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Assessing the Risk of Establishment of *Rhagoletis cerasi* (Diptera: Tephritidae) in the United States and Globally

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Abstract

The European cherry fruit fly, *Rhagoletis cerasi* (L.) (Diptera: Tephritidae), is a highly destructive pest of cherries (*Prunus* spp.) (Rosaceae) in Europe and Asia. In 2016, *R. cerasi* was detected in Ontario, Canada, and in 2017 in New York State, USA, the first records of this pest in North America. The initial detections in Canada caused concern for the major cherry-growing states of Michigan, Washington, Oregon, and California in the United States. Establishment of *R. cerasi* in the United States could restrict cherry exports to other markets and increase costs needed for fly control, but it is unknown if *R. cerasi* can establish in U.S. commercial cherry regions. Here, we used the CLIMEX ecological niche model to determine the risk of establishment of *R. cerasi* in the United States and globally. Within the United States under a no-irrigation scenario, *R. cerasi* would establish in the East and West Coasts; however, under an irrigation scenario, its distribution would expand to the major cherry-growing regions in the interior of central and eastern Washington and in California. Results also showed that if introduced, *R. cerasi* would likely establish in eastern China, Japan, the Koreas, Australia, New Zealand, South America, South Africa, Mexico, and Canada. Host plant (*Prunus* spp. and *Lonicera* spp. [Caprifoliaceae]) presence, although not included in models, would affect fly establishment. Our results stress the importance of surveying for *R. cerasi* to prevent its spread and establishment within the United States and other countries.

Key words: European cherry fruit fly, ecological niche model, CLIMEX, irrigation, California

The European cherry fruit fly, *Rhagoletis cerasi* (L.) (Diptera: Tephritidae), is a highly destructive pest of cherries (*Prunus* spp.) (Rosaceae) in Europe and Asia. It was detected for the first time in North America on 27 June 2016 in an urban park located in Mississauga, Ontario, Canada, in association with invasive honeysuckle (*Lonicera* spp.) (Caprifoliaceae) (CFIA 2017). In 2017, it was detected in Niagara County in New York State, USA (Anonymous 2017a). Due to the initial detections of *R. cerasi* in Ontario, the United States Department of Agriculture's Animal and Plant Health Inspection Service (USDA-APHIS) implemented restrictions for the importation of *R. cerasi* host commodities from Canada into the United States on 23 May 2017 (USDA-APHIS 2017). Its presence in Canada and New York has caused concern for the major cherry-growing states of Michigan, Washington, Oregon, and California in the United States. Washington, California, and Oregon are the major producers of sweet cherry (*Prunus avium* (L.) L.) in the United States, and Michigan is the major tart cherry (*Prunus cerasus* L.) producer (NASS 2017). Both cherry species were introduced into the United States and are native to Europe and western Asia, where they are hosts of *R. cerasi* (Daniel and Grunder 2012).

The biology of *R. cerasi* has been well studied in Europe and Asia (Daniel and Grunder 2012). Adult fly phenology and diapause schedules are closely linked to the phenology of host plants (Boller et al. 1998), which for *R. cerasi* are *P. avium*, *P. cerasus*, *Prunus malaleb* L. (Boller and Bush 1974), *Prunus serotina* Ehrh. (Hendel 1927), *Berberis vulgaris* L. (Berberidaceae) (Boller and Bush 1974), and the honeysuckles *Lonicera tartarica* L. (Bush and Boller 1977) and *Lonicera xylosteum* L. (Boller and Bush 1974). *R. cerasi* is a univoltine species with a short period (4–8 wk) of adult occurrence in the wild (Kovanci and Kovanci 2006a,b; Stamenković et al. 2012). There is a long pupal diapause that spans from summer to the middle of winter (Moraiti et al. 2012a). Temperatures <5°C for ~180 d are needed for maximum adult emergence (Daniel and Grunder 2012). Postdiapause development may be long or short in cold or warm areas, respectively (Papanastasiou et al. 2011). Synchronization of adult occurrence with host fruiting period and seasonality of developmental events might be the two most important factors that determine the probability of fly establishment in a given area (Zwölfer 1983). *Rhagoletis cerasi* is a wide-ranging species present in 30 and 8 countries in Europe and Asia, respectively (USDA-APHIS-PPQ 2017). The species comprises northern and southern races (Boller et al. 1976) as well as *Prunus* and *Lonicera* host races (Boller et al. 1998). There is cytoplasmic incompatibility among fly populations caused by *Wolbachia* infections, but geographic distributions of *Wolbachia* infections do not seem affected by host race (Riegler and Stauffer 2002).

The wide range of *R. cerasi* in Europe suggests the fly would be able to establish across varied habitats in the United States, including in cherry-growing regions where it could restrict cherry exports to other markets. Because of the size of the U.S. cherry industry, the economic impact of its establishment would be significant. In 2016, the United States exported the second highest dollar value of sweet cherries in the world, at US$455.5 million (Workman 2017). Its presence could increase costs needed for fly control. Although sprays currently directed against the western cherry fruit fly *Rhagoletis indifferens* Curran (Diptera: Tephritidae) (western United States) and the eastern cherry fruit fly *Rhagoletis cingulata* (Loew) (Diptera: Tephritidae) (eastern United States) are very effective (Wise et al. 2012, Smith 2017) and may also control *R. cerasi*, additional pest pressure from *R. cerasi* could increase numbers of sprays needed, especially in regions like California that lack *R. indifferens* in their commercial production areas (Dowell and Penrose 2012) but that could be suitable for *R. cerasi*. If models predict *R. cerasi* can establish in those regions, then pest control advisors and growers there need to be prepared for managing the pest.

