USING GARP TO PREDICT THE RANGE OF *AEDES AEGYPTI* IN CHINA

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Abstract. Dengue fever and dengue hemorrhagic fever are common mosquito-borne diseases in tropical and subtropical regions, and are mainly transmitted by the mosquito *Aedes aegypti* (Diptera: Culicidae). The international trade of used tires, coupled with its anthropophilic habit, has enabled *Ae. aegypti* to colonise new areas in China. We used Genetic Algorithum Rule-Set Production (GARP) to predict the putative current distribution of *Ae. aegypti* based on data on its distribution 20 years ago and compared this predicted distribution with the known current distribution. The putative distribution corresponded perfectly to the existing distribution. We conclude that GARP is a valid method to predict the putative future distribution of *Ae. aegypti*, and therefore is an important tool for the surveillance of mosquito-borne diseases in general.

Keywords: GARP, *Aedes aegypti*, putative distribution, prediction, China

INTRODUCTION

The *Aedes aegypti* mosquito is widely distributed in tropical and subtropical regions, roughly between the mean temperature 20°C isotherms during the hottest month in both hemispheres. In addition to being a nuisance, *Ae. aegypti* is a vector of infectious diseases such as dengue fever (DF) and dengue hemorrhagic fever (DHF) throughout most of China (Black and Bennet, 2002). DF and DHF currently occur in over 100 countries, with 60 million cases, and causing 30,000 deaths, each year (Clarke, 2002; WHO, 2012). DHF is now the primary cause of hospitalization and death among children in many Southeast Asian countries (Gubler, 1998).

The incidence of DF continues to increase with the spread of *Ae. aegypti*. DF is now one of the most widely distributed, and most harmful arboviruses in the world (Gubler, 1998). Because there is no

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vaccine or cure for this disease, vector prevention and control are the only ways of reducing its incidence. The ability to accurately predict the putative distribution of *Ae. aegypti* therefore greatly facilitates the surveillance and control of this pest.

Traditional vector surveillance methods have been hampered by the difficulty of implementing real-time spatial orientation analysis. The development of Genetic Algorithm Rule-set Production (GARP) has solved this problem. GARP not only takes account of the various factors that affect mosquito distribution in specific environments, it also quickly identifies spatial and temporal trends in a species' distribution, thereby allowing timely intervention and more cost-effective allocation of limited public health resources (Adjemian *et al*, 2006).

GARP uses existing information on a species' distribution and environmental data to predict its niche-based ecological requirements and putative distribution. GARP was originally developed by David Stockwell in the mid-1990s and subsequently improved at the San Diego Supercomputer Center (Chen, 2008). The principle of GARP is to explore non-random relationship between the environmental characteristics of a species' known and putative ranges (Jia *et al*, 2005). Peterson and Vieglais (2001) predicted the putative distribution of *Anoplophora nobilis* from a GARP-based niche model. Similarly, Benedict *et al* (2007) used GARP to predict the putative global distribution of *Aedes albopictus*, thereby informing efforts to control and monitor this pest.

In this paper, we assess the accuracy of GARP-based predictions of species' range by using GARP to predict the distribution of *Ae. aegypti* in China from information collected 20 years ago and comparing this putative range with the species' actual range based on current data.

MATERIALS AND METHODS

Ethics statement

No specific permits were required for this study. All experiments were conducted within state-owned land in China. Therefore, the local ethics committee deemed that approval was unnecessary.

Past distribution

GARP niche prediction models need information on the stable distribution of a species to predict its putative range. We used information on the distribution of *Aedes aegypti* in China collected 20 years ago (Lu, 1990), from a total of 91 locations, to inform the GARP model.

GARP model parameters

We provided the GARP model with the mean 1961-1990s values of 14 environmental factors, including topographic features, altitude, slope gradient, vegetative cover, the accumulation and flow of water used for irrigation, annual mean, maximum and minimum temperatures, annual precipitation, annual evaporation, annual humidity, annual radiation and annual frost periods. The grid resolution of all layers was 0.1°.

