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How environmental conditions impact mosquito ecology and Japanese encephalitis: An eco-epidemiological approach

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ABSTRACT

Japanese encephalitis (JE) is one of the major vector-borne diseases in Southeast Asia and the Western Pacific region, posing a threat to human health. In rural and suburban areas, traditional rice farming and intensive pig breeding provide an ideal environment for both mosquito development and the transmission of JEV among human beings. Combining surveillance data for mosquito vectors, human JE cases, and environmental conditions in Changsha, China, 2004–2009, generalized threshold models were constructed to project the mosquito and JE dynamics. Temperature and rainfall were found to be closely associated with mosquito density at 1, and 4 month lag, respectively. The two thresholds, maximum temperature of 22–23 °C for mosquito development and minimum temperature of 25–26 °C for JEV transmission, play key roles in the ecology of JEV. The model predicts that, in the upper regime, a 1 g/m^3 increase in absolute humidity would on average increase human cases by 68–84%. A shift in mosquito species composition in 2007 was observed, and possibly caused by a drought. Effective predictive models could be used in risk management to provide early warnings for potential JE transmission.

1. Introduction

Japanese encephalitis virus (JEV) is an arbovirus that belongs to the Flaviviridae family and endemic to large parts of Asia and the Pacific (Solomon, 2006). It is estimated that approximately 68,000 people suffer from this disease every year, causing approximately 10,000–15,000 deaths in more than 20 countries, including districts of Asia and the Pacific (Campbell et al., 2011; Erlanger et al., 2009; Solomon, 2006). The disease can cause irreversible neurological damage, and serious viral encephalitis has a fatality rate of approximately 35–40%, with some regions rate as high as 70% (Halstead and Jacobson, 2008; Lindenbach et al., 2007).

JE is transmitted by *Culex* mosquito species. *Culex tritaeniorhynchus*, which as the primary vector, prefers to breed in irrigated rice paddies and feed on pigs. Swine, including domestic and feral pigs, serve as amplifying hosts of JEV in endemic areas. All of these epidemiological characteristics provide an ideal environment both for the amplification of mosquito population density and the transmission of JEV among humans (Zheng et al., 2012), which constitute pig-associated rural domestic cycles together with mosquitoes (Le Flohic et al., 2013; Scherer et al., 1959).

As a mosquito-borne disease, environmental factors play a significant role in JEV transmission. Weather factors, including temperature and precipitation, have been reported to drive the JE transmission by affecting the mosquito life cycle including the development time of immature mosquito stages and mosquito density (Gingrich et al., 1992; Murty et al., 2010; Olson et al., 1983; Reisen et al., 1976; Vythilingam et al., 1997). A higher temperature has been found to increase the

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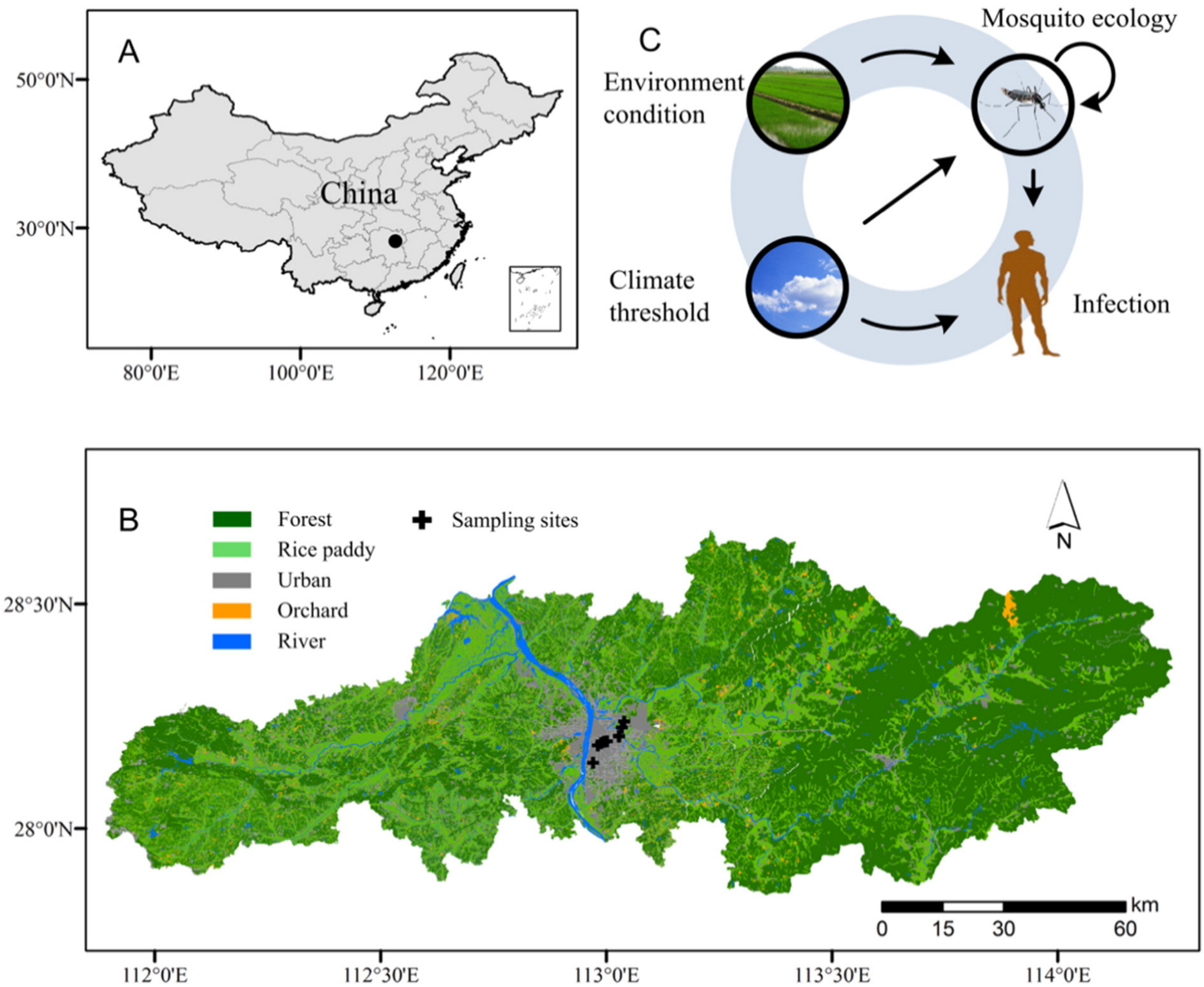

