Source Areas and Migratory Trajectories of *Locusta migratoria migratoria* (Orthoptera: Acrididae) in the Border Region of Tacheng, Xinjiang, China and Adjacent Regions[1]

Bing-Jie Yu, Ji-Wei Mai[2], Xiao Chen, Chun-Yu Xu, Yun Chen, Kai-Li Cao, Ye Xu, Jashenko Roman[3], and Rong Ji[4]

International Research Center of Cross-border Pest Management in Central Asia, Key Laboratory of Conservation and Management of Species Diversity in Xinjiang, College of Life Sciences, Xinjiang Normal University, Urumqi 830054, China

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Abstract The Hybrid Single Particle Lagrangian Integrated Trajectory Model and meteorological graphics software (Grads and ArcGIS) were used to analyze source areas and migratory trajectories of a population of *Locusta migratoria migratoria* (L.) (Orthoptera: Acrididae) in the Tacheng region of Xinjiang, China that borders with eastern Kazakhstan. The source areas of these locusts migrating into the Tacheng region are distributed near Lake Alakol, Lake Zaisan, eastern Lake Balkhash, the Irtysh River, and Ayaguz River in Kazakhstan. Locusts follow nine migratory trajectories in their invasion of Tacheng. On the respective migration dates, a westerly wind, northerly wind, or northwesterly wind, the latter being the prevailing wind direction, occurred at 950 hPa over the source areas. At migration heights of 300, 500, and 800 m above mean sea level, the air temperatures ranged from 25.0–31.0°C, 21.5–26.0°C, and 21.0–25.0°C, respectively. The concept of insect migration pattern in Central Asia is proposed, but a series of theoretical and empirical studies will be needed to provide support for this postulation.

Key Words Sino-Kazakhstan border, *Locusta migratoria migratoria*, trajectory analysis, source area, Central Asia insect migration pattern

Locusta migratoria migratoria (L.) (Orthoptera: Acrididae) is a pest with long-distance migration that is characterized by abrupt and unpredictable population outbreaks (Zhang and Yan 2000, Seino et al. 2010, Otuka 2013). Opportunities to initiate control tactics and strategies can be easily missed, giving rise to huge crop losses. Thus, an essential prerequisite for timely monitoring, forecasting, and control of this pest is to identify source areas and migratory trajectories.

The Hybrid Single Particle Lagrangian Integrated Trajectory Model (HYSPLIT), developed by the National Oceanic and Atmospheric Administration and Australia's Bureau of Meteorology, is used to compute air particle sources, trajectories, and dispersion or deposition. The model has been used successfully to simulate the migratory process of insect pests (Sheng et al. 2011, Syobu et al. 2012, Hu et al.

[1]Received 24 November 2018; accepted for publication 7 February 2019.
[2]School of Life Sciences, Lanzhou University, Lanzhou 730000, China.
[3]Al-Farabi Kazakh National University, Almaty 480078, Kazakhstan.
[4]Corresponding author (email: jirong@xjnu.edu.cn).

2014, Liu et al. 2016), including identification of source areas and migration trajectories of *Cnaphalocrocis medinalis* Guenée, *Loxostege sticticalis* L., *Sogatella fucifera* Horváth, *Nilaparvata lugens* Stål, and others (Hua et al. 2002, Feng et al. 2003, Wood et al. 2009, Sheng et al. 2011, Hu et al. 2013). It also can provide for decision-making in pest management systems by accurately predicting the migration timing of pests (Feng et al. 2003, Qi et al. 2014, Guo et al. 2015, Westbrook et al. 2016).

In short, the dimensions of the model domain are $1° \times 1°$ grid points at a horizontal resolution of 100 km. Thirty-three vertical layers are available with the model ceiling at 100 hPa. Wind direction usually serves as a critical factor in determining the migratory pathways of pests as well as the likelihood that they arrive at their migration destination (Liu et al. 2004, Hu et al. 2014). The horizontal temperature distribution of migration pattern determines the horizontal areas into which migratory pests can migrate (Hou et al. 2003, Tang 2011).