Based on the fly's known global distribution, the USDA's Center for Plant Health Science and Technology (USDA-CPHST 2016a) predicted the potential range of *R. cerasi* to include USDA plant hardiness zones 2–10. USDA-APHIS (2017) predicted *R. cerasi* could establish in plant hardiness zones 2–6 or 7. USDA-CPHST (2016a) also produced a combined host (sweet and tart cherry) density map for *R. cerasi* within the continental United States, but it did not directly relate areas of high cherry density to potential distributions of the fly. As of yet, the fly's potential distribution in the United States has not been determined using rigorous predictive ecological niche models. In addition to the United States, many other countries outside of Europe and Asia, where *R. cerasi* does not occur, also produce cherries. Establishment of the fly in those countries could impact cherry export and import policies in the United States and all cherry-producing countries; thus, it should be predicted using ecological niche models as well.

Here, we used the ecological niche model CLIMEX to determine the risk of establishment of *R. cerasi* in the United States and globally. Findings are discussed with respect to factors affecting the fly's potential distribution, relationships between the fly's potential distribution and host plant presence, and the potential threat of the fly to the U.S. cherry industry. We also compare findings for *R. cerasi* with those for *R. indifferens* from previous work.

Materials and Methods

CLIMEX relies on biologically meaningful physiological parameters for mapping the distributions of organisms (Sutherst and Maywald 1985, Kriticos 2012, Kriticos et al. 2015) and has been used for many groups of plants and animals, including tephritid fruit flies (e.g., Sridhar et al. 2014, Kumar et al. 2014). We chose not to use the Maximum Entropy (MaxEnt) method (Phillips et al. 2006, Elith et al. 2010), which relies on presence points of an organism, because we found insufficient numbers of exact occurrence points for *R. cerasi* to develop a reliable model. Specifically, while there are some research-grade *R. cerasi* occurrence points in Europe (Kovanci and Kovanci 2006b, GBIF 2012, Augustinos et al. 2014, Moraiti et al. 2014), there are currently only two *R. cerasi* occurrence records for North America (Anonymous 2017a, CFIA 2017).

We parametrized the *R. cerasi* CLIMEX model using the built-in temperate species template in CLIMEX version 4 (Kriticos 2012, Kriticos et al. 2015). CLIMEX does not provide actual probability risks of establishment, as its major output is an ecoclimatic index (EI) that represents relative environmental suitability of a site for a given species to live there. Details of diapause regulation of *R. cerasi* are vitally important for determining the risk of a temperate fly establishing within any given region. CLIMEX relies heavily on parameters associated with diapause for its output, specifically diapause day length, induction temperature, termination temperature, and minimum number of days below DPT0 needed to complete diapause (Table 1); the DPT0 is the average weekly minimum temperature (for winter diapause) or maximum temperature (for summer diapause) that induces diapause (Kriticos et al. 2015). These are the four key parameters for predicting establishment of all temperate insects studied thus far and are known to be representative and reasonable (Kriticos et al. 2015). CLIMEX uses air temperatures even though soil temperatures might be more important for survival and development of *R. cerasi* considering that pupae spend more than 9 mo in the soil (Daniel and Grunder 2012). However, although soil temperatures are not used in CLIMEX, soil parameters are included in CLIMEX in the moisture index (MI) (Table 1). In addition, soil and air temperatures are both reliable for phenological models of *R. cerasi* emergence (Nježić et al. 2017). These along with other stress-related parameters, such as cold stress, heat stress, and dry stress, are highly effective in determining the relative suitability of a site for a given species (Sutherst and Maywald 1985, Kriticos et al. 2015).

We set the diapause induction temperature (DPT0) to 13°C based on the average October temperature in the *R. cerasi* core distribution range (Germany). The diapause termination temperature (DPT1) was set to 8°C (Moraiti et al. 2014), while the minimum number of days below DPT0 needed to complete diapause (DPD) was set to 180 d (Daniel and Grunder 2012). The lower temperature threshold for growth (DV0), the lower optimum temperature for growth (DV1), and the upper optimum temperature for growth (DV3) were set to 5, 12, and 29.5°C, respectively (Vallo et al. 1976, Baker and Miller 1978, Kovanci and Kovanci 2006b, Daniel and Grunder 2012). We set the *number of degree days above DV0 to complete diapause* (PDD) to 430 d (Baker and Miller 1978). In CLIMEX model theory, the *cold stress Temperature Threshold* (TTCS) is ≤DV0, while the *Heat Stress Temperature Threshold* (TTHS) is ≥DV3 (Kriticos et al. 2015). Following these rules, we iteratively set the TTCS to 5°C, and the TTHS to 34°C to match the observed distribution of *R. cerasi* in Europe and Asia. All other parameters (Table 1) were also adjusted to fit the observed distribution of *R. cerasi* in Europe and Asia.

