

Updated bioclimatic modeling of *Armillaria solidipes* in the Intermountain Region (USA)

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Introduction

Armillaria root disease is one of the leading causes of growth loss and mortality in coniferous forests of the western USA (Lockman and Kearns 2016; Kim et al. 2022). In 2019, a collaborative project was started to learn more about Armillaria root disease in the Intermountain Region (USDA Forest Service Region 4). Recent surveys suggested that Armillaria root disease was increasing on trees in Utah, particularly at higher elevations than was previously observed (John Guyon, per. comm.). Previous and subsequent surveys using DNA-based identification revealed that *A. solidipes* (formerly known as North American *A. ostoyae*) was the predominant cause of Armillaria root disease in Utah (McDonald 1999, Hanna unpublished data). Earlier modeling efforts produced preliminary predictions of the geographic distribution of suitable climate for *A. solidipes* in the Intermountain Region of the USA (Hanna et al. 2021, Kim et al. 2021). These earlier models were limited due to COVID-19-related delays in field surveys and lack of availability of higher resolution bioclimatic grids. Currently, the higher resolution CMIP6 (Coupled Model Intercomparison Project Phase 6) bioclimatic grids are available at 30-second (ca. 1-km) resolution and additional locations of DNA-confirmed *A. solidipes* have been determined. Refined models are presented based on the newly available information. Information from this project will provide insights for improving other existing bioclimatic models and/or developing new models for *Armillaria*, other forest pathogens, and/or forest hosts in other regions of western North America. These tools can inform forest managers about how climate change might influence the spatial distribution of suitable climate for this Armillaria root disease pathogen and its hosts, which is an important consideration for forest management in the Intermountain Region.

Objectives

The objectives of this project are to (i) update and refine *A. solidipes* bioclimatic models specific to the Intermountain Region [Forest Service Intermountain Region (Region 4)]. Improvements over previous models (Kim et al. 2021) include additional confirmed locations (increased from 19 to 28) of *A. solidipes* and higher resolution grids [from 2.5-minute (ca. 4-km) resolution to 30-second (ca. 1-km) resolution]; (ii) compare these specific regional models (Figures 1B-F) using 28-point locations to the western North American model from Kim et al. (2021; Figure 2) that used 382-point locations (363 locations outside of the Intermountain Region); and (iii) model the potential future distribution of suitable climate space for *A. solidipes* in the Intermountain Region under climate-change scenarios (based on historic climate suitability), interpret results, and provide access for forest managers to use these data for forest planning.

