, and roadside maintenance alters light availability; soil texture, compaction, and chemistry; and increases water runoff along the road corridor (Spellerberg 1998), all of which effect the vegetation (e.g., Gelbard and Belnap 2003; McDougall et al. 2018; Seipel et al. 2012). Disturbance of roadsides due to maintenance and other activities (e.g., off-road driving, emergency uses, fire), removes vegetation and creates open gaps with more light and other resources than undisturbed areas. Typically, plants that invade roadsides are expected to be colonizing, short-lived species that grow well in disturbed areas and use resources very efficiently (McDougall et al. 2018). For instance, Šerá (2010) found that primary roads in the Czech Republic were indeed dominated by annual rapid, short-lived colonizers.

Ventenata dubia (Leers) Coss. (ventenata, North Africa grass) is a winter annual grass, native to southern Europe and northern Africa, and a relatively recent invasive species to the north-western United States of America (Jones et al. 2018). It was first recorded across grasslands in Washington and Idaho in the 1950's and has spread along roadways and into sagebrush steppe and Palouse prairie rangelands, pastures—primarily *Phleum pratense* L.—hay fields, winter grain and conservation reserve program land throughout the inland Pacific Northwest and into the Northern Great Plains (Northam and Callihan 1992; Wallace et al. 2015). It was first documented in Montana in the 1990's and is now reported in 18 Montana counties, occurring along roadsides and in pastures and rangeland (Harvey et al. 2020). *Ventenata dubia* was designated as a noxious weed in Montana in 2019, meaning that landowners are mandated by law to control it where it occurs, and a better understanding of the species' biology, ecology, and management is required (Harvey and Mangold 2019).

Ventenata dubia is likely spread by vehicles travelling along roadways (Fryer 2017; Lass and Prather 2007) and through infested hay (Fryer 2017; Wallace et al. 2015). Since this species is still relatively new to the region, little information has been published about its habitat niche and distribution potential. In the Pacific Northwest it was first observed in wetter sites but has spread to drier habitats over the last 30 years (Jones et al. 2020). Species distribution modeling (SDM) is a well-established technique to evaluate climate and environmental requirements of a species, and project the potential habitat range for the species of interest. The technique has become an essential tool in ecology, biogeography, species conservation and natural resource management (Adhikari et al. 2019a, b; Franklin 2013; Guisan and Thuiller 2005). Species distribution modelling can also be used to help prioritize management, by identifying areas to survey for the target species and to monitor for effectiveness of management (Rew et al. 2007). Overall, the goal of this research was to determine the climate and land use cover most suitable for *V. dubia* to help inform management of this species. Specifically, our study aimed to 1) identify the main climate factors that control the distribution of *V. dubia,* 2) quantify projected expansion of suitable habitat across two spatial extents: road corridors of Gallatin County and the entire Gallatin County, Montana under current and future climate scenarios, 3) compare the susceptibility of the roadsides and other land uses to invasion by *V. dubia*, and 4) quantify projected cover of *V. dubia* in different land use cover types. Our study is based in Gallatin County, Montana, USA. Though, we surveyed for *V. dubia* along roadsides, our results will provide a basis for landscapes with similar climate and geography to strategize management of *V. dubia.*

Methods

Gallatin County (6,820 km^2) is our study area, consisting of sweeping valleys and mountain ridges in southwest Montana within the Rocky Mountains (Fig. 1). The county is intertwined by a 1,226 km long road network (paved and unpaved). There are a mix of land uses including crop production, grasslands (rangeland) and forests with a mix of private

