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Short Communication

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Short Communication

Potential distribution and spread of Japanese beetle in Washington State

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The Japanese beetle, *Popillia japonica* (Newman, 1841) (Coleoptera: Scarabaeidae), was first detected in southern Washington State in 2020. Widespread trapping efforts ensued, and over 23,000 individuals were collected in both 2021 and 2022 in this region known for specialty crop production. The invasion of Japanese beetle is of major concern as it feeds on over 300 plant species and has shown an ability to spread across landscapes. Here, we created a habitat suitability model for Japanese beetle in Washington and used dispersal models to forecast invasion scenarios. Our models predict that the area of current establishment occurs in a region with highly suitable habitat. Moreover, vast areas of habitat that are likely highly suitable for Japanese beetle occur in coastal areas of western Washington, with medium to highly suitable habitat in central and eastern Washington. Dispersal models suggested that the beetle could spread throughout Washington within 20 years without management, which justifies quarantine and eradication measures. Timely map-based predictions can be useful tools to guide management of invasive species while also increasing citizen engagement to invaders.

Key words: invasive species, quarantine, risk assessment, survey, detection

Introduction

Japanese beetle, *Popillia japonica* (Newman, 1841) (Coleoptera: Scarabaeidae), is a notorious invasive pest in the eastern and midwestern United States. Adults of the species feed voraciously on over 300 plant species, while larvae feed in the soil on roots of turf and other plants (Potter and Held 2002). Japanese beetle adults are strong flyers and can readily be relocated via movement of goods and people. Dispersal models, and studies conducted in the United States and Europe, show beetle populations expand at a rate between 8 and 15 km/yr in newly invaded regions (Fleming 1972, Allsopp 1996, Lessio et al. 2022, Mondino et al. 2022).

Japanese beetle individuals were first detected in central southern Washington in 2020 in a trap located in a commercial parking lot. More widespread trapping efforts for Japanese beetle ensued in 2021 (900 traps) and 2022 (2,300 traps) in Washington, and over 23,000 beetles were trapped around the cities of Grandview and Sunnyside. This area is known for specialty crop production, with considerable acreage planted to potentially susceptible crops including grapes, hops, and cherries. Given that the beetle has recently established, it is crucial to implement effective approaches to quarantine and eradicate these populations (Reaser et al. 2020). In quarantined areas of Washington, the insecticide Acelepryn is applied for control, and yard debris, potted plants, soil with vegetation, and other items are quarantined due to their high risk of spreading the pest (WSDA 2022). These methods were useful in eradicating former Colorado and California establishments (Althoff and Rice 2022).

Ongoing efforts to quarantine and eradicate Japanese beetle would benefit from a more precise understanding of its potential distribution in Washington as well as estimates of invasive spread. In this short communication we address these 2 goals, first by building habitat suitability models for Japanese beetle in Washington, and second by performing dispersal simulations to predict invasive spread. Our forecasts can be used to aid in effective surveillance and eradication strategies to prevent further spread of this devastating invader.

Materials and Methods

Habitat Suitability Modeling

We used 2 approaches to estimate habitat suitability for Japanese beetle. Our "physiological model" used a technique similar to the CLIMEX platform by relating specific physiological thresholds of Japanese beetle to climatic variables in a spatial context, identifying areas that could allow for survival and development (Kearney and Porter 2009, Grünig et al. 2020). Our "correlative niche model" used the platform MAXENT to relate species occurrence records to environmental variables across geographic space (Peterson et al. 2011). We also created an ensemble model that averaged predictions of the 2 models on a pixel-by-pixel basis. More information on each of the 2 primary models is provided in the sections to follow. All model predictions were deposited in Open Science Framework at https://osf.io/7spjf, they can be viewed and modified in any GIS platform. A HTML file was also provided for interactive view of ensemble model prediction.

Physiological Model.

The approach to building a physiological habitat suitability model, widely exemplified by CLIMEX (Jung et al. 2016), is to model a species' fundamental niche and project these requirements onto geographic spaces to identify potential habitat (Peterson et al. 2015). Typically, physiological data are obtained through controlled experiments, such as studies that assess survival, development, or fecundity at variable temperatures. By relating the physiological thresholds to climate variables over space (e.g., spatial temperature data), areas where conditions are suitable for the species to survive and develop are identified (Kearney and Porter 2009).

