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Invasion of the Land of Samurai: Potential Spread of Old-World Screwworm to Japan under Climate Change

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Abstract: Temperatures have fluctuated dramatically throughout our planet's long history, and in recent decades, global warming has become a more visible indicator of climate change. Climate change has several effects on different economic sectors, especially the livestock industry. The Old-world screwworm (OWS), *Chrysomya bezziana* (Villeneuve, 1914), is one of the most destructive insect pests which is invading new regions as a result of climate change. The economic loss in livestock business due to invasion of OWS was previously assessed by FAO in Iraq to be USD 8,555,000. Other areas at risk of invasion with OWS in the future include Japan. Therefore, maximum entropy implemented in MaxEnt was used to model predictive risk maps of OWS invasion to Japan based on two representative concentration pathways (RCPs), 2.6 and 8.5, for 2050 and 2070. The Area Under Curve (AUC) indicates high model performance, with a value equal to 0.89 (±0.001). In addition, the True Skill Statistics (TSS) value was equal to 0.7. The resulting models indicate the unsuitability of the northern territory of Japan for invasion by OWS. The main island's southern costs show high and very high invasion suitability, respectively, and both Kyushu and Okinawa are at high risk of invasion with OWS. The predicted risk maps can be considered a warning sign for the Japanese quarantine authority to hasten a control program in order to protect the livestock industry from this devastating pest.

Keywords: climate change; species distribution modeling; livestock industry; old-world screwworm; MaxEnt

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1. Introduction

The livestock industry forms one of the most effective economic sectors in both agricultural and non-agricultural countries [1–3]. In some cases, it can reach half of the total agricultural economy (e.g., Brazil and the USA) [4–6]. By 2050, global demand for animal products is predicted to quadruple, owing primarily to rising global living standards [7]. Several constraints facing such a rising economy include low genetic outcomes of native animals, water shortages, lack of marketing infrastructure, and global warming [8–10].

Greenhouse gas (GHG) emissions, which are produced due to several industrial and anthropogenic activities, are the primary cause of global climate change [11]. Climate change and global warming have a severe negative effect on the livestock industry [12,13]. The changing climate destroys natural pastures throughout the world and affects animal fitness and health, especially in tropical and subtropical regions, and encourages the resurgence and expansion of livestock pests in temperate and sub-cold areas [14–16]. The formation of a new climatological niche encourages many species of livestock pests to invade new geographical regions where their ancestors have never previously been present [17]. Flies of order Diptera form the largest share of livestock pests [18]. With their strong flying ability, their likelihood of expanding to a new area through either their own capability or through trade and transportations networks is predictable [19].

Screwworm flies of the family Calliphoridae are considered a major destructive veterinary pest, and can be fatal to all warm-blooded animals [20]. There are two economically important species of screwworms throughout the globe: the New World screwworm (NWS), *Cochliomyia hominivorax* (Coquerel, 1858), which is native to central and south America, and Old-World screwworm (OWS), *Chrysomya bezziana* (Villeneuve, 1914), which is native to Sub Saharan Africa, the Indian sub-continent, and Southeast Asia as far as Papua New Guinea and is invasive in the Gulf region, including Iraq [21,22]. The larval instars of these flies form the economic stage, as they induced a disease called myiasis [23]. Myiasis is caused due to the burrowing of larva laid by females on animal wounds or natural openings in the flesh of animals. This mode of life supports bacterial infection and encourages other species of flies to lay their eggs [24]. The world organization for animal health (OIE) classifies the myiasis caused by NWS and OWS on List B of diseases, which includes animal illnesses that are of public health and/or socioeconomic importance [25,26].

Females of the OWS deposit their eggs in masses ranging from 150 to 500 eggs at the edge of wounds or near body orifices. Under hot and wet climatic conditions, the hatched larvae developed into the third instar in two days. The screwworm burrows deep in the wound until only the caudal ends are observable. The entire larval stage lasts 5 to 6 days and the pupal stage remain for about 7 to 9 days [23]. The prevention of infestation by OWS is established by environmental hygiene. Keeping areas free of decaying organic matter such as trash, decaying plants, and excreta can prevent the flies from being attracted to target animals [24].