Aedes aegypti distribution

Aedes aegypti was thought to be confined to China's coastal provinces, however, it was recently reported in Ruili, Yunnan Province (Wang *et al*, 2006). We carried out a thorough investigation to verify the presence of *Ae. aegypti* in Ruili City and surrounding areas in 2010.

We sampled mosquitoes mainly at used tire storage centers. At each storage center we randomly selected 10 mosquito breeding sites and collected all the larvae

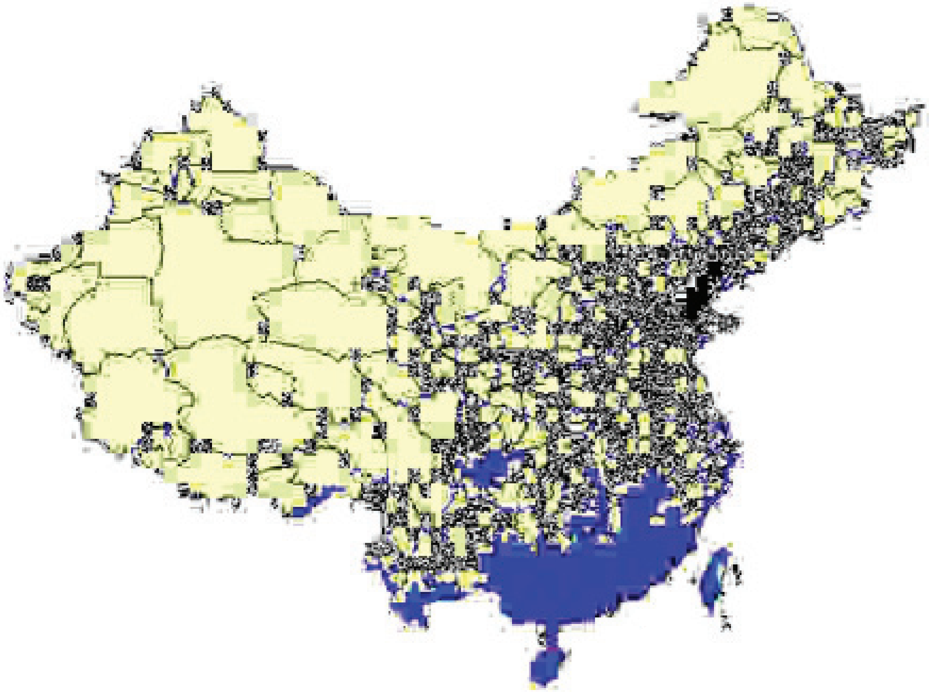

Fig 1–The putative range of *Aedes aegypti* in China predicted by GARP. The putative range of *Aedes aegypti* includes Hainan, Guangdong, Guangxi, part of the border areas of south-eastern Tibet, western and southern border areas of Yunnan, parts of southern Guizhou, southern Hunan, areas adjacent to Chongqing City, and parts of Jiangxi and Fujian.

therein. Larvae were reared individually in a laboratory, and associated larval and pupal skins were mounted. All specimens were identified using standard taxonomic keys.

RESULTS

Putative range

Previous publications indicated that the distribution of *Ae. albopictus* is determined by several environmental variables, such as winter and summer temperature, precipitation patterns, photoperiod, etc (Alto and Juliano, 2001). We provided GARP with data on 14 environmental factors and used ArcGis to display predicted range of *Ae. aegypti* (Fig 1).

The putative range of *Ae. aegypti* includes Hainan, Guangdong, Guangxi, part of the border areas of south-eastern Tibet, western and southern border areas of Yunnan, parts of southern Guizhou, southern Hunan, areas adjacent to Chongqing City, and parts of Jiangxi and Fujian.

