Climate matching models for *Ceratapion basicorne* (Coleoptera: Apionidae), a biocontrol agent of yellow starthistle

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Abstract

Ceratapion basicorne (Illiger) (Coleoptera: Apionidae), a weevil native to Europe and western Asia, shows promise for enhancing the control of yellow starthistle (*Centaurea solstitialis* L.), an invasive annual forb in the western U.S. However, a paucity of data on this biocontrol agent's environmental constraints has made it difficult to assess the suitability of potential release locations. Climate matching models were developed for *C. basicorne* to help identify areas of the western U.S. with similar climates to the source area of breeding colonies being used for releases (home location). The models used climate variables derived from daily estimates of minimum temperature, maximum temperature, precipitation, and soil moisture for a 30-year period spanning 1991−2020 at 1-km^2 resolution. Of the areas where *C. solstitialis* is known to occur, the Central California Foothills, Eastern Cascades Foothills, Columbia Plateau, and mountainous parts of northcentral Utah had the most similar climates to the home location. Of these areas, the Eastern Cascades foothills in northeastern California and Wasatch Range in Utah occurred at a similar latitude as the home location, which may be important to consider if *C. basicorne* has photoperiodic diapause. The least similar climates occurred in wet coastal regions, high-elevation (cold) mountains, and hot deserts; however, *C. solstitialis* has not been detected in most of these areas. The development of process-based models for predicting the establishment of this agent will require a more detailed understanding of the agent's requirements for development and survival.

Key words: environmental similarity, Climatch, CLIMEX indices, decision support

Introduction

Ceratapion basicorne (Illiger) (Coleoptera: Apionidae), locally known as the yellow starthistle rosette weevil, is being reared and studied for use in the biological control of yellow starthistle, *Centaurea solstitialis* L. (Asterales: Asteraceae), in the U.S. There is a well-documented need to complement existing biocontrol for *C. solstitialis* because it is not yet under control over most of its range despite three decades of releasing seedhead feeding insects (Piper, 2001; DiTomaso et al., 2006; Pitcairn et al., 2006). *Ceratapion basicorne* shows promise for improving control of this weed because, unlike currently established biocontrol agents, it can kill whole plants and reduce the growth and reproduction of survivors (Clement et al., 1989; Uygur et al., 2005; Smith and Drew, 2006). Since its approval for release in 2019, *C. basicorne* has been released in a handful of locations in California (Oneto, 2021) and Idaho, but establishment at these sites has not been confirmed.

Presently, all breeding colonies of *C. basicorne* in the U.S. are derived from a single location in Kilkis, Greece (home location), which represents only a subset of climates and photoperiods where the species occurs in its native range in Europe and western Asia (Fig. 1) (Alonso-Zarazaga, 1990; GBIF.org, 2024a). The influence of photoperiod and climate on the development and survival of *C. basicorne* is not well understood, which has made it challenging to rear insects in large numbers and to identify areas with potentially suitable environments for establishment (Smith and Drew, 2006; Smith and Park, 2022). *Centaurea solstitialis* occurs over a wide range of climates and photoperiods in the U.S. (DiTomaso et al., 2006; Pitcairn et al., 2006; Innes and Zouhar, 2021), which may be problematic for the establishment of *C. basicorne* if the agent is locally adapted to environments in the home location. Obtaining insects from additional areas in the native range is difficult because the U.S. Department of Agriculture (USDA) Animal and Plant Health Inspection Service (APHIS) requires rigorous host-specificity testing from each new location.

The objective of this study was to model the similarity of climates in the home location of *C. basicorne* to those in the western U.S. (away locations) to identify potentially suitable areas for the agent's establishment. Climate matching models are regularly used for species in new environments, such as biocontrol agents and invasive pests, particularly when little information exists on the species' ecology and geographical distribution (Robertson et al., 2008; Kriticos, 2012; Venette, 2017; Kriticos et al., 2021). Despite their simplicity, they may exhibit high rates of accuracy in predicting areas suitable for the establishment of introduced species (Howeth et al., 2016; Roigé and Phillips, 2021). Releasing biocontrol agents in areas that are climatically matched to their geographic origins in the native range may increase chances of establishment because agents often have existing adaptations to climates in these new locations (Harms et al., 2020; Harms et al., 2021).

Materials and Methods

Modeling was conducted in R version 4.3 (R Development Core Team, 2023).

