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RESEARCH ARTICLE
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Dynamics of the Abundance and Spatial Structure of the Moroccan Locust for Preventive Population Control and Management

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ABSTRACT

The study analyzed the long-term dynamics and spatial structure of Moroccan locust populations in Kazakhstan to assess phytosanitary risks and develop preventive management strategies. Annual field surveys conducted from 1999 to 2024 in the Turkestan and Jambyl regions provided data on colonization area, population density, and key colonization metrics, including relative, basic, and absolute population indices. Population dynamics were further evaluated using integral indices, including the coefficients of distribution, colonization, reproduction, and progradation, along with the energies of distribution and reproduction. Statistical analysis of 25 years of observations, including comparisons with solar activity indicators, enabled the identification of population phases and predictors of outbreak development. The findings revealed that the Moroccan locust exhibits eruptive population dynamics with four characteristic phases: depression, population growth, mass reproduction, and population decline. Major outbreaks occurred in 2017 and 2024, when reproduction and distribution indices peaked, exemplified by a coefficient of progradation of 168.8 and a reproduction coefficient of 5.11 in 2024. A significant correlation (r = 0.627) was found between increases in locust abundance and the population's phase state, with climatic anomalies and anthropogenic disturbances identified as the main risk factors. The results support the conclusion that preventive monitoring and early detection of changes in population abundance provide a more effective and environmentally sound alternative to large-scale chemical treatments. A preventive population management strategy—built on continuous monitoring and the timely evaluation of integral indices—enables early recognition of critical phases in population development, facilitating rapid intervention to reduce the frequency and severity of outbreaks and enhance phytosanitary security.

Keywords: Correct analysis of locust invasions; Invasion risk factors; Moroccan locust abundance dynamics; Population management.

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INTRODUCTION

The problems of mass reproduction and invasion of locust pests are closely related to solving global issues such as climate warming, reducing anthropogenic pressure, controlling desertification, and restoring biological diversity. Locust invasions are a significant threat to global food security and economic stability, particularly in agricultural regions vulnerable to these outbreaks. For instance, the desert locust epidemic of 2019–2020 underscored the persistent nature of these challenges, bringing locust-related research to the academic forefront due to its severe impact on food security and economies in affected regions (Mitra et al., 2024). In Kazakhstan, locust invasions are fraught with catastrophic consequences for the agro-industrial complex and the national economy. Ecological monitoring is crucial for the early detection of such pests, enabling the implementation of measures to prevent their proliferation and mitigate the resultant damage (Muhamediyeva & Madrakhimov, 2023).

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Gregarious locust species, such as the Italian locust (*Calliptamus italicus* L.), the Asian locust (*Locusta migratoria* L.), and the Moroccan locust (*Dociostaurus maroccanus* Thunb), are distinguished from other species by their unique phase transformation capability. This involves existing in different phases: solitary, transitional, and gregarious. An increase in locust abundance triggers the appearance of signs of the transitional phase. With a multiple increase in population density, locusts enter the gregarious phase, rapidly forming vast hopper bands that can span about 400-600 hectares. With a multiple increase in population density, locusts enter the gregarious phase, rapidly forming vast marching bands of nymphs, which later develop into gigantic flying swarms of adults.

The larvae are exceptionally destructive, with their food consumption doubling with each age. Each individual can consume an amount of food equivalent to its weight daily, totaling at least 100-300 grams of green mass over its lifetime. Given that these populations can number in millions and billions, their cumulative impact is immense. The nymphs in bands are exceptionally destructive, with their food consumption doubling with each age... Once they gain wings, locusts unite into gigantic swarms, comprising hundreds of millions of specimens, capable of traversing immense distances—more than 100-200 km per day—and devastating everything in their path. Consequently, gregarious locusts can destroy thousands of tons of plants daily, positioning them alongside droughts, fires, and other natural disasters as major risks in agriculture. Recent mass reproductions of gregarious locust species have been linked to global climate warming, shifts in solar activity, preceding droughts, and failures in adhering to chemical treatment technologies. This complex interplay of factors highlights the need for a re-evaluation of current control paradigms. Research indicates that changes in rainfall patterns, a direct consequence of climate change, trigger desert locust outbreaks and expand potential invasion areas, making continuous monitoring and data refinement crucial for predictive models (Kimathi et al., 2020). Furthermore, continental-scale understanding of compound locust risks and their underlying climatic drivers, such as synchronized outbreaks dominated by concurrent winds or inundations, is vital for developing coordinated and predictive control strategies (Liu et al., 2024). Studies predicting the potential distribution of locusts under various climate change scenarios emphasize the role of environmental shifts in the spread of these pests (Saha et al., 2021).

The strategy for controlling locust abundance must evolve in response to scientific advancements, improved technical and financial support, and a heightened commitment to environmental protection. Traditional chemical controls, while historically prevalent, are increasingly recognized for their limitations, including the development of resistance, high economic costs, and adverse environmental impacts. These methods have been shown to have toxic effects that persist for extended periods, and their widespread application can be economically unsustainable (Rahimi, 2024). Instead, there is a growing consensus towards more environmentally friendly and sustainable approaches.

Preventive management strategies, particularly for species like *Dociostaurus maroccanus*, are gaining traction. This involves integrating ecological monitoring and advanced modeling to anticipate and mitigate outbreaks. Mathematical models that simulate locust behavior, including flight patterns, propagation, and harmfulness, offer valuable insights for effective control measures within an Integrated Pest Management framework (Muhamediyeva & Madrakhimov, 2023). Advances in remote sensing and Geographic Information Systems provide powerful tools for monitoring locust distribution and density over large areas, although ground-based surveys remain essential for confirming presence and developmental stages (Muhamediyeva & Madrakhimov, 2023). Forecasting models using satellite remote sensing data and machine learning are being developed to predict locust occurrence at high resolutions, identifying key environmental risk factors (Marescot et al., 2025). These systems aim to enhance early response mechanisms, especially for detecting the early stages of swarming in remote, vast breeding areas (Landmann et al., 2023). The design and development of IoT solutions for locust monitoring are also emerging to overcome the limitations of traditional survey techniques, enabling real-time monitoring and precise forecasting (Tan et al., 2021). Accurate forecasting and early intervention treatments, supported by GIS-based decision support systems, represent best practices in locust management (Hunter, 2024).