Our physiological model calculated a suitability index for Japanese beetle by coupling the beetle's physiological data with gridded monthly mean, minimum, and maximum temperature data. This suitability index is calculated on a cell basis in a spatial raster layer (grid size 1 km) by multiplying a temperature index, a growing index, and a killing index (Grünig et al. 2020). We obtained physiological parameters from a previous Japanese beetle model that calculated a low development threshold (10°C), a growing degree requirement for the life cycle (525 DD), and cold (–15°C) and heat (34°C) tolerant temperatures (Kistner-Thomas 2019). We also used a low development threshold of 15°C following the recent degree day model (Ebbenga et al. 2022). Our final physiological models were averaged based on these 2 low thresholds. The raster data for monthly mean, minimum and maximum temperatures were obtained by CHELSE (Karger et al. 2020).

Correlative Niche Model.

Correlative niche models assess ecological requirements of a species by associating environmental factors with occurrence records (Peterson et al. 2011), often using the MAXENT platform (Phillips et al. 2017). We built a habitat suitability model using MAXENT and occurrence records from Zhu et al. (2016), iNaturalist (www.inaturalist.org), and the Global Biodiversity Information Facility (www.gbif.org) using the *spocc* package in R (Owens et al. 2023). A total of 845 records were retained after applying a filter of 50 km between records to limit sampling bias (Warren and Seifert 2011). We used a "random" method to select 10,000 pseudo-absence records from the "accessible" areas, where the accessible areas were delimited by creating a minimum convex polygon around observed points and applying 400 km buffers (Barbet-Massin et al. 2012).

Environmental data included 6 variables that constrain Japanese beetle populations (Zhu et al. 2016): (i) annual mean temperature, (ii) max temperature of warmest month, (iii) minimum temperature of coldest month, (iv) annual precipitation, and (v, vi) the precipitation of the wettest and driest months. These variables were interpolated and spatially averaged; air temperature and precipitation were measured from weather stations with annual trends and extremes were summarized (Fick and Hijmans 2017). Japanese beetle larvae rely on soil temperature to develop. Studies also show that rainfall in July and August are limiting factors in earlier stage (i.e., egg and 1st instars) development (Hanula 1990). Annual mean and extremes (max temperature of warmest month, min temperature of coldest month) of soil temperatures measured at 0–5 cm depth (soiltempproject.com), and precipitation of July and August (worldclim.org) were therefore also included in the MAXENT model. Although these variables can be collinear, MAXENT accounts for redundant variables in the approach (Feng et al. 2019). All variables had a resolution of 1 km. In MAXENT, we used the fine-tune setting to minimize model complexity and overfitting (Warren and Seifert 2011, Muscarella et al. 2014). MAXENT models were fine-tuned using the block method and AIC criteria in the *ENMeval* package in R (Muscarella et al. 2014).

