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Declining Lake Water Levels and Suitable Wind Conditions Promote Locust Outbreaks and Migration in the Kazakhstan–China Area

Shiqian Feng [1,†], Xiao Chang [1,†], Jianguo Wu [2], Yun Li [3], Zehua Zhang [1,4], Li Zhao [5] and Xiongbing Tu [1,*]

[1] State Key Laboratory for Biology of Plant Diseases and Insect Pests, Institute of Plant Protection, Chinese Academy of Agricultural Sciences, Beijing 100193, China; fengshiqian@caas.cn (S.F.); changxiao0814@163.com (X.C.); zhangzehua@caas.cn (Z.Z.)
[2] Xinjiang Uygur Autonomous Region Locust and Rodent Pest Forecasting and Control Center Station, Urumqi 830000, China; zhbshuju@163.com
[3] Central Station for Forecasting and Controlling Locusts and Rats in Altay Region, Aletai 836500, China; 15289465183@163.com
[4] Institute of Western Agriculture, Chinese Academy of Agricultural Sciences, Changji 831100, China
[5] College of Agriculture, Xinjiang Agricultural University, Urumqi 830052, China; xjkcjys@163.com
* Correspondence: xbtu@ippcaas.cn
† These authors contributed equally to this work.

Abstract

Outbreaks of locust plagues are becoming increasingly frequent against the backdrop of climate change. Locust outbreaks in the Caucasus and Central Asia, especially in Kazakhstan, pose continuous threats to neighboring countries, including China, Kyrgyzstan, and more. However, locust outbreak forecasts and migration movement are yet to be studied in this area. In our study, we collected water level data in major lakes and water bodies, as well as annual average precipitation in the past 15 years in Kazakhstan, to analyze their contributions to locust outbreaks. Multiple linear regression analysis revealed a significant negative correlation between overall lake water level and the following year's locust outbreak area in Kazakhstan. Considering that the overall lake water levels in 2023 and 2024 reached a quite low level historically, we predicted heavy locust outbreaks in 2025. Furthermore, through wind field analysis and wind-born trajectory modeling, we identified two migration routes of locusts from Kazakhstan into Xinjiang, China, riding the northwest wind, with lakes near the Sino-Kazakhstan border as the main sources. Overall, our study identified high locust outbreak challenges in Kazakhstan in recent years and determined two wind-supported migration routes of locusts invading China, which are significant for guiding monitoring and prevention efforts in the Sino-Kazakhstan border area.

Keywords: locust; Kazakhstan–China border; lake water level; wind; migration

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1. Introduction

Locust plagues represent a global disaster; among these, approximately 50 species are considered major pests, affecting one-tenth of the world's population [1]. The Food and Agriculture Organization (FAO) has established two special projects due to their widely damage: *Schistocerca gregaria* in Africa and West and South Asia and migratory locusts (including the *Locusta migratoria*, *Calliptamus italicus*, and *Dociostaurus maroccanus*) in the Caucasus and Central Asia. Desert locusts are particularly noted for their transcontinental migration, which causes widespread damage [2] and has been the subject of extensive

research. However, research on migratory locusts in the Caucasus and Central Asia is relatively limited despite the fact that these species pose a serious threat to this region and neighboring countries [3]. For example, in 2008, a major outbreak of the Asian migratory locust occurred in Kazakhstan, severely impacting local agriculture and livestock production and migrating into Xinjiang, China, with extensive damage in the Tacheng and Altay regions [4].

According to the FAO's Locust Watch records for the migratory locusts, Kazakhstan contains the largest area affected by locusts in this region. In 2023, locust outbreaks covered a total area of 11,362,818 hectares in the region, with 7,659,217 hectares located within Kazakhstan, accounting for approximately 67.4% of the total area, making it the dominant locust outbreak zone in the Caucasus and Central Asia (Figure 1) [3]. Kazakhstan is situated in the arid zone of Central Asia and experiences a continental climate with an average annual precipitation of 250 mm [5]. Over 80% of its territory consists of deserts and steppes, with about 270 species of locusts recorded in the country; the most harmful to agricultural land are 15–20 species [6]. Among these, the Asian migratory locust (*Locusta migratoria migratoria*), the Italian locust (*Calliptanus italicus*), and the Moroccan locust (*Dociostaurus maroccanus*) are the most harmful. During locust outbreaks, locusts attack cereal crops, leguminous plants, fruits, and vegetables, severely harming wheat, rice, corn, alfalfa, and clover [7].