The Moroccan locust is one of the most dangerous pests, annually causing significant agricultural damage in various countries worldwide, including the southern part of Kazakhstan. Dangerous foci of Moroccan locusts are concentrated in the south and southeast of Kazakhstan, specifically in the Turkestan and Jambyl regions. Outbreaks of mass reproduction and invasions of Moroccan locusts regularly occur in the Turkestan region, with dangerous foci located in Saryagash, Keles, Otyrar, Ordabasy, Shardara and Arys districts at altitudes ranging from 190-380 meters, and in Kazygurt, Tole Bi, and Sayram districts at altitudes of 650-1.100 meters above sea level. The arrival of locust swarms and their egg-laying in the Jambyl region also leads to the formation of dangerous foci, necessitating active phytosanitary measures to protect crops. The increasing frequency and intensity of these invasions underscore the urgency for robust, scientifically informed management strategies. The need for regional cooperation and sustainable management practices using environmentally friendly control agents, especially for the Moroccan locust, has been highlighted in recent studies (Khairov et al., 2024). Approaches such as using entomopathogenic fungi as biological control agents, whose efficacy can be influenced by climate variability, are part of the ongoing research into sustainable solutions (Kamga et al., 2022). Furthermore, investigations into chemical attractants, such as *faeces' odours*, suggest potential for managing hopper bands by diverting them from crops, offering an alternative to traditional chemical pesticides with reduced environmental impact (Vernier et al., 2022).

This paper aims to analyze the long-term dynamics of the abundance and spatial structure of the Moroccan locust population to assess the phytosanitary situation and determine the trend of locust development in these critical agricultural zones of Kazakhstan.

MATERIALS & METHODS

The study aimed at identifying the abundance dynamics and spatial structure of the Moroccan locust in the southern regions of Kazakhstan. The work covered a multi-year period (1999-2024) and was carried out in areas with stable pest foci in the Turkestan and Jambyl regions. To obtain the initial data, route surveys of agricultural lands and natural pastures were carried out. The boundaries of distribution areas, colonization areas (Acol), and the density of larvae (nymphs in bands) and imago (adults in swarms) at the accounting sites were determined. The surveys were conducted according to standard phytosanitary monitoring methods adopted in the plant protection system, with a record of the abundance of specimens per $1m^2$ and Acol in ha. The study of the dynamics of the abundance and structure of the population of the Moroccan locust was carried out using population indicators and abundance indices calculated with the following formulas (1-7):

$$P_{rel} = \frac{A_{col} \times 100}{A_{sur}} \quad (1)$$

where P_{rel} is the relative population (%), A_{col} is the colonized area (ha), and A_{sur} is the surveyed area (ha).

$$P_{bas} = P_{den} \quad (2)$$

where P_{bas} is the basic population (specimens·m^{-2}) and P_{den} is the density in populated areas.

$$P_{bas} = \frac{P_{rel} \times P_{bas}}{100} \quad (3)$$

where P_{bas} is the absolute population (specimens per surveyed area).

$$C_{dis} = \frac{A_{col}(j)}{A_{col}(j-1)} \quad (4)$$

Units: dimensionless

Interpretation: $C_{dis} > 1$: spreading into new territory

$C_{dis} < 1$: contraction of range

$$C_{col} = \frac{P_{den}(j)}{P_{den}(j-1)} \quad (5)$$

Units: dimensionless

Interpretation: Ccol > 1: increasing density and successful colonization

Ccol < 1: reduced density

$$C_{rep} = C_{dis} \times C_{rep} \quad (6)$$

Units: dimensionless

Interpretation: High values indicate rapid reproductive expansion.

$$C_{pro} = E_{dis} \times E_{rep} \quad (7)$$

Units: dimensionless

Interpretation: Indicates the potential for transition to a mass-reproduction (gregarization) phase.

Where A_{col} is the area colonized by the pest (ha); A_{sur} is the surveyed area (ha); P^{den} is the population density in colonized areas (specimens·m^{-2}); P_{rel} is the relative population (%); P_{bas} is the basic population, in specimens per unit of populated area; P_{abs} is the basic population expressed as density (specimens·m^{-2}); C_{dis} is the coefficient of distribution, describing changes in the colonized area between years; C_{col} is the coefficient of colonization, describing changes in population density between years; C_{rep} is the coefficient of reproduction; E_{dis} is the energy of distribution; E_{rep} is the energy of reproduction; C_{pro} is the coefficient of progradation; (j) is the year under analysis; (j-1) is the previous year.

Ethical and Regulatory Context of Locust Control Practices

The manuscript implicitly addresses the ethical and regulatory dimensions of locust management by documenting multiple violations and procedural shortcomings in pesticide application during the 2017 and 2024 Moroccan locust invasions. These deficiencies reflect a broader problem of inadequate compliance with established regulations and best practices. For instance, the manuscript describes "numerous cases of non-compliance with chemical control regulations" in 2017 and notes that, in 2024, critical procedural requirements—such as meeting alarm deadlines for the initiation of chemical treatments—were not observed. Moreover, during aerial applications using AN-2 aircraft, key technical standards for ultra-low-volume spraying were violated, particularly regarding formulation compatibility and sprayer configuration. These cases suggest that although regulatory frameworks existed, they were either ignored, inconsistently enforced, or insufficiently detailed to ensure proper implementation. The manuscript also highlights issues related to product performance and compliance with efficacy standards. Specifically, the failure to ensure the effectiveness of the Thiamethoxam SC formulation in 2024 resulted in low biological efficiency, underscoring weaknesses in ensuring that registered pesticides are used correctly and achieve their intended outcomes. In addition, large untreated areas or "blank spots" left during control operations in both 2017 and 2024 became sources of persistent locust foci, facilitating further migration and colonization. Such omissions point to operational lapses that may stem from inadequate regulatory oversight, insufficient monitoring capacity, or systemic organizational inefficiencies. Environmental risk mitigation emerges as another critical ethical concern. The manuscript explicitly states that the massive and repeated use of chemicals "increases the pesticide burden on ecosystems," as evidenced by the heightened environmental load observed after repeated anti-locust treatments in 2017. This recognition forms the basis for the authors' argument in favor of transitioning from conventional chemical-based interventions to more sustainable and ecologically responsible approaches. By advocating preventive strategies and environmentally friendly alternatives, the manuscript positions ethical stewardship and regulatory compliance as essential components of effective and sustainable locust management.

Quality Assurance and Quality Control (QA/QC)

All field data collection followed standardized phytosanitary monitoring procedures established by the national plant protection system. Surveyors received mandatory annual training delivered by the Zh. Zhiembaev Kazakh Research Institute of Plant Protection and Quarantine, with certification required before participation in seasonal surveys. Training included species identification, phase-state diagnostics, quadrat sampling, and GPS-based delineation of colonized areas. Population density (Pden) was measured using 1 m² quadrats placed at fixed intervals along survey routes. To ensure consistency among surveyors, quadrat counts were calibrated at the beginning of each season through parallel sampling, where multiple surveyors simultaneously recorded densities at the same sites. Discrepancies exceeding 10% were resolved through retraining and repeated calibration. All spatial boundaries of colonized areas (Acol) were recorded using handheld GPS devices (accuracy ±3–5m). GPS receivers were checked weekly against fixed reference points to confirm positional accuracy, and any units showing drift were recalibrated or replaced. Survey routes were logged automatically to ensure full spatial coverage. Data were entered daily into standardized field forms and cross-checked by a second team member for completeness and plausibility. Missing or inconsistent entries were verified through return visits whenever feasible; otherwise, such entries were flagged and excluded from index calculations. Annual datasets were reviewed centrally to ensure consistency in measurement units, coordinate systems, and classification schemes before being included in long-term analyses.