In the study reported here, HYSPLIT was used to compute and identify geographic sources and migratory trajectories of *L. m. migratoria* in Tacheng and its neighboring geographic areas. This Central Asian region consists of five central Asia countries (Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan), Xinjiang Province in China, and southern Siberia. Some border areas in the region are subject to occasional outbreaks of migratory locusts, which can also spread to neighboring countries via cross-border migration (Altizer et al. 2011). For example, Tacheng is located in the northwestern border region of Xinjiang, China, adjoining eastern Kazakhstan (Fig. 1). The adjacent region between Tacheng and East Kazakhstan is dominated by desert and semidesert habitats. Swamp areas of the Tacheng region are routinely damaged by *L. m. migratoria*, and the border region serves as a breeding place not only for local infestations of *L. m. migratoria* but also for the *L. m. migratoria* population that migrates into this region from neighboring countries or regions. The total area of agricultural crops damaged in this area is approximately 355,000 ha, with economic losses valued at 4.86×10^6 USD (Fan and Wang 1995, Wang et al. 2011).

During their long-distance migration, locusts rely on wind-borne transportation and a suitable migration temperature, following a certain migratory trajectory to arrive at their destination. However, existing studies have rarely addressed the source areas or migratory trajectories of *L. m. migratoria* in the border region of Tacheng and its adjacent areas. This lack of knowledge has seriously affected our ability to conduct accurate and timely monitoring and prediction and subsequent implementation of control tactics over cross-border damage of *L. m. migratoria* in this region. Thus, with regard to the *L. m. migratoria* population migrating into the border region of Tacheng, two hypotheses were proposed: (a) during migration, wind direction and air temperature facilitate the migration of *L. m. migratoria* to their destination, that is there is an association between wind direction, air temperature, and migratory trajectories; and (b) according to the biological habits of *L. m. migratoria*, their interregional source areas are distributed in tidal flats and swamp areas around lakes and rivers with unstable water levels. To test these two hypotheses, we collected and analyzed data on the cross-border migrations of *L. m. migratoria* in the border region of Tacheng dating to the 1980s and selected the years that experienced the most serious cross-border migration as examples to determine the source areas, migratory trajectories, and wind and air temperature

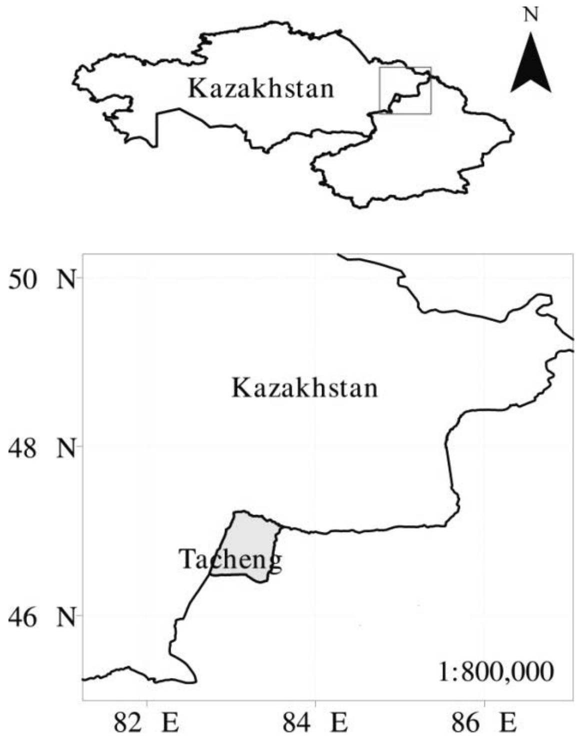

Fig. 1. Geographical location of Tacheng, Xinjiang, China.

characteristics during migration of the *L. m. migratoria* into the Tacheng border region. Our ultimate objective was to provide a decision-making basis for initiating timely and effective monitoring of populations and implementing control tactics to manage the cross-border damage of these locusts.

Materials and Methods

Data sources. Pest data and information on the cross-border migrations of *L. m. migratoria* in the border region of Xinjiang, China and its adjacent regions were provided by the Center for Prediction and Forecasting Pests and Rodents of the Department of Animal Husbandry of Xinjiang Uygur Autonomous Regions and the Station for Forecasting and Control of Locusts and Rodents of Tacheng Region of Xinjiang. Meteorological data on wind direction and air temperature were downloaded from the Final Operational Global Analysis (FNL) data of the National Centers for Environmental Prediction (horizontal resolution: 1° × 1°; temporal resolution: 6 h) on 7 August 2018. A Chinese map of provincial districts (1:4,000,000) were downloaded from the official website of the National Geomatics Center of China on 6 July 2018.