Climate matching models

Climate matching models for *C. basicorne* used averages of minimum and maximum temperatures (T_{max} and T_{min}, respectively), precipitation, and soil moisture for a 30-year period spanning 1991−2020. Moisture factors were included because water is a known limiting resource for *C. solstitialis* in the western U.S. (Dukes, 2001; Dukes, 2002; Dlugosch et al., 2015), and it may therefore indirectly influence the success of *C. basicorne*. Daily temperature and precipitation data were derived from the Daymet dataset for North America at 1-km^2 resolution (Thornton et al., 2020; Thornton et al., 2021) (https://daymet.ornl.gov/getdata, accessed 17 May 2024) and the E-OBS dataset for Europe at 0.1° deg resolution (*ca.* 11.1 km^2; https://surfobs.climate.copernicus.eu, accessed 13 Jul 2022) (Cornes et al., 2018). Daily soil moisture estimates at the first 5 cm depth were derived from the Simple Terrestrial Hydrosphere model, version 2 (SiTHv2) at 0.1° deg resolution (Zhang et al., 2024). SiTHv2 data were downscaled to 1-km^2 resolution for the western U.S. to match the resolution of Daymet data. All datasets were temporally aggregated to a weekly and monthly resolution for modeling.

The first climate matching model used ‘match index’ equations derived from the “Match Climates” function in CLIMEX v. 4 (Kriticos et al., 2016). R was used instead of CLIMEX because it allows climate data to have any spatial and temporal resolution, whereas CLIMEX uses coarse-scale (10′ = *ca.* 18.5 km^2) climate normals for a period (1961−1990) that is no longer included in official U.S. climate normals due to global warming (Lindsey, 2021). Appendix S1 presents the equations used for calculating the temperature index (I_t), soil moisture index (I_{sm}) moisture index (I_m), and composite match index (CMI) from weekly climate data (Appendix S1). Index values range from 0 (poorly matched) to 1 (perfectly matched) (Sutherst and Maywald, 1985; Kriticos et al., 2016).

The second climate matching model used the Climatch algorithm (“climatch_vec” function) in the *Euclimatch* R package v. 1.0.1 (Hubbard et al., 2023). Climatch uses a metric similar to Euclidean distance to calculate the ‘climate distance’ between home and away locations (Crombie et al., 2008; ABARES, 2020; Erickson et al., 2022). The model used six bioclimatic variables derived from 30-year averages of monthly temperature, precipitation, and soil moisture using the “bcvars” function in the *predicts* R package 0.1.11 (Hijmans et al., 2023). These included T_{max} of the warmest month (bio5), T_{min} of the coldest month (bio6), annual precipitation (bio12), highest monthly soil moisture (bio29), and lowest monthly soil moisture (bio30). Four models were developed to estimate similarity based on temperature (bio 5 and bio6), precipitation (bio12), soil moisture (bio29 and bio30), and all variables. Weekly climate data were not used because Climatch predicted complete dissimilarity (score = 0) across the entire western U.S. Decreasing scores with an increasing number of variables occurs because the model captures more sources of variation and therefore presents stricter criteria for climate matching (Burner et al., 2023).

The latitude of 41 °N was delineated on model outputs to indicate areas that experience similar daylengths as the home location for *C. basicorne*. Local adaptation in photoperiodic diapause across latitudes has been demonstrated in a range of insect species in seasonal environments (Tauber and Tauber, 1976; Gotthard and Wheat, 2019). Releasing *C. basicorne* at similar latitudes as the home location may reduce the likelihood of diapause occurring at inappropriate times (Grevstad et al., 2022).

Model predictions were binarized and overlayed with a county-level status map for *C. solstitialis* to identify areas where the host and well-matched climates for *C. basicorne* co-occurred. Threshold values of 0.6 and 0.1 were used to binarize predictions based on the CMI (Sutherst, 2003; Kriticos, 2012; Venette, 2017) and Climatch score, respectively. Presence records for *C. solstitialis* were derived from the Early Detection and Distribution Mapping System (N = 32482) (EDDMapS, 2024) and the Global Biodiversity Information Facility (N =

8153) (GBIF.org, 2024b). A single record was retained for each county, for a total of 182 records from 11 states.

Results

According to both climate matching models, the most similar climates to the home location of *C. basicorne* occurred in parts of California (Central Valley Foothills, Central and South Coast of California, and the Eastern Cascades foothills), northern Arizona and southwestern Colorado, and the northern Great Basin in Nevada and Utah (Central Basin and Range and Wasatch Mountains) and in the Pacific Northwest (Columbia Plateau, Northern Basin and Range, Blue Mountains, and Snake River Plain) (Fig. 2). Parts of New Mexico and the Great Plains region were also well-matched; however, *C. solstitialis* has not been detected in most of those areas. In considering both climate and photoperiod in areas with *C. solstitialis*, the most similar environments occurred in the Eastern Cascades foothills in northeastern California and the Wasatch Mountains in Utah.