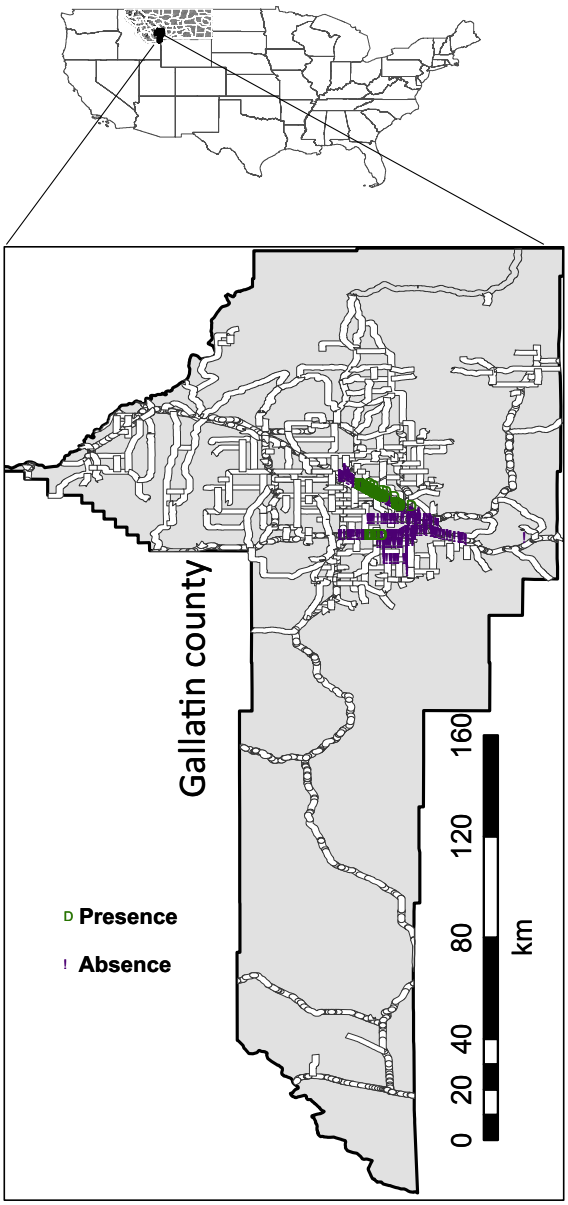


Fig. 1 Map of study area showing *Ventenata dubia* presence and absence locations along surveyed major and main roads in Gallatin County, Montana, USA. The study site comprises an area of 6,820 km^2. The presence and absence records of *V. dubia* were collected along 354 km of roadsides during 2019–2020 surveys

and public land ownerships. The area is characterized by a semiarid, continental type of climate with cold winters and mild warm summers at high elevation. There are considerable climatic differences across the county due to the elevation range (1,234 – 3,199 m) and varying topography. The main city, and initial focus point for this research is Bozeman (− 110.05 W, 45.6835 N) at an elevation of 1463 m. The 30-year average climate for Bozeman consists of a high temperature of 13.9 C and minimum of − 0.6 C, with 429 mm of precipitation (US Climate 2021).

Roadside survey for Ventenata dubia

We surveyed for *V. dubia* along main and major connector roads (federal, state, and county) from Bozeman to the county line in all directions. The surveyed area started in Bozeman as this was the site of previously known infestations. The survey protocol entailed field data collection by a team of two, a driver and an observer who drove at slow speeds (3.2—16.1 kph) along both edges of a road: we have used this approach in other studies (Adhikari et al. 2020) and have found this speed along with sampling both sides of the road provide good detection. A global positioning system (GPS) was used to collect information on *V. dubia* occurrence (presence/absence) along the road corridor. Both sides of 182 km of roads were recorded for a total observed distance of 364 km. The same roads were surveyed in 2019 and 2020 to allow for annual variability in climate and plant occurrence, and improved detection accuracy. Surveying took place over 10 days in 2019 (July 12, 16, 19, 26, 30 and August 1, 5, 6,7 and 8), and 12 days in 2020 (Monday-Thursday July 13–30). Out of 364 km surveyed with 10 m section, *V. dubia* was present in 2% of the total sections. The data were converted to presence/absence records for each section of roadside, and if *V. dubia* was observed in a location in either year it was considered a presence, thus any duplicate data were removed. A total of 467 presence records were recorded along the surveyed roads (Fig. 1). An equal number of absence records were randomly sampled.

Climatic and environmental predictors of Ventenata dubia distribution

Climate variables from Multivariate Adaptive Constructive Analogs (MACA) products at 4 km spatial resolution were used to project habitat suitability of *V. dubia* in this study. Variables included monthly average minimum and maximum temperatures, precipitation, potential evapotranspiration (PET), vapor

pressure deficit (VPD), relative humidity (RH), and solar radiation (SR). The MACA products were derived by a statistical downscaling method and calibrated with observed meteorological dataset (i.e., training dataset) to make compatible spatial patterns after correcting historical biases (Abatzoglou and Brown 2012). The 4 km spatial data were then statistically downscaled to 1 km spatial resolution. These historic climate data were summarized as the monthly average for the period of 1980–2006. In addition to the climatic variables, we used available soil water holding capacity (ASWHC) and percent sand (Miller and White 1998) as other environmental predictors.