Trajectory analysis. Trajectory analysis adopted the HYSPLIT model, which was developed by the National Oceanic and Atmospheric Administration and

Australia's Bureau of Meteorology. Online simulation was performed on the basis of the FNL data.

The migration trajectories and relevant parameters of *L. m. migratoria* were analyzed using the HYSPLIT model as follows: (a) the current migration date of landing in the border region of Tacheng was deemed as immigration date, and the 2 days before and after that were combined into one period of immigration; (b) the locusts displace downwind (Wang et al. 2011), with suitable flight temperature ranges between 31.4–34.0°C, and they cannot fly at an air temperature below 19°C (You et al. 1954); (c) migrants frequently fly at approximately 300–800 m above mean sea level (MSL), specifically at heights 300, 500, and 800 m MSL; and (d) take-off mostly occurs at around 1900 h (You et al. 1954), so the simulation started 1900 h (Universal Coordinated Time: 1100 h) each day and continued for 24 h.

The basis of determining an effective migratory trajectory for *L. m. migratoria*: (a) the time that the trajectory termination point conforms to the take-off site of pests, and (b) there are numerous sources at the trajectory termination point.

After importing the qualified landing points calculated by HYSPLIT 4.8 into ArcGIS 10.0 developed by Environmental Systems Research Institute (Redlands, CA), the effective trajectory determination criteria were used in combination to identify effective landing points. After that, these landing points were superimposed and mapped onto the base map to analyze the range of 24-h landing points and determine the source areas of the *L. m. migratoria* migrating into the border region of Tacheng, Xinjiang, China and its adjacent regions.

Wind and air temperatures. Based on the terrain and topography of the areas of immigration and areas of emigration and the high-altitude air temperature suitable for migration (at 950 hPa standard pressure level corresponding to a height of 300–500 m MSL), we chose to analyze the wind direction frequencies at the 950-hPa standard pressure level. Grads software developed by National Science Foundation, National Oceanic and Atmospheric Administration, and the National Aeronautics and Space Agency was used to analyze FNL meteorological data and obtain the main wind direction frequencies at the 950-hPa standard pressure level and the high-altitude air temperature at 300, 500, and 800 m MSL of various source areas. Wind direction frequencies were summarized according to meteorological classification standards for right cardinal wind directions, that is northerly (N), northeasterly (NE), easterly (E), southeasterly (SE), southerly (S), southwesterly (SW), westerly (W), and northwesterly (NW). Wind direction frequency was calculated and expressed as the occurrence of specific wind direction relative to proportion of the total number of occurrences of various wind directions over a period of time.

Results

Historical pest occurrence data. Since the 1980s, the Tacheng border region has experienced 10 cross-border migrations of *L. m. migratoria* that occurred in 1984, 1985, 1999, 2000, 2005, and 2008. Among these, the 1999, 2000, and 2008 occurrences were especially serious. The *L. m. migratoria* population migrating into the Tacheng border region in 1999 had a mean density of 299.5/m^2, and the concentrated landing zone occupied an area of 540.0 ha. The cross-border

Table 1. Location, population density, and extent of area infested by migrating *L. migratoria migratoria* into the Tacheng area of Sino-Kazakhstan border.

Date	Location	Population Density (per m^2)	Infested Area (ha)
12 September 1984	Kurrus Prairie	17.5	5.0
5 September 1985	Kurrus Prairie	17.5	6.0
3–4 July1999	Emin County	652.5	170.0
6 July 1999	Trumpet Mountain	200.0	165.0
8 July 1999	Toli County	60.0	70.0
9–10 July 1999	Balikun 206	255.0	90.0
6 August 1999	Timbuktu Port	330.0	45.0
28 July 2000	Trumpet Mountain	15.0	150.0
4 July 2005	Timbuktu Port	9.0	5.0
12 June 2008	206-207 Border Line	45.0	40.0

migrations that occurred in 2000 and 2008 had mean population densities of 15.0/m^2 and 12.5/m^2, respectively, and the areas of their concentrated landing zones were 150.0 ha and 40.0 ha, respectively (Table 1). According to the analysis, the annual cross-border migration of *L. m. migratoria* in the Tacheng border region has occurred progressively earlier since the 1980s, with the latest migration occurring on 12 September 1984, and the earliest migration occurring on 13 June 2008. The results also showed that the cross-border migration of *L. m. migratoria* in the Tacheng border region varied by month. Cross-border migration occurred six times in July (60% of migration events), twice in September (20% of events), and once in each of June and August (10% of events each).