Dynamic Analysis

To establish patterns of development of Moroccan locust populations, a statistical analysis of population indicators and abundance indices over 25 years was performed. The data were compared with the values of solar activity (Wolf numbers, W), which made it possible to identify possible links between climatic factors and mass reproduction outbreaks.

Determination of Population Dynamics Phases

Based on the dynamics of the indicators, the main gradation phases were identified (depression, population growth, mass reproduction, and population decline). Diagnostic criteria were applied to each phase: minimum and maximum values for Cdis, Ccol, Crep, Edis, Erep, and Cpro. Thus, the applied methodology enabled comprehensive characterization of the long-term dynamics of the Moroccan locust, identification of periods of depression and mass-reproduction outbreaks, and assessment of the importance of climatic and anthropogenic factors for predicting its abundance.

RESULTS AND DISCUSSION

Diagnostic Predictors of the State of Moroccan Locust Populations

Gregarious locusts are characterized by extreme abundance dynamics and phase variability (Durgabai et al., 2018; Gómez et al., 2018; Skawsang et al., 2019; Xiao et al., 2019; de Oliveira Aparecido et al., 2020; Humphreys et al., 2022; Latif et al., 2022; Lawton et al., 2022; Ibrahim et al., 2022; Anand, 2024; Shaik et al., 2024; Swarnkar et al., 2024; Kapoor et al., 2025; Shafique et al., 2025). To establish patterns of changes in the dynamics of the abundance of Moroccan locusts and diagnostic predictors of the forecast of the state of populations, data on the dynamics of the abundance and population structure of the species in Kazakhstan for the period 1999-2024 were analyzed. The data on the relative, main, and absolute population of the Moroccan locust, as well as the W number (indicator of solar activity), are presented in Table 1. While significant historical context for locust invasions in Kazakhstan dates to 1997, the detailed population data presented in Table 1 begins from 1999, reflecting the start of consistent annual surveys for this study. The long-term trends observed in Moroccan locust populations, such as the increases in relative and basic population densities, are supported by consistent annual survey efforts conducted over 25 years, ensuring the reliability of our comparative analysis.

Data on the abundance indices of Moroccan locusts (Cdis, Ccol, Crep, Edis, Erep, Cpro) for the period from 1999 to 2024 are presented in Table 2. Data on the abundance indices of Moroccan locusts (Cdis, Ccol, Crep, Edis, Erep, Cpro) and the W number (indicator of solar activity) for the period 1999-2024 are illustrated in Fig. 1 and 2. It can be seen from the data in Table 1, 2 and Fig. 1 and 2 that the measurements of the abundance level and the abundance indices of the Moroccan locust characterize the abundance dynamics of the species in different dimensions. The values of abundance level measurements and abundance indices should be considered as the interaction of three processes (distribution, colonization, and reproduction). The following gradation phases of the Moroccan locust have been established for the period from 1999 to 2024 (Table 3).

As can be seen from the data in Table 2-3 and Fig. 1-2, according to the diagnostic signs of the gradation phases, the mass reproduction of the Moroccan locust took place in 2017 and 2024. During the years of mass reproduction of locusts, the abundance indices tend to maximize. For example, in 2017 (the year of mass reproduction), the indicators of abundance indices reached a maximum: Cdis = 1.83; Ccol = 3.71; Crep = 6.78; Edis = 2.18; Erep = 8.67; Cpro = 18.9. In 2024 (the year of mass reproduction), the indices of the abundance indices reached a maximum: Cdis = 2.47; Ccol = 2.07; Crep = 5.11; Edis = 7.28; Erep = 23.19; Cpro = 168.8.

According to the diagnostic signs of the gradation phases, 2021 also indicates mass reproduction, when the indicators of the abundance indices reached a maximum. It turned out that in 2019-2020, in the Turkestan region and certain districts of the Jambyl region, cold weather returned to -5 frosts in the spring and snow cover reached 20 cm, which caused a massive death of larvae and a sharp decrease in locust population. Thus, compared to 2018, the colonization of Moroccan locusts in 2019 decreased by 732.447ha or 96.8%; in 2020 by 604.111ha or 79.9%; and in 2021 by 575.211ha or 76.0%. Therefore, we believe that in 2021, there was a population growth of the Moroccan locust. Based on the analysis of the long-term dynamics of

Table 1: Land colonization by Moroccan locusts, 1999-2024

Years	W numbers (indicator of solar activity)	Surveyed, thousandha Asur	Colonized, thousandha Acol	Population		
				Prel, %	Specimens (m^2, Pbas)	
				relative	basic	absolute
1999	136.30	552.20	33.80	25.00	6.00	1.50
2000	173.90	608.40	188.40	30.97	14.50	4.48
2001	170.40	481.80	106.30	22.06	10.10	2.22
2002	163.60	190.00	25.00	13.15	19.00	2.51
2003	99.30	132.00	29.70	22.50	13.50	3.04
2004	65.30	264.00	133.30	50.49	8.80	4.44
2005	45.80	510.00	125.90	24.68	19.10	4.72
2006	24.70	558.00	104.60	18.74	14.70	2.75
2007	12.60	564.50	109.80	19.45	8.20	1.59
2008	4.20	754.20	251.70	33.37	11.10	3.71
2009	4.90	761.30	113.70	14.94	22.00	3.29
2010	24.90	717.70	181.00	25.210	6.20	1.57
2011	80.80	729.00	168.40	23.10	7.90	1.82
2012	84.50	807.20	258.10	31.97	8.50	2.72
2013	94.00	1.065.60	254.50	23.70	6.90	1.65
2014	113.30	999.10	232.30	23.24	7.60	1.81
2015	69.80	911.00	240.20	26.40	5.10	1.34
2016	39.80	1.056.70	332.30	31.45	5.50	1.73
2017	21.70	2.230.20	963.60	57.70	20.40	11.70
2018	7.00	1.981.30	756.40	38.10	17.70	6.70
2019	3.60	1.716.30	23.90	1.39	4.50	0.06
2020	8.80	1,697.30	152.30	8.90	6.60	0.50
2021	29.60	1,611.80	181.20	11.17	7.40	0.82
2022	83.10	985.00	59.50	6.00	4.40	0.26
2023	99.50	955.50	171.20	17.88	6.90	1.23
2024	147.00	983.30	435.50	44.30	14.30	6.35
_ S x	55.930	536.36	215.08	12.98	5.40	2.49
Δx	170.30	2098.20	939.70	56.31	17.60	11.64

Note: Survey methodology, intensity, and geographic coverage for all population parameters presented in this table remained consistent throughout the 1999–2024 period, following national standard phytosanitary monitoring protocols.