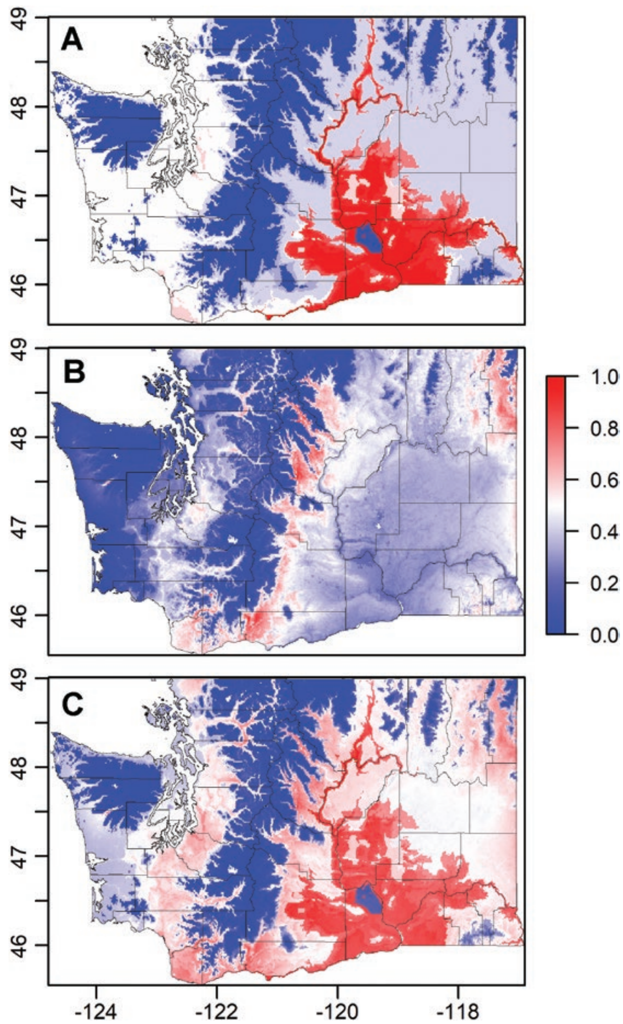

Fig. 1. The predicted habitat suitability for Japanese beetle based on A) the physiological model, B) the correlative niche model, and C) the ensemble model. Value range from 0.0 (habitat is completely unsuitable) to 1.0 (habitat has maximum suitability) (See online version for color figure).

Model Evaluation.

To assess models, 50% of records were used for model training and 50% for evaluation. We used the partial area under the receiver operating characteristic curve (partial ROC) approach for evaluation (Peterson et al. 2008). The partial ROC approach uses the AUC ratio (area under the ROC curve) to test model performance, ranging from 0 to 2, with values of 1 representing random performance. The physiological model was also evaluated using the partial ROC approach and using the same testing data as the MAXENT model.

Dispersal Simulations

We conducted dispersal simulations to predict spread of Japanese beetle in Washington using the *MigClim* package in R (Engler et al. 2012). MigClim simulates dispersal away from an incursion zone using a time step, which we set as 1 year because Japanese beetle completes 1 generation a year in Washington State. We used records on Japanese beetle detections in Washington as the "incursion population". *MigClim* also incorporates habitat suitability values, as only potentially suitable grid cells can be sites for establishment. This required us to convert our habitat suitability predictions from the ensemble model into binary values (suitable or unsuitable); this was achieved using a 5% omission error threshold from the calibration records (i.e., 5th training threshold). We chose a conservative threshold that allowed us to identify potential suitable habitats for establishment.

We ran simulations for 20 years with 2 scenarios: (i) short-distance dispersal only and (ii) both short- and long-distance dispersal. To define short-distance dispersal, studies in the United States and Italy show populations regularly spread between 7 and 15 km/yr (Allsopp 1996, Mondino et al. 2022). We used a value of 15 km/yr along with a dispersal kernel that assumed an exponential decline in movement at greater distances. We used 30 km/yr for long-distance dispersal based on values seen in flight studies (Lessio et al. 2022). While longer-distance dispersal via human activity is possible, we chose conservative values that likely capture the vast majority of human-mediated dispersal. We set the dispersal probability within any suitable grid cell as 1; this reflects our assumption that all patches occupied by Japanese beetle can be future sources of dispersal. We also assumed there are no geographic barriers to dispersal.

Results

Both the physiological (AUC = 1.54) and correlative niche models (AUC = 1.81) showed strong performance. Globally, the models