Source areas. The more serious cross-border migrations (i.e., 1999, 2000, and 2008) were further analyzed. A reverse trajectory analysis on 3, 4, and 6 July 1999 indicated that the source area of the *L. m. migratoria* migration into the Tacheng border region was located near Lake Zaisan (47.07–47.64°N, 84.2–84.97°E) in Kazakhstan. Likewise, reverse trajectory analysis indicated the source area for the migration on 6 August 1999 was near the Irtysh River (49.35–50.57°N, 79.63–81.37°E) in Kazakhstan, the source area for the migration on 8 July 1999 was near eastern Lake Balkhash (46.32–46.962°N, 77.96–78.03°E) in Kazakhstan, the source area for the migration on 9–10 July 1999 was located near Lake Alakol (45.41–46.54°N, 79.63–81.37°E) in Kazakhstan, the source area of the migration on 28 July 2000 was located near the Ayaguz River (47.69–47.70°N, 79.20–79.67°E) in Kazakhstan, and the source area of the migration on 13 June 2008 was located near Irtysh River (49.82–50.51°N, 77.21–79.89°E) in Kazakhstan.

Cross-border migration trajectories. Reverse trajectory analysis provides outputs of hourly trajectory points that can be connected to create a curve known as a migratory trajectory. According to these analyses, *L. m. migratoria* populations migrating into the Tacheng border region in 1999 had six cross-border migratory trajectories: (a) *L. m. migratoria* uniformly migrated from near Lake Zaisan (84.97° E, 47.36° N) in Kazakhstan, by way of Pociliket (83.27°E, 46.96°N) and Kastialara (83.22°E, 46.71°N) at flight heights of 300, 500, and 800 m MSL, into the Tacheng border region; (b) *L. m. migratoria* uniformly migrated from near Lake Zaisan (83.3°E, 47.2°N) in Kazakhstan, by way of Saleorian (83.19°E, 46.86°N) and Gerriek (82.71°E, 46.359°N) at flight heights of 300, 500, and 800 m MSL, into the Tacheng border region; (c) *L. m. migratoria* migrated from the Irtysh River banks (80.67°E, 50.34°N) in Kazakhstan, by way of Georgeyevka (81.92°E, 48.95°N) and Makanchi (82.39°E, 46.83°N) at flight heights of 300 and 500 m MSL, into the Tacheng border region, whereas at the flight height of 800 m MSL, they migrated from near Irtysh River in Kazakhstan, by way of Suwolkebulake (79.65°E, 49.46°N) and Makanchi (82.39°E, 46.83°N), into the Tacheng border region; (d) *L. m. migratoria* uniformly migrated from near Lake Alakol (81.38°E, 46.56°N) in Kazakhstan, by way of Deruriba (82.03°E, 45.33°N) at flight heights of 300, 500, and 800 m MSL, into the Tacheng border region, and; (e) *L. m. migratoria* uniformly migrated from near Lake Balkhash (78.029°E, 46.321°N), by way of Aktogay (79.27°E, 46.34°N) and Urdzhar (81.86°E, 46.45°N) at flight heights of 300, 500, and 800 m MSL, into the Tacheng border region (Fig. 2A).

In 2000, the migratory trajectories of *L. m. migratoria* at flight heights of 300, 500, and 800 m MSL suggested a uniform migration from near the Ayaguz River (79.20°E, 47.704°N) in Kazakhstan, by way of Taskesken (79.43°E, 46.95°N) and Makanchi (82.46°E, 46.32°N), into the Tacheng border region (Fig. 2B). And in 2008, the *L. m. migratoria* migratory trajectories into the Tacheng border region were from near the Irtysh River (79.58°E, 49.51°N) in Kazakhstan, by way of Ekibastuz (79.91°E, 49.39°N) and Makanchi (82.25°E, 46.91°N), at the flight height of 300 m MSL, and from near the Irtysh River in Kazakhstan, by way of Suwolkebulake (79.95°E, 49.86°N) and Makanchi (82.25°E, 46.91°N), at flight heights of 500 and 800 m MSL (Fig. 2C).

Wind and air temperatures. The times of migration observed in 1999, 2000, and 2008 were characterized by different wind direction frequencies and air temperatures. Temperatures measured during the observed migrations ranged from 21.0 to 30.0°C, while the predominant directional winds were either northerly (three migration events), westerly (two migration events), or northwesterly (two migration events) (Table 2).