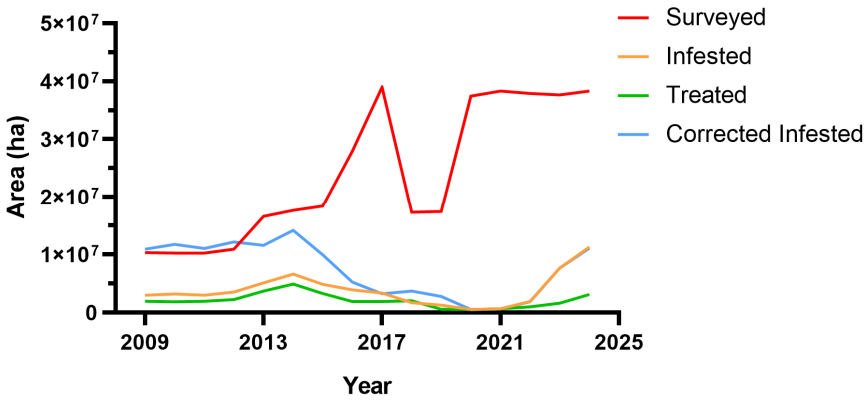


Figure 1. The surveyed, infested, and treated areas of locust in Kazakhstan from 2009 to 2024. The data was retrieved from Locust Watch (FAO), in the Caucasus and Central Asia (https://www.fao.org/locusts-cca/activities/annual-workshops/en/, accessed on 13 May 2025).

The growth and development of locusts are influenced by various environmental factors, with outbreaks resulting from a complex interaction of climate, vegetation, soil, and other factors [8]. Research has shown that climate significantly affects locust outbreaks, with temperature and precipitation being the most critical factors [9,10]. These factors can significantly impact the growth rate and oviposition of locusts [11,12]. In arid regions, particularly in countries with a temperate continental climate, water availability plays a crucial role in determining the occurrence and spread of locusts. As is proved in Kazakhstan, natural precipitation, lakes, and rivers are important factors influencing locust outbreaks and distribution [13]. Additionally, these factors directly affect the physicochemical properties of the soil, which in turn significantly influence locust oviposition and egg hatching. For instance, migratory locusts typically prefer to lay eggs in soils with a water content of 10–20%, low salinity (0.2–1.2%), and sparse vegetation [14]. Therefore, the role of drought in promoting locust outbreaks warrants special attention.

With global climate change, extreme weather events are becoming more frequent, contributing to the conditions that lead to locust outbreaks and plagues [15]. For example, in 2018, the Indian Ocean Dipole phenomenon resulted in increased rainfall in the desert

regions of the Arabian Peninsula, creating favorable conditions for plant growth and the breeding and development of desert locusts. This led to a surge in the desert locust population; however, a prolonged drought in 2019 reduced food availability, causing the locusts to swarm and migrate, resulting in a severe plague [16,17]. In locust-prone areas near lakes, water levels are a critical determinant of locust outbreaks. Excessive water sources (precipitation and rivers) can raise lake levels, flood locust eggs, and lead to a decline in population due to insect diseases [18,19]. Conversely, insufficient water supply can increase the area of exposed mudflats or riverbeds, promoting the growth of grasses, which provide an ideal environment for locust oviposition and development [20]. In these areas, the low vegetation cover and irregular and discontinuous patches of shrubs and grasslands make it easier for solitary locust nymphs to aggregate, increasing the likelihood of forming locust bands and supporting their swarming behavior [21,22].