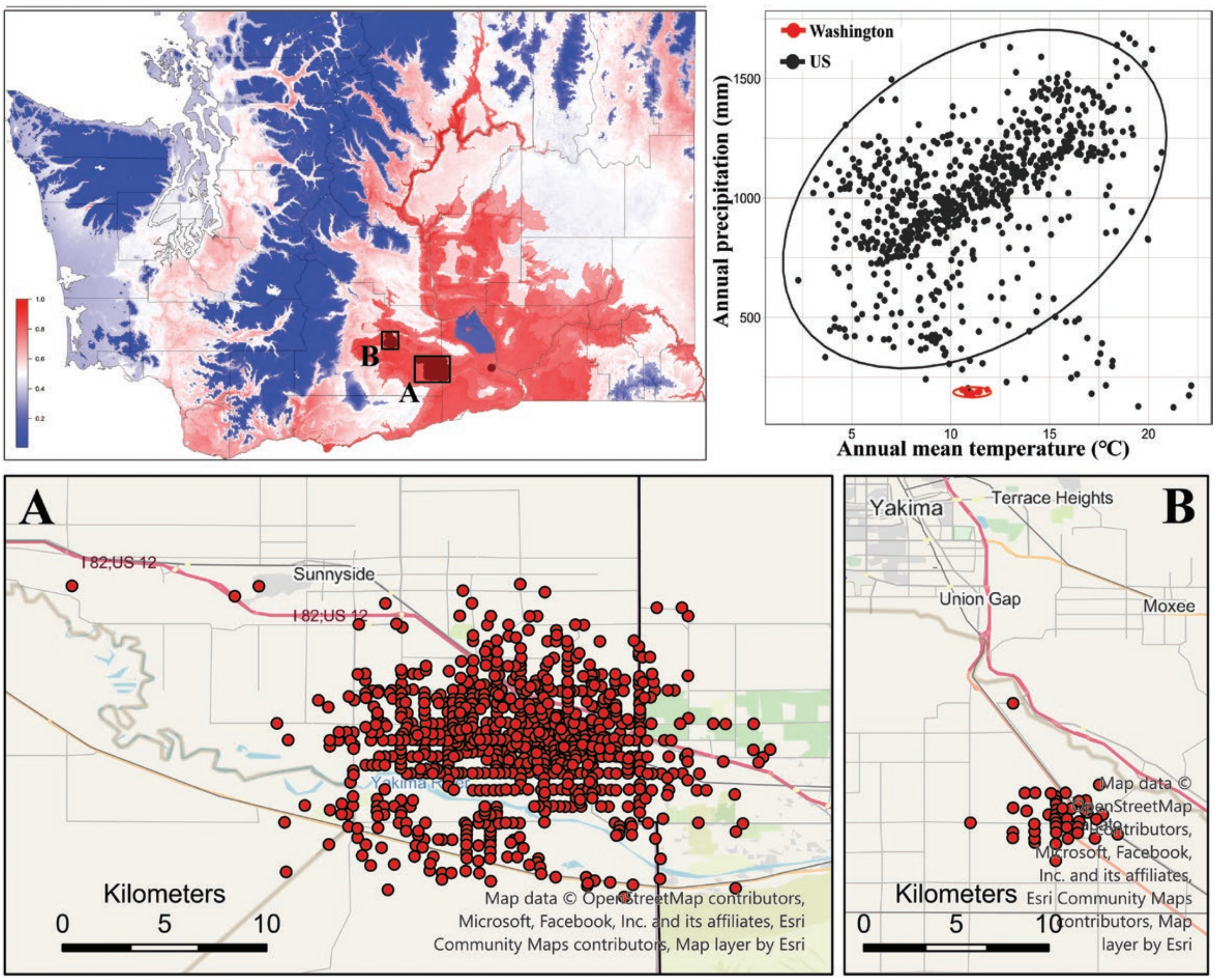

Fig. 2. Shown in the top left panel are habitat suitability values from the ensemble model overlaid with the distribution of established Japanese beetle populations (areas A and B which are zoomed into in panels A and B). In the top right panel, we show the annual mean temperature and annual rainfall for all occurrence records in the United States and Washington (A and B) specifically (See online version for color figure).

