Current and potential distribution of *Senecio madagascariensis* Poir. (fireweed), an invasive alien plant in Japan

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Introduction

Fireweed (also called Madagascar fireweed, Madagascar ragwort or Madagascar groundsel; *Senecio madagascariensis* Poir., Asteraceae) is a short-lived perennial (sometimes, annual) plant native to South Africa and Madagascar (Hilliard 1977). This plant is an invasive weed becoming naturalized over a wide range of the world, and has caused agricultural damage mainly due to its toxicity to livestock. In Japan, fireweed was first found in 1976, and has been spreading throughout the country. In this study, the current distribution of fireweed in Japan was investigated. Using a maximum entropy ecological niche modeling algorithm, the relationship between the distribution records of fireweed and climatic variables was modeled, and the potential distribution of fireweed was predicted. Many growing sites of fireweed have been observed on the Pacific coast and Seto Inland Sea coast. The northern and southern ends of the current distribution were the Pacific coast of southern Tohoku (36.9172°N, 140.8613°E) and southern Kyushu (31.5654°N, 130.3438°E), respectively. The results of modeling showed that mean temperature in the warmest quarter was the most influential predictor, and suggested that geographical distribution of fireweed in Japan is restricted mainly by temperature, not by precipitation. The predicted areas of potential distribution were mainly on the Pacific coast and eastern Seto Inland Sea coast. Of the regions where fireweed had not been found, the following regions were predicted as potential distribution areas of fireweed: southern Kanto region along Tokyo Bay, coastal area of western Tokai region, western part of Seto Inland Sea coast and northern Kyushu. The Pacific coast of central Tohoku (39.058°N, 141.843°E) was predicted as the northern end of the potential distribution, and Amami-oshima Island (28.304°N, 129.519°E) as the southern end.

Abstract

The short-lived perennial (sometimes annual) plant, *Senecio madagascariensis* Poir. (fireweed) is native to South Africa and Madagascar. This plant is an invasive weed becoming naturalized over a wide range of the world, and has caused agricultural damage mainly due to its toxicity to livestock. In Japan, fireweed was first found in 1976, and has been spreading throughout the country. In this study, the current distribution of fireweed in Japan was investigated. Using a maximum entropy ecological niche modeling algorithm, the relationship between the distribution records of fireweed and climatic variables was modeled, and the potential distribution of fireweed was predicted. Many growing sites of fireweed have been observed on the Pacific coast and Seto Inland Sea coast. The northern and southern ends of the current distribution were the Pacific coast of southern Tohoku (36.9172°N, 140.8613°E) and southern Kyushu (31.5654°N, 130.3438°E), respectively. The results of modeling showed that mean temperature in the warmest quarter was the most influential predictor, and suggested that geographical distribution of fireweed in Japan is restricted mainly by temperature, not by precipitation. The predicted areas of potential distribution were mainly on the Pacific coast and eastern Seto Inland Sea coast. Of the regions where fireweed had not been found, the following regions were predicted as potential distribution areas of fireweed: southern Kanto region along Tokyo Bay, coastal area of western Tokai region, western part of Seto Inland Sea coast and northern Kyushu. The Pacific coast of central Tohoku (39.058°N, 141.843°E) was predicted as the northern end of the potential distribution, and Amami-oshima Island (28.304°N, 129.519°E) as the southern end.
pyrrolizidine alkaloids poisoning than cattle and horses (Cheek 1998), fireweed was implicated in the death of 10 sheep in Australia (Seaman 1987). Since Iwasaki (2007) suggested that fireweed has an allelopathic effect on other plants, it is also supposed that invading fireweed depresses the yield of some crops.

In Japan, fireweed was first found on coastal reclaimed land in Naruto City, Tokushima Prefecture, in the eastern Shikoku region (see Figure 1) in 1976 (Kinoshita et al. 1999). Since then, fireweed has spread over western Japan (Kinoshita et al. 1999; Nakanishi 2001; Kochi Prefecture, Makino Memorial Foundation of Kochi Prefecture 2009). Moreover, fireweed reached the Tohoku region of northeastern Japan in 2006 (Fukushima Prefecture 2007). Fireweed was designated as an IAS (Invasive Alien Species) under the Invasive Alien Species Act (which prohibits bringing, moving and growing a designated species) in 2006 by the Japanese Government. It is important to predict the potential distribution of fireweed to work out a control plan for this species.