In Kazakhstan, several significant lakes (including Alakol Lake, Zaysan Lake, Balkhash Lake, etc.) near the Sino-Kazakhstan border are surrounded by wetlands and mudflats that serve as breeding grounds for migratory locusts. Previous research has demonstrated that lowering water levels in these lakes and expanding exposed mudflats contribute to the outbreak of locusts in the surrounding regions [13]. During periods of lake water recession, exposed reed growth areas become ideal sites for locust oviposition and development, leading to locust outbreaks. Conversely, in years with higher water levels and lower temperatures, locust infestations are significantly reduced [23]. Kazakhstan shares borders with China in the Xinjiang region, and the natural geography and ecological environments of the two areas are highly similar. Historical monitoring data suggest that locusts from the above-mentioned important lakes are likely to migrate by the wind into Xinjiang, China. Yu et al. [24] used trajectory analysis to preliminarily identify that the Asian migratory locusts detected in Tacheng, Xinjiang, China, likely originated from Kazakhstan's inland waters, including Zaysan Lake, the Irtysh River, and Balkhash Lake.

In recent years, there have been significant fluctuations in precipitation and water levels in major lakes and rivers in Kazakhstan. According to FAO monitoring data, the area of grassland affected by locusts in Kazakhstan reached a peak level historically in 2024 [25]. This poses a great threat to the biosecurity and food security of neighboring countries, including China. In this study, we clarified the correlation between precipitation, lake water level, and river water level with locust outbreaks and further identified the characteristics of wind fields and migration routes along the Kazakhstan–China border.

2. Materials and Methods

2.1. Data Collection and Processing

Locust survey and infestation data were obtained from the annual reports of the FAO Locust Watch Project and the Technical Workshop on Locusts in the Caucasus and Central Asia (https://www.fao.org/locusts-cca/activities/annual-workshops/en/, accessed on 11 March 2025) since 2009. Annual precipitation data for Kazakhstan were collected from the Climate Change Knowledge Portal (https://climateknowledgeportal.worldbank.org/country/kazakhstan/climate-data-historical, accessed on 11 March 2025), covering the period from 1901 to 2022. Lakes larger than 1000 km^2 were selected to calculate the overall lake water levels, including Alakol Lake (2919 km^2), Balkhash Lake (16,400 km^2), Kapchagay Reservoir (1846 km^2), Zaysan Lake (1810 km^2), Tengiz Lake (1590 km^2), and the North Aral Sea (3300 km^2). Sasykkol Lake (744 km^2) was also included due to its close relationship with Alakol Lake and its proximity to the Sino-Kazakhstan border. Major rivers longer than 1000 km were included in the analyses, such as the Irtysh River (4248 km), Esil River (2450 km), Ili River (1439 km), Shu River (1186 km), Syrdarya River (2212 km), and Ural River (2428 km). Water level monitoring data for the lakes and rivers from 2003

to 2024 were retrieved from the Database for Hydrological Time Series of Inland Waters (https://dahiti.dgfi.tum.de/en/, accessed on 11 March 2025).

Before conducting official analyses, the locust infestation data and the lake and river water level data were corrected. The locust infestation data were adjusted to the corrected locust infestation area (CLIA) using the formula

$$\mathrm{CLIA} = \log_{10}(\mathrm{LIA}/\mathrm{SA} \times 1{,}000{,}000)$$

where LIA is the real observed locust infestation area, and SA is the real survey area. And the CLIA represented the locust infestation area in the surveyed 1,000,000 km^2 area.

Corrected lake water level (CLWL) and corrected river water level (CRWL) were calculated for further analyses, which were firstly centered and balanced by their real area/length in inner Kazakhstan using the formula

$$\mathrm{CLWL} = (\mathrm{LWL} - \mathrm{ALWL}) \times \mathrm{LA}/1000$$

where LWL is the observed lake water level in a certain year and ALWL is the averaged lake water level. LA is the lake area for each lake.

$$\mathrm{CRWL} = (\mathrm{RWL} - \mathrm{ARWL}) \times \mathrm{RL}/1000$$

where RWL is the observed river water level in a certain year and ARWL is the averaged river water level. RL is the river length for each river.

2.2. Multiple Linear Regression Analysis

Multiple linear regression analysis (MLRA) was leveraged to find the best-fitting linear equation that describes how precipitation, lake water level, and river water level influence the locust infestation area. The multiple linear regression model is specified as follows:

$$\mathrm{CLIA} = \beta 0 + \beta 1 \times \mathrm{AP} + \beta 2 \times \mathrm{CLWL} + \beta 3 \times \mathrm{CRWL} + \varepsilon$$

where $\beta 0$ is the intercept; $\beta 1$, $\beta 2$, and $\beta 3$ are the coefficients for the variables; and ε is the error term.