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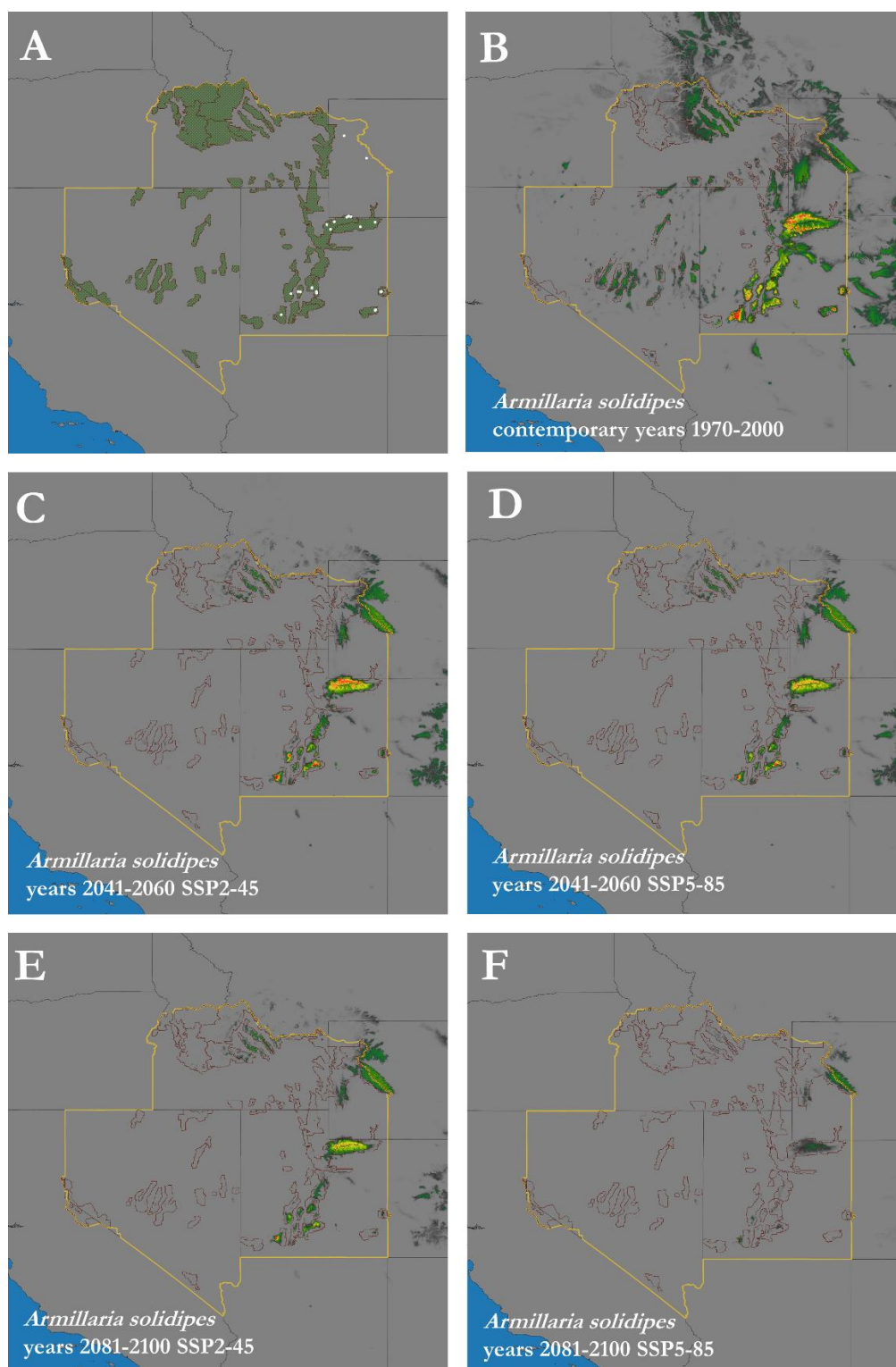


Figure 1: A: *Armillaria solidipes* GPS point locations used for the models. B: Contemporary bioclimatic prediction model for the years 1970-2000. C-F: Bioclimatic predictive distribution models based on two future climate emissions scenarios (SSP2-45 and SSP5-85) and projected for two future time periods (years 2041-2060 and years

2061-2100) using 30-sec resolution (~1km) CMIP6 downscaled data (WorldClim v2.1).

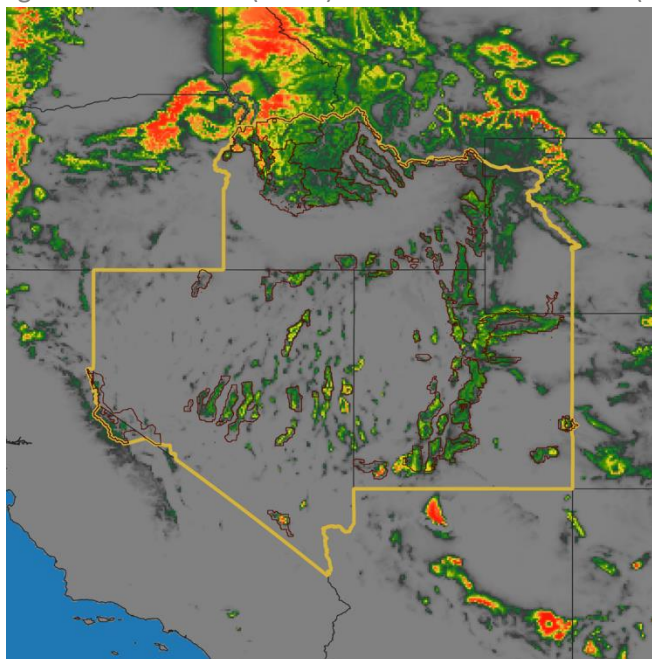
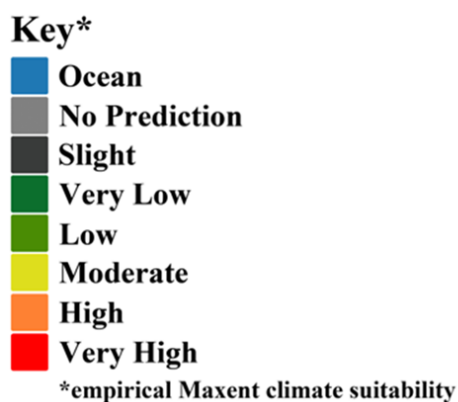