Discussion

The source areas of *L. m. migratoria* in Kazakhstan are characterized by an estimated 6 million ha of agricultural crops. *Locusta m. migratoria* infested approximately 220,000 ha in 1999, 750,000 ha in 2000, and 450,000 ha in 2008 (Azhbenov et al. 2015, Huang and Zhu 2001, Propastin 2013). Economic losses were reported in each of those years with 2.28 million USD in total losses in 2000 alone (Huang and Zhu 2001).

The migration behavior of insects is influenced by environmental conditions and internal physiological factors (Jiang and Luo 2008), and atmospheric winds and air

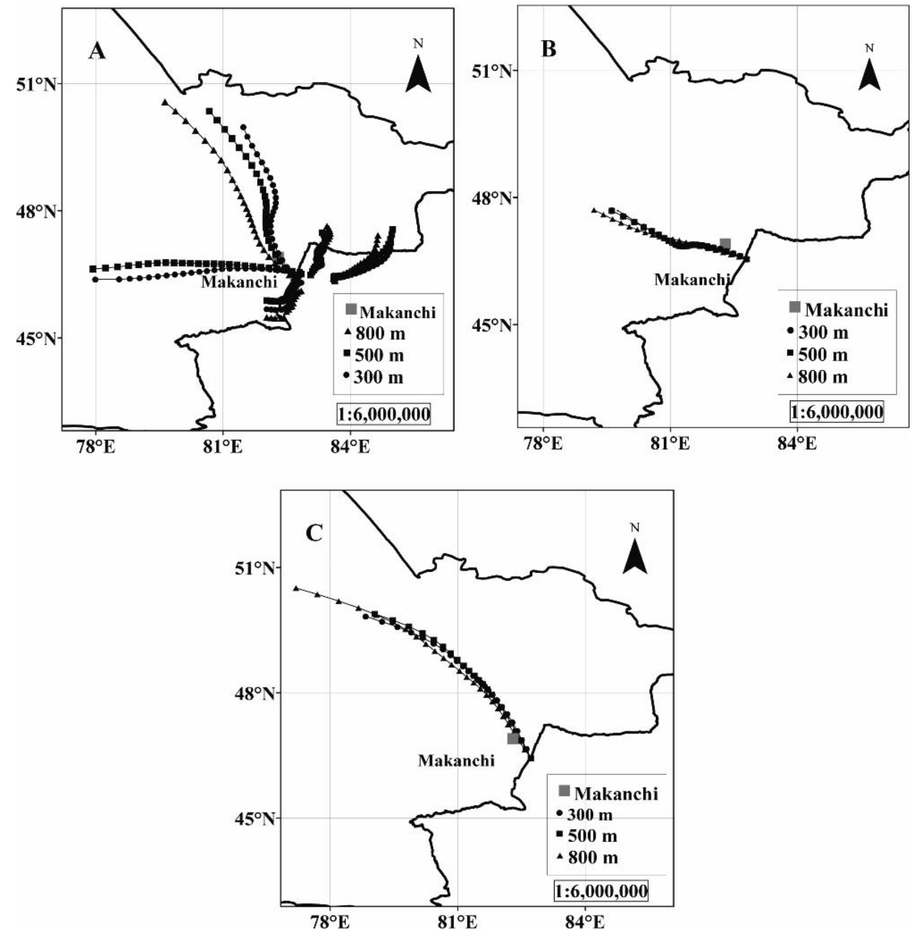

Fig. 2. Cross-border migratory trajectories of *L. m. migratoria* landing near Tacheng at the Sino-Kazakhstan border region in 1999 (A), 2000 (B), and 2008 (C).

temperatures are also significant contributing factors (Hou et al. 2003, Bai et al. 2010). Both wind direction and air temperature facilitate the migration of insects. The analyses reported in this study demonstrated that prevailing winds over the source areas of *L. m. migratoria* migration events, which were mainly westerly, northerly, or northwesterly winds, affected the migratory trajectories (Fig. 2). Furthermore, we determined that temperatures at altitudes of 300–500 MSL would support successful *L. m. migratoria* migrations.

Other factors that impact migration that are beyond these analyses and the scope of this study include terrain topography, host plant condition at the source and at the destination sites, and weather conditions at both sites. For example, in winter of 1998, the mean air temperature near Lake Alakol in Kazakhstan was

Table 2. Air temperatures at 300, 500, and 800 MSL and wind direction frequencies at 950 hPa at locations of sources of migrating populations of *L. m. migratoria* into the Tacheng border area from Kazakhstan.