Table 2: Abundance indices of Moroccan locusts, 1999-2024

Years	Coefficient of distribution Cdis	Coefficient of colonization Ccol	Coefficient of reproduction Crep	Energy of distribution Edis	Energy of reproduction Erep	Coefficient of progradation Cpro
1999	1.92	0.46	0.88	1.63	2.25	3.66
2000	1.24	2.41	2.98	2.38	2.62	6.23
2001	0.71	0.69	0.48	0.88	1.43	1.25
2002	1.13	0.91	1.02	0.80	0.48	0.38
2003	0.90	1.46	1.31	1.01	1.33	1.34
2004	2.24	0.65	1.45	2.01	1.89	3.79
2005	0.48	2.17	1.04	1.07	1.51	1.62
2006	0.75	0.76	0.57	0.36	0.59	0.21
2007	1.03	0.55	0.56	0.77	0.31	0.23
2008	1.71	1.35	2.30	1.76	1.28	2.25
2009	0.44	1.98	0.87	0.75	2.00	1.5
2010	1.68	0.28	0.47	0.73	0.40	0.29
2011	0.91	1.26	1.14	1.53	0.54	0.82
2012	1.38	1.07	1.47	1.26	1.68	2.11
2013	0.74	0.81	0.59	1.02	0.87	0.88
2014	0.98	1.09	1.06	0.72	0.62	0.45
2015	1.13	0.66	0.74	1.11	0.78	0.87
2016	1.19	1.08	1.28	1.34	0.95	1.27
2017	1.83	3.71	6.78	2.18	8.67	18.9
2018	0.66	0.87	0.57	1.21	3.86	4.67
2019	0.03	0.25	0.007	0.02	0.004	0.001
2020	6.4	1.46	9.34	0.19	0.06	0.01
2021	1.25	1.12	1.4	8.0	13.07	104.5
2022	0.54	0.60	0.32	0.67	0.44	0.29
2023	2.95	1.54	4.54	1.59	1.45	2.30
2024	2.47	2.07	5.11	7.28	23.19	168.8
_ S x	1.22	0.77	2.21	1.86	5.04	37.81
Δx	6.37	3.46	9.33	7.98	23.19	168.80

Table 3: Gradation phases of the Moroccan locust for the period from 1999 to 2024

Dynamic phase	Diagnostic indicators	Years
Depression	Cdis, Ccol, Crep → min Edis, Erep, Cpro → min	1999, 2002, 2006, 2007, 2010, 2011, 2014, 2015, 2019
Population growth	Cdis, Ccol, Crep → min-max Edis, Erep, Cpro → min-max	2000, 2003, 2004, 2008, 2012, 2016, 2021, 2023
Mass reproduction	Cdis, Ccol, Crep → max Edis, Erep, Cpro → max	2017, 2024
Peak abundance	Cdis, Ccol, Crep → max Edis, Erep, Cpro → max	
Population decline	Cdis, Ccol, Crep → max-min Edis, Erep, Cpro → max-min	2001, 2005, 2009, 2013, 2018, 2020, 2022

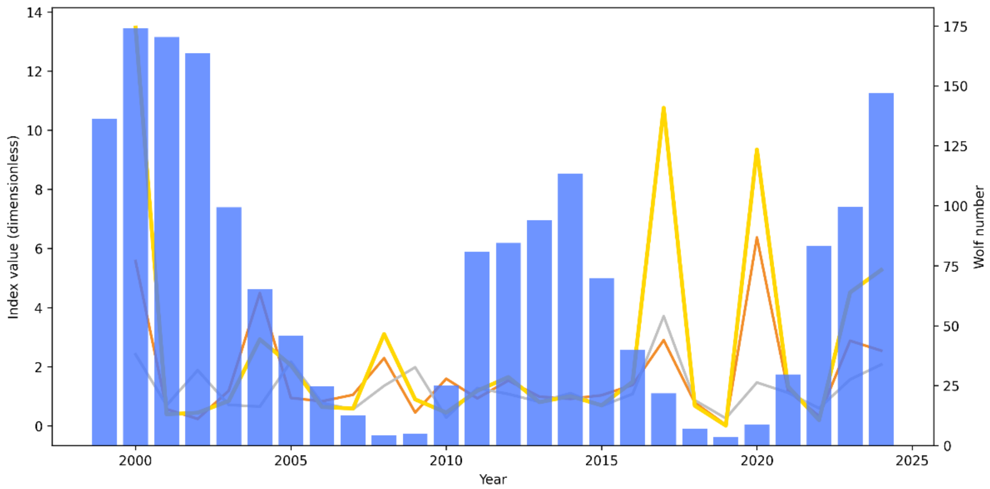

Fig. 1: Annual Dynamics of Distribution, Colonization, and Reproduction Indices of the Moroccan Locust (1999–2024)

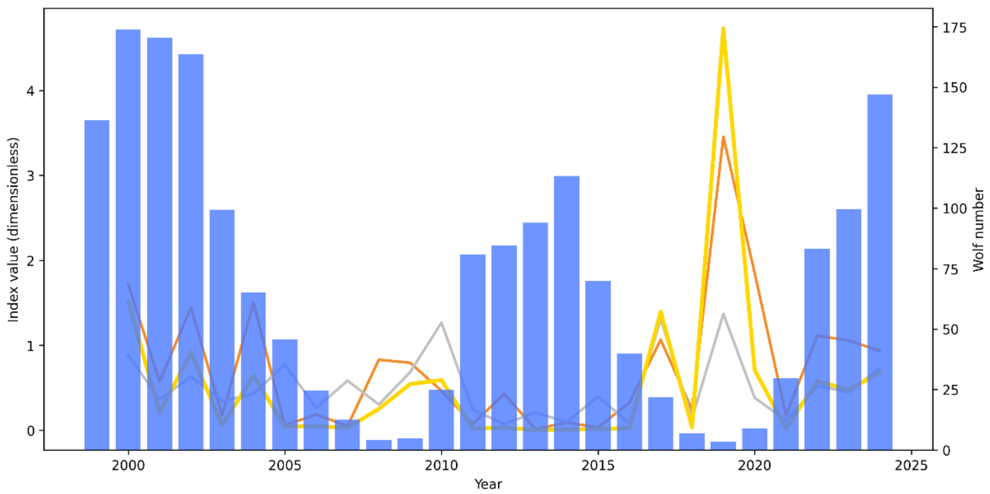

Fig. 2: Energetic Indices and Progradation Coefficient of the Moroccan Locust (1999–2024)

the Moroccan locust abundance, the following conclusions can be drawn. The dynamics of the Moroccan locust abundance belong to the eruptive type (Azhbenov et al., 2017). The gradation cycle consists of four phases (depression – population growth – mass reproduction – population decline) besides the peak abundance. For the forecast of mass reproduction outbreaks, the variations of Cdis, Ccol, Crep, Edis, Erep, and Cpro in different years are of the most significant value.

