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POTENTIAL GLOBAL RANGE EXPANSION OF A NEW INVASIVE SPECIES, THE ERYTHRINA GALL WASP, *QUADRASTICHUS ERYTHRINAE* KIM (INSECTA: HYMENOPTERA: EULOPHIDAE)

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ABSTRACT. **–** Erythrina gall wasp, *Quadrastichus erythrinae* Kim, was first described in 2004. It has become a gall-inducing invader and can result in the death of *Erythrina* trees in affected areas. The most serious aspect of the threat was its enormous expansion rate and sudden outbreaks. The aim of this paper is to predict the potential geographical distribution of erythrina gall wasp on a global scale. The Genetic Algorithm for Rule-Set Prediction (GARP) was used to analyze its potential expansion based on occurrence records and environmental data. The results indicate that *Q. erythrinae* will affect wide areas of Asia, Africa, Oceania, South America, and reach the southern part of North America. The predicted potential range is far-reaching and pan-tropical, and includes tropical rainforest, tropical monsoon, subtropical monsoon and tropical savannah climates. Vegetation types and humidity are predicted to be limiting factors for its spread. Based on the currently reported distribution pattern and predicted ranges of expansion of the erythrina gall wasp, it is possible that Africa was the area of origin.

KEY WORDS. **–** Invasion, GARP, Eulophidae, coral trees, *Erythrina.*

INTRODUCTION

Erythrina gall wasp (EGW), *Quadrastichus erythrinae* Kim, belongs to Hymenoptera, Eulophidae, Tetrastichinae, and was described first in 2004 as a new species from Singapore, Mauritius and Reunion Islands (Kim et al., 2004). Only nine genera of Tetrastichinae are known to be involved in gall induction, such as *Quadrastichodella*, *Oncastichus*, *Epichrysocharis*, *Aprostocetus*, *Paragaleopsomyia*, *Ceratoneura*, *Exurus*, *Leptocybe* and *Quadrastichus* (LaSalle, 2005; Mendel et al., 2004; Kim et al., 2004). Some of gall-inducing wasps have been recorded as invasive pests, such as *Quadrastichodella nova* Girault (Flock, 1957; Timberlake, 1957; as *Flockiella eucalypti* Timberlake), *Epichrysocharis burwelli* Schauff (Schauff & Garrison, 2000), *Aprostocetus* sp. (Beardsley & Perreira, 2000) and *Q. erythrinae* Kim (Kim et al., 2004; Yang et al., 2004). EGW is the first invader in the genus *Quadrastichus*, and is a serious threat to natural environments and landscaping.

Although its exact origin remains unknown, it has caused serious problems in the affected areas, and its invasive speed is incredible. EGW has been shown to damage coral trees (*Erythrina*) in southern Taiwan, China in 2003. Since then, it has rapidly spread throughout the island (Yang et al., 2004). On China mainland, EGW was detected on Shenzhen City of Guangdong Province in July, 2005 (http://www.china.org.cn/chinese/huanjing/962038.htm). In Hawaii, EGW was first detected on Manoa, Oahu in April, 2005. Recent investigations have revealed that EGW has spread rapidly across the island. On 21 July, its damage was reported from Kona on the Big Island. On 26 July, it was found at Lihue Airport on Kauai. On 30 July, it was reported in the Kahului area of Maui. On 9 August, it was detected in Molokai (Heu et al., 2005). Since the first report of EGW in 2004, it has turned up in China, Hawaii and India.

The most frightening danger of EGW is that their host coral trees are highly associated with ornamental, farming and fishing industries. EGW has attacked hosts that include *E. variegata, E. variegata var. orientalis, E. corallodendron, E. cristagalli, E. abyssinica, E. berteroana*, *E. sandwicensis*, *E. indica* and *E. fusca* (http://pestworld.stjohn.hawaii.edu/pat/MayJul05.pdf; Kim et al., 2004; Yang et al., 2004). For example, EGW is killing off almost all coral trees on Oahu, both endemic species (the wiliwili, *E. sandwicensis*) and cultivated species (the Indian coral trees, *E. indica*) (http://www.hear.org/issues/wiliwilionmaui). The tall wiliwili is often used as windbreaks around farms and nurseries, as a highway noise and privacy buffer, and used in Hawaiian tradition to craft surfboards, canoe outriggers and fish net floats (http://pestworld.stjohn.hawaii.edu/pat/MayJul05.pdf). The threat is being taken so seriously that scientists have reportedly begun to bank wiliwilil seeds as a precaution in case the extant population is completely destroyed. Many old and valuable coral trees are planted in the southern part of China, such as Quanzhou City of Fujian Province, which is famous as "Erythrina City" for planting coral trees, described more than seven hundreds years by Marco Polo. If the spread of the gall wasp extends to Quanzhou, the valuable coral trees would be threatened and the city would suffer disaster.