Collinearity analysis

We considered eighty-six climate and environmental predictors for constructing the SDM (Appendix 1); the number of variables is high because we included all months for our climate variables. Collinearity of predictors was assessed by Pearson's correlation coefficient to minimize multi-collinearity issues by considering only one predictor when two predictors were highly correlated > 0.70 (Dormann et al. 2007). Highly collinear predictors do not uniquely contribute to the model, but such collinearity among predictors can be problematic when assessing significance of individual parameters. Therefore, we eliminated highly correlated predictors from the initial sets of environmental variables. During the model development, we selected only one variable from each pair of correlated variables which was based on ecological knowledge of a species' relationship with its environment. For example, if April and May were correlated, we excluded April because it often too cold for plant growth whereas May is more suitable. In total 14 uncorrelated variables were retained (Fig. 2).

Future climate data

To understand how *V. dubia* distribution could be impacted by climate change, we adopted climate change scenarios with the same sets of future (2011 to 2040) environmental predictors as in the historical period (1981 to 2005) but projected by a general circulation model (GCM). The scenarios were generated from the experiments conducted under the fifth assessment of Coupled Model Intercomparison

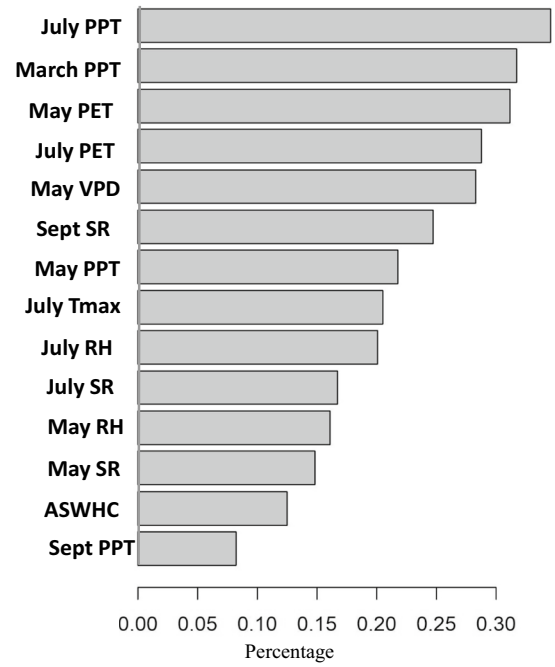


Fig. 2 Relative importance of climate and environmental variables for *Ventenata dubia*. Abbreviation – ASWHC: available soil water holding capacity, PET: potential evapotranspiration, PPT: precipitation, RH: relative humidity, SR: solar radiation, Tmax: maximum temperature, VPD: vapor pressure deficit. Sept: September

Project Phase 5 (CMIP5) for the Intergovernmental Panel on Climate Change (IPCC). The climate change scenarios include a medium (RCP4.5) and high (RCP8.5) representative concentration pathway from 2011 to 2040. The medium and high scenarios represent the amount of anthropogenic forcing, 4.5 W/m^2 and 8.5 W/m^2 respectively, consistent with increases in atmospheric greenhouse gases at current rates (Moss et al. 2010). Climate predictors for the future period from 2011–2040 were averaged from a warm and dry climate scenario predicted by CCSM4 GCM. The CCSM4 moderately captures overall spread of future projections of our climate variables across the study area (Adhikari et al. 2019a, b). Adhikari et al. (2019a, b) evaluated eight GCMs that best represented the climate of the study area to investigate which GCM can best represent the climate projection. They selected a GCM because it showed moderate increase (in between

higher and lower increases) of precipitation and temperature.

Modeling approach, evaluation and analysis

We selected algorithms for five models within an ensemble framework to create a bioclimatic niche model of *V. dubia* for the current and future scenarios using Biomod2 software programmed in R environment (Thuiller et al. 2016). The models included Generalized Linear Models, Random Forest (Magness et al. 2008; Prasad et al. 2006), Artificial Neural Network (ANN, Olden et al. 2008), classification tree analysis (CRT, Breiman 2017), and Flexible Discriminant Analysis (FDA, Hastie et al. 1994). The ensemble model output considered the mean suitable value for each route.