Correct Analysis of Locust Invasions in Kazakhstan

A correct analysis of locust invasions in Kazakhstan was made with an assessment of significant risk factors. The establishment of the main patterns of the mass reproduction outbreak and locust invasion is important for a general analysis of the phytosanitary situation and determining the locust development trends.

Mass Reproduction and Invasion of Locusts in 1997-2003

The mass reproduction and invasion of locusts in 1997-2003 was one of the largest invasions in the last 50 years. During 1997-1998, migrations of hopper bands and swarms of Italian, Asian, and Moroccan locusts were observed, but they remained without proper phytosanitary control. On the contrary, the volume of phytosanitary measures decreased: colonized areas with the abundance above the economic injury level for locusts remained untreated, reaching 1 million ha in 1997, 1 million ha in 1998, and over 2 million ha in 1999. In conditions of acute drought, the migration activity of insects increased, and as a result of the spread of locust swarms from untreated lands, numerous foci formed in new territories (Kurishbaev & Azhbenov, 2013). At the peak of locust reproduction in 1999, long-range migrations became widespread and covered a vast area of about 140 million ha, or half of the territory of Kazakhstan. Dangerous locust foci formed on waste lands and inhard-to-reach territories: in the Ryn Desert, in the Taysoygan sands, Greater Barsuki, Ayghyrqum, Saryesik-Atyrau Desert, along the water shores of the Caspian Sea, in the system of Kamys-Samar lakes, along the banks and thickets of the rivers Syr Darya, Ural, Torgay, Irgiz, and Chu, and lakes Balkhash, Sasykkol, and Alakol. Migration of locusts to other territories reached up to 1.000-1.200 km from their habitats. As a result of the mass swarming of locusts, four large foci were formed: the northeastern (about 60 million ha), western (about 30 million ha), Torgay-Aral (about 18 million ha), and southeastern (about 5 million ha). The unprecedented swarming of locusts dramatically changed the phytosanitary situation. The insects that arrived in mass not only caused significant damage to the land but also managed to leave offspring. In autumn, more than a thousand pods per 1m^2 were detected, and an exceptional density of more than 5,200 pods per 1m^2 was detected in the Taysoygan sands of the Atyrau region.

The high destructiveness of locusts caused significant damage to agriculture: the harvest of grain crops on 220 thousand ha was destroyed; the economic damage amounted to 2.5 billion tenge. Appropriate measures were taken to protect agricultural land. Chemical control was carried out in 2000 on 8.1 million ha, in 2001 on 4.8 million ha, and in 2002 on 1.2 million ha. Furthermore, the agrotechnical method was used on 5 million ha. Unprecedented measures temporarily reduced the abundance of locusts, which led to a decrease in the volume of chemical control to 506 thousand ha. Despite intensive chemical treatments, the trend in locust abundance has been increasing since 2005. By 2014, the Acol above the economic injury level had risen by 8.4 times, and the volume of anti-locust treatments had reached 4 million 246.3 thousand ha (Kurishbaev & Azhbenov, 2013).

Mass Invasion of Locusts in 2012-2014

In 2012-2014, the locust invasion was caused by mass migrations to agricultural lands both from the border territories of Russia and from locust permanent reservations in Kazakhstan (Ryn Desert, Taysoygan Sands, Greater Barsuki, Ayghyrqum, Mamyt Sands, Aiyyrkyzyl Sands, etc.). The conditions for chemical control were very harsh: severe drought and high temperatures shifted the timing of treatments by 10-14 days, sometimes making them 20 days earlier than usual. The personnel performing the treatments were unprepared for such conditions: spraying equipment arrived at the treatment sites with a long delay of up to 7-10 days; the regulations for the use of preparations, in particular chitin and adonis synthesis inhibitors, were not followed. Massive chemical treatments did not ensure the extermination of dangerous pests. Some areas, which were heavily populated by locusts, remained untreated, contributing to the migration of newly formed swarms and the mass colonization of new territories. The locusts acquired wings and formed swarms that migrated in mass and colonized new territories in Atyrau, West Kazakhstan, Aktobe, Kyzylorda, and Kostanay regions, in Zharkain and Esil districts of Akmola region. The swarming of locusts altered the phytosanitary situation in colonized foci, as the locust insects that arrived in large numbers have left offspring. In the fall of 2012, more than 100 pods per 1m^2 were found in soil excavations, and an exceptionally high density of more than 2.000-4.000 pods per 1m^2 was found in the Aktobe and Kostanay regions (Kurishbaev & Azhbenov, 2013).

Mass Invasion of Moroccan Locusts in 2017

In 2017, the invasion of Moroccan locusts in southern Kazakhstan appeared to be exacerbated by the low efficiency of chemical treatments, potentially due to numerous cases of non-compliance with chemical control regulations. Some dangerous locust foci reportedly remained untreated, which could have contributed to the migration of newly formed swarms and the mass colonization of new territories. Risk factors that may have influenced these invasions include reported violations of chemical treatment technology, such as unacceptable delays in the start of chemical treatments and non-compliance with optimal treatment deadlines; violations of chemical treatment regulations; the use of non-certified spraying equipment; a lack of Global Positioning System navigators on ground sprayers; and instances of blank spots with dangerous locust foci. This period of increased Moroccan locust activity in southern Kazakhstan led to a sharp deterioration in the phytosanitary situation: compared to 2016, the Acol above the economic injury level increased by 524.234ha in 2017 and by 442.914ha in 2018; plantings and harvests of green crops and other farm crops were destroyed by destructive insects; the high-risk area for locust damage increased 16-fold; and repeated anti-locust treatments led to an increase in the pesticide burden on ecosystems. Kazakhstan's stock of pesticides was used against migrating Moroccan locusts, which raised concerns about phytosanitary security in the event of a similar phytosanitary situation in other regions.

Mass Invasion of Moroccan Locusts in 2024

In 2024, in the Saryagash district of the Turkestan region, several reported violations during chemical air treatments using an AN-2 aircraft against Moroccan locusts with the preparation Thiamethoxam SC may have impacted their effectiveness. These included instances where the regulations for chemical treatments were not followed; the alarm deadlines for the beginning of chemical treatment were not met; and when performing aerial treatments using an AN-2 aircraft, the requirements for the effectiveness of chemical treatments using the "ultra-low volume spraying" method were reportedly not met regarding the compatibility of the formulation of the preparations and the applied parts of the sprayers. Consequently, the intended effectiveness of the Thiamethoxam SC preparation was not ensured. Following these chemical aircraft treatments in the Saryagash district of the Turkestan region, numerous foci of Moroccan locusts were found on agricultural land, suggesting a low biological efficiency of the chemical applications. The surviving locust larvae formed dense hopper bands after chemical treatments, and having reached the adult stage, then developed into flying swarms that migrated to the territories of the Arys, Saryagash, Keles, Kazygurt, Ordabasy, and Shardara districts of the Turkestan region, Bayzak, Jambyl, Jualy, Talas, Merki, and Chui districts of the Jambyl region.