Although the wasp invader might ultimately impact on many regions of the world, no previous attempt has been made to estimate its worldwide potential distribution. Many scientists have used the Genetic Algorithm for Rule-Set Prediction (GARP) Modelling System to predict the potential distribution of biological entities (Peterson, 2001; Anderson et al., 2002; Hidalgo-Mihart et al., 2004; McNyset, 2005). Using this model, this study has predicted the potential distribution of EGW worldwide, and has estimated the expansion limits of EGW in different continents where it may spread.

MATERIAL AND METHODS

***Model description.* –** Geographic distributional prediction was generated using Desktop GARP v1.1.6 (DG) downloaded from http://www.lifemapper.org/desktopgarp/. Desktop GARP was originally developed (Stockwell & Noble, 1992) based on an algorithm which was derived from ecological

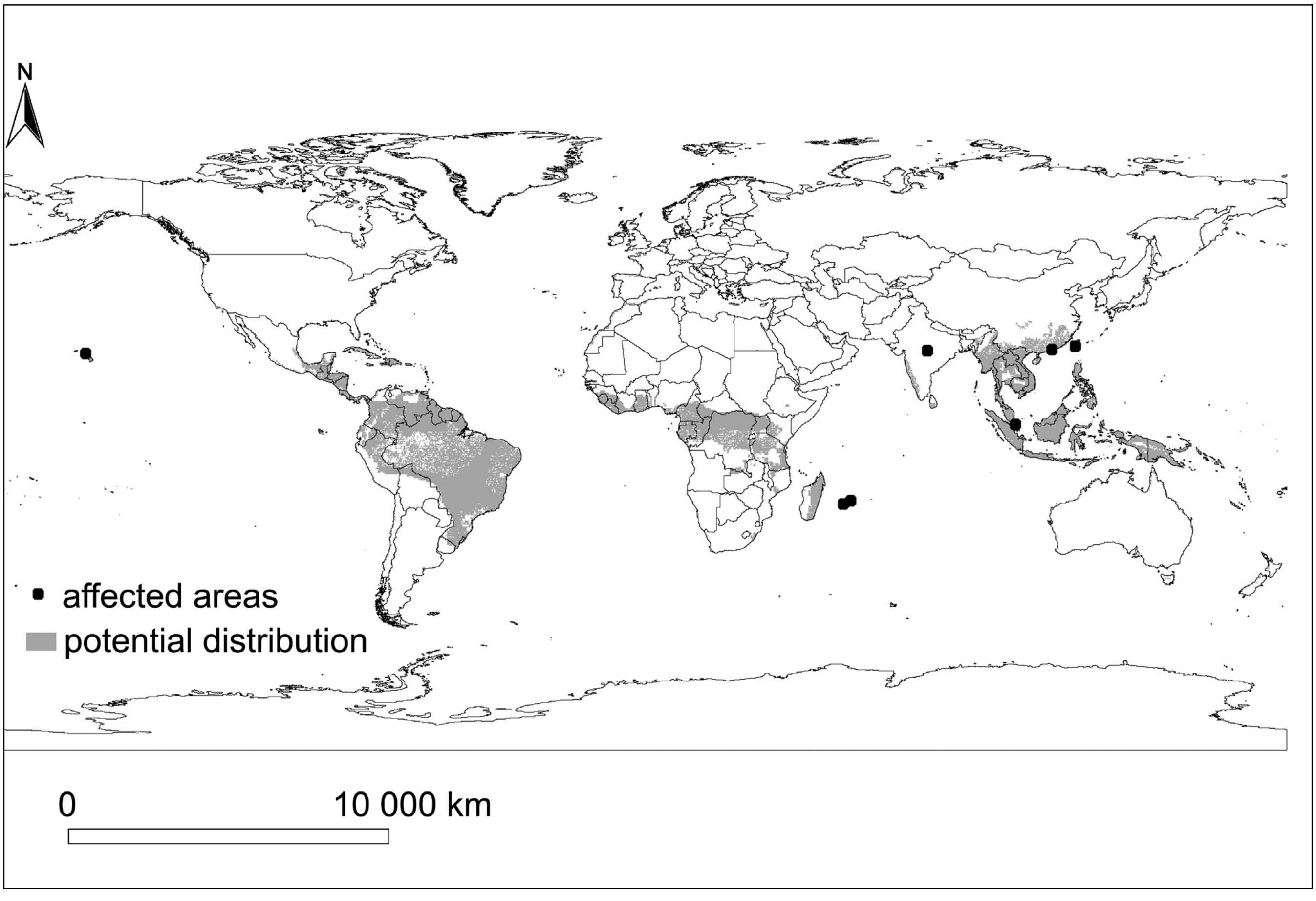

Fig. 1. Potential global range of erythrina gall wasp. The gray shadow indicates the potential expanding range, and the white blank areas indicate where infestation is unlikely.

niches of species evaluating correlations between distributional occurrences and environmental characteristics. The GARP model is projected onto geographic maps resulting in GIS grids, and ArcView v3.2 is used to display the potential expanding areas and current distribution.

A three-step Desktop GARP process was followed: i) modelling niches in ecological space with the current locations in native range, ii) evaluating these models with predictive accuracy based on 1250 points resampled from the test data set, and iii) projecting the models to ranges that could be invaded or interesting areas.

In this paper, the first and the third steps were modified. The current locations of EGW were used to build the modelling niches (McNyset, 2005), as the entire world is of potential interest in terms of EGW spread.