The R^2 value was calculated to indicate the proportion of variance in the dependent variable that is predictable from the independent variables. The F-statistic was used to test the overall significance of the model, and coefficients were tested using *t*-tests. The analysis was performed using Python 3.9, utilizing the "pandas" library for data manipulation and "statsmodels" for statistical modeling.

2.3. Pearson Correlation Analyses

We conducted an additional analysis to determine how precipitation, lake water levels, and river water levels correlated with the locust infestation area, calculating the Pearson correlation coefficient (r). The correlation coefficient is negative when the correlation coefficient is less than 0, and positive when it is greater than 0. The greater the absolute value of the correlation coefficient is, the stronger the correlation is; the closer the correlation coefficient is to 1 or −1, the stronger the correlation; and the closer the correlation coefficient is to 0, the weaker the correlation [26].

2.4. Wind Field Analyses

Wind field data, including geopotential height, U-component, and V-component of the wind, were retrieved from the National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) global reanalysis data (Final

Operational Global Analysis, FNL) for the period from 2008 to 2022. The data were collected at 6 h intervals with a spatial resolution of 1.0° × 1.0°. The flying height of the desert locust is approximately 200 m. The overall wind field conditions from 1 June to 31 August were plotted, with separate analyses for 1–10 June, 11–20 June, 21–30 June, 1–10 July, 11–20 July, 21–31 July, 1–10 August, 11–20 August, and 21–31 August shown in Figure S1. Wind data extraction was conducted using GrADS 2.1, and map data were obtained from the Global Aviation Data Management (GADM) database (https://gadm.org/download_country_v3.html, accessed on 9 March 2025).

2.5. Windborne Migration Simulations

Based on the historical monitoring data from Yu et al. [24], locusts migrated across the Sino-Kazakhstan border around 10th July, which was chosen as the start day for backward trajectory simulations. We used a CentOS 7.4 server for trajectory modeling in Professor Gao Hu's lab in Nanjing Agricultural University [27,28]. The Weather Research and Forecasting (WRF) model (version 3.8, https://www.mmm.ucar.edu/wrf-model-general, accessed on 9 March 2025) was used to produce a high-resolution atmospheric background for the trajectory calculations (https://www.mmm.ucar.edu/weather-research-and-forecasting-model, accessed on 9 March 2025). During WRF analyses, FNL data from NCEP were selected as the meteorological data for the model input. The flight height is 300 m to 600 m, with the take-off time at 19:00 and a flight duration of 10 h. The WRF settings are wrf_core = 'ARW', map_proj = 'lambert'. The start points are located in Tacheng in Tacheng Region and Jimunai County in Altay Region.

3. Results

3.1. Overall Lake Water Level Influenced the Locust Area in the Following Year

The impact of three factors (Kazakhstan's annual average precipitation, overall lake water levels, and overall river water levels) on the area of locust infestation was analyzed using the multiple linear regression method (Table 1). The result revealed that the annual average precipitation, overall lake water levels, and overall river water levels had no significant overall impact on the locust infestation area for the same year ($F = 0.4777$, $p = 0.705$; $R^2 = 0.125$). Each factor had no significant influence on the locust infestation area in the current year ($p > 0.05$). However, based on empirical patterns of locust occurrence observed in desert locust and other locusts, the previous year's precipitation and water body condition are likely to have a significant impact on the current year's locust occurrences. Therefore, we conducted a Time-lag analysis to investigate the effects of the three factors on the locust infestation area in the following year. Specifically, the correlation between variables in the present year and locust area in the next year was analyzed. In contrast to the lack of significant impact observed for the current year's locust infestation area, the time-lag analysis revealed a significant overall impact on the locust infestation area in the following year ($F = 4.951$, $p = 0.0268$; $R^2 = 0.623$). Specifically, overall lake water level had a significant negative effect on locust infestation area in the subsequent year (Figure 2A, $\beta = -0.0656$, $p = 0.013$), while the other two factors did not significantly influence locust occurrence in the following year.