In the Eastern Hemisphere, particularly in Iraq during the 1990s, the FAO estimated the economic loss to the livestock industry due to OWS invasion to be USD 8,555,000 US [22]. Other research studies have estimated annual losses in the livestock industry in Australia to be equal to AUD 500 million due to the possible incursion of the OWS to Australian territory from nearby Papua New Guinea or through animal trading with the Gulf region [27]. The cases of Australia and Japan are very similar with respect to possible invasion by the OWS from nearby countries due to climatic changes; however, the Japanese case has never studied for invasion of this pest before.

Japan is an island country located in East Asia. It boarded to the west by the Sea of Japan, to the north by the Sea of Okhotsk, by the East China Sea and Taiwan to the south and the Pacific Ocean to the east. Japan is divided into eight administrative regions and forty-seven prefectures (Figure 1) [28]. As one of the world's most highly industrialized countries, Japan must take into account the global food supply and security situation and shift toward the safe production of high-quality beef utilizing indigenous pasture resources, therefore reducing its reliance on imported meat [29]. In 2018, the net production amount of the agricultural livestock industry in Japan was estimated to be around JPY 3.21 trillion [30]. This number was said to be enlarged by the spread of animal farms throughout different parts of the country, especially the southern islands [31]. The OWS has never been recorded in Japan, although it is a widespread pest in neighboring China [32]. A recent study modeling the status of OWS through the world using geographical information systems (GIS) and mathematical modeling indicates the critical situation of Japan [33].

Models based on GIS and mathematical modeling can be used as an early warning of the redistribution of animal pests during the climate change process [34]. CLIMEX, GARP, HABITAT, and MaxEnt are some of the most widely used programs for estimating the current and future distribution patterns of specific species under various climate change scenarios [35–37]. MaxEnt is the most efficient and precise modeling program using Maximum Entropy [38,39]. One of the most pressing immediate goals of such modeling techniques is to develop risk maps for economically relevant livestock and human health pests [33,40]. Therefore, the present study aims to evaluate the possibility of the future invasion of Japan and its growing livestock production sector with OWS *C. bezziana* under different climate change scenarios in 2050 and 2070.