Once the *R. cerasi* CLIMEX parameters were deemed reasonable based on the known biology of the species, we ran CLIMEX models using the gridded dataset, CM10 World 1975H V1.1, with and without irrigation scenarios (Kriticos et al. 2015). For the irrigation scenario, +3.6 mm monthly top-up was selected. We selected this scenario to assess the potential distribution of *R. cerasi* under ample moisture conditions. CLIMEX results were exported to ArcGIS V. 4.1 (ESRI 2014) and the EI values were reclassified into three reasonable classes. Generally, habitats with EI values of 0–10 are considered unsuitable, while habitats with EI values above 10 are considered suitable (Kriticos et al. 2015).

Results

The CLIMEX model indicated that cold stress (CS) and moisture stress (MS) were the two most sensitive and important parameters

Table 1. Parameters used in CLIMEX for predicting the global risk of establishment of *R. cerasi*

Parameter	Description	Value
Temperature index (TI)		
DV0	Lower temperature threshold for growth	5°C
DV1	Lower optimum temperature for growth	12°C
DV2	Upper optimum temperature for growth	29.5°C
DV3	Upper temperature threshold for growth	34°C
PDD	Number of degree days above DV0 needed to complete one generation	430
Moisture index (MI)		
SM0	Lower soil moisture threshold	0.2
SM1	Lower optimum soil moisture	0.8
SM2	Upper optimum soil moisture	1.2
SM3	Upper soil moisture threshold	2
Cold stress (CS)		
TTCS	Temperature threshold for cold stress	5°C
THCS	Cold stress accumulation rate	0/wk
Heat stress (HS)		
TTHS	Temperature threshold for heat stress	34°C
THHS	Heat stress accumulation rate	0.001/wk
Dry stress (DS)		
SMDS	Soil moisture threshold for dry stress	0.2
HDS	Dry stress accumulation rate	−0.0001/wk
Wet stress (WS)		
SMWS	Soil moisture threshold for wet stress	2
HWS	Wet stress accumulation rate	0.002/wk
Diapause index		
DPD0	Diapause induction day length	11 h
DPT0	Diapause induction temperature	13°C
DPT1	Diapause termination temperature	8°C
DPD	Minimum number of days below DPT0 needed to complete diapause	180 d

that limit the distribution of *R. cerasi*. This result was obtained by keeping all other parameters the same and modifying CS and MS parameters one at a time. Differences in terms of increased or decreased suitability of habitats were then observed. When a parameter was sensitive, a notable change was observed; when a parameter was not sensitive, very little or no change was observed.

If introduced within the United States under no-irrigation, the model predicted that *R. cerasi* would establish in the eastern as well as the northwestern part of the country (Fig. 1a). This includes the major cherry-growing area in Michigan, along the eastern shores of Lake Michigan in the Grand Traverse Bay region, where EIs are 21–50. However, under irrigation, more areas in the United States become suitable for *R. cerasi*. Specifically, suitable habitats would expand westward to North Dakota south to Kansas. More important for the cherry industry is that suitable habitats would expand to the western cherry-producing states of Montana, Oregon, Idaho, and Utah (Fig. 1b). They would also expand to the coast of California and the interior of southern California, including in cherry-growing regions. Regions of Morgan Hill, Gilroy, and Hollister in central California (EIs of 21–50), and Lodi, Linden, and Stockton in the north (EIs of 11–20), six of the nine major cherry-growing regions in the state (Anonymous 2017b), have suitable habitats for *R. cerasi,* with irrigation. Bakersfield, Fresno, and Sacramento were the three cherry-growing regions in California with unsuitable habitat for *R. cerasi* (Fig. 2). Under irrigation within Washington, the Yakima Valley and Wenatchee areas (in blue in Fig. 1b), which are the major cherry producers in the state (Anonymous 2003), also have suitable habitats, although the EIs there are 11–20 rather than 21–50 (Fig. 1b).

Modifying CS parameters for Europe expanded the potential distribution of *R. cerasi* northward into the Scandinavian countries, and eastward into western Russia, Kazakhstan, and China. Modifying the MS parameters for Europe and Asia altered the potential distribution of *R. cerasi* southward into Iran, Turkey, Spain, and Portugal. The distribution of *R. cerasi* in northern Africa, South America, South Africa, and southern Australia was also explained mostly by changes in CS and MS values. The CLIMEX model predicted suitable habitats for *R. cerasi* in Canada and in European countries where the fly is reported, but the model also identified suitable habitats in England, where it has not been reported (Figs. 3 and 4).

Under no-irrigation, the CLIMEX model predicted suitable habitats for *R. cerasi* in most cherry-growing countries in Europe where the fly occurs, including France, Germany, the Netherlands, and Scandinavian countries (Fig. 3a). However, suitable habitats also occur in Europe and Asia outside the known presence points. Under no-irrigation, suitable habitats occur in central Mexico, parts of South America, central and northeastern China, the Koreas and Japan, southeastern Australia, and New Zealand (Fig. 3a). Under irrigation, the predicted potential distribution of *R. cerasi* expanded; notable expansions were to most of Chile, parts of Argentina, southwestern Australia, northern Africa, Iran, southern Portugal, southern Spain, the island of Crete, and regions of southern Africa (Figs. 3b and 4).