Using the BIOMOD function "Variable Importance" allows us to estimate the relative importance of each variable with respect to predictive ability in the model. The higher the relative importance value, the more influence the variable has on a species presence. A value of 0 assumes no influence of the variable in the distribution. We performed the Mantel test to examine spatial autocorrelation using R package "ecodist", and no corrections were needed.

The accuracy of the model was assessed from the data generated by the split-sample. The data were randomly split in a ratio so that 80% of the data were used for model development and 20% for model evaluation with threefold cross-validation (Thuiller et al. 2016). We used the area under the curve values (AUC) of receiver operator characteristic (ROC) curves to assess the model performance. The model evaluation methods inherit different weights to multiple prediction errors such as omission, commission or confusion. A model with the AUC value < 0.70 is considered poor, 0.7–0.9 considered moderate, and > 0.9 considered good (Fielding and Bell 1997).

We assessed AUC scores secured by the ensemble model to evaluate the model performance for *V. dubia*, and the relative influence of the predictors on habitat projections. The model first projected probability of distribution of the species for the entirety of Gallatin County; we then arbitrarily created a 250 m buffer along both sides of the road network for each climate scenario. Our analysis focused on two extents i.e., road network versus the entire county (> 250 m from the road). The general consensus is that the distance of 250 m from the roadside can be heavily affected by human disturbance but is wider than officially required by Montana standards. Within the 250 m buffer of roads and the entire Gallatin County, we categorized continue probability or habitat suitability (continuous raster) of *V. dubia* into two categories, suitable habitat with a value > 0.51 and unsuitable with a value < 0.51 for each climate scenario. The conversion of continuous probability to binary raster is not arbitrary. The algorithm searches exhaustively to find a threshold that minimizes both commission and omission error and finds the best threshold.

Land ownership classifications

We quantified the projected area covered by *V. dubia* across different land use land cover classes using the National Land Cover Data (NLCD) for 2016 (Dewitz 2019). The NLCD is a raster dataset of 30 m resolution with 16 Land Use Land Cover (LULC) classes for conterminous USA. We regrouped the NLCD data into the five new land use classes: Developed (developed open space, developed low intensity, developed medium intensity, and developed high intensity), forest (deciduous forests, evergreen forests and mixed forests), shrubland, grassland, and agriculture (hays/pasture and cultivated) area. The NLCD "Open Water and Wetlands" cover classes were not considered during the analysis, and barren was removed due to low representation ($<0.002\%$). Reclassified land classes were overlaid on the projected roadside habitat map of *V. dubia*, and we estimated the projected infested area across each land use cover class.

Results

The variables that had the most influence on *V. dubia* were retained in the models, these included precipitation, PET, relative humidity and solar radiation for various spring through autumn months (Fig. 2). The most influential variables for *V. dubia* were July and March precipitation with other variables being important but having less influence (Fig. 2).

The growing season months were important for precipitation (March, May, July and September) (April and June were excluded due to correlations), whereas higher PET, lower relative humidity and higher solar radiation were important early and mid-summer (May and July), along with solar radiation in

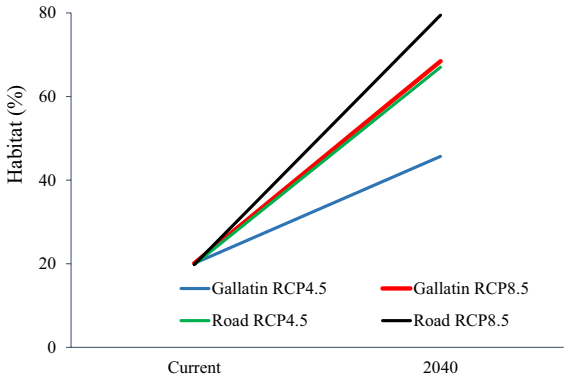


Fig. 3 Projected habitat percent infested with *Ventenata dubia* across road networks and Gallatin County, Montana, USA, from current to future climate change scenarios RCP4.5 and RCP8.5

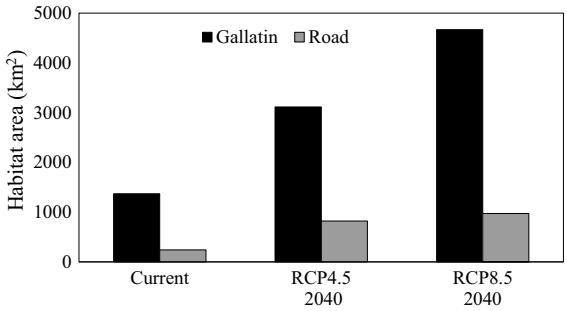


Fig. 4 Projected current and future habitat area of *Ventenata dubia* for the road corridor (1,226 km^2 total) and Gallatin County (6,829 km^2 total), Montana, USA, under future climate change scenarios RCP4.5 and RCP8.5

September. Other important variables included vapor pressure deficit in May, maximum temperature in July and available soil water holding capacity.