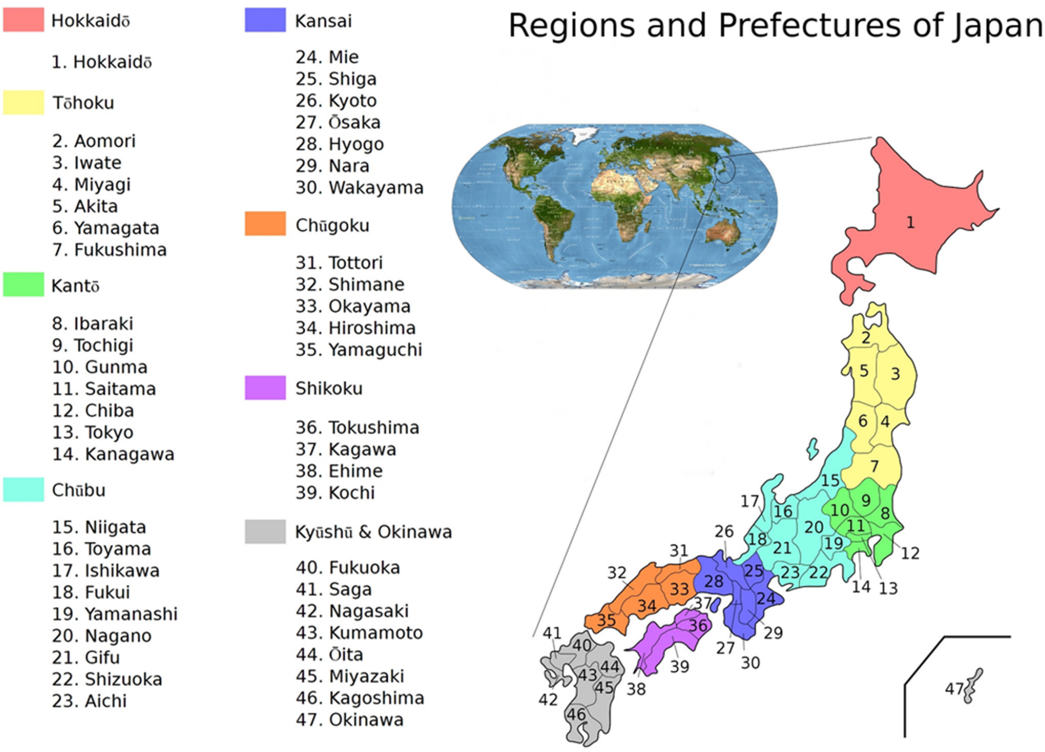

Figure 1. Map showing detailed administrative regions and the forty-seven prefectures of Japan.

2. Materials and Methods

2.1. Occurrence Records

All existing records on adult flies and larvae of medical and veterinary OWS cases were collected from the literature [41–44]. The OWS records in the digital database (www.cabi.org (accessed on 10 May 2021)) were taken into account as well [45]. Duplicated records and those with high spatial uncertainty were removed [33,39]. The data were transformed into comma-delimited (CSV) forms and used to assess the likelihood of invasion of OWS in Japan [33].

2.2. Bioclimatic Data Layers

Bioclimatic data with a spatial resolution of around 5 km^2 were downloaded from www.worldclim.org (accessed on 18 January 2021). To illustrate the current global climate, a total of fifteen climatic variables were used. These covariates were originally obtained from monthly temperature and rainfall measurements and collected from meteorological stations between 1950 and 2000.

For current data, all bioclimatic layers were converted into the ASCII format using ArcGIS v 10.7. Due to known spatial artifacts, bioclimatic layers 8–9 and 18–19 were eliminated [33,46]. In addition, Pearson's correlation was used to hinder auto-correlation and multicollinearity among bioclimatic variables at (r2 |0.8|) [39]. This was accomplished using ArcGIS 10.3's SDM Tools feature (Universal tool: Explore climate data: Remove highly correlated variable) [9,39].

For future data, in order to account for the future distribution of OWS based on carbon dioxide emission in 2050 (average of estimates for 2041–2060) and 2070 (average of predictions for 2061–2080) we used parallel datasets from two representative concentration paths (RCPs), 2.6 and 8.5 (https://www.worldclim.org/data/cmip6/cmip6climate.html) (accessed on 18 January 2021) [33,47]. These future data layers were converted to the ASCII format via ArcGIS v 10.7. The climatic data for the selected variables were clipped to Japanese territory. The Meteorological Research Institute's global climate model (MRI-CGCM3) (https://www.worldclim.org/data/cmip6/cmip6_clim5m.html) (accessed on

18 January 2021) for the years 2050 and 2070 was used to analyze the effects of climate change on future OWS invasion in Japan. These statistics are part of the IPCC's Fifth Assessment Report's current GCM climate estimates.

2.3. Invasion Modeling

MaxEnt package has previously been used to predict the future invasion of OWS in Japan. Yet, the artificial intelligence of maximum entropy is often regarded as the most widely used software for simulating species distributions using presence-only data [33,39,48]. Furthermore, even with little occurrence data on an invasive pest, MaxEnt can estimate the probability distribution [48]. In our models, 75% of the occurrence records were utilized to train the model, whereas 25% of the records were used to test the model. The maximum number of background points was 10,000, while the maximum number of iterations was 1000. In addition, ten-fold cross-validation was performed on the procedure, which increased the model's performance [49]. After removing the correlation, and based on the Jackknife function of MaxEnt, a collection of five biologically significant bioclimatic variables were chosen to construct the final projected models in the future: (Bio 1) Annual mean temperature; (Bio 3) Isothermality; (Bio 6) Minimum temperature for the coldest month; (Bio 10) Mean temperature for the warmest quarter; and (Bio 11) Mean temperature for the coldest quarter. The five most important variables were related to temperature. The current world bioclimatic factors chosen were then entered as Environmental data in the MaxEnt interface while the clipped Japanese future bioclimatic data were pathed through the projection found in the MaxEnt interface during each program run in order to generate future risk maps for Japan.