Table 1. The results of the multiple linear regression analysis.

Analyses	Variables	β/Value	*p*
Variables' influence on locust infestation area in the current year	Average annual precipitation	2.36×10^{-6}	0.822
	Corrected Lake Water Level	4.77×10^{-5}	0.405
	Corrected River Water Level	-6.45×10^{-5}	0.551
	Interception	3.305	<0.001
Variables' influence on locust infestation area in the following year	Average annual precipitation	−0.003	0.455
	Corrected Lake Water Level	−0.0806	0.006 *
	Corrected River Water Level	0.0894	0.054
	Interception	5.9614	<0.001

* indicate significant difference at $p < 0.05$.

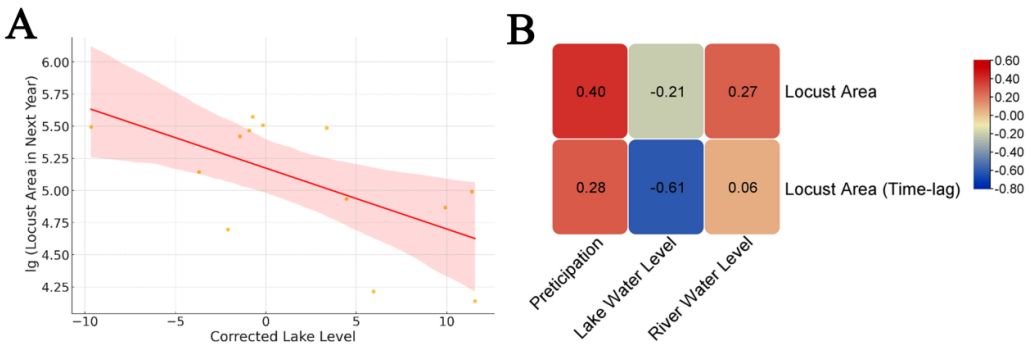


Figure 2. Correlation analysis between climatic and hydrological factors and locust infestation area. (**A**): Pearson correlation coefficients between each climatic and hydrological factor and locust infestation area. (**B**): Impact of overall lake water levels on locust infestation area in the following year. The locust outbreak area was transferred into log10 data, and the corrected overall lake water level was used.

Moreover, we explored the correlation between the three factors and the locust infestation area (for both the current and following years) using Pearson correlation analysis (Figure 2B). The results revealed that lake water level had a strong negative correlation with locust infestation area in the following year (r = −0.61). In contrast, the correlations between the other factors and locust infestation area were weak, with r values ranging from −0.21 to 0.4.

3.2. Locusts in Kazakhstan Under the Outbreak Stage

Given the explosive growth in the area of locust plague in recent years, it is evident that the locust infestation area in Kazakhstan is expected to expand significantly in 2025. Additionally, according to the FAO Locust Watch Project and the Locusts in Caucasus and Central Asia Session, the total locust infestation in Kazakhstan by the end of May has increased by 6.15% compared to the same period last year. Considering the high temperatures from June to August that favor rapid locust growth and reproduction, it is conservatively estimated that the current locust population is more than double that of the same period last year, potentially approaching or exceeding the highest levels in the past 16 years.

3.3. Wind Field Data Supports Locust's Migration from Kazakhstan to Altay and Tacheng Regions in China

Historically, there have been multiple records of locust invasions from the steppes of Kazakhstan into the Tacheng and Altay regions of Xinjiang, China. To understand these patterns, we analyzed the wind field characteristics during June, July, and August over historical periods. Initially, we generated the average wind field for June to August from

2008 to 2022 (Figure 3A). We also examined the average wind fields for the specific periods from 1 June to 31 August, either as a whole (Figure 3A) or with 10 days as a step (Figure S1: 1–10 June, 11–20 June, 21–30 June, 1–10 July, 11–20 July, 21–31 July, 1–10 August, 11–20 August, and 21–31 August). All analyses revealed the same result that two migratory routes exist for the locusts to invade the Chinese side.