Discussion

Cold stress was one key factor affecting the potential distribution and risk of establishment of *R. cerasi*. Vallo et al. (1976) found that chilling *R. cerasi* pupae at 1°C was suboptimal for high fly emergence rates and recommended storage at 4–5°C. In contrast, storage at 5–6 mo at 5°C optimized (>80%) emergence. Thus, 5°C was used in CLIMEX as the threshold for cold stress. However, a caveat to

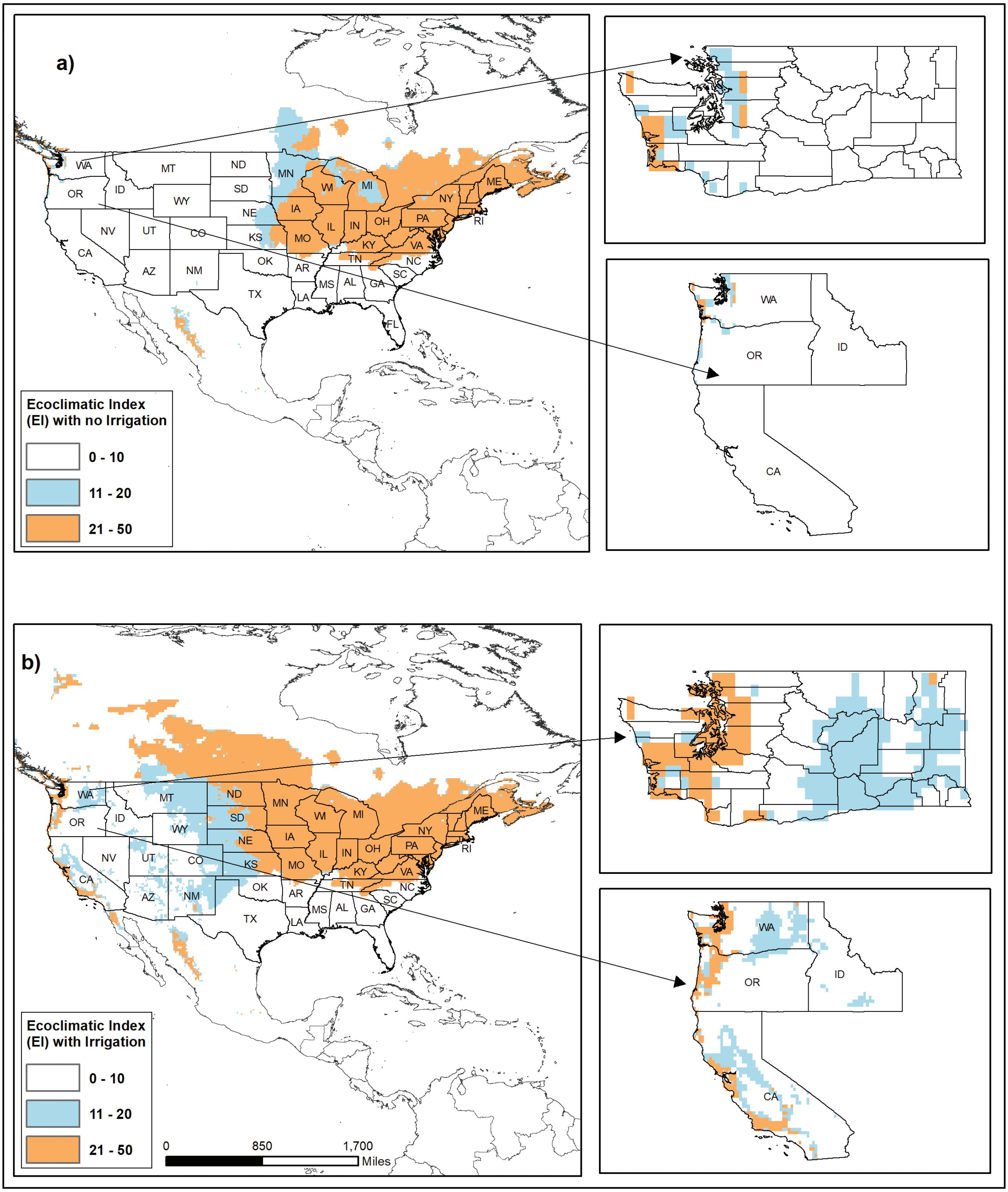

Fig. 1. Potential distribution of *Rhagoletis cerasi* in the United States predicted using CLIMEX: a) under no-irrigation scenario and b) under +3.6 mm top-up irrigation scenario. EI values ranging from 0 to 10, 11 to 20, and 21 to 50 indicate unsuitable, moderately suitable, and highly suitable habitats, respectively. Inset maps show the potential distribution of *R. cerasi* in Washington (WA), Oregon (OR), California (CA), and Idaho (ID).

cold stress affecting *R. cerasi* is that the fly can survive in highly variable habitats, such as in highland and coastal regions of Greece (Papanastasiou et al. 2011, Moraiti et al. 2012b). In humid highland Greece, the minimum temperature is −17.6°C; the maximum is 37°C; in drier coastal Greece, the minimum temperature is −6.6°C; the maximum is 37.8°C. The fly has adapted to different conditions there by varying diapause traits and regulating times of peak carbohydrate and glycogen reserves needed for survival (Papanastasiou et al. 2011). Thus, cold stress may differ depending on where fly populations evolved.