2.4. Performance of Models

The area under the curve (AUC) was used to measure model performance, with its value ranging from 0 (random discrimination) to 1 (perfect discrimination) [50]. AUC values below 0.5 suggested a poor fit, whilst AUC values above 0.75 showed a good fit [50]. In addition, True Skill Statistics (TSS) was used to measure the accuracy of the projected models [33,51]. TSS values varied from 0 to 1, with positive values near 1 indicating a strong link between the predictive model and the distribution and negative values indicating a weak association [51].

3. Results

A total of 104 localities with OWS occurrence records were used to evaluate the potential invasion of such pests to Japan under changing climatic conditions. All localities were distributed through sub-Saharan Africa and southern Asia.

3.1. Modeling Evaluation

The model performance as evaluated using the Area Under Curve (AUC) was equal to 0.89 ($\pm$0.001). The AUC value was generally higher in continuous species distribution modeling than in discontinuous modeling. The true Skill Statistics (TSS) results supported the high performance of the model, where it was equal to 0.7.

3.2. OWS Risk Maps under Two Climate Change Scenarios: 2050

From two representative concentration pathways (RCPs), 2.6 and 8.5, for 2050, two risk maps of OWS through Japanese territory were generated (Figure 2). The overall distribution pattern of OWS indicates the unsuitability of northern Japan as a supposed habitat of this species in the future. Regions such as Hokkaido and Tohoku will not be at any risk of OWS invasion. The Southern coasts of the main island show high and very high suitability of OWS, respectively especially for RCP 2.6. The southern part of the country is at high and very high risk of OWS invasion (Figure 3a,b), with Kyushu and Okinawa presenting a perfect habitat for OWS. Their nearness to the Asian mainland increases the risk of OWS invasion through this region.