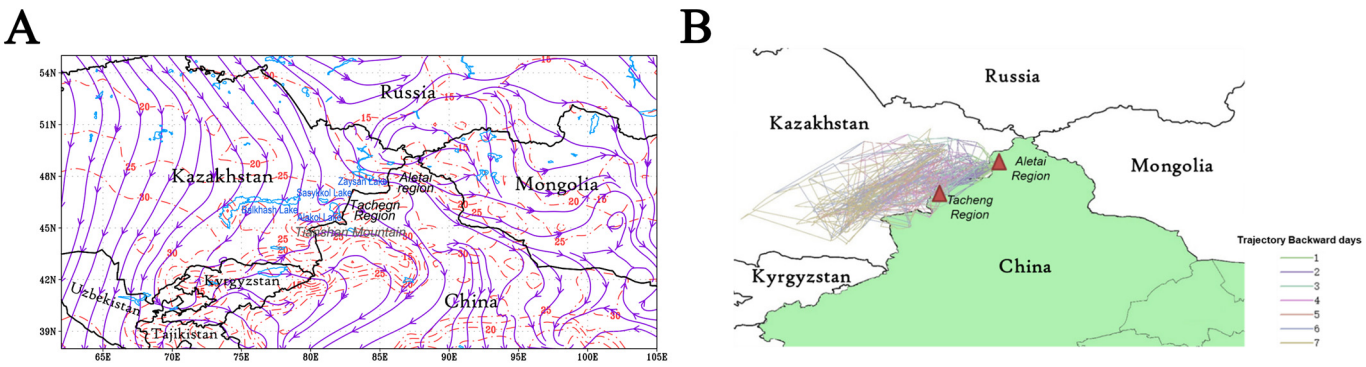


Figure 3. Wind field and wind-born trajectory modeling in the Kazakhstan–China area. (**A**): Average wind fields (purple solid lines) and average temperatures (red isotherms) along the Sino-Kazakhstan border from June to August 2008–2022. The purple lines with arrows show wind directions. (**B**): Simulated backward trajectories of the two routes based on the wind field data in 2023. Simulations were conducted from 19:00 p.m. to next 5:00 a.m. for 7 days. Each color indicates the trajectories on different days.

The first route is from the Zaysan Lake region in Kazakhstan towards the Altay region in China, following the northwest wind. The surrounding area of Zaysan Lake provides a favorable environment for the growth and reproduction of locusts, particularly the Asian migratory locust. During the dry period, the extensively exposed lake shores provide excellent conditions for locusts to lay their eggs. The locust population grows rapidly and forms swarms, which then migrate with the northwest winds to invade the Altay region.

The second route is from the regions of Balkhash Lake, Sasykkol Lake, and Alakol Lake in Kazakhstan towards the Tacheng region in China. These regions provide suitable conditions for the reproduction of locusts. The locust swarms migrate southwards with the north winds, and upon encountering the Tianshan Mountains, they move eastwards, entering the Tacheng region.

3.4. Modeling Windborne Migration Along the 2 Routes

Furthermore, we conducted backward trajectory simulations using wind field data to estimate the sources of locust invasions in the Altay and Tacheng regions. By analyzing wind field data from 20 July 2023 and setting the Altay and Tacheng regions as the reference points, we performed a maximum 7-day backward trajectory analysis. The results indicated that the sources of the locusts were from Balkhash Lake, Zaysan Lake, and Alakol Lake regions in Kazakhstan, thereby further validating the findings from the wind field analysis (Figure 3B).

4. Discussion

Our study revealed a strong negative correlation between lake water levels and the locust outbreak area in the following year. Statistical data indicate that the water level in Kazakhstan's inland waters has been steadily decreasing, reaching its lowest point in nearly 15 years in 2023 and 2024, indicating locust outbreaks in 2024 and 2025. The updated news and monitoring reports proved our results this year [29]. On 15 July 2024, a team from Xinjiang Normal University, led by Prof. Ji Rong, captured three Asian migratory

locusts from Kazakhstan in Tacheng, Xinjiang. Subsequently, the whole Xinjiang Uyghur Autonomous Region prepared quickly to fight against the arrival of the migratory locusts from Kazakhstan. However, heavy rain appeared on the Kazakhstan side, which was proved to promote the landing of locusts before they entered the China side [30]. However, it is not the time to relax, as preliminary statistics in 2024 suggest that lake water levels continue to decline in Kazakhstan, indicating that the area affected by locust outbreaks in Kazakhstan is expanding, and there are still great challenges to prepare for the management of migratory locusts in Xinjiang, China.