Though Sindel and Michael (1989) believed that low temperature, specifically frost, is an important factor in limiting the distribution of fireweed in Australia based on the results of greenhouse experiments, the results of additional experiments suggested that frost may not be as important a factor in limiting the spread of fireweed (reviewed by Sindel et al. 2008). On the other hand, Sindel and Michael (1992) suggested that high temperature may limit plant survival. Additionally, fireweed can adapt to a semiarid environment (Marohasy 1989). Sindel and Michael (1992) predicted the potential distribution of fireweed in Australia based on the macroclimatic environment. They pointed out that the range of annual precipitation in the habitat of fireweed in Africa and South America, which is the most significant bioclimatic factor on a continental scale in these regions, was similar to that in Australia. Recently, Sindel et al. (2008) confirmed that the current distribution of fireweed had not yet reached its potential distribution as predicted in 1992.

In recent years, ecological niche modeling has been used for a tool to assess potential geographic distributions of various organisms: coral (Tittensor et al. 2009), insects (Ward 2007; Roura-Pascual et al. 2009), amphibians (Kozak and Wiens 2006; Pawar et al. 2007; Rissler and Apodaca 2007), reptiles (Pawar et al. 2007; Pearson et al. 2007), birds (Hernandez et al. 2008), mammals (Hernandez et al. 2008) and plants (Guisan et al. 2007; Fitzpatrick et al. 2008; Loarie

![Figure 1](image-url) Map of the study area with the recorded growing sites of fireweed (*Senecio madagascariensis*; n = 251) indicated as closed red circles.
et al. 2008). It has also been applied to predicting the invasive potential of alien species (Ficetola et al. 2007; Ward 2007; Giovanelli et al. 2008; Roura-Pascual et al. 2009), providing information for control of an invasion.

In this study, the current distribution of fireweed in Japan was firstly investigated. Secondly, using a maximum entropy ecological niche modeling algorithm, the relationship between the distribution records of fireweed and climatic variables was modeled to identify the climatic parameters determining the distribution. Finally, the potential distribution of fireweed was predicted using the model.

Materials and methods

Investigation of current distribution of fireweed

Information about the sites where fireweed was growing in Japan was taken from the literature (Kinoshita et al. 1999; Nakanishi 2001; Sugino 2008; Kochi Prefecture, Makino Memorial Foundation of Kochi Prefecture 2009), a mailing list (including information from non-experts), public websites, newspapers and personal communication (only experts). Private websites such as blogs were also referred to. Based on the information obtained, a field survey was carried out from July 2009 to August 2010. The fireweed growing sites were attended, and the geographic information recorded at each site using a GPS receiver, eTrex Vista C (Garmin International, Inc., Olathe, KS, USA). For the following analysis, the data obtained mainly by the field survey and partly from the literature and personal communication were used. The Tokyo Datum was used as the geographical coordinate system in this paper.

Macroclimatic data for making prediction of potential distribution

Sindel and Michael (1992) successfully predicted the potential distribution of fireweed in coastal south-eastern Australia, mainly New South Wales, based on a range of 16 parameters (as shown in Table 1) indicating the macroclimatic environment at the fireweed growing sites. They used BIOCLIM (Busby 1986), a bioclimatic prediction system to make their prediction. In that system, various parameters of the climate were estimated for each 0.5 degree grid around the world. In recent years, many researchers used CLIMEX (Sutherst et al. 1999), a climate and population modeling solution, to predict the potential distribution of invasive species (Potter et al. 2009; Watt et al. 2009; Chejara et al. 2010). In the CLIMEX system, the climate estimates for each 0.5 degree grid are derived from about 2400 meteorological stations worldwide (Sutherst et al. 1999). On the other hand, Japanese climate conditions may be considerably different within each 0.5 degree grid, since Japan is an island country, and has a widely ranging topography. In the Mesh Climatic Data 2000 (Japan Meteorological Agency 2002), a climatic database, the climate parameters in each of the third mesh (about 1 km²) only for Japan were estimated based on the climate data (values of an average year, taken over 30 years from 1971 to 2000) from about 1000 meteorological stations. Thus, the Mesh Climatic Data 2000 has a finer geographical scale than BIOCLIM or CLIMEX, and may have higher accuracy for Japan. Though the WorldClim database (Hijmans et al. 2005), a climatic database, has the same spatial solution as the Mesh Climatic Data 2000, it is based on the older data (from 1960 to 1990). Therefore, the 16 climates variables estimated by the Mesh Climatic Data 2000 were used for the following analysis.