The least similar climates to the home location of *C. basicorne* occurred in very wet areas, such as the Coast Range in western Oregon and Washington, as well as very cold areas, such as high-elevation parts of the Cascades and Rocky Mountains (Figs. 2 and 3). Additionally, much of the desert Southwest, including the Mojave and Sonoran deserts, was poorly matched owing to hot temperatures and low precipitation and soil moisture (Fig. 3b, c). Parts of northwestern California and western Oregon were well-matched in terms of temperature but poorly matched in terms of precipitation and soil moisture (Fig. 3). In general, *C. solstitialis* has not been detected in areas with poorly matched climates for *C. basicorne* (Fig. 2).

According to the CMI, many areas in the Rocky Mountains and Great Plains region (e.g., eastern Montana, Wyoming, and Colorado) were as climatic similar to the home location for *C. basicorne* as certain parts of California and the Pacific Northwest (Fig. 2). Conversely, the Climatch model predicted relatively low similarity for most areas outside of California and the Pacific Northwest (Fig. 2), owing primarily to dissimilarity in extremes in monthly temperatures (i.e., bio5 and bio6) (Fig. 3a). The different equations and datasets used for modeling likely explain these differences.

Discussion

Climate matching models for *C. basicorne* predicted similar climates to the home location of the agent across most regions of the western U.S. where *C. solstitialis* is widespread and abundant, including much of central and northern California and the Columbia Plateau (DiTomaso et al., 2006; Pitcairn et al., 2006; Innes and Zouhar, 2021). The Eastern Cascades foothills region was highly matched region in terms of both climate and photoperiod, which suggests that it may be ideal for releases if *C. basicorne* has photoperiodic diapause. Well-matched climates also occurred in the Central and South Coast of California and in the foothills surrounding the Central Valley, where a small number of releases have already occurred. The duration of the developmental window for *C. basicorne* to feed and lay eggs is likely to be more restricted in northern areas, such as the Columbia Plateau, because temperatures that support rosette growth arrive much later in the spring. Additionally, insects may emerge too early in northern locations if they use photoperiod as a cue for diapause termination.

Centaurea solstitialis has been spreading eastward in the Intermountain West, where it is listed as a high priority weed for eradication in many states. The Greater Salt Lake City region may be ideal for *C. basicorne* because it has similar photoperiods and climates to the home location and the weed is particularly abundant (Rieder, 2005). Northeastern Colorado had moderately matched climates and similar photoperiods; however, *C. solstitialis* is not presently well-established in this area.

Areas with well-matched climates for *C. basicorne* only partially overlapped with an estimate of the potential distribution of this agent in the western U.S. according to a physiologically-based model (Gutierrez et al., 2017). The latter model made several assumptions about *C. basicorne*'s thermal biology and excluded parts of its native range in the potential distribution, which suggests that further refinements may be needed. Climate matching models were less complex and included both temperature and moisture factors, which may also explain discordance in predictions. For example, the physiologically-based model predicted the highest density of *C. basicorne* in western Oregon, but this area was poorly matched to the home location owing to high moisture according to climate matching models.

The development of process-based models for predicting the establishment of *C. basicorne* will require data on the agent's development and survival under different conditions. Observations of breeding colonies to date suggest that the duration of cold temperatures is an important stimulus to terminate reproductive diapause, and that diapause after one generation might be obligatory, at least under the tested photoperiods (Smith and Drew, 2006; Smith and Park, 2022). Future work should estimate *C. basicorne*'s temperature thresholds for development, degree-day requirements for different life stages, tolerances to thermal stresses, and potential responses to environmental cues such as photoperiod.

Data Availability Statement

Data and scripts from this study are available at GitHub (https://github.com/bbarker505/CEBA_climMatch) and the Dryad Digital Repository: doi: 10.5061/dryad.vmcvdnd2w (Barker 2024).

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Fig. 1. Occurrence records for *C. basicorne* in its native range. Records were derived from peer-reviewed literature (Alonso-Zarazaga, 1990), the Global Biodiversity Information Facility (GBIF.org, 2024a), and unpublished field data. The red triangle depicts the home location for all present breeding colonies in the U.S. (Kilkis, Greece).

Fig. 2. Climate matching predictions for *C. basicorne* in the western U.S according to (A) the CLIMEX-based composite match index (CMI) and (B) the Climatch score based on all bioclimate variables. Higher CMI values and Climatch scores indicate greater climatic similarity to the home location (Kilkis, Greece) (left panels). The county-level status of *C. solstitialis* (detected vs. undetected) is shown in areas that are climatically matched for *C. basicorne* based on the two models (CMI ≥ 0.6 and Climatch score ≥ 0.1) (right panels). All maps depict the latitude of the home location (dashed line) to indicate areas with similar photoperiod.

Fig. 3. Climate matching predictions for *C. basicorne* in the western U.S. according to CLIMEX-based models (left panels) and Climatch models (right panels) that used only (A) temperature, (B) precipitation, and (C) soil moisture variables. Maps depict the latitude of the home location (dashed line) to indicate areas with similar photoperiod. I_t = temperature index, I_m = moisture index, and I_{sm} = soil moisture index