Figure 2: Contemporary *Armillaria solidipes* bioclimatic prediction model from Kim et al. (2021) based on 382 *A. solidipes* point locations across western North America overlayed onto the Intermountain Region.



Key for Figures 1 and 2: Yellow lines on maps indicate the Intermountain Region boundary (Forest Service region 4) and the burgundy lines [surrounding green polygons (USDA forest lands) in Figure 1A] indicate USDA forest boundaries. White dots in Figure 1A indicate point locations used for the Maxent modeling.

Methods

We built upon the methods, data, and lessons from previous studies (Kim et al. 2006, Klopfenstein et al. 2009, Ross-Davis et al. 2012, Hanna et al. 2016, Hanna et al. 2021, Kim et al. 2021, 2023) to improve *A. solidipes* models for the Intermountain Region. Maximum Entropy (MaxEnt) bioclimatic modeling (Phillips et al. 2006) was used with 19 bioclimate grids from WorldClim version 2.1 (Fick and Hijmans 2017) coupled with 28 GPS occurrence locations for *A. solidipes* confirmed via DNA sequencing (Figure 1A). A contemporary model was produced based on climate data from 1970–2000 (Figure 1B). The model was computed from 20 replicate runs using cross-validation.

Predictive distribution models based on future-climate scenarios were also projected for two future time periods (years 2041-2060 and years 2061-2100) using 30-second (ca. 1-km) resolution CMIP6 downscaled data (WorldClim

v2.1). Two different Shared Socioeconomic Pathways (SSPs), detailing expected future CO₂ concentrations, were paired with the “Canadian Ocean Ecosystem model” (CanESM5-CanOE) global climate model (GCM) (Christian et al. 2022). In general, five SSPs narratives describe the broad socioeconomic trends that could shape future society, and we used two scenarios: SSP2-45 (a “middle of the road” future, where trends do not shift markedly from historical patterns) and SSP5-85 (a “fossil-fueled development” future, which follows a path of rapid and unconstrained growth in economic output and fossil fuel-based energy use) (Figure 3).