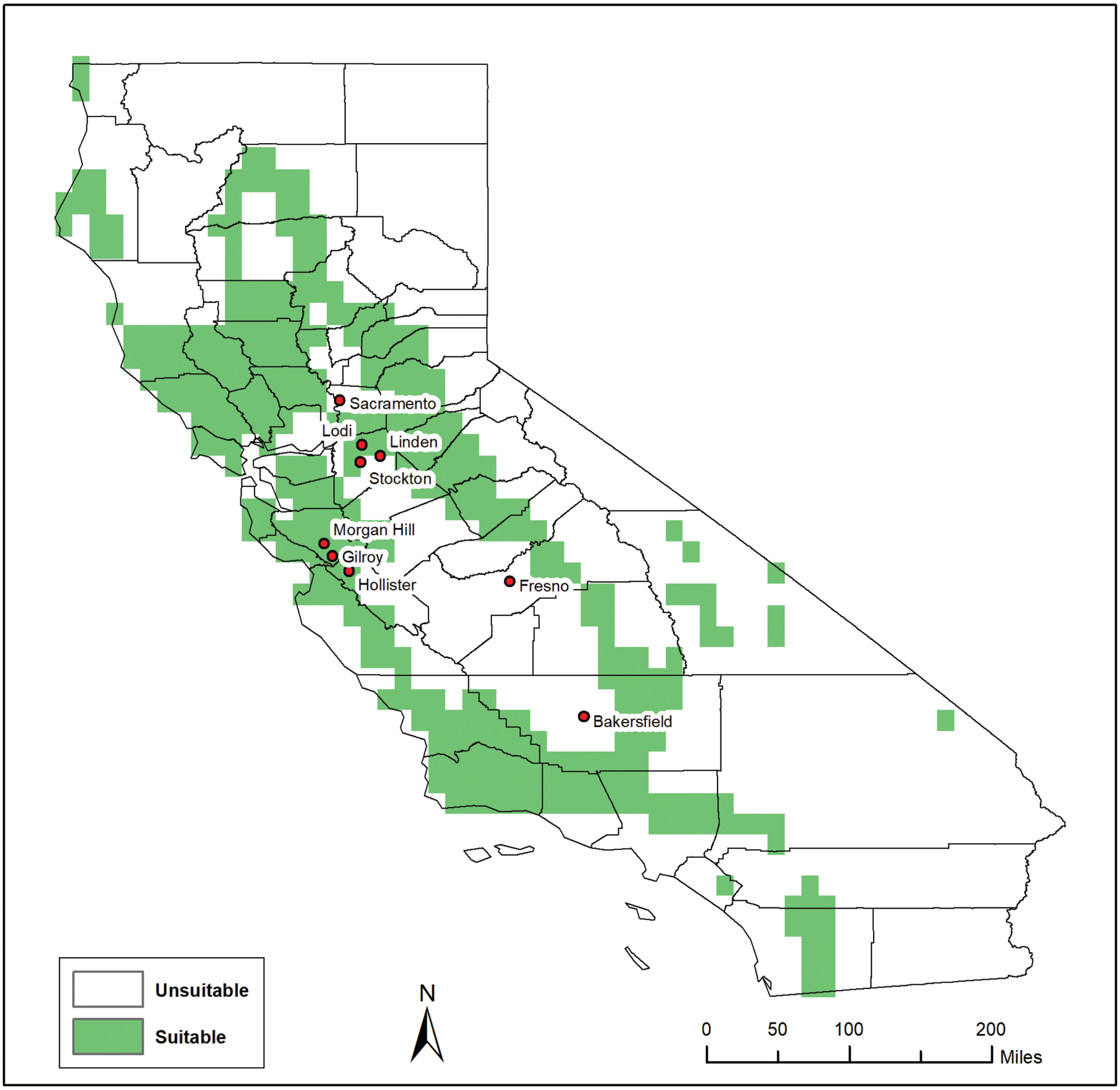

Fig. 2. Cherry-growing regions of California and their relative suitability for *R. cerasi* establishment. Based on our CLIMEX model, the cherry-growing regions of Sacramento, Fresno, and Bakersfield are unsuitable for *R. cerasi* establishment.

Moisture stress was the other key factor affecting the potential distribution and risk of establishment of *R. cerasi*. Apparently pre- or post-winter *R. cerasi* pupae survive better in higher than lower moisture or humidity environments. Diapausing pupae are protected within puparia and can survive dry and hot summers (Papanastasiou et al. 2011) and, therefore, are somewhat desiccant tolerant, but pupal mortality is high. In one study, only 37–65% of larvae pupated and only 7–50% of pupae in soil produced adult flies in spring (Boller 1966). Even under an irrigation scenario within Washington in the United States, drier cherry-growing regions in the Yakima Valley and Wenatchee had EIs of 11–20, whereas wetter regions west of the Cascade Mountain Range had EIs of 21–50 (Figs. 1b, 5a and c), suggesting that irrigated Yakima and Wenatchee areas are not optimal habitats and fly survival there would be relatively low. However, as cherry fruit-importing countries would have zero tolerance for any pest *Rhagoletis* fly larvae in fruit (Smith 2017), even low pupal survival is a concern.