Model ensemble output showed excellent agreement in predicting observed distribution of *V. dubia* across Gallatin County with AUC value of 0.98 with sensitivity (0.98) and specificity (0.94). Twenty percent of the available road corridor is currently suitable habitat for *V. dubia* (Fig. 3.), covering 243 km^2 (Fig. 4). *Ventenata dubia* is projected to increase under both scenarios, but most under RCP8.5 (Fig. 3). The roadside area suitable for *V. dubia* is projected to dramatically increase, by 239% (822 km^2) under RCP4.5 and 302% (974 km^2) under RCP8.5 (Fig. 4 and 5). This equates to 67% and 79% of the road corridor being projected as suitable for *V. dubia* under RCP4.5 and RCP8.5 climate scenarios in 2040, respectively (Fig. 3). Across the entire Gallatin County, the model projected 1,371 km^2 suitable habitat range of *V. dubia* under current climate (Fig. 4) which is 20% of the total county (Fig. 3). Projected habitat of *V. dubia* was always greater under high emission scenario RCP 8.5 compared to RCP 4.5 (Figs. 3, 4 and 5). Among future climates, the model again projected the greatest increase in suitable *V. dubia* habitat at 240% (4,669 km^2) under RCP 8.5 compared with 79% (3,116 km^2) under RCP4.5 for the year of 2040.

Based on national land cover data, the land adjacent to the road corridor consists mainly of forest (43%, 2,875 km^2), followed by shrubland (24%, 1589 km^2), then equal amounts of agricultural and grasslands (14%, 95 km^2 each) with developed land representing only 3% (191 km^2) of the county. Under current climate conditions the model predicted greatest cover of *V. dubia* in shrubland (37%), similar amounts in forest (32%) and developed land (31%), and less but again similar amounts in grassland (18%) and agriculture (17%) (Tables 1; Figs. 5 and 6). *Ventenata*

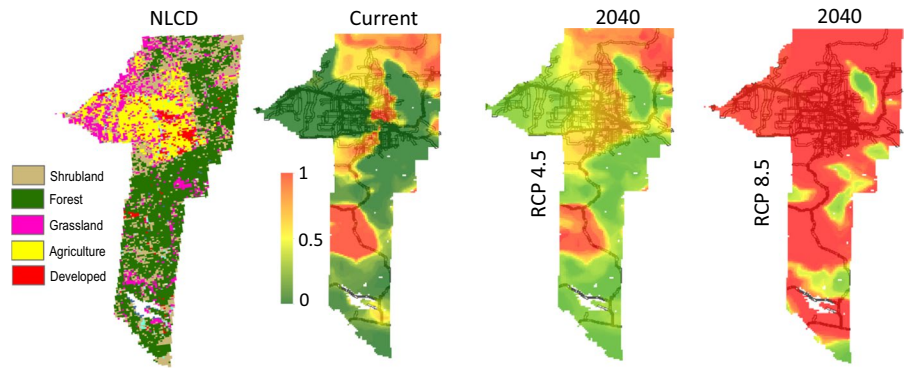


Fig. 5 Presence of different land use cover types in Gallatin County, Montana, USA, and probability of current and future distribution of *Ventenata dubia* across the county under climate change scenarios RCP4.5 and RCP8.5 for the year 2040. Maps of land use class types used NLCD, 2016 cover data

Table 1 Current and projected percent change in suitable area of *Ventenata dubia* in different land use types in Gallatin County, Montana. Current is now, and future is 2040 under RCP4.5 and RCP8.5 scenarios. LULC = Land Use Land Cover

LULC	Current	RCP4.5 2040	RCP8.5
Developed	31	196	226
Agriculture	17	425	484
Grassland	18	278	442
Shrubland	37	99	169
Forests	32	60	207