Main CMIP6 SSP Scenarios

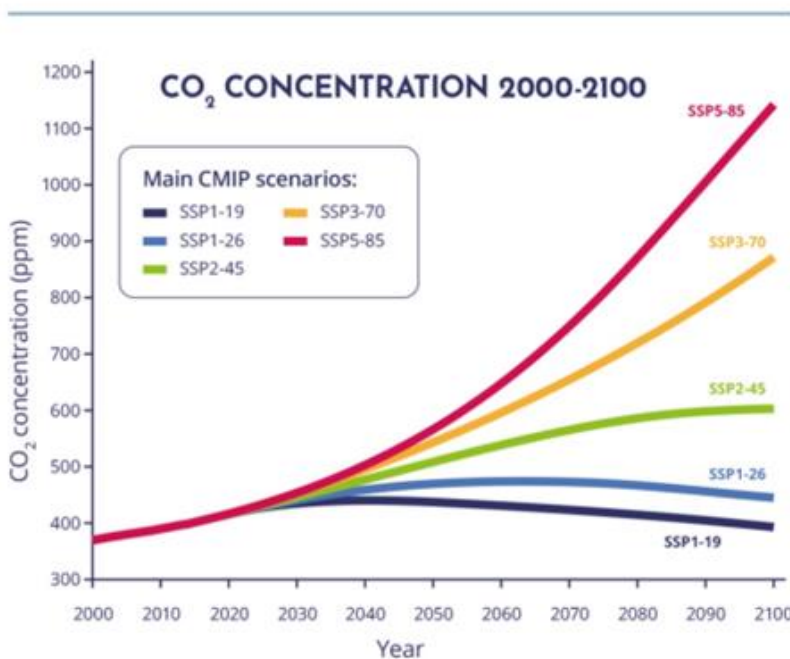


Figure 3: Comparison of CMIP6 SSP emissions scenarios. SSP2-45 (some carbon mitigation and a declining population) and SSP5-85 (“business as usual” scenario) were used for this study. From: “CONSTRAIN (2020) ZERO IN ON: A new generation of climate models, COVID-19 and the Paris Agreement,” by D. Rosen, A. Nauels, K.B. Tokarska, C. McKenna, C.-F. Schleussner, J. Rogelj, and P. Forster, 2020, The CONSTRAIN Project Annual Report 2020, DOI:10.5281/zenodo.4282461. CC BY 4.0.

Results and Discussion

For the contemporary predictive model, the climate variables Max Temperature of Warmest Month (bio5 = 52.1) and Precipitation Seasonality (bio15 = 41.4) had the highest permutation-importance values. The model was scored an average area-under-curve (AUC) score of 0.97 with a standard deviation of 0.098. An AUC score of 1 represents a perfect model, while AUC scores below 0.5 are considered worse than random.

The results of the bioclimatic models for the Intermountain Region show predicted declines in overall climate suitability for *A. solidipes* within the region. These predictions correspond with other previous predictions for host species in the region (Rehfeldt et al. 2006, Rehfeldt et al. 2009, Hanna et al. 2015, Kim et al. 2021, 2023). As the climate warms, the predicted trend is for species’ suitable climate space to shift northward and/or higher in elevation where optimal climate exists for species survival; however, climates may continue warming to a point where even the highest elevations in a region are too warm for a species’ survival. Since the contemporary model shows historic climate data from 1970-2000, it seems likely that some shifts in climate suitability for *A. solidipes* have already occurred, as evident from observed field reports (John Guyon, per. comm.). For example, *A. solidipes*

was not found during additional surveys within areas predicted to have some climate suitability in Nevada and southern Idaho according to the contemporary model. These preliminary observations raise the possibility that the climate suitability in some of these areas may already be closer to the 2041-2060 model than the contemporary model.

Another interesting aspect from this study is the comparison of these Intermountain Region-specific models (Figures 1B-1F) to western North America model from Kim et al. (2021; Figure 2) that was developed using *A. solidipes* locations throughout western North America. The contemporary “all locations” western North America model (Figure 2) shows distinctly different predictions for *A. solidipes* in the Intermountain Region than the Intermountain Region-specific model that solely uses Intermountain Region point locations. Previous studies have shown genetic variation within *A. solidipes* that may correspond to distinct subspecies or populations within *A. solidipes* (Hanna 2005, Hanna et al. 2007). If such genetic differences represent distinct groups within *A. solidipes*, these groups have perhaps evolved with distinct adaptations to climate. Population genetic studies of *A. solidipes* in western North America are needed to investigate this hypothesis. If distinct genetic groups of *A. solidipes* are found, they could be modeled separately to improve the bioclimatic model predictions for *A. solidipes* in western North America, while also identifying threats associated with movement of these genetic groups under contemporary and projected future climates.

Products from this project will guide forest management by providing decision-support tools that predict potential distribution of suitable climate for *Armillaria* root disease under present and future climate scenarios. Management recommendations will offer strategies to reduce *Armillaria* root disease for projected future climates based on climatic adaptation of tree species in relation to *Armillaria*. These decision-support tools will provide guidance for field units for project planning, NEPA documents, and forest plan revisions. This information can also be incorporated into National Disease Risk maps, which will help develop appropriate disease management protocols. In addition, this project can be readily adapted to other important forest pathogens (endemic and invasive).

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