As can be seen from Fig. 3 and 4, after the Moroccan locust invasions in 2024, the phytosanitary situation worsened: Compared to 2023, the colonization of the territory by Moroccan locusts increased by 314.289ha in 2024 in the Turkestan region, and by 69.289ha in the Jambyl region. The massive distribution of locusts was facilitated by changes in the phase state of Moroccan locust populations in 2023-2024: in the Turkestan region, the percentage of gregarious phase increased from 67% in 2023 to 83% in 2024; in the Jambyl region, from 47% in 2023 to 86% in 2024. We established that the phase state of the population is an important predictor of the forecast of Moroccan locust invasions: the correlation coefficient of the growth of the abundance of Moroccan locusts with the phase state of the population is relatively high and amounts to r = 0.627.

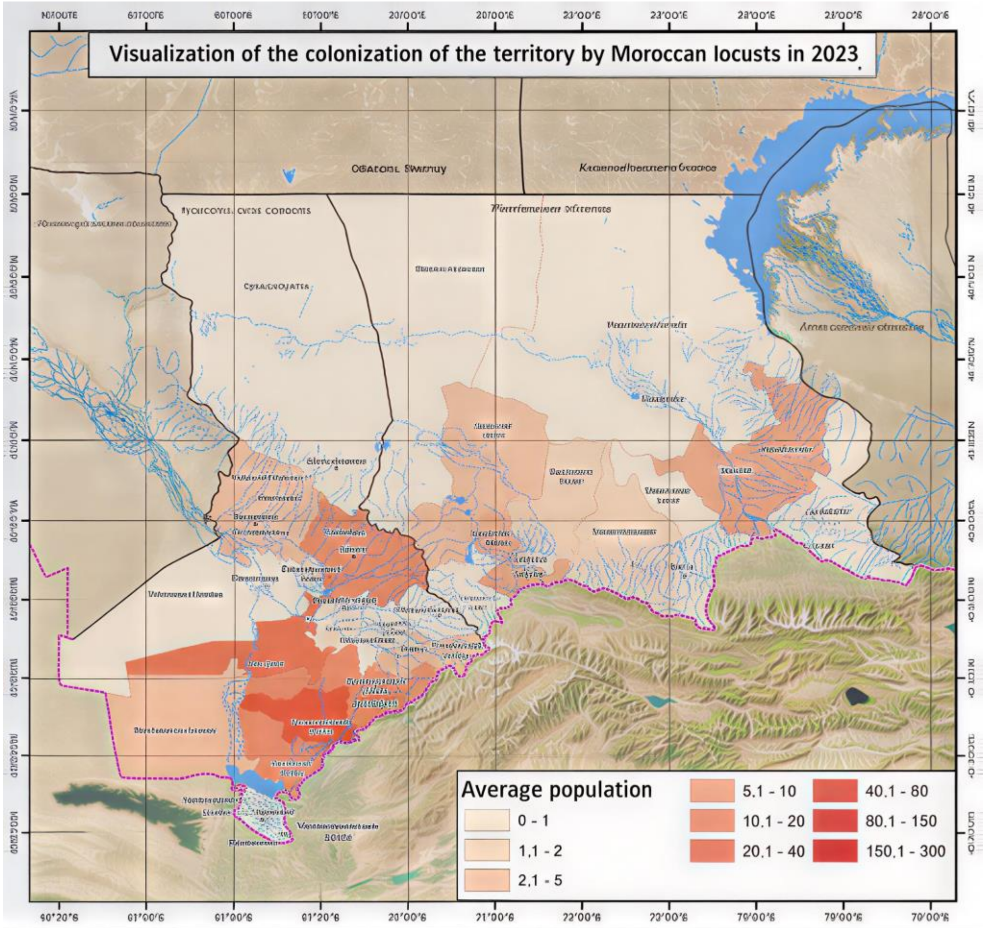

Fig. 3: Visualization of the average population of Moroccan locusts before the invasion (Turkestan and Jambyl regions, 2023).

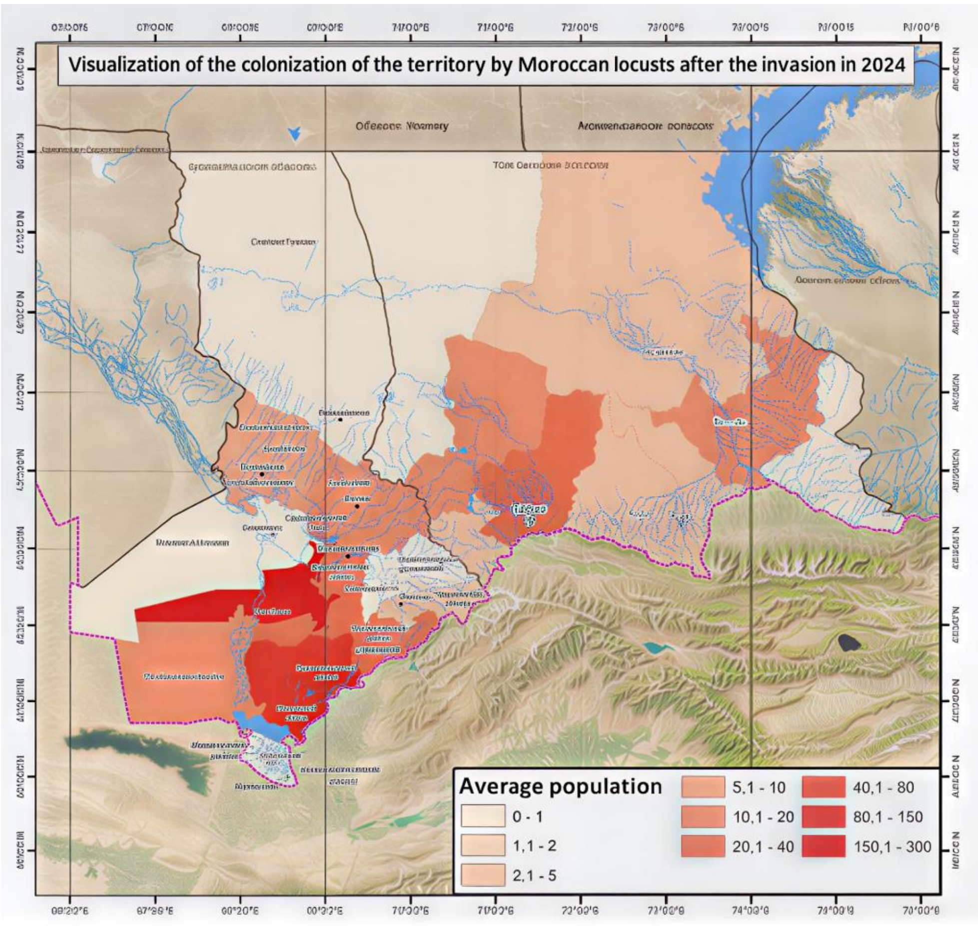

Fig. 4: Visualization of the average population of Moroccan locusts after the invasion (Turkestan and Jambyl regions, 2024).