Migration Date	Source Ocation	Temperature (°C) at Altitudes (MSL)			Wind Direction Frequencies (%) at 950 hPa*				
		300	500	800	N	W	NW	SW	S
2–3 July 1999	Lake Zaisan	27.0	23.5	23.5	83.3	16.7	0	0	0
5 July 1999	Lake Zaisan	31.0	22.5	24.0	41.7	33.3	25	0	0
7 July 1999	Lake Balkash	28.0	22.5	21.0	0	46.2	0	30.8	23.0
8–9 July 1999	Lake Alakol	25.0	24.0	21.0	0	50.0	0	33.3	16.7
5 August 1999	Irtysh River	30.0	25.5	27.0	41.7	33.3	0	25.0	0
27 July 2000	Ayaguz River	26.0	24.0	23.0	0	16.7	50.0	33.3	0
12 June 2008	Irtysh River	29.0	26.0	25.0	25.0	0	58.3	16.7	0

* Wind direction frequency calculated and expressed as percentage of occurrence of specific wind direction relative to total number of wind directions observed over a period of time during the migration event.

−8.69°C, which was higher than in other years, thus providing a favorable condition for overwintering of locust eggs and the development of populations in early 1999. Lower precipitation levels in that area in summer 1999 resulted in high-frequency wing movement and long duration flights of the locusts (Liu et al. 2017). Liu et al. (2016) reported that suitable terrain and topography also facilitate the long-distance migration of insects. Indeed, the Sino-Kazakhstan border area has a flat topography, and the vegetation types, soil physical-chemical properties, and climatic conditions are favorable for *L. m. migratoria* migration (Liu et al. 2017).

The migration insect pattern refers to the specific environment in which the migratory behaviors of insects are shaped, and it consists of ground resource allocation and atmospheric physical environment (Zhang 1992). So far, worldwide insect migration patterns have been identified in East Asia, North America, South America, Africa, Europe, and Australia. The Central Asia region has a typical continental climate, and its natural landscape mainly consists of temperate grassland, desert, and semidesert. Essentially, different countries or regions in Central Asia are similar to each other in terms of natural geography, ecological environment, biological resources, and others; so, the cross-border migration of insects to neighboring countries or regions is frequently observed (Stolyarov 2000, Zhang et al. 2010, Altizer et al. 2011, Guo et al. 2011b, Wang et al. 2011, Kokanova 2014, Azhbenov et al. 2015, Popova et al. 2016). According to the basic conditions of insect migration patterns and insect migration data in the Central Asia region, our study suggests that an insect migration pattern exists in Central Asia. However, further studies are needed for verification.

Successful insect migration, as shown by trajectory analysis with HYSPLIT, is dependent upon favorable and suitable conditions at source and destination areas (Feng and Zhai 2002, Otuka et al. 2012, Stefanescu et al. 2013). *Locusta m. migratoria* in the border region of Tacheng, Xinjiang, China has two types of sources, for example local sources and interregional sources. Local source areas are mainly distributed near South Lake of Tacheng, near the Emil River, and in the swamp areas between the Emin River and its branch of the Ayaguz River. Interregional source areas are mainly distributed near Lake Alakol, Lake Zaisan, eastern Lake Balkhash, the Irtysh River, and the Ayaguz River in Kazakhstan. As apparent in this study, the migrating locusts follow nine trajectories from their sources into the Tacheng border area. The various source areas are characterized by tidal flats, a variety of vegetation types, and plentiful growth of reeds that support breeding activities. Soil pH, salinity, and organic content are suitable for locust egg pod development (Yu and Hou 2004, Liu et al. 2017, Guo et al. 2011a, Li et al. 2011, Yao et al. 2016, Yin et al. 2017, Kurmet et al. 2014).

The results of this study provide a decision-making framework for predicting locust emigration from interregional source areas and, thus, initiation of timely management tactics at the destination site. It also establishes a scientific foundation for using insect radar monitoring to forecast outbreaks in the border region of Tacheng and adjacent regions. More research is required to confirm. Furthermore, the Tacheng border region is also the breeding area for *L. m. migratoria*; therefore, the possibility that southerly or southeasterly prevailing winds might assist migration from China into Kazakhstan requires additional study.

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