Prediction of potential distribution with ecological niche modeling

Recently, Phillips et al. (2006) introduced the use of the maximum entropy method (Maxent) for modeling species geographic distributions with presence-only data (see also Phillips 2008; Phillips and Dudik 2008). Maxent is a

<table>
<thead>
<tr>
<th>Climate variable†</th>
<th>Maximum value</th>
<th>Minimum value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Japan</td>
<td>Australia</td>
<td>Japan</td>
</tr>
<tr>
<td>Annual mean temp</td>
<td>17.5</td>
<td>20.1</td>
</tr>
<tr>
<td>Mean min coolest</td>
<td>3.8</td>
<td>8.6</td>
</tr>
<tr>
<td>Mean max warmest</td>
<td>33.2</td>
<td>33.1</td>
</tr>
<tr>
<td>Annual temp range</td>
<td>23.9</td>
<td>27.3</td>
</tr>
<tr>
<td>Mean temp coolest</td>
<td>8.9</td>
<td>15.3</td>
</tr>
<tr>
<td>Mean temp warmest</td>
<td>26.4</td>
<td>25.4</td>
</tr>
<tr>
<td>Mean temp wettest</td>
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</tr>
<tr>
<td>Mean temp driest</td>
<td>11.0</td>
<td>22.8</td>
</tr>
</tbody>
</table>

† All temperatures are in °C and precipitations in mm.
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general-purpose machine learning method with a simple and precise mathematical formulation, and it has a number of aspects that make it well-suited for species distribution modeling. To approximate an unknown probability distribution, the Maxent algorithm seeks the distribution with maximum entropy subject to the constraint that the expected feature values under the estimated distribution equal the empirically obtained values, on the basis of maximum entropy principle. For modeling species distributions, the unknown probability becomes the species distribution probability, and the features in the pixels of the target area comprise the environmental variables.

The relationship between the distribution records of fireweed and climatic variables was modeled using Maxent version 3.3.3a (which is available at the following website: http://www.cs.princeton.edu/~schapire/maxent/). The software default settings were adopted for model building. Among the three types of probability value formats available in the Maxent software, the cumulative value format was selected for the prediction. The cumulative value for a pixel (mesh) is computed as the sum of the probability of that pixel and all other pixels with equal or lower values, multiplied by 100 to produce a percentage. For model evaluation, receiver operating characteristic (ROC) analysis was used. The area under the ROC curve (AUC), which can be an indicator of the accuracy of model prediction, was calculated. The AUC ranges from 0.5 (random accuracy) to a maximum value of 1.0 (perfect discrimination). The 380 196 meshes were divided into 31 sets because the program could not run without dividing the data into smaller sets. The program for each of the datasets was run, randomly retaining 70% of the data for model training and the remaining 30% for testing, to assess the average performance of the resulting models. The contribution of each climatic variable to the established model was evaluated with jackknife tests. In the jackknife test, each variable is excluded in turn from the modeling framework, and a model is created with the remaining variables (i.e. drop contribution). Alone contributions were also calculated by creating new models with only one variable. To make prediction maps, a cumulative threshold value that balances training omission, predicted area and threshold value (i.e. balancing commission and omission errors) was used (Phillips et al. 2006). In making prediction maps, all of the distribution records were used.

Results and discussion

Current distribution of fireweed and climate variables on the growing sites

Fireweed sites were found in 17 of the 47 prefectures of Japan, and geographic information was collected on 251 points (included 69 municipalities; Figure 1). Many fireweed sites were observed on the Pacific coast and eastern Seto Inland Sea coast, especially in the areas around Awaji Island and Osaka Bay. The northern end of the current distribution in Japan was the Pacific coast of the southern Tohoku region (36.9172°N, 140.8613°E, Iwaki City, Fukushima Prefecture), and the southern end was the southern Kyushu region (31.5654°N, 130.3438°E, Hoki City, Kagoshima Prefecture). Most of growing sites were extremely disturbed (artificially or naturally) areas such as roadsides, road slopes, developed lands, flood plains and sea shores. Fireweed sites were also found on fallow fields and orchards.

Table 1 lists the climate profiles for fireweed based on 251 sites in Japan and 137 sites in Australia (as reported by Sindel and Michael 1992) for comparison. Compared with the data from Japan and Australia, the maximum and/or minimum values of several parameters were considerably different. It seemed that Japanese sites had hotter summers and colder winters than the Australian sites. It is evident based on the molecular analysis that the origins of invasive fireweed population in Australia (also Hawaii) are KwaZulu-Natal, South Africa (Scott et al. 1998; Radford et al. 2000; Gardner et al. 2006; Le Roux et al. 2006). On the other hand, Kinoshita et al. (1999) presumed that fireweed population in Japan came from Kentucky with seeds for revegetation; however, the origins were unknown. To specify the origins of fireweed in Japan is required for discussing the differences between the climate variables in fireweed growing sites in Japan and Australia.