Environment data. – Desktop GARP offers flexibility in choice of base environmental data layers. These layers include elevation, slope, aspect and climatic variables, which are derived from the http://www.lifemapper.org/desktopgarp/. The vegetation layer is derived from http://www.ngdc.noaa.gov/seg/cdroms/ged_iib/. There are 15 layers with the same pixel size of 0.1 degree. The environmental variables were input for niche model of EGW to minimize model omission error, which is the error failing to predict known presence. Twenty niche models were generated using N-1 variables. Every model reached accuracy convergence (0.01) before reaching the designated maximum iterations (1000).

Distributions of EGW. – Records of current locations were collected until August, 2005. Records show that EGW has been spreading in 6 countries and regions on 3 continents, i.e., Singapore, Mauritius, Reunion, Hawaii, China, and India (Kim et al., 2004; Yang et al., 2004; http://www.china.org.cn/chinese/huanjing/962038.htm). This study failed to verify the exact distribution recorded in India; therefore, the analysis did not include locations in India.

RESULTS

The worldwide range is illustrated (Fig. 1) including present affected areas. Fig. 2 and 3 show the potential range of Asia and Africa in detail. The results show that EGW may affect wide areas of Asia, Africa, South America, Oceania, and the southern part of North America. Its potential expansion may cover all of the tropical and subtropical areas in the global, which includes the whole tropical rainforest, most of the tropical monsoon, subtropical monsoon, and part of tropical savanna climates.

The predicted range of its expansion is mainly located between 30°N and 35°S. Within this range, EGW is most likely to be distributed along coast areas. For example, it might reach the coast of California in USA, Morocco, Algeria,