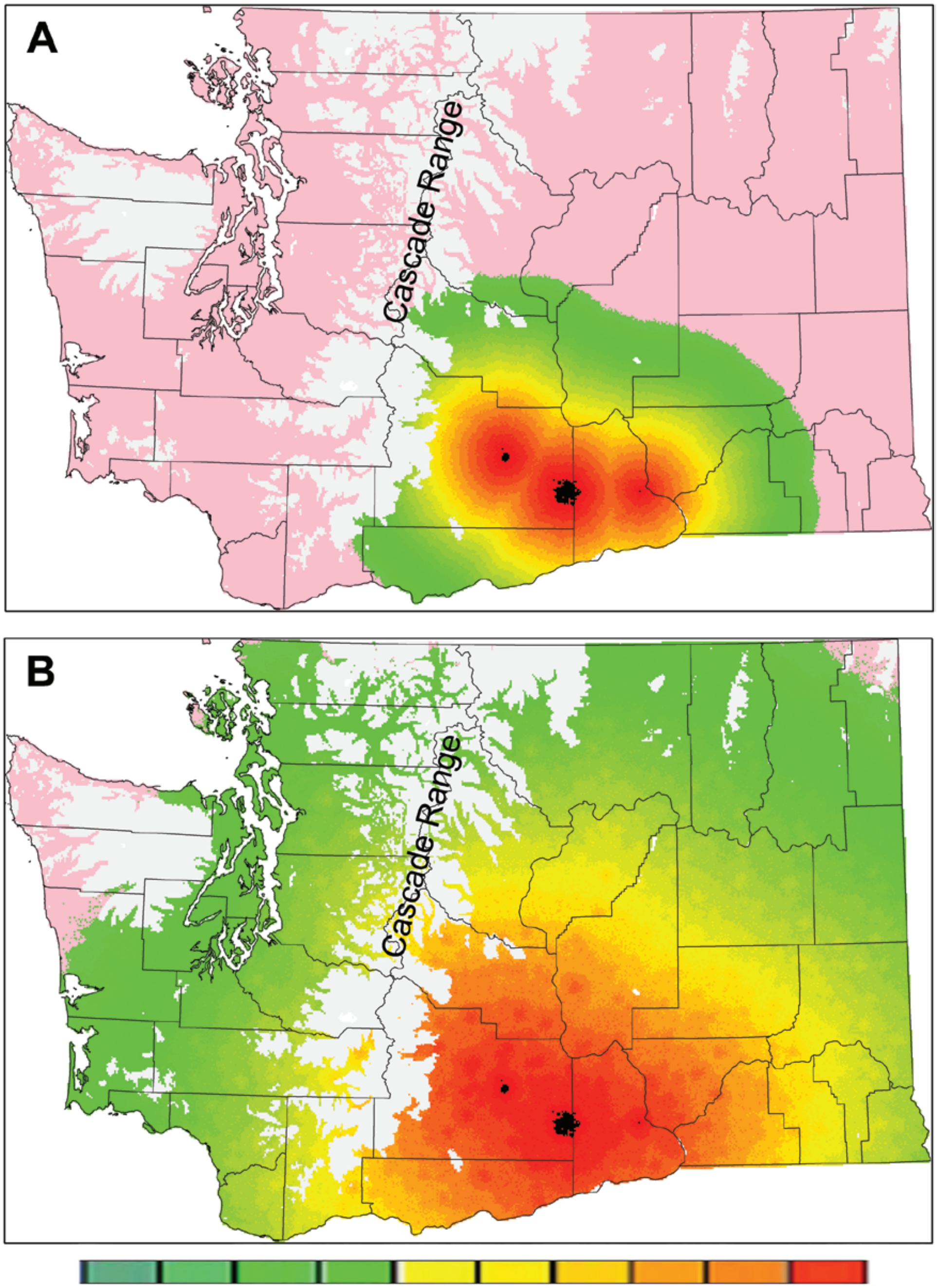

Fig. 3. Estimated spread of Japanese beetle in Washington State under 2 dispersal scenarios: A) short-distance only and B) both short- and long-distance. Each distinct color represents 2 dispersal steps (total 20) (red = current; yellow = 10-year prediction; green = 20-year prediction) (See online version for color figure).

were positively correlated (Spearman rank correlation = 0.63). However, the models showed less congruence in Washington State (Spearman rank correlation = 0.18) (Fig. 1A and B). In Washington, the 2 models showed high suitability in low elevation areas along the western coast, but predictions contrasted in the inland of the state (Fig. 1A and B). An ensemble model that averaged the 2 predictions was generated to reduce the uncertainty and to conduct the dispersal simulations (Figs. 1 and 2). With the ensemble model, the majority of low-elevation coastal areas were highly suitable, and vast areas in central and eastern Washington have medium to high suitability (Fig. 1C). Projections of occupied climate spaces in the United States also showed that beetle populations in Washington occupy a relatively small climate space that consists of drier and colder conditions than other invaded regions of the United States (Figs. 1 and 2).