Of the 14 ecological factors that could affect the distribution of *Ae. aegypti*, temperature is probably the most important. Research on *Ae. albopictus* has shown that a January mean temperature of 0ºC significantly reduced the survival rate of diapause eggs (Knudsen *et al*, 1996; Medlock *et al*, 2006) and that an annual mean temperature of 11°C appears to be the threshold temperature for adult survival (Kobayashi *et al*, 2002). Apart from tem-

Table 1
Community structure and surrounding environment of *Aedes aegypti* breeding grounds.

Species	Nongen		Yingang		Huopai		Lanlanhe		Jiegao	
	NU	SE	NU	SE	NU	SE	NU	SE	NU	SE
Ae. aegypti	35	MPD	13	SPD and bamboo forest	137	GPD	2	MIP	155	Cement water tank in toilets
Ae. albopictus	....		27		2		45		....	
Ae. harveyi	....		....		....		15		....	
Cx. pipiens quinquefasciatus	112		284		96		35		....	
Cx. nigropunctatus	....		....		34		....		....	
Ar. subalbatus	....		....		....		....		....	
Ar. flavus	....		....		....		65		....	
Tx. splendens	....		13		....		....		....	
Tx. kempi	....		1		....		....		....	

NU, number; SE, surrounding environment; MPD, moderate human population density; SPD, smaller human population density; GPD, greater human population density; MIP, minimal human population density.

perature, annual precipitation is probably another important indicator of habitat suitability since this is directly related to the maintenance of larval habitat. Five hundred milimeters appears to be the threshold value for larval survival in *Ae. albopictus* (Mitchell, 1995; Eritja *et al*, 2005). Annual rainfall throughout the entire putative range is more than 1,200 mm so precipitation is not considered a limiting factor. Comparison of the putative range with the mean January isotherm, mean July isotherm and the mean annual temperature in recent decades (Fig 2) indicates that a January mean temperature >8ºC is the most important limiting factor for *Ae. aegypti*. Mean annual temperature throughout the putative range exceeds 16ºC. For example, January and July mean temperatures, and the mean annual temperature for Ruili City, a new breeding ground for *Ae. aegypti*, are 8-12ºC, 24-28ºC and 16-20ºC, respectively.

The distribution of *Aedes aegypti* in Ruili City, Yunnan Province

The first record of *Ae. aegypti* in Yunnan Province was from a lorry park in Jiegao Port, near Ruili City in 2002. We regarded this lorry park as the center of the species' distribution in Yunnan and surveyed outwards from this central point. We found a total of five additional breeding grounds; one in a residential area of Jiegao (1 km from the lorry park), and four in used tire storage centers located in Nongen Village (1.5 km from the lorry park), Yingang Village (2.5 km from lorry park), Huopai Village (3 km from the lorry park) and at the Lanlanhe maintenance depot (11 km from the lorry park) (Table 1).

The results show that *Ae. aegypti* population density is positively correlated with human population density but inversely proportional to *Ae. albopictus* population density. Since the first discovery of *Ae. aegypti* at Jiegao in February 2002, the species has since spread into Ruili City and as far north as the Lanlanhe maintenance gang depot.