The temperatures flies are exposed to at postdiapause will affect timing of fly emergence and thus synchronization with host fruit development in an area, affecting the risk or speed of fly establishment. In Turkey, Kovanci and Kovanci (2006a) found degree-day predictions for *R. cerasi* captures were delayed with increases in altitude. First emergence of flies at 150 m occurred after 583 degree-days (DD), while at 1,170 m it occurred after 668 DD (Kovanci and Kovanci 2006b). However, there are also commonalities in heat requirements for fly emergence across European countries, supporting our use of a single *upper optimum temperature for growth* (DV3) parameter in CLIMEX (Table 1). Specifically, to predict first adult emergence dates, Leski (1963) reported 320 DD at a base threshold of 7°C for flies in Poland. Boller (1964) reported 430 DD above 5°C for flies in

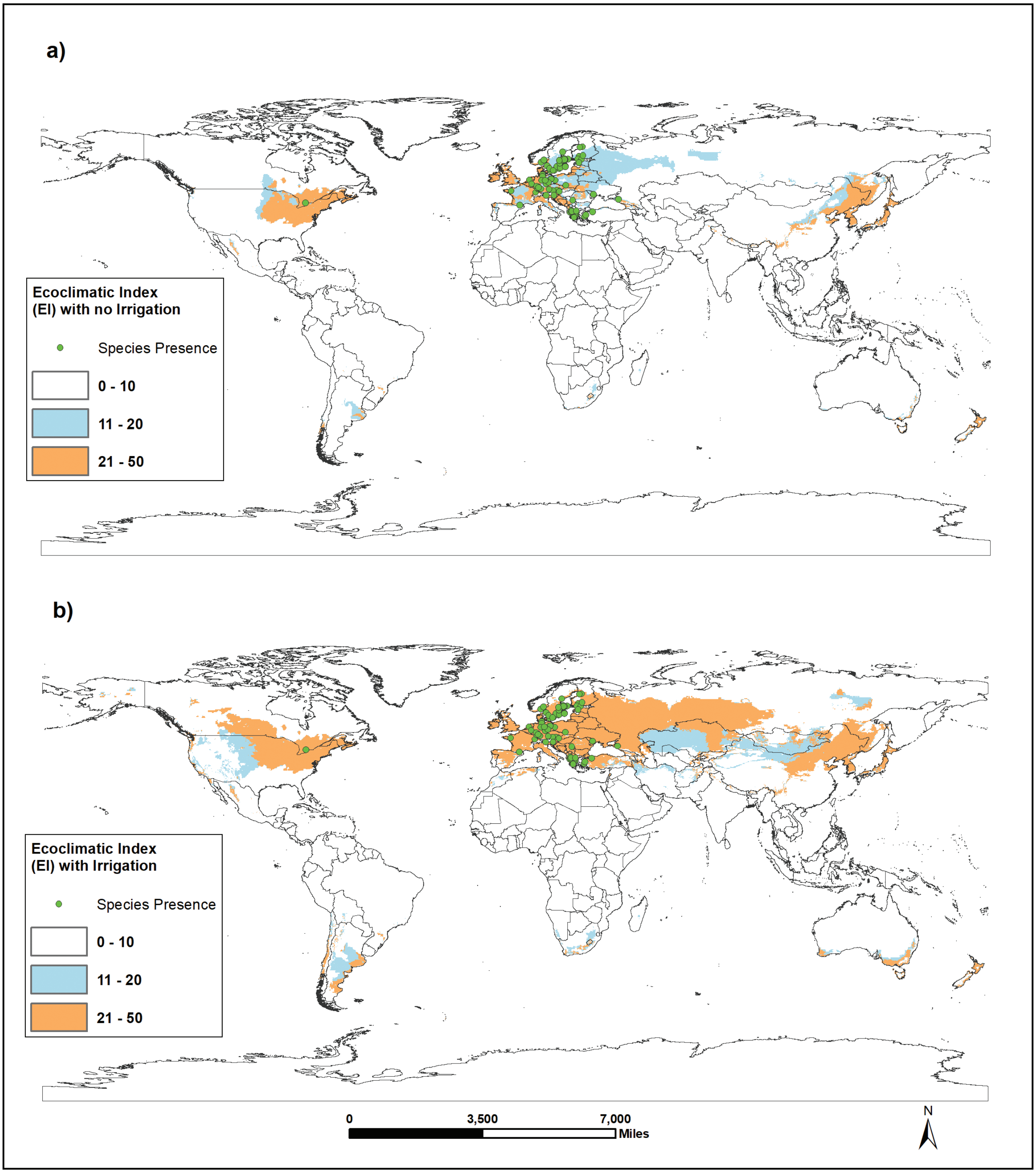

Fig. 3. Potential global distribution of *R. cerasi* predicted using CLIMEX: a) under no-irrigation scenario and b) under +3.6 mm top-up irrigation scenario. Green circles indicate *R. cerasi* presence locations from the literature. EI values ranging from 0 to 10, 11 to 20, and 21 to 50 indicate unsuitable, moderately suitable, and highly suitable habitats, respectively.

Switzerland. Baker and Miller (1978) reported 321 DD above 6.8°C for flies in Italy, Czechoslovakia, Austria, and Switzerland, stating that this DD accumulation gave the same estimates for practical forecasting as that derived by Boller (1964). Finally, Nježić et al. (2017) reported 435 DD at 5°C for flies in Bosnia and Herzegovina.