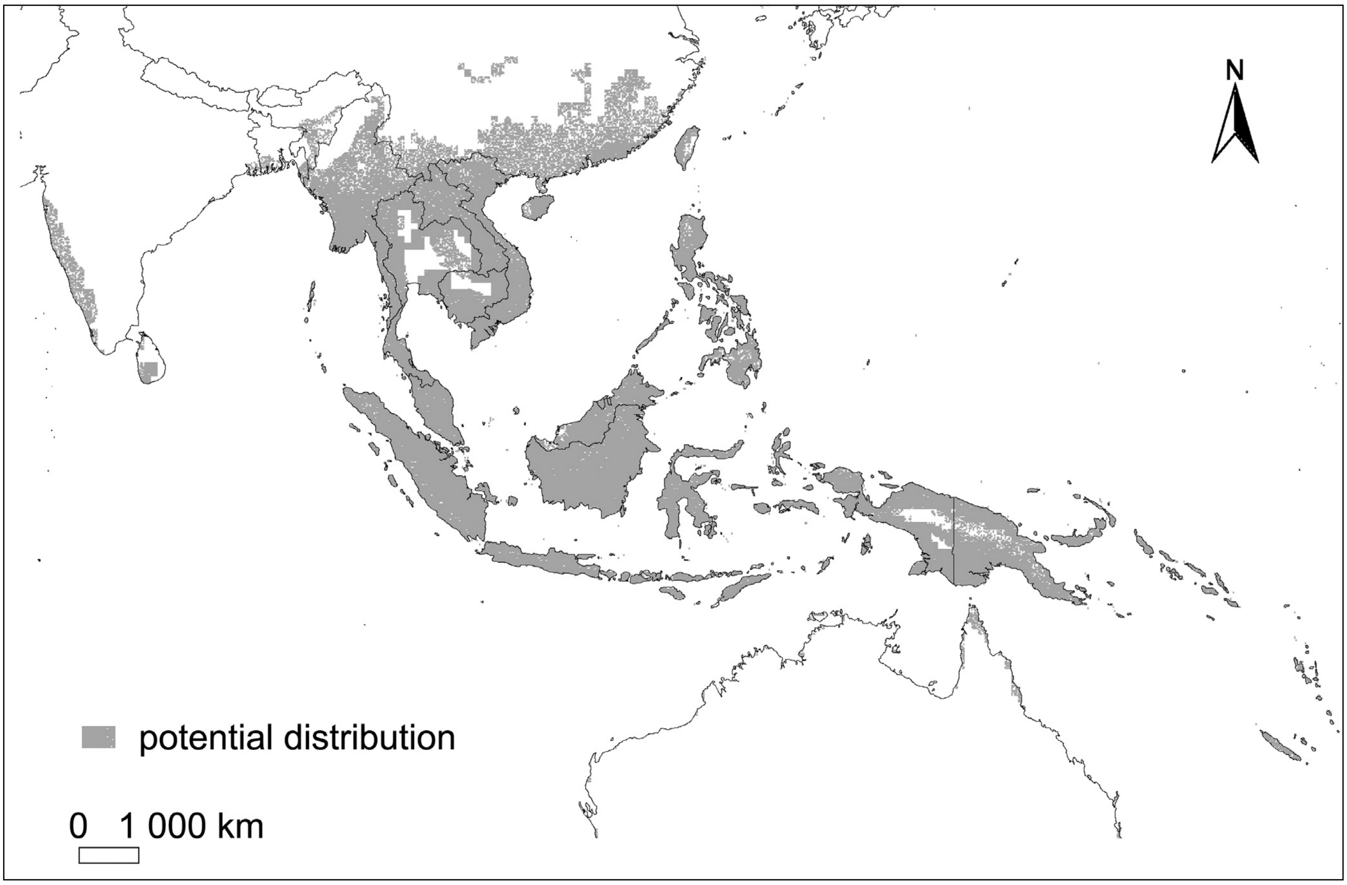

Fig. 2. Potential expansion areas of erythrina gall wasp in Asia and Australia.

Western Sahara, Mauritania and Japan in the northern areas of its predicted range. In southern areas, EGW might reach the coast of Chile, Angola, Namibia, South Africa, Australia and New Zealand. The potential distributions not only include many islands (such as Fiji, Solomon Islands, New Caledonia, Vanuatu, New Zealand, Philippinens, Malaysia, Guam and Samoa) but also inlands (such as Brazil, Bangladesh and Tanzania). The potential expansion of EGW takes on various patterns in different continents.

Fig. 1 shows the potential expansion of EGW based on currently affected locations. The first detected sites lie in the seaports and airports, and takes on the scattered pattern of distribution in a global scale.

In Asia, the potential expansion extends to about 30°N in the north line and covers the area from South East Asia to the north of Australia, covering tropical rainforest, tropical monsoon and subtropical monsoon climates (Fig. 2). The north line of the potential distribution is complex, and includes areas of the south west coastline of India and southern Sri Lanka on the Indian Peninsula, and adjacent countries, such as India and Bangladesh, China, Burma, Thailand, Laos and Vietnam. The Yangtse River is the northern limit in China. In Africa, its predicted range extends from 9°N to 30°S, covering tropical rainforest and some of tropical savannah and subtropical monsoon climates, such as Zaire, Madagascar, Mozambique, Tanzania (Fig. 3). In America, the potential expansion for EGW is between 26°N and 35°S. The appropriate type of climates is similar to that in Asia and Africa. In South America, areas of arid grassland and tree savannah are likely to be attacked. Its potential range may include few areas of Florida, then along the Gulf of Mexico and Caribbean Sea, to the most areas of Colombia, Ecuador, Peru, Brazil, French Guiana, Suriname, Guyana and Venezuela, and parts of Bolivia, Paraguay, Argentina and Uruguay.

The predictive accuracy was high in the world. There were more affected locations in Hawaii and Taiwan than other detected areas, so the accuracy of them could inform predictive capacity in other areas. In Hawaii, all occurrence sites lie in the predictive potential distribution (Fig. 4). The accuracy of prediction for Taiwan is over 73% (Fig. 5).