Comparing the putative range predicted by GARP with actual *Ae. aegypti*

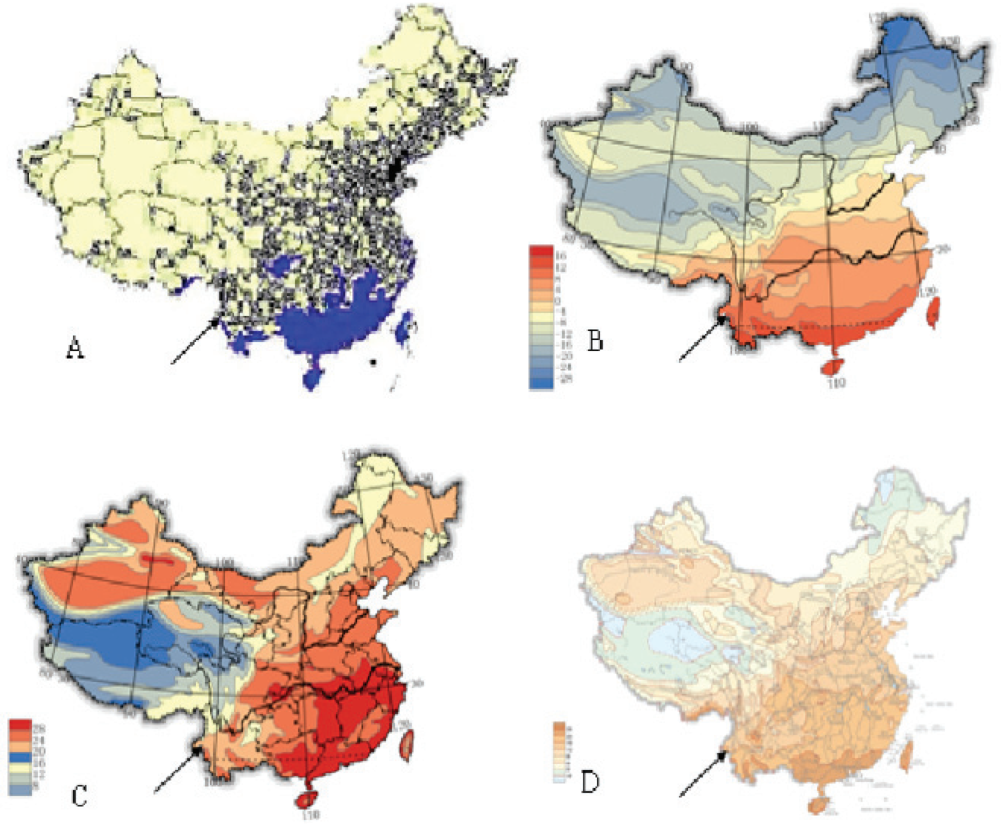

Fig 2–Map of China indicating: A) The putative range of *Aedes aegypti*; B) Mean January isotherm; C) Mean July isotherm; D) Mean annual temperature. (Arrows indicate the location of Ruili City, a new *Aedes aegypti* breeding ground).

survey results indicates that the predicted range corresponds closely to the species' actual range.

DISCUSSION

Previous studies indicated that *Ae. aegypti* was only found south of latitude 22º North, a region including coastal areas of Taiwan, Hainan, Guangdong, Guangxi and some offshore islands (Lu, 1997). However, following development of border trade, tourism and global warming, *Ae. aegypti* has expanded its range. A survey conducted in 2006 in Hainan Province found *Ae. aegypti* in Danzhou City and Lingshui County (Wu *et al*, 2010) and there have since been confirmed reports of the species from the Leizhou Peninsula in Guangdong Province (Lin, 1996; Cai *et al*, 2007).

Our 2010 investigation in Yunnan confirmed that *Ae. aegypti* has not only invaded Ruili City from Jiegao Port but has spread as far north as the Lanlanhe maintenance depot. In the same year, Shuhua Dong confirmed the presence of *Ae. aegypti* in Mangshi City in Yunnan Province, about 70 km from Ruili City (Dong *et al*, 2011). Based on the above information, it is clear that *Aedes aegypti* has spread north of latitude 25º.

Due to its advanced model algorithms and integration with environmental data from various regions of the world, GARP only requires the user to provide information on the distribution of the target species. In addition to climatic factors, GARP is capable to integrate agrotypes, vegetation distribution and other abiotic factors to predict a species putative distribution. According to Gowdown and Peterson, GARP can accurately predict the distribution of a target species on the basis of as few as 10-30 known distribution loci (Peterson and Vieglais, 2001).

Unlike *Ae. albopictus*, *Ae. aegypti* is not able to induce photoperiodic egg diapause in order to overwinter in temperate regions (Hawley, 1988), Hence, the survival of *Ae. aegypti* is strongly influenced by January mean temperature. We found that a minimum January mean temperature of 8ºC and a minimum annual mean temperature of 16ºC are threshold values for the establishment of *Ae. aegypti* in China. Almost all the putative range of *Ae. aegypti* is in the Oriental Realm, which is the typical breeding ground for almost all of the subgenus *Stegomyia*, including *Ae. aegypti*. Although the most northern part of the putative range extends as far 30º North, at this latitude the species is confined to parts of Chongqing City and Fujian Province which have more diverse vegetation, abundant water and are relatively warm.