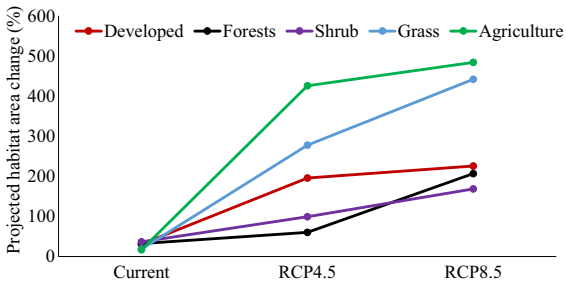


Fig. 6 Projected *Ventenata dubia* habitat change (%) for the different land use cover types by 2040 under RCP4.5 and RCP8.5

Table 2 Current and projected area of *Ventenata dubia* (km^2) for different land cover classes in Gallatin County, Montana, under RCP4.5 and RCP8.5 climate change projections for 2040. LULC = Land Use Land Cover

LULC	Current	RCP4.5 2040	RCP8.5
Developed	59	173	191
Agriculture	164	860	956
Grassland	174	657	943
Shrubland	581	1158	1560
Forests	930	1491	2850

dubia expansion across different land use cover types of Gallatin County was projected to be higher under RCP8.5 compared to that of RCP4.5. The projected expansion of *V. dubia* was greatest on agricultural land (425% (860 km^2) and 484% (956 km^2)) and grassland (278% (657 km^2) and 442% (943 km^2)) under RCP4.5 and RCP8.5, respectively (Table 2; Fig. 6). The least increase was in forest, where only a 60% increase was projected under RCP4.5 (Table 2; Fig. 6).

Discussion

Coupling our current knowledge of *V. dubia* infestation locations with environmental factors allowed us to create predictive habitat suitability maps that identified areas at high risk of invasion in Gallatin County, Montana, USA. Our modeling approach projected the extent of habitat suitability of *V. dubia* under different climate scenarios across the road network and the entire county. The model ensemble showed excellent model performance using AUC model evaluation metrics, providing an accurate fit to the current distribution of *V. dubia* in Gallatin County. The ensemble modeling approach we adopted here avoids predictive variability associated with single models, because ensemble-forecasting generates a consensus prediction by combining the predictions from multiple techniques (Araújo and New 2007). The occurrence of *V. dubia* is most strongly associated with growing season through fall precipitation (wetter March, May, July and September), early and mid-summer (May and July) potential evapotranspiration, relative humidity and solar radiation, with September also being important for solar radiation; in addition, May vapor pressure deficit, July maximum temperature and available soil water holding capacity were important. These variables explained most of the variation in distribution of *V. dubia* across our study area and relate to the species' life-history (Wallace et al. 2015). *Ventenata dubia* is a fall germinating annual species, and in our region precipitation and warmth are important for germination in September. The species then overwinters in a dormant state, often protected from thermal extremes by snow, and starts to grow again in spring when increasing solar gain melts the snow and recharges the soil moisture, and spring and early summer climate variables support growth and reproduction. So the most influential variables correspond with when the species is most actively growing.

The expansion of non-native plant populations with time is primarily associated with climate and other environmental filters (Averett et al. 2016). Understanding which climate variables are most important for individual species provides the capacity to model how a species' distribution will alter as our climate continues to change. Southwest Montana is projected to increase in average temperature by mid-century (1.5 C and 2.5 C for RCP4.5 and RCP8.5, respectively), and get wetter annually

(13–19 mm and 19–25 mm for RCP4.5 and RCP8.5, respectively) but have drier summers (Whitlock et al. 2017). In our study, the changing climate scenarios both predicted increases in *V. dubia*, though more so with RCP8.5 than RCP4.5. The projected increases in *V. dubia* were greater along the road corridor than county-wide. Among the land use cover types, agriculture land and grassland were highly likely to be infested by *V. dubia*, and grasslands were much more impacted under the RCP8.5 than RCP4.5 scenario. The prediction of *V. dubia* invading grasslands and agricultural lands more than other habitats matches with information from Idaho where the species has been present for a longer time period (Wallace et al. 2015). The estimates of future expansion are calculated from the amount of coverage in the current climate, and as such reflect changes in climate. The smaller proportion of *V. dubia* occurrence in agriculture and grassland could infer that these areas are less suitable for this species under current climate conditions, or that the species has yet to disperse there because it is at the early stage of invasion. However, greater proportional occurrence under future climate infers that these areas might be more suitable for *V. dubia* distribution under the future climate scenarios. While road corridors are their own ecosystem due to their construction and maintenance, they are generally vegetated by perennial grasses, with some forbs and low shrubs. Thus, the roadside vegetation is most similar to grasslands in our county, potentially explaining why the roadside increase is similar to adjacent grasslands and greater than the entire county predictions (Gallatin—46% and 68% vs Road—67% and 79% under RCP4.5 and RCP8.5, respectively).