DISCUSSION

The potential expansion of EGW in the global scale was predicted using the Desktop GARP. The results indicate that predictive potential ranges are far-reaching and pan-tropical, which are likely to affect five continents and all of the tropical and subtropical areas in the world (Fig. 1). Tropical and subtropical climates are the main climate types in the potential expansion. The potential distribution suggests that EGW prefers warm and humid areas, which are consistent with the distribution of coral trees. Coral trees are found throughout the tropics and extend into warm temperate areas such as South Africa, the Himalayas, southern China, the Rio de la Plata region of Argentina and southern United States (Kass, 1998). Vegetation type and humidity are important factors in the potential spread of EGW.

The main differences between potential expansion and affected areas can be summarized as follows. On the one hand, although there are no records of detection in South America and Oceania until August, 2005, the predictive results show the potential expansion extending to there. The host and the environment there meet the essential requirements for EGW. For example, *E. cristagalli* L. is native to Brazil, and is the national tree (flower) in Argentina, Uruguay and Chile. The potential distribution of the Oceania includes many islands, where the environment is similar to that of the Hawaiian Islands or Malaysia. Therefore the potential distribution for South America and Oceania is reasonable. According to the latest report of New Pest Advisory, EGW has been found in Guam and American Samoa (Heu et al., 2006). On the other hand, Penghu Islands, Lutao and the southernmost points in Taiwan were not included in potential expansion, where damage has been reported. This is possibly because the areas are not included in the environmental layer of GARP, and are regarded as sea rather than islands by the software. However, they fell very close to potential expansion and in accordance with the predictive tendency as a whole (Fig. 5). The landform of Taiwan is mountainous in the middle east,

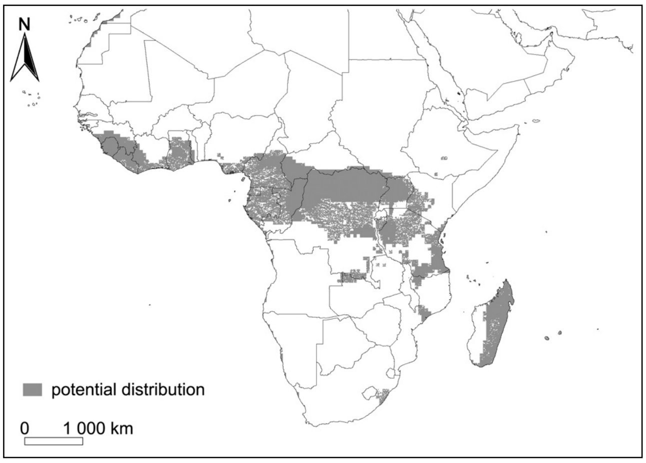

Fig. 3. Potential expansion areas of erythrina gall wasp in Africa.

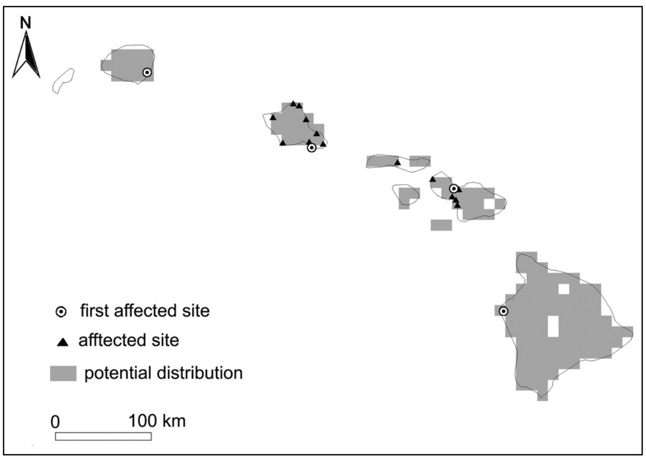

Fig. 4. Potential expansion areas of erythrina gall wasp in Hawaii.

such as Central Mountains ridge and Jade Mountains, while the landform is low land in the west. The predictive result shows that the west is more appropriate than the middle east of Taiwan, which is consistent with the environment of the common character of most reported sites. To sum up, the predictive potential ranges cover most of affected areas globally, such as affected areas in Hawaii. According to the latest "affected areas" report of EGW, affected coral trees were detected in Xiamen City in Fujian Province, Sanya City and Wanning County in Hainan Province, China in October 2005 (http://www.cas.cn/html/Dir/2005/10/25/13/53/05.htm). The three locations have been included in the potential expanding ranges, and tally with the currently expanding tendency, that is, harbor cities are one of the first attacked sites. Heu et al. (2006) also reported the new distribution of EGW in Asia. It has been found the damage of EGW in Thailand, Okinawa and Hongkong, and Philippines is very likely suspicious to be attacked. All of these new regions are included in the potential expansion areas in this study. In the future, it is necessary to obtain more detail environmental and distribution data to get the more accurate predictive results.