Presence of introduced host sweet and tart cherry trees clearly is a factor affecting risk of *R. cerasi* establishment in the United States. Our CLIMEX model did not model tree responses, but irrigation allows these trees to survive in regions where they otherwise could not, especially in the drier western United States. In addition, irrigation and plantings by humans affect tree density and thus risk of spread and establishment. However, CLIMEX under a no-irrigation scenario predicted high risk of establishment of *R. cerasi* in the eastern United States, where introduced cherry density (USDA-CPHST 2016a) is low to high. Similarly, CLIMEX predicted highly suitable habitats exist in the northwestern United States, west of the Cascade Mountain Range

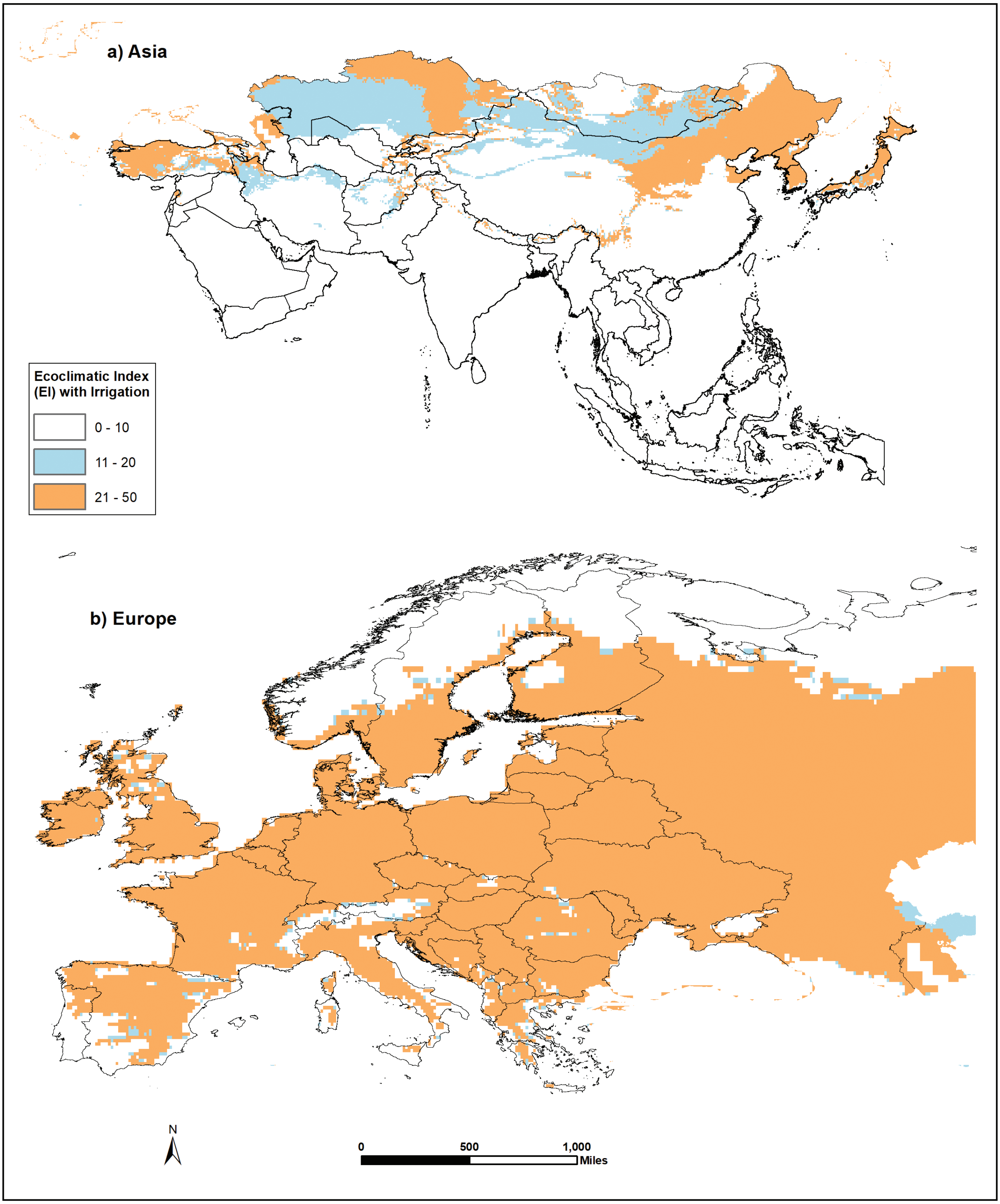

Fig. 4. Potential distribution of *R. cerasi* in a) Asia and b) Europe, based on CLIMEX model developed under +3.6 mm top-up irrigation scenario.

where introduced cherry density is low (USDA-CPHST 2016a). For practical use, our CLIMEX maps indicating degrees of habitat suitability may need some modification to account for sweet and tart cherry tree presence and density, which together could affect fly spread.

CLIMEX also did not model distributions of different types of native cherries (*Prunus* spp.) that could affect the risk of *R. cerasi* establishment. The distribution map of black cherry, *P. serotina*, in the eastern United States (Little 1971) overlaps areas of high risk for *R. cerasi* under no-irrigation, so flies could exploit this plant where it is abundant even if sweet and tart cherries are scarce. In the western United States, native bitter cherry, *Prunus emarginata* (Dougl. ex Hook.) Eaton, the ancestral host of *R. indifferens* (Frick et al. 1954), occurs.