GARP predicts the distribution of a species in multi-dimensional space. Some authors maintain that variation in the number of sampling points between parts of a species' range can result in a discrepancy between its putative and actual ranges (Peterson and Cohoon, 1999). Such discrepancies may be caused by two factors: 1) The putative range includes significant areas of unsuitable habitat; and 2) Shift in a species' ecological habits, interspecific competition, geographical isolation, human activity or other ecological factors cause parts of the predicted range to be no longer suitable for the species. In this case the area of the putative range exceeds that of the actual range (Fielding and Bell, 1997). In this case not all suitable areas are occupied by the species.

Previous research on *Ae. albopictus* showed that human factors, such as population density and distance to human settlements, affected the species' distribution (Richards *et al*, 2006). The same appears true of *Ae. aegypti*. In addition to climatic factors, the distribution of *Ae. aegypti* is affected by: 1) Human population density. *Ae. aegypti* is anthropophilic and larvae prefer man-made water containers in human population settlements (Preechaporn *et al*, 2006). Therefore, the greater human population density, the bigger the *Ae. aegypti* population; 2) The population density of *Ae. albopictus*. *Ae. albopictus* larvae are competitively superior to those of *Ae. aegypti* (Juliano, 1991; Barrera, 1996; Daugherty *et al*, 2000) so the abundance and range of *Ae. aegypti* is negatively correlated with that of *Ae. albopictus* (Nasci *et al*, 1989; Hobbs *et al*, 1991; Mekuria and Hyatt, 1995; O'Meara *et al*, 1995); and 3) The population density of *Toxorhynchites* spp. *Toxorhynchites* spp larvae feed on the larvae of other mosquito species therefore the abundance of *Aedes aegypti* is negatively correlated with that of larvae of this genus.

Many studies have demonstrated that *Ae. aegypti* predominantly rests (Scott *et al*, 2000), feeds (Russell *et al*, 1969) and oviposits in human dwellings (Makiya, 1968). Females tend to distribute their eggs among several water receptacles

(Fay and Perry, 1965; Chadee *et al*, 1990; Chadee and Corbet, 1993; Chadee, 1997) and avoid ovipositing in receptacles that already contain *Ae. aegypti* larvae (Chadee *et al*, 1990). This strategy benefits offspring by decreasing sibling competition and spreading risk. Since eggs are often laid in bodies of water in man-made objects, such as used tires, this also increases the potential for the spread through human agency.

In Ruili City, for example, many *Ae. aegypti* breeding grounds were in used tire storage centers and the species's spread in this region is clearly related to the trade in used tires. Moreover, trade in flowers, bonsai trees and rubber is very frequent in Yunnan Province, all of which exacerbates the spread of *Ae. aegypti*.

Its anthropophilic nature, together with trade in used tires and other man-made water receptacles, has enabled *Ae. aegypti* to expand its range in China. Strict inspection and quarantine measures throughout the species' putative range are required to control the concomitant spread of DF and DHF.

In conclusion, since there are currently no vaccines or treatment, vector control is the only way to reduce the global incidence of DF and DHF. We found that a January mean temperature >8ºC was the most important factor for the establishment of *Ae. aegypti*. Mean annual temperatures throughout the predicted range exceeded 16ºC. The putative distribution of this species in China predicted by GARP from data collected 20 years ago corresponded to its current range. The ability to predict areas that are likely to be colonized by *Ae. aegypti* so that these can be prioritized for surveillance is crucial to reducing the prevalence of DF and DHF. Our results provide further evidence that GARP is a powerful tool in the prevention and control of vectors and vector-borne diseases.