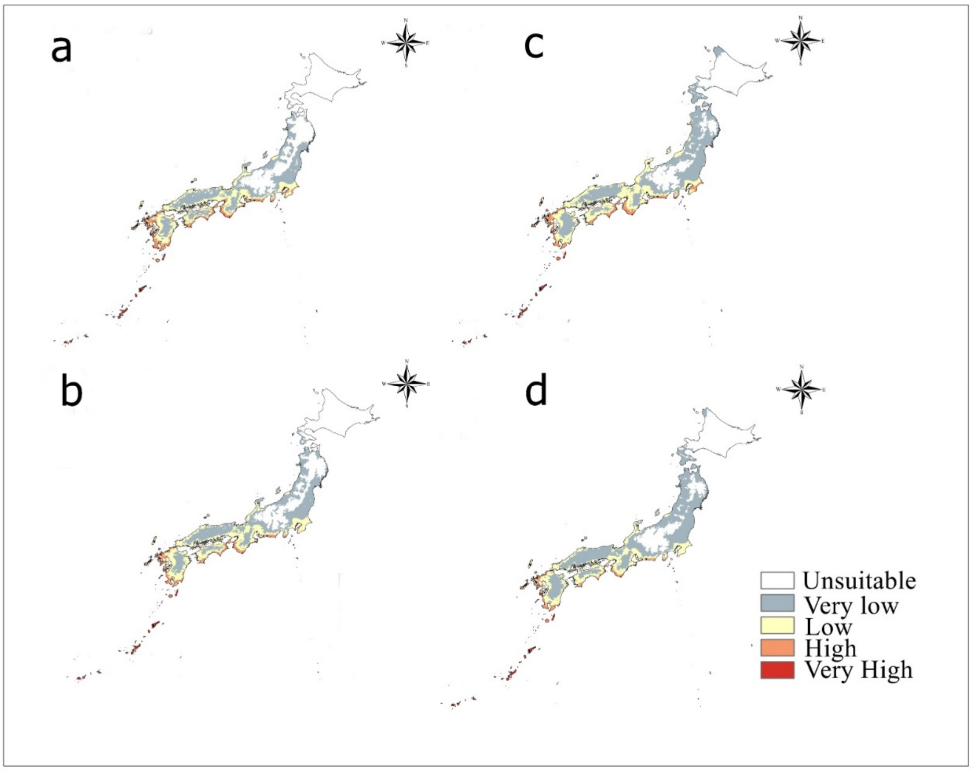

Figure 2. Risk map of future potential invasion of OWS to Japan under two representative concentration pathways: (**a**) RCP 2.6 in 2050, (**b**) RCP 8.5 in 2050, (**c**) RCP 2.6 in 2070, and (**d**) RCP 8.5 in 2070.

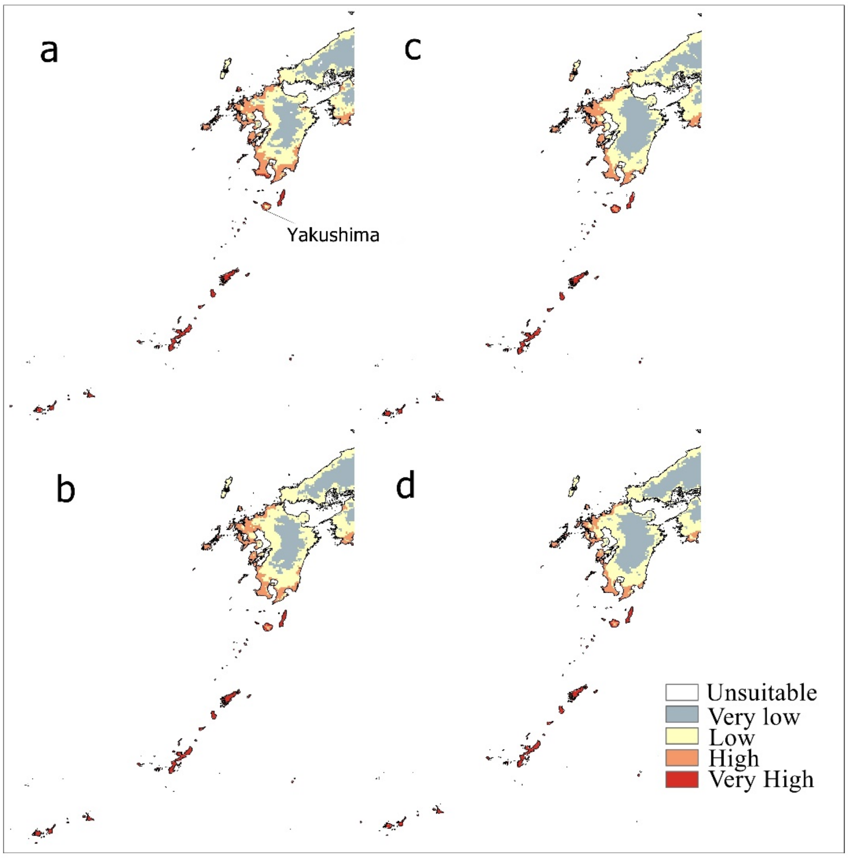

Figure 3. Illustrated zonation of the Southern regions of Japan with a high and very high risk of invasion with OWS in the future: (**a**) RCP 2.6 in 2050, (**b**) RCP 8.5 in 2050, (**c**) RCP 2.6 in 2070, and (**d**) RCP 8.5 in 2070.

3.3. OWS Risk Maps under Two Climate Change Scenarios: 2070

The generated risk maps of RCPs 2.6 and 8.5 for 2070 are not significantly different from those generated for 2050 (Figure 2). Northern Japan will not be at risk, although many of its parts transfer from unsuitable to very low risk, especially in the Tohoku region. Southern Japan shows a high to very high risk of OWS invasion (Figure 3c,d). The risk map of RCP 2.6 shows the worst-case scenario, particularly for most of the main island.