Fig. 1. The study area of Changsha in South China with sampling sites labeled in points, and the environment–mosquito–Japanese encephalitis model. (A) Study area, Changsha, South China. (B) The land use of Changsha and the sampling sites, and (C) an overview of the environment–mosquito–Japanese encephalitis model. The series of models link meteorological data with rice paddy fields, mosquito dynamics, and human cases. The model formulation is given in Materials and methods.

rates of virus replication and dissemination (Kilpatrick et al., 2008), and results in a shorter time from mosquito infection to transmission of the virus to humans (Takahashi, 1976). Furthermore, higher temperatures may change human behavior and provide more contact opportunities between human and mosquitoes. Hence, weather factors are highly related to the occurrence of JE (Konno et al., 1966).

JEV antibody levels among pigs, vaccination coverage (especially population immunity), the species of mosquitoes to be infected, were considered to affect JE transmission among humans directly (Zheng et al., 2012). JEV transmission is related to agricultural activities, which involve the transmission cycles of mosquitoes in rice paddies and interaction with human beings in the farmland. It is apparent that rice paddies are the preferred development sites for mosquito vectors, which provide an important transmission site for mosquitoes (Henrich et al., 2003; Impoinvil et al., 2011; Masuoka et al., 2010; Richards et al., 2010).

Since 1951, China has been one of the countries worldwide with the highest incidence of JE (Gao et al., 2010; Wang et al., 2009), with notified cases accounting for half of the total number of global cases (Campbell et al., 2011). Hunan Province is one of the most highly endemic areas in China, with more than 140,000 cases being reported between 1951 and 2000, and 18,000 deaths (Guo and Li, 2002).

Changsha is the capital city of Hunan Province in Central China, between 27°–28°N and 111°–114°E (Fig. 1A), consisting of one municipal district and four counties, with a total population of about 6.2 million people in 2005. The annual mean temperature is roughly 17 °C. The mean summer and winter temperatures are approximately 30 °C and 5 °C respectively, while annual rainfall is typically between 1350 and 1550 mm. Subtropical double-harvest rice is the main crop and widely distributed in Changsha, and farmers reside less than 50 m away from their rice paddies. Furthermore, pigs, which are an important economic resource for farmers, are raised in pens close to residences, causing JEV transmission.

We tried to examine risk factors in the JE transmission to identify possible thresholds of environmental conditions, which may have made significant contributions to the development of the abundance of mosquito vectors and JE epidemic. Using environmental data

Table 1
Cross-correlation coefficients of the environment variables and mosquito density.

Variables	Lag 0	Lag 1	Lag 2	Lag 3	Lag 4	Lag 5
Mean temperature	0.52*	0.57*	0.50*	0.28	−0.03	−0.32*
Minimum temperature	0.53*	0.58*	0.50*	0.28	−0.03	−0.32*
Maximum temperature	0.51*	0.56*	0.50*	0.27	−0.04	−0.32*
Rainfall	0.02	0.15	0.28*	0.35*	0.39*	0.29*
Absolute humidity	0.53*	0.59*	0.50*	0.29	−0.01	−0.31*
NDVI of rice paddy	0.57*	0.59*	0.40*	0.10	−0.15	−0.42*
TVDI of rice paddy	−0.01	0.06	−0.01	−0.11	−0.02	0.03

* $P < 0.05$.