Established ecological niche modeling and contribution of climatic variables

The AUC values from the predictive models of 176 training and 75 testing occurrence data for fireweed were considerably high, with mean AUCs of 0.982 and 0.973, respectively, for the training and the test data suggesting the high predictive power of the model.

Mean temperature in the warmest quarter was the most influential predictor among the 16 climatic parameters, followed by mean minimum temperature in the coolest month, mean temperature in the coolest quarter and annual mean temperature, when the variable contributions were evaluated in isolation with a jackknife test (Figure 2). All the alone contributions of the eight variables derived from precipitation data were lower than those of the eight variables derived from temperature data. Thus, it was suggested that the geographical distribution of fireweed in Japan is restricted mainly by temperature, not by precipitation.

Response curves of fireweed to the gradients of the two most influential predictors, mean temperature in the warmest quarter and mean minimum temperature in the
The coolest month, indicated that fireweed reacted to the two temperature components in unimodal and symmetric manners (Figure 3). The most suitable value of mean temperature in the warmest quarter for fireweed was 25.4°C, and the range was between 23.5 and 27.7°C, which exceeded the threshold value of 1.704. Similarly, the most suitable value of mean minimum temperature in the coolest month was 1.9°C, and the range was between −1.7 and 4.8°C, which exceeded the threshold. These results also suggest that fireweed adapts to the hotter summers and colder winters found in Japan than in Australia (see Table 1).

Geographical distribution of a given plant species may be determined by not only climate condition, but geological features, soil properties and so on. In Japan, the data of topography, geological features, soil properties and land use for the third meshes are also available. On the other hand, as mentioned above, most of growing sites were extremely disturbed areas. Therefore, it was considered that the use of these variables for prediction would not be appropriate, and the prediction using only climate variables was made.

**Potential distribution of fireweed**

Development of the prediction map processed the distribution probabilities derived from the macroclimate-based ecological niche modeling with a threshold value of 1.704, to classify below-threshold values as predicted absence and transform them into null values (Figure 4). The predicted areas of potential distribution were mainly on the Pacific coast and Seto Inland Sea coast. Most of neighboring regions of the growing sites were predicted to be ‘suitable’, especially the coastal region centered on Awaji Island. Of the regions where fireweed had not been found, the following regions were predicted as potential distributed areas of fireweed: the southern Kanto region along Tokyo Bay, the coastal area of the western Tokai region, the western part of Seto Inland Sea coast and the northern Kyushu region. All the meshes of Hokkaido, most meshes in the northern Tohoku region and the Sea of Japan coast were not predicted as suitable for fireweed. The northern end of the mesh exceeding the threshold value was the Sea of Japan coast in the northern Tohoku region (39.871°N, 139.844°E, Oga City, Akita Prefecture). However, this was not predicted to be the northern end of potential distribution because there was only one mesh exceeding the threshold value in...
this area. Therefore it was predicted that the pacific coast of central Tohoku (39.058°N, 141.843°E, Ofunato City, Iwate Prefecture) was the northern end of potential distribution. Though each mesh on Iriomote Island (24.287°N, 123.894°E, Taketomi Town, Okinawa Prefecture) and the northern part of Okinawa Island (26.729°N, 128.294°E, Kunigami Village, Okinawa Prefecture) exceeded the threshold value, similarly, they were not predicted to be the southern end of potential distribution. It was predicted that Amami-oshima Island (28.304°N, 129.519°E, Tatsugo Town, Kagoshima Prefecture) was the southern end of the potential distribution.

Fireweed may reproduce mainly by seeds while vegetative reproduction of this species has also been observed (reviewed by Sindel 2009). Many growing sites in artificially disturbed areas were observed in this field survey. Therefore, it is predicted that human activity unintentionally disperses the seeds of fireweed, for example, by moving soil and sand for civil engineering works. Though great agricultural damage by fireweed has not been reported in Japan at present, the invasion of fireweed should be under surveillance in the potential distributed areas; especially in the neighboring regions to growing sites.

Acknowledgments

This study was funded by the Ministry of Agriculture, Forestry and Fisheries of Japan (MAFF) and carried out under the guidance of the Animal Products Safety Division, Food Safety and Consumer Affairs Bureau of MAFF. I am grateful to Reiko Baba, Setsuko Desaki, Masahito Inoue, Koji Kaneko, Shunji Kurokawa, Kazuo Murai, Kentaro Murakami, Makoto Ogawa, Tadahisa Ohmachi, Akira Sakamoto, Yoshiro Sato, Takao Sugino and Shuji Uyemura for providing information about fireweed growing sites. I would like to thank Katsuhiro Aikawa and Shigeru Miyazaki for supporting this research. The assistance of Chisato Tsutsumi in the field is gratefully acknowledged.

References