As a newly invasive species, the expansion rate of EGW was abnormally quick, which raises significant concerns about its speed of expansion and its potential threat for global outbreaks. The area of origin for EGW and its mechanism of spread remain unknown. Based on the reported distribution pattern and predicted the potential ranges of expansion, there are three conjectures.

Firstly, EGW is not capable of long distance flight between all the regions in its current distribution. Thus, the expansion of EGW is most likely to occur as a result of human activity. The current affected sites are disjunctive, and most of them lie in the edge of land or islands. The increased introductions and transfers of coral trees among different countries in recent years have created many potential opportunities for EGW entering into various ranges.

Secondly, the predictive results show that the expanding tendency in the future may go further inland, spreading out from the initial point of invasion. This could be especially true in the middle of Africa and South America. This gives a clue to enlarge the investigation range of the gall wasp.

Thirdly, what is the origin of EGW? It has been reported that EGW only attacked coral trees until now (http://pestworld.stjohn.hawaii.edu/pat/MayJul05.pdf; Kim et al., 2004; Yang et al., 2004). Thus there is a hypothesis that an affinity would be built between the origin of EGW and the origin of *Erythrina*. *Erythrina* has a pan-tropical distribution, originating in South America and Africa (Kass, 1998). However, there is no evidence for a South American origin of EGW except that there are coral trees there. Furthermore, there are many kinds of *Erythrina* trees attacked by EGW, and the first host cannot be identified. Thus, it is not logical and inadvisable to identify the native place of EGW by its host. In Asia, the attacked areas are far smaller than the areas that would be attacked by EGW with its quickly expansive speed. Thus, Asia cannot be the original site of EGW. Australia also cannot be the original site of EGW. There are many researchers who have carried out many investigations about the gall-inducing wasps in Australia, but they did not find EGW (Timberlake, 1957; Bou_ek, 1988; Graham, 1987; Headrick et al., 1995; Schauff & Garrison, 2000; Mendel et al., 2004; LaSalle, 2005; Ikeda, 1999). Some other *Quadrastichus* species (not *Q. erythrinae*) were known to form galls on coral trees in Africa (van Staden et al., 1977; Annecke & Moran, 1982). Until now, *Quadrastichus* gall inducers on coral trees are only known from Africa except EGW. Thus, it is possible that EGW originated from Africa. The fact that the first records of EGW as a pest species were from Islands off the east coast of Africa (Reunion and Mauritius) supports this hypothesis. Other authors also considered that it was reasonable to suppose that Africa is the original site of EGW (John LaSalle pers. comm.).

If Africa is the original range of EGW, why are there no records at present? The primary reason is that the incidence of EGW may not reach as high levels of damage as in its invasive ranges - so there are probably natural enemies of some form or the other which limit its population in its native range, or a symbiotic relationship between EGW and its original host built during long term evolution. However, all these are only presumptions and need to be validated with further investigations.

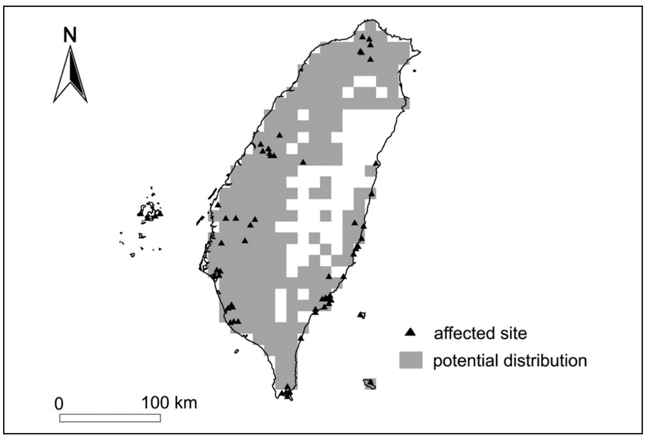

Fig. 5. Potential expansion areas of erythrina gall wasp in Taiwan.

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