Invasive species can be transported and spread unintentionally to new habitats along road corridors faster than they can spread through primary dispersal (Adhikari et al. 2020; Hulme 2009; Rew et al. 2018). Our models showed 20% of the roadsides are currently suitable for *V. dubia* and that suitability increases in the future. However, our models are predicting habitat suitability and do not incorporate dispersal, as such they demonstrate the potential of *V. dubia* assuming high propagule pressure throughout the study area. Previous studies have demonstrated that road corridors and vehicles that move along them are strong conduits for dispersal and that roadside management practices provide suitable gaps for new seed establishment (e.g. Adhikari et al. 2020; Rew et al. 2018; Taylor et al. 2012; Vakhlamova et al. 2016). As the number of vehicles in Gallatin County and the entire state of Montana increase (Montana Department of Transportation, 2021), it is likely that more seeds of *V. dubia* will be transported and widely dispersed. Because seeds will be spread along the road corridor, they will also then move into adjacent lands where environmental filters are still suitable for *V. dubia*. Our models suggest that agricultural lands and grasslands will become more suitable as the climate changes, and where these habitats are proximal to busy highways or higher road density, and are disturbed in other ways, there is likely to be more successful invasion.

Documented impacts of *V. dubia* are limited but noteworthy and highlight why management practices that prevent the invasion of *V. dubia* are desirable. Range, pasture, and natural areas impacted by *V. dubia* result in decreased plant community richness and diversity, low forage production, and potentially increased soil erosion due to the species' shallow root structure. Prather and Steele (2009) found that pasture, grass-hay and grasslands of north-central Idaho experienced a significant decline in forage production because of *V. dubia* invasion. In some situations, timing of hay harvest schedules had to be altered to avoid export losses due to *V. dubia* (Wallace et al. 2015). *Ventenata dubia* has been associated with a decrease in plant species richness and diversity in the Palouse prairie and Canyon lands (Jones et al. 2020), and a decline in nesting success of insect-eating birds due to a loss of biodiversity in conservation lands in northern Idaho (Jones et al. 2018). Furthermore, *V. dubia* has displaced *Bromus tectorum* (cheatgrass or downy brome) in the Snake River Canyon grasslands of Idaho (Wallace et al. 2015). This is particularly alarming because *V. dubia* appears to be avoided by livestock, possibly due to its high silica content (Prather and Steele 2009). The silica content of *V. dubia* was found to be about 9% as compared to 3% for *B. tectorum* and 4% for *Pseudoroegneria spicata* (bluebunch wheatgrass) (Mangold, unpublished data). Fortunately, increases in *V. dubia* have not been observed after fire in Pacific Northwest temperate grasslands (Ridder et al. 2021) nor elsewhere. When rangelands become infested by species like *V. dubia,* however, the invasive, annual grasses create fuel for fire, and this fuel dries out quickly due to high

surface-to-volume ratio, which in-turn, can extend the fire season to earlier in summer (Rottler et al. 2015).

The economic cost of controlling invasive species is increasing every year. Montana alone spends millions of dollars to control invasive species annually. For example, the state spent $12 million on control and management of noxious weeds in 2018 (Burch 2020). *Ventenata dubia* is a relatively new invader (~30 years) in Montana. A guiding principle of integrated weed management is that addressing a species closer to the beginning of an invasion is more effective than waiting until later, when the species is widely distributed and well-established (Hobbs and Humphries 1995). This guiding principle is supported by the Montana Noxious Weed Management Plan (Montana Department of Agriculture 2017) where early detection is emphasized under the broad management goals of prevention, detection, and rapid response. Furthermore, as all habitats are not similar in terms of invasion susceptibility (Lonsdale 1999), species distribution models provide the capacity to prioritize which areas and habitats are more prone to invasion in order to develop the most effective local scale management plan (Rew et al. 2005; 2007). The current study addresses this by improving our understanding of the potential spatial extent *of V. dubia* in Gallatin County under current and future climates and evaluating habitat preferences of the species. The fact that the road corridors are likely to become increasingly infested by *V. dubia* as the climate changes suggests an important first step in the management of this species will be periodic monitoring to evaluate the efficacy of control strategies and search for new populations, preferably along the predicted suitability gradient (Rew et al. 2007). In this way the best control strategies can be determined and used, and if control strategies differ along the environmental suitability gradient, a more adaptive approach should be developed. Searching for new populations can be prioritized by starting with the highest risk areas on the environmental suitability map, especially where they coincide with the highest risk land uses (agriculture, grassland), and continuing to lower risk areas as resources allow. Locating new populations along road corridors is vital as these populations will act as source populations, invading into adjacent land, particularly grasslands and agriculture.