Significant Risk Factors for Locust Invasions

The most important factor contributing to the unprecedented invasion of locusts in 1997-2003 was the fundamental structural changes in agricultural landscapes due to the withdrawal of arable land from cultivation and the emergence of wasteland (Azhbenov et al., 2015, 2017, 2024; Baibussenov et al., 2021, 2022; Githae & Kuria, 2021; Iranipour et al., 2017; Kurishbaev & Azhbenov, 2013; Lachininskii et al., 2023; Maeno et al., 2021). The reduction of the area under grain crops by more than 2 times led to the appearance of deposits of different ages, which created favorable conditions for the colonization of locusts. A significant risk factor for the invasions was the insufficient financing of work on locusts, the weakening of phytosanitary control, and the reduction of phytosanitary measures. Locust-infested areas with the abundance above the economic injury level that remained untreated in 1997-1998 equaled 1 million ha, and in 1999, over 2 million ha. As a result of the distribution of locust swarms from untreated areas, numerous foci formed on new lands.

A significant factor in the invasion of locusts in 2012-2014 was mass migrations of locust swarms from the border territories of the Russian Federation and from reservation sites in Kazakhstan (Ryn Desert, Taysoygan sands, Greater Barsuki, Ayghyrqum, Mamyt sands, Aiyyrkyzyl sands, etc.). Serious omissions were made in the organization of chemical control. The colonized areas remained untreated, which contributed to the migration of swarms and the settlement of new territories. The locusts acquired wings and formed swarms that migrated massively to the territories in Atyrau, West Kazakhstan, Aktobe, Kyzylorda, Kostanay, and Akmola regions. A significant risk factor for Moroccan locust infestations in 2017 and 2024 are violations of chemical treatment technology: leaving blank spots with locust foci; non-compliance with optimal treatment times; violations of treatment regulations; use of non-certified spraying equipment; lack of GPS navigators on sprayers; the requirements of treatments using the "ultra-low volume spraying" method were not met when testing the preparation formulas with the applied parts of the sprayers. The locust invasion in 2017 led to a deterioration of the phytosanitary situation: plantings and harvests of green crops and other crops were destroyed by locusts; the high-risk area for locust damage increased 16-fold. Following the 2024 invasion of the Moroccan locust, the territory's colonization with locusts increased by 314,289ha in the Turkestan region and by 69,289ha in the Jambyl region.

The long-term analysis of Moroccan locust populations in Kazakhstan, spanning from 1999 to 2024, reveals a cyclical pattern of abundance characterized by eruptive dynamics. This pattern, encompassing phases of depression, population growth, mass reproduction, and decline, is fundamentally driven by the locust's remarkable phenotypic plasticity, particularly its density-dependent phase polyphenism (Foquet et al., 2021). The transition from a solitary, cryptic phase to a gregarious, swarming phase is a complex biological phenomenon influenced by a multitude of interacting factors, including population density, environmental cues, and neurobiological changes (Anton & Rößler, 2021; Petelski et al., 2024). Recent research has further elucidated the molecular underpinnings of this plasticity, demonstrating how gene expression can vary across species and contribute to the distinct behavioral, morphological, and physiological changes observed during phase transition (Foquet et al., 2021).

The current study's findings, particularly the significant increases in the coefficient of progradation (e.g., 168.8 in 2024) and the coefficient of reproduction (e.g., 5.11 in 2024) during mass outbreaks, align with the understanding that high population densities are critical triggers for gregarious behavior. These periods of maximal reproductive and distributional indices serve as crucial diagnostic predictors for forecasting mass reproduction outbreaks, underscoring the importance of early detection in preventive management. The observed correlation coefficient of $r = 0.627$ between the growth of Moroccan locust abundance and the population's phase state further emphasizes the predictive power of monitoring phase changes.

Phase Transformation of Locusts and Behavioral Ecology

Gregarization-initiating mechanisms, namely those where tactile, visual and chemical communication are implicated, have key roles to play (Martín-Blázquez et al., 2017; Cabon et al., 2025). Existing models propose aggregation results from positive feedback loops amongst pheromal communication, attraction behaviors, and nearby density (Chang et al., 2023). Chemicals like 4-vinylanisole (4VA) have emerged as initiators of crowding and transition of phases (Guo et al., 2025). In addition, the vomeronasal system processes social and food cues, and this affects aggregation and food searching behavior (Petelski et al., 2024). These results are additions to earlier "self-propelled particle" models, and collective motion of locust swarms involves decision-making behavior dependent upon the context and not merely mechanical alignment (Sayin et al., 2025). Environmental influences can induce epigenetically mediated phase transitions, while parental experiences can affect offspring traits such as hatching synchrony, enhancing swarm formation potential (Burggren & Méndez-Sánchez, 2023; Zhu et al., 2024). Such studies underscore the multilevel plasticity of locust populations and their capacity to synchronize developmental and behavioral responses to crowding and climate.

Climate Sensitivity and the 2020-2022 FA

The 2020-2022 desert locust outbreak, as illustrated by FAO technical reports, was the most severe of the last few decades, devastating crops all the way across East Africa, the Arabian Peninsula, and South Asia. The FAO Desert Locust Information Service attributed this epidemic to unprecedented rainfall by cyclones in the Arabian Sea, making extensive breeding sites (FAO, 2021; Bitanihirwe et al., 2021). This incident showed the impact of anomalies within the climate to enhance locust reproduction and migration, relating locust ecology to broader climatic dynamics on the planet (Salih et al., 2020; Kimathi et al., 2020). Recent modeling studies confirm this link. Simulation scenarios including temperature-responsive reproduction and survival parameters reveal that slight climatic shifts are able to provoke nonlinear population responses, including sudden surges and declines (Mamo et al., 2025). Studies using habitat suitability models such as MaxEnt predict that because of global warming, locust distribution patterns are bound to change while some peripheral habits would narrow, primary suitable areas are predicted to expand, particularly in the region of Central Asia and East Africa (Saha et al., 2021; Wu et al., 2022; Tang et al., 2023). The most significant parameters of these models are the coldest-month minimum temperature, driest-quarter mean temperature, and yearly precipitation, supporting the fact that warming trends and unpredictable rainfall provide auspicious breeding circumstances (Tang et al., 2023; Mitra et al., 2024). These reports by the FAO stress the fact that unabating climate unpredictability and vegetation alterations require intensified early warning systems, bringing together remote sensing, field observations, and the application of the biophysical model.