4. Discussion

The old-world screwworm is a very dangerous veterinary parasite with fatal potentiality in all warm-blooded animals [52,53]. The most common effect of its parasitic lifestyle is tissue destruction. The maggots of OWS burrow into and feed on the living tissue, causing severe injury and even death in untreated cases [24]. Such an effect on animal tissue opens the way to secondary infection by bacteria and encourages other parasitic flies to lay their eggs on the affected body part [25]. Throughout its native range in Africa and Asia the OWS is considered a neglected veterinary issue, with very little literature available on its biology and ecology [33]. The only socioeconomic study on OWS was done in Iraq, where the fly was introduced as invasive species and caused great economic loss to the livestock industry in the country [54,55]. Recently, the species distribution modeling technique has been used to evaluate the current and future status of OWS throughout the world, indicating Australia and Japan as especially vulnerable countries on the periphery of the screwworm's natural range [33]. The annual losses to Australia's livestock industry in the event of prospective OWS incursion are projected to be around AUD 500 million, while Japan is not discussed as a risk area for OWS invasion.

Japan's dairy and beef industries are worth more than USD 10 billion, with 4.56 million cattle, 9.61 million pigs, 294 million poultry, and 11,000 sheep [56]. This growing livestock industry faces the unevaluated risk of OWS invasion due to climate change [57]. Meanwhile, climate change is expected to influence feed crops and forage quality, animal and milk production, livestock illnesses, and animal reproduction as well [23]. The present work represents the first early warning of OWS invasion in Japan and assesses the suitability of Japanese territory as habitat for such pests in the near (2050) and long (2070) future term.

The results of the generated risk maps indicate that the livestock industry in Hokkaido, in northern Japan, is safe from OWS invasion. The growth of the livestock sector of the northern island will not face any risk of myiases in either the short or the long term. The cold weather of the region, even accounting for climate change, will continue to limit OWS expansion, as the annual mean temperature (Bio 1) forms the main factor affecting OWS distribution [33]. On the other hand, climate change can be expected to produce new ecological niches in the southern part of the country. Kyushu and Okinawa form very suitable habitats for the OWS in all generated risk maps. Kagoshima (Figure 1, 46) is the main agriculture production prefecture in Kyushu. With about 200 islands, it occupies 600 Km in southern Japan, all of which show a very high risk of future OWS invasion. The small island of Yakushima (Figure 3) in Kagoshima prefecture, for example, is home to livestock production worth about JPY 250 million, 20% of the livestock economy of Kagoshima [31]. In the future this growing livestock economy will be at risk of myiasis in both the short and long term due to climate change. In the southern islands, the high and very high suitability of the southern coasts of Japan's main island under future climate change scenarios is unlikely to have an effect, as most of this region has no livestock farms; however, attention should be taken to imported live animals received through the harbors on this coast in order to prevent the establishment of a small population of OWS that could subsequently transfer to southern Japan.

The four produced risk maps of OWS show a non-significant difference in the potential invasion of this pest through Japanese territory; from analysis of them, we can see that the rise of temperature due to climate change and global warming will favor species expansion up to a certain limit. The map generated for high CO_2 emission at RCP 8.5 in 2070 shows less suitability than that for CO_2 emissions at RCP 2.6 in 2070; such a result indicates that at certain very high temperatures, the OWS will not have the ability to extend its range.

The produced maps have several limitations; they are solely dependent on climatological data in the absence of clear future data about human population, land cover, and host animal distribution. This does not, however, reduce the importance of these maps as a very early warning to the Japanese quarantine authorities to take care in preventing any invasion of OWS into the islands. Furthermore, it encourages additional studies about this destructive veterinary pest throughout its native range, as well as the socioeconomic effect of this pest, in case it invades the land of Samurai.

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