Our results identified new habitats along the road corridor and in the adjacent land of Gallatin County that may be at risk of invasion by *V. dubia*. Many of the surrounding counties and states have similar climate and land use cover types, *V. dubia* is highly likely to be spread along busy road corridors beyond Gallatin County, as seeds attached to increasing numbers of vehicles. The species will then spread into adjacent lands where environmental filters are suitable. Road corridors in the state are already infested with many noxious weed species, some of which are also predicted to increase as the climate changes (Adhikari et al. 2020). Exactly how the invasive and native species will interact as the climate continues to change is unknown but should be considered (Crossman and Bass 2007; Crossman et al. 2011). However, not all species have equal potential to invade, and all habitats are not equally threatened by invasion to the same degree (Lonsdale 1999). The degree of invasion in a particular habitat depends on the traits of invasive species, the environment of recipient habitat, and the propagule pressure with which invasive species are entering into the recipient habitat (Rejmánek et al. 2005). Our study highlights climate variables and land use cover types most at risk to *V. dubia* invasion now and in the future, and these maps can be used to help prioritize monitoring and management of those populations that pose the greatest threat to habitats.

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Data availability statement Data generated during this study can be available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare no conflict of interests.

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Table 3 List of predictors used for species distribution of each species before multicollinarity assessment

Available soil water holding capacity	Potential evapotranspiration_Dec	Precipitation_December
Potential evapotranspiration_January	Precipitation_January	Relative humidity_January
Potential evapotranspiration_February	Precipitation_February	Relative humidity_February
Potential evapotranspiration_March	Precipitation_March	Relative humidity_March
Potential evapotranspiration_April	Precipitation_April	Relative humidity_April
Potential evapotranspiration_May	Precipitation_May	Relative humidity_May
Potential evapotranspiration_June	Precipitation_June	Relative humidity_June
Potential evapotranspiration_July	Precipitation_July	Relative humidity_July
Potential evapotranspiration_August	Precipitation_August	Relative humidity_August
Potential evapotranspiration_Sept	Precipitation_September	Relative humidity_September
Potential evapotranspiration_Oct	Precipitation_October	Relative humidity_October
Potential evapotranspiration_Nov	Precipitation_November	Relative humidity_November
Relative humidity_December	Minimum temperature_May	Vapor pressure deficit_October
Maximum temperature_January	Minimum temperature_June	Vapor pressure deficit_November
Maximum temperature_February	Minimum temperature_July	Vapor pressure deficit_December
Maximum temperature_March	Minimum temperature_August	Solar radiation_January
Maximum temperature_April	Minimum temperature_September	Solar radiation_February
Maximum temperature_May	Minimum temperature_October	Solar radiation_March
Maximum temperature_June	Minimum temperature_November	Solar radiation_April
Maximum temperature_July	Minimum temperature_December	Solar radiation_May
Maximum temperature_August	Vapor pressure deficit_January	Solar radiation_June
Maximum temperature_September	Vapor pressure deficit_February	Solar radiation_July
Maximum temperature_October	Vapor pressure deficit_March	Solar radiation_August
Maximum temperature_November	Vapor pressure deficit_April	Solar radiation_September
Maximum temperature_December	Vapor pressure deficit_May	Solar radiation_October
Minimum temperature_January	Vapor pressure deficit_June	Solar radiation_November
Minimum temperature_February	Vapor pressure deficit_July	Solar radiation_December
Minimum temperature_March	Vapor pressure deficit_August	
Minimum temperature_April	Vapor pressure deficit_September	

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Appendix

See Table 3

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