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REFERENCES

Adjemian JCZ, Girvetz EH , Beckett L, Foley JE. Analysis of Genetic Algorithm for Rule-Set Production (GARP) modeling approach for predicting distributions of fleas implicated as vectors of plague, *Yersinia pestis*, in California. *J Med Entomol* 2006; 43: 93-103.

Alto B, Juliano SA. Precipitation and temperature effects on populations of *Aedes albopictus* (Diptera: Culicidae): implications for range expansion. *J Med Entomol* 2001; 38: 646-56.

Barrera R. Competition and resistance to starvation in larvae of container-inhabiting mosquitoes. *Ecol Entomol* 1996; 21: 117-27.

Benedict MQ, Levine RS, Hawley WA, Lounibos LP. Spread of the tiger: global risk of invasion by the mosquito *Aedes albopictus*. *Vector Borne Zoonotic Dis* 2007; 7: 76-81.

Black WK, Bennett KE, Gorrochotegue-Escalante N, *et al*. Flavivirus susceptibility in *Aedes aegypti*. *Arch Med Res* 2002; 33: 379-88.

Cai C, Wang A, Xu B, *et al*. [Investigation of distribution, ecological status, density and seasonal growth-decline of *Aegypti* in Leizhou Peninsula]. *Chin Front Health Quarant* 2007; 30: 361-465.

Chen L. Ecological niche modeling as a predictive tool: Asiatic freshwater fishes in north America. University of Kansas, 2008.

Chadee DD. Effects of forced egg-retention on the oviposition patterns of female *Aedes aegypti* (Diptera: Culicidae). *Bull Entomol Res* 1997; 87: 649-51.

Chadee DD, Corbet P. An improved method for detecting substrate preferences shown by mosquitoes that exhibit skip oviposition. *Phys Entomol* 1993; 18: 114-8.

Chadee DD, Corbet PS, Greenwood JD. Egg-laying yellow fever mosquitoes avoid sites containing eggs laid by themselves or by conspecifics. *Entomol Exp Appl* 1990; 57: 295-8.

Clarke T. Dengue virus: break-bone fever. Nature 2002; 416(6882): 672-4.

Daugherty MP, Alto BW, Juliano SA. Invertebrate carcasses as a resource for competing *Aedes albopictus* and *Aedes aegypti* (Diptera: Culicidae). *J Med Entomol* 2000; 37: 364-72.

Dong S, Pan S, Ma L, Lei J, Zhou H. [Survey of *Aedes aegypti* distribution in Mangshi, Yunnan]. *Chin J Vector Biol Control* 2011; 22: 592-4.

Eritja R, Escosa R, Lucientes J, *et al*. Worldwide invasion of vector mosquitoes: present European distribution and challenges for Spain. *Bio Invasions* 2005; 7: 87-97.

Fay RW, Perry AS. Laboratory studies of ovipositional preferences of *Aedes aegypti*. *Mosq News* 1965; 25: 276-81.

Fielding AL, Bell JF. A review of methods for the assessment of prediction errors in conservation presence/absence models. *Environ Conserv* 1997; 24: 38-49.

Gubler D. Dengue and dengue hemorrhagic fever. *Clin Microbiol Rev* 1998; 11: 480-96.

Hawley WA. Biology of *Aedes albopictus*. *J Am Mosq Contr Assoc* 1988; 4 (suppl 1): 2-39.

Hobbs JE, Hughes EA, Eichold BH 2nd. Replacement of *Aedes aegypti* by *Aedes albopictus* in Mobile, Alabama. *J Am Mosq Control Assoc* 1991; 7: 488-9.

Jia WH, Zhou YL, ding SL. The methods and technologies in pest risk analysis. *J Northwest Sci-Tech Univ Agric Forestry* (*Natural Sci Ed*) 2005; 33(1) (in Chinese with English abstract).

Juliano S. Species introduction and replacement among mosquitoes: interspecific resource competition or apparent competition? *Ecology* 1991; 79: 255-68.

Knudsen AB, Romi R, Majori G. Occurrence and spread in Italy of *Aedes albopictus*, with implications for its introduction into other parts of Europe. *J Am Mosq Control Assoc* 1996; 12: 177-83.