The short-distance dispersal simulations show Japanese beetles could spread and occupy most habitat in central-southern Washington within 20 years (Fig. 3A). Simulations that included both short- and long-distance dispersal suggest the beetle could spread across the entire state within the same 20-year period (Fig. 3B). Both dispersal simulations show that without preventative management, the beetle could occupy central southern Washington State within 10 years (Fig. 3B). However, dispersal models show that the Cascade Mountain Range could be a barrier against westward expansion, especially in short-distance only simulations (Fig. 3A).

Discussion

Our habitat suitability predictions are largely congruent with other models for Japanese beetles in other invaded regions worldwide (Zhu et al. 2016, Kistner-Thomas 2019) and show broad areas of suitable habitat in Washington and globally (Figs. 1 and 2). While beetle populations currently found in Washington are confined to the cities of Sunnyside and Grandview, both models found large patches of suitable habitat around these locations (Figs. 1 and 2). Given that vast acreage of high-valuable specialty crops such as grapes, hops, and cherries are produced in the region, further spread of Japanese beetles could be devastating for Washington's agricultural industry. Present Washington State populations were established in a relative dry area (i.e., annual precipitation < 250 mm, Fig. 2), so further spread should be carefully monitored to verify whether they have adapted to even drier conditions.

By complementing our habitat suitability models with dispersal simulations, our study not only estimated potential regions that could be suitable for Japanese beetle, but also how quickly beetles might reach uninvaded areas. Both short- and long-distance dispersal simulations suggest beetle populations could rapidly expand throughout south-central Washington and potentially the entire state within 20 years. While the Cascade Mountain range might serve as a barrier to dispersal, Japanese beetle have shown an ability to hitchhike with humans over long distances (Potter and Held 2002). Western Washington has considerable acreage planted to high-value small fruit and vegetable crops that might also be susceptible to Japanese beetle, combined with a large urban population that could be impacted by these pests. Given predictions that habitat in Western Washington is likely even more suitable than the region currently invaded, it is imperative that quarantine efforts prevent further spread of the beetle west beyond the Cascades. Long-term monitor data could help us estimate a real expansion rate and validate our dispersal model.

Early detection and rapid response are the most cost-effective ways to minimize impacts of emerging invasive species (Reaser et al. 2020). So far, Japanese beetle is confined to 2 large but relatively isolated areas (Fig. 2A and B), and it is critical to prevent their further expansion. In September 2022, the Washington State Department of Agriculture established a quarantine zone to limit movement of certain items within the infested area (WSDA 2022), aimed at eradicating the southern establishment zone in close proximity to considerable specialty crop production (Fig. 2A). While the initial quarantine zone did not include the northwestern establishment zone (Fig. 2B), recently an emergency rule was filed to expand the present quarantine in the southern establishment zone (WSDA 2022).

Our map-based forecasts can aid efforts to identify future quarantine zones and provide timely support for decision making for ongoing monitoring and eradication programs. Moreover, habitat suitability modeling can aid in engaging citizens to monitor "high risk" zones to help the track progress of an invasion. Additional monitoring is likely needed to aid in eradicating the northwestern establishment zone within Washington that is not included in present expanded quarantines (Fig. 2B). For Japanese beetle and other invasive species, studies like the one conducted here can help identify patches where establishment is likely and eradication efforts can be focused on reducing the spread of invasive species.

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Author Contributions

Gengping Zhu (Conceptualization-Lead, Formal analysis-Lead, Methodology-Equal, Validation-Lead, Writing – original draft-Lead, Writing – review & editing-Lead), Liesl Oeller (Formal analysis-Equal, Writing – review & editing-Equal), Rian Wojahn (Data curation-Equal, Resources-Equal, Visualization-Equal), Camilo Acosta (Data curation-Equal, Resources-Equal, Visualization-Equal), Joshua Milnes (Data curation-Equal, Resources-Equal, Visualization-Equal, Writing – review & editing-Equal), David Crowder (Conceptualization-Equal, Formal analysis-Equal, Funding acquisition-Equal, Methodology-Equal, Supervision-Equal, Validation-Equal, Writing – review & editing-Equal), Gengping Zhu (Conceptualization-Equal, Data curation-Equal, Formal analysis-Equal, Investigation-Equal, Methodology-Equal, Validation-Equal, Writing – original draft-Equal).

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