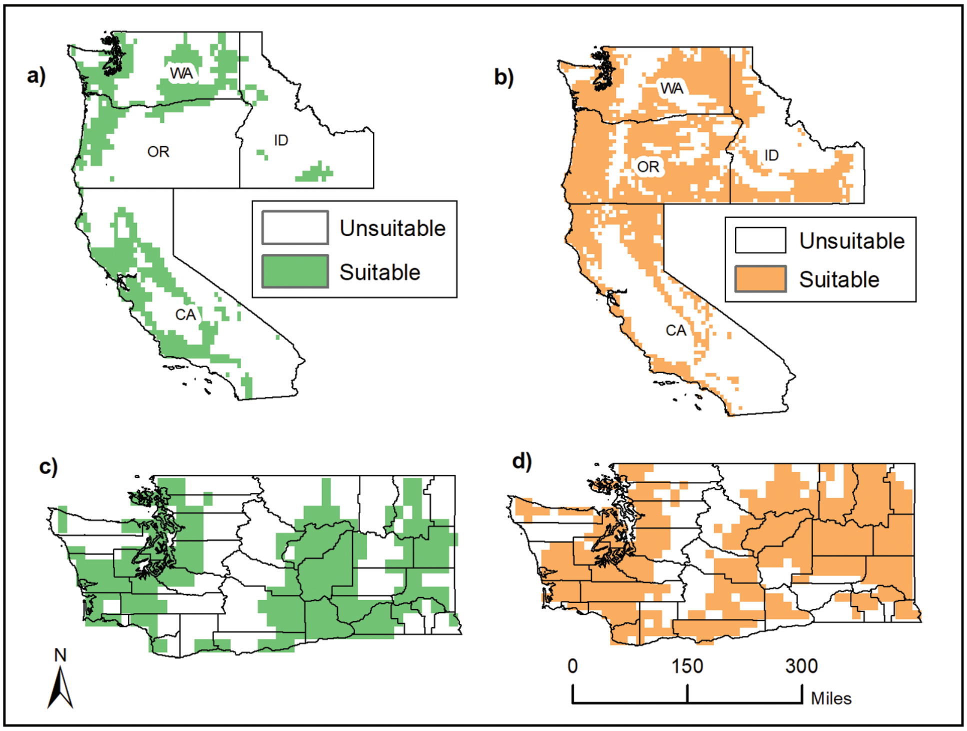

Fig. 5. Comparison of *Rhagoletis cerasi* and *R. indifferens* potential distribution maps based on CLIMEX models: a) *R. cerasi* in western United States, b) *R. indifferens* in western United States, c) *R. cerasi* in Washington, and d) *R. indifferens* in Washington. *R. indifferens* potential distribution maps for the western United States were first created by Kumar et al. (2014a).

The distribution of *P. emarginata* (Little 1976) also overlaps that of the *R. cerasi* potential distribution based on CLIMEX, suggesting this plant needs to be included in predicting risk of establishment of *R. cerasi*, assuming the fly can utilize its fruits.

The distributions of honeysuckles (*Lonicera* spp.) in the United States were also not modeled by CLIMEX and could affect the risk of *R. cerasi* establishment there. *R. cerasi* detections in Canada were associated with *Lonicera* spp. (CFIA 2017), and since a *Lonicera* host race occurs in Europe (Boller et al. 1998), the distribution of *Lonicera* spp. in the United States needs needs to be superimposed on the CLIMEX predictive maps to more fully assess risk of *R. cerasi* establishment. *L. tartarica*, native to Asia, occurs over a wide range across the northern United States; *L. xylosteum*, native to Europe, occurs in the northeastern United States, Great Lakes states, and western Washington (Swearingen and Bargeron 2016). These ranges overlap our predicted suitable regions for *R. cerasi.*

Comparisons of potential distributions of *R. indifferens* (Kumar et al. 2014) with that of *R. cerasi* in the western United States indicated that significant range overlap between species for Washington, western Oregon, and western California (Fig. 5). This is not surprising as thermal requirements for breaking diapause in related insect species can be similar (Jarošik et al. 2011). Similar to *R. cerasi* (Vallo et al. 1976), *R. indifferens* requires 5 mo at 4.4°C to maximize (80%) emergence (Frick et al. 1954). However, *R. cerasi* may tolerate warmer temperatures (Papanastasiou et al. 2011) than *R. indifferens*, as CLIMEX predicted that habitats in California cherry-growing areas are suitable for *R. cerasi* and not for *R. indifferens* (Kumar et al. 2014). The potential for *R. cerasi* to establish in irrigated cherry-growing regions of central California means integrated pest management practices for California cherries could be altered in the future.

In addition to the United States, the CLIMEX model predicted high risk of *R. cerasi* establishment in Canada, China, Japan, South America, Australia, and South Africa, but modifying cold and moisture stress parameters significantly altered the fly's potential range. For instance, eliminating moisture stress through irrigation increased chances *R. cerasi* will establish in southern Turkey, southern Portugal, southern Spain, and northern Africa, as well as western Russia and Kazakhstan. Highly suitable habitats for *R. cerasi* under an irrigation scenario were found in cherry-growing areas in three countries outside the United States that were ranked among the top 15 sweet cherry exporters in 2016 (Workman 2017). These are Chile, first in exports at US$802.5 million; New Zealand, ninth at US$47.6 million; and Australia, tenth at US$42.3 million.

Our results stress the importance of surveying for *R. cerasi* to reduce the risks of its spread and establishment within the United States and other countries. Early detection of *R. cerasi* to prevent spread can be accomplished using time-tested sticky traps and ammonium carbonate or acetate lures (Katsoyannos et al. 2000, USDA-APHIS-PPQ 2004, Daniel et al. 2014, USDA-CPHST 2016b). If early detection fails to prevent the fly from establishing, then pest management costs could increase. The experience of growers in Europe and Asia should help with control of *R. cerasi*, if it establishes around cherry orchards in previously uninfested regions.

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