Previous studies have primarily focused on single lakes or single-year data, which are limited in geographic scope and time frame. Migratory locusts are capable of long-distance migration, providing abundant insect sources to other suitable habitats [31]. Therefore, considering the water levels of major lakes within the region as a whole is crucial for accurate prediction and forecasting. The mudflats and reed beds around lakes and rivers provide abundant food sources for locusts, and the soil's pH, salinity, and organic matter content are conducive to the development of locust eggs [32,33]. As lake water levels in Kazakhstan continue to decline, more mudflats will be exposed, offering locusts increased opportunities for oviposition and development, likely leading to more severe locust plagues in the country.

There have been multiple recorded instances of locust invasions from the grasslands of Kazakhstan to Tacheng and Altay regions in Xinjiang, China [34]. To determine locust migration routes from Kazakhstan, we utilized wind field data from June to August to conduct trajectory modeling, the results revealed that locusts invading the Altay region followed the northwesterly winds from the Zaysan Lake area in Kazakhstan, while those invading the Tacheng region originated from the Balkhash Lake, Sasykkol Lake, and Alakol Lake areas in Kazakhstan. [24] conducted a reverse trajectory analysis during the most severe years of Asian migratory locust invasion in Xinjiang, China, and found the same locust resources from the lakes and river regions of Kazakhstan.

The main agricultural pests in the Caucasus and Central Asia include three species of locusts: Asian migratory locust, Italian locust, and Moroccan locust. In 2020, Moroccan locusts were recorded for the first time in southern Kazakhstan as an invasive species [35]. Reports indicate that locusts in Kazakhstan have posed a severe threat to local farmland in recent years and have spread over 2.5 million hectares in 2024 [29], among which the Moroccan locust is the dominant species. Currently, both the Asian migratory locust and the Italian locust have invaded Xinjiang, China, from Kazakhstan [32]; however, the Moroccan locust was not observed in China. Along the border between China and other Central Asian countries, the west wind is dominant from June to August (Figure 3A), which helps insects with high migratory ability to move eastward. The Moroccan locust possesses a high ability to fly, which should allow them to enter China's border [36]. Therefore, continuous monitoring of this potential invasive locust should be an important task.

Furthermore, other potential invasion routes from Kazakhstan should also be considered. Wind field analysis and locust detection data indicate that locusts such as the Asian migratory locust can enter the Altay and Tacheng regions from Kazakhstan, carried by northwest winds. Xinjiang Uygur Autonomous Region is a cornerstone of agricultural production in China, with its strategic importance underscored by its substantial contributions to food security, economic development, and regional stability. As a result, we should pay more attention to monitoring the new activities and new migrations of locusts in Kazakhstan against the backdrop of climate change, taking management measures to ensure biosecurity and food safety in the Kazakhstan–China area.

5. Conclusions

This study revealed a significant negative correlation between lake water levels and locust outbreak areas in the following year in Kazakhstan. Wind field analysis and wind-born trajectory modeling supported these locusts to migrate through two routes into China, posing great threats to the biosecurity and food safety in China. Thus, close monitoring measures and comprehensive management strategies are necessary in Kazakhstan's neighboring countries.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/agronomy15071514/s1. Figure S1. Average wind fields (purple solid lines) and average temperatures (red isotherms) along the Sino-Kazakhstan border from June to August, 2008–2022, with a step of 10 days (9 time periods: 1–10 June, 11–20 June, 21–30 June, 1–10 July, 11–20 July, 21–31 July, 1–10 August, 11–20 August, and 21–31 August). The purple lines with arrows show wind directions.

Author Contributions: X.T. and Z.Z. proposed the concept and designed the research; S.F. and X.C. collected the data and performed the analyses; J.W., Y.L. and L.Z. guided the analyses; S.F., X.C. and J.W. wrote the manuscript. All authors modified the final version of the manuscript. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

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