Kobayashi M, Nihei N, Kurihara T. Analysis of northern distribution of *Aedes albopictus* (Diptera: Culicidae) in Japan by geographical information system. *J Med Entomol* 2002; 39: 4-11.

Lin K. [Distribution and control of *Aedes aegypti* in Zhanjiang]. *Chin J Front Health Quarant* 1996; 19: 336-9.

Lu B. [Vector of dengue fever and its prevention in China]. BeiJing: Guizhou People's Press, 1990.

Lu, B. [Fauna of China. Insecta Diptera. Culicidae]. BeiJing: Science Press, 1997.

Makiya K. Population dynamics of larvae overwintering in southern Japan. *Jpn J Sanit Zool* 1968; 19: 223-9.

Medlock JM, Avenell D, Barrass I, Leach S. Analysis of the potential for survival and seasonal activity of *Aedes albopictus* (Diptera: Culicidae) in the United Kingdom. *J Vector Ecol* 2006; 31: 292-304.

Mekuria Y, Hyatt M. *Aedes albopictus* in South Carolina. *J Am Mosq Control Assoc* 1995; 5: 399-414.

Mitchell CJ. Geographic spread of *Aedes albopictus* and potential for involvement in arbovirus cycles in the Mediterranean basin. *J Vector Ecol* 1995; 20: 44-58.

Nasci RS, Hare SG, Willis FS. Interspecific mating between Louisiana strains of *Aedes albopictus* and *Aedes aegypti* in the field and the laboratory. *J Am Mosq Control Assoc* 1989; 5: 416-21.

O'Meara GF, Evans LF Jr, Gettman AD, Cuda JP. Spread of *Aedes albopictus* and declines of *Aedes aegypti* (Diptera: Culicidae) in Florida. *J Med Entomol* 1995; 32: 554-62.

Peterson A, Cohoon K. Sensitivity of distributional prediction algorithms to geographic data completeness. *Ecol Model* 1999; 117:

159-64.

Peterson A, Vieglais D. Predicting species invasions using ecological niche modeling: new approaches from bioinformatics attack a pressing problem. *Bio Sci* 2001; 51: 363-71.

Preechaporn W, Jaroensutasinee M, Jaroensutasinee K. The larval ecology of *Aedes aegypti* and *Aedes albopictus* in three topographical areas of southern Thailand. *Dengue Bull* 2006; 30: 204-13.

Richards SL, Apperson CS, Ghosh SK, Cheshire HM, Zeichner BC. Spatial analysis of *Aedes albopictus* (Diptera: Culicidae) oviposition in suburban neighborhoods of a piedmont community in North Carolina. *J Med Entomol* 2006; 43: 976-89.

Reiter P, Amador MA, Anderson RA, Clark GG. Short report: dispersal of *Aedes aegypti* in an urban area after blood feeding as demonstrated by rubidium- marked eggs. *Am J Trop Med Hyg* 1995; 52: 177-9.

Russell PK, Gould DJ, Yuill TM, Nisalak A, Winter PE. Short report: dispersal of *Aedes aegypti* in an urban area after blood feeding as demonstrated by rubidium marked eggs. *Am J Trop Med Hyg* 1969; 18: 580-3.

Scott TW, Amerasinghe PH, Morkison AC, *et al*. Longitudinal studies of *Aedes aegypti* (Diptera: Culicidae) in Thailand and Puerto Rico: blood feeding frequency. *J Med Entomol* 2000; 37: 89-101.

Wang PU, Zhou HN, *et al*. The distribution of Dengue vector: *Aedes aegypti* in Yunnan Province. *Chin Vector Biol Control* 2006; 17: 507-8 (in Chineses with English abstract).

World Health Organization (WHO). Dengue and dengue haemorrhagic fever. Fact sheet, Geneva: WHO, 2012.

Wu JY, Lun ZR, James AA, *et al*. Dengue fever in mainland China. *Am J Trop Med Hyg* 2010; 83: 664-71.