Preventive and UAV-Based Control Strategies

Traditional chemical spraying remains a dominant but flawed strategy—its environmental costs, limited effectiveness, and harm to natural enemies often prolong invasions (Hunter, 2024; Rahimi, 2024). Experiences from Kazakhstan and neighboring regions demonstrate that delayed responses, underfinancing, and weak phytosanitary capacity exacerbate the scale of infestations. Consequently, preventive population control and management strategies are gaining prominence as a more effective and environmentally friendly alternative (Lecoq & Cease, 2022; Hunter, 2024). This approach is rooted in advanced monitoring and early detection of changes in pest abundance and phase state (Soubeyrand et al., 2024; Baraka et al., 2025). Technological improvements of remote sensing and unmanned aerial vehicles are revolutionizing early detection and selective intervention. Satellite imagery of high resolution, associated with machine learning, makes possible near-real-time detection of vegetation greenness and soil moisture anomalies revealing likely breeding sites (Klein et al., 2021; Marescot et al., 2025). UAVs, on the other hand, enable fast reconnaissance of unreachable sites and are capable of carrying payloads for precision application of pesticides with reduced collateral effects (Matthews, 2021; Zhao et al., 2023). Such systems plot "prescription maps" of site-specific application, minimizing chemical application and expenditures. Geospatial artificial intelligence, specifically deep learning models calibrated using FAO and region-wide datasets, is enhancing the ability to predict locust suitability of habitat under future warming scenarios (Landmann et al., 2023; Yusuf et al., 2024). Incorporation of these data-based tools within national locust centers strengthens early warning capabilities and allows for the coordinated response by ECLAF and FAO networks.

Towards Integrated and Sustainable Management

Contemporary Integrated Pest Management (IPM) prioritizes a holistic approach that integrates monitoring, ecological modeling, and biological control techniques. The utilization of environmentally sustainable biopesticides, particularly those derived from Metarhizium acridum, is increasingly being implemented in preventive measures throughout Africa and Asia (Lecoq & Cease, 2022; Kamga et al., 2022; Ochieng' et al., 2023). These biological agents effectively reduce pest populations while maintaining the integrity of ecosystems. Upcoming experiments examine natural baits such as the odor of faeces to manipulate locust movement and disrupt aggregation (Vernier et al., 2022). Biosynthesis and aggregation pheromone disruption, such as 4-vinylanisole, are new frontiers of selective chemical ecology strategies (Guo et al., 2025). Analytical indices, including distribution, colonization, and progradation coefficients, are still useful diagnostic indices for the detection of pre-outbreak conditions. Tracking these indices supplies quantitative thresholds of initiating pre-emptive measures pre-dating the time of population explosions (Hunter, 2024). FAO's "Manual for the Implementation of Environmental, Health, and Safety Standards for the Control of Locusts" of 2022 particularly lays importance on the requirement of environmental compliance and safety of operation both for chemical and biological treatments. International Collaboration and Future Directions Globally widespread locust invasions require inter-country collaboration. The Global Locust Initiative advocates for the combination of ecological research, socioeconomic information, and latest technologies to construct resilience for vulnerable areas (Gao et al., 2020; Ries et al., 2024). We must construct adaptive means of governing through the intersection of national early warning systems, intercontinental leadership by FAO and ECLAC, and open data sharing to mitigate the increasing threat of climatically induced outbreaks. Ongoing investment in leadership by the FAO, alongside shared-access systems of modeling and surveillance aided by UAVs, will make increasingly accurate and environmentally sustainable interventions for future influxes possible. Synthesis of genetic, ecological, and technological insights within early detection systems amounts to a paradigm shift toward anticipatory resilience and so prevents ecological harm and economic loss associated with locust invasions.

Conclusion

The abundance dynamics of the Moroccan locust exhibit a distinctly eruptive pattern, characterized by a gradation cycle that progresses through four sequential phases: depression, population growth, mass reproduction, and population decline, in addition to a peak abundance stage. For forecasting the likelihood and intensity of mass-reproduction events, the interannual variation of key population indicators—Cdis, Ccol, Crep, Edis, Erep, and Cpro—is of critical predictive value. These coefficients collectively capture changes in distribution, density, reproductive potential, and overall population progradation, thereby serving as essential tools for assessing outbreak risk. The manuscript also highlights the negative consequences associated with the traditional practice of large-scale chemical control during locust migration periods. First, chemical treatments often demonstrate low biological effectiveness, failing to ensure sufficient suppression of high-density pest populations. Second, the indiscriminate use of insecticides eliminates natural enemies and disrupts natural epizootics, ultimately prolonging the duration and severity of invasions. Third, operational gaps—such as "blank spots" left untreated—create persistent foci that promote continued migration and enhance the risk of subsequent invasions. Finally, the massive and repeated application of pesticides elevates environmental contamination and increases the cumulative toxic burden on ecosystems. Given these limitations, the strategy for locust population management must evolve in line with scientific advances, technological capacity, financial feasibility, and increasing societal emphasis on environmental protection. Environmentally sustainable and alternative control approaches are now recognized as preferable, particularly from an ecological and long-term management perspective. A viable alternative to the historical "chemical press" is the preventive population control and management strategy, which centers on intensive monitoring and early detection of changes in locust abundance. By enabling timely, targeted intervention, this approach reduces both the frequency and magnitude of locust outbreaks. Importantly, preventive management incorporates comprehensive preparedness and contingency components, allowing for adaptive responses under diverse ecological and operational scenarios.

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Conflict of Interest: None.

Data Availability: Data available upon request from the corresponding author.

Ethics Statement: This study was based on long-term field monitoring of insect pest populations (Moroccan locust, Dociostaurus maroccanus) and did not involve experiments on humans or vertebrate animals. All field surveys, data collection, and monitoring activities were conducted in accordance with the institutional guidelines and phytosanitary regulations of the Zh. Zhiembaev Kazakh Research Institute of Plant Protection and Quarantine (Republic of Kazakhstan), as well as relevant national regulatory standards.

Author's Contribution: VA developed the study concept and methodological framework and supervised the research; AD coordinated field data collection, performed GIS and index calculations, and prepared figures, tables, and the final manuscript; ZhN carried out field surveys, validated density data, and contributed to interpreting long-term dynamics; KB curated data, performed statistical checks, and assisted with index recalculations and supplementary materials; SA supported field logistics, verified colonized-area boundaries, and reviewed phytosanitary procedures; AZh compiled archival monitoring data, conducted the literature review, and assisted with data validation and formatting. All authors have read and approved the final manuscript.

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