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ROLE OF METEOROLOGICAL FACTOR IN LONG-TERM POPULATION DYNAMICS OF THE EUROPEAN CORN BORER, *Ostrinia nubilalis* Hbn., IN KRASNODAR AREA: THE ANALYSIS OF LIFE TABLES

A.N. FROLOV, I.V. GRUSHEVAYA

All-Russian Research Institute of Plant Protection, 3, sh. Podbel'skogo, St. Petersburg, 196608 Russia, e-mail entomology@vizr.spb.ru (✉ corresponding author), grushevaya_12@mail.ru
ORCID:
Frolov A.N. orcid.org/0000-0002-6942-9951
Grushevaya I.V. orcid.org/0000-0003-4751-5442
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Abstract

The European corn borer, *Ostrinia nubilalis* Hbn. is one of the most dangerous pests of maize. Though weather, mostly air temperature and humidity, demonstrate their important influence on distribution, population level and development terms of the European corn borer, the accuracy of forecasting models remains rather low to predict pest population dynamics. The aim of our work consists in the comparison of meteorological data with the demographic indicators characterizing long-term population fluctuations in the European corn borer to identify the most significant meteorological criteria for the forecast of pest population dynamics. Observations of insect population dynamics conducted during 1994-2018 on maize fields in vicinity of village Botanika (Gulkevichi District, Krasnodar Area; 45°12′51″ N and 40°47′41″ E) during 1994-2018, and data obtained in 2018 were only used for verification of the dependence established on data array for 1994-2017. We estimated density of insect population at all stages of life cycle from egg to adult. The meteorological information was obtained from the Otrado-Kuban meteorological station located in the center of the territory of the test field location. Mortality for the different periods of insect development (eggs, I-II and III-V instar larvae, pupae, adults) was estimated as $K = \log N_1 - \log N_2$, where N_1 and N_2 are density of insects for the corresponding periods. Mortality for generation was calculates as $K = \log N_o - \log N_f$, where N_o and N_f is density of eggs and egg-laying females of the current generation. The breeding index per generation was calculated as $I = N_{t+1}/N_t$, where N_t and N_{t+1} is density of eggs for the current (t) and the following (t + 1) generation, respectively. Two generations of the European corn borer annually develop in Krasnodar area, and size of population during the first generation usually grows, while those in second generation decreases. The demographic characteristics of insect statistically significant correlate with meteorological factors only during time interval from the third decade of May to the first decade of June when the peak of egg oviposition and mass hatching of I instar larvae of the first pest generation usually occur. Egg mortality shows the closest negative correlation with air temperatures and positive correlation with moisture (water drops and vapor). No association of demographic indicators with meteorological factors during oviposition and hatching of second-generation larvae was found probably due to formation of high and dense maize crops with a microclimate favorable for insect development. Thus, the data obtained demonstrate that the last decade of May — the first decade of June is the only critical period during the European corn borer development in the region. Based on the findings, we drown a 3D linear contour diagram of the European corn borer first generation egg mortality as dependent on mean daily air temperature and relative atmospheric humidity during the last decade of May. This dependence is of interest in terms of an improved model for short-term forecast of pest population dynamics in Krasnodar Area.

Keywords: European corn borer, population dynamics, demography, egg mortality, air temperature, air humidity, Krasnodar Area

The European corn borer, *Ostrinia nubilalis* Hbn. is one of the most dangerous pests of maize, the loss of grain yield from which in Eastern Europe is still very high [1-4]. Despite a significant number of publications devoted to this insect both in Russia [5-7] and abroad [8-11], many features of its ecology remain insufficiently disclosed [12]. The significant role of meteorological conditions, primarily temperature and humidity, in the distribution and abundance, as well as the timing of the corn borer development, has been convincingly shown [13-17]. However, the accuracy of the forecast, which is based on meteorological information, remains low [18].

The domestic theory of phytosanitary forecasting is underlaid by the Victor E. Shelford's law of tolerance which is based on the effects of limiting environmental factors during critical periods of the life cycle of a harmful species [19]. The population genetics study of genus *Ostrinia* members [1] distinguishes the following critical periods in the corn borer life cycle: pupation of overwintered larvae; mating and oviposition by butterflies; start of larval feeding [20]. It is understood that the viability of the population during these periods is determined by meteorological factors: the average daily temperature and the amount of precipitation over a period from a 11 °C threshold transition to the start of pupation of hibernating larvae; the amount of rainfall during the oviposition; the absence of showers, strong winds, high temperatures and other extreme meteorological phenomena in the initial period of larval feeding [20].

Disclosing patterns of harmful insects' population dynamics is among the most important aspect of plant protection, since the reliability of forecasts of the harmful species reproduction depends on a completeness of knowledge about all affecting factors and the accuracy of the models used [19].

In the present work, we first proved the decisive contribution of the death of corn borer eggs in the population dynamics of its first generation in the season. A reliable relationship between insect mortality and meteorological factors is found in the interval limited by decade III of May to decade I of June, when mass egg laying and hatching of the first instar larvae of the first generations usually occur.

Our aim was to compare meteorological data with demographic indicators characterizing long-term population fluctuations of corn borer local population, and to identify the most significant meteorological criteria for predicting the dynamics of the pest population.

Materials and methods. Observations were carried out in the vicinity of the village Botanika (Krasnodar Territory, Gulkevichsky District; 45°12′51″N and 40°47′41″E) in 1994-2018. Data for the 2018 season were used exclusively to verify dependencies established on the data array for 1994-2017. The scientific crop rotation of the VIR Kuban experimental station (VIR KES), a total area of 284 hectares, was the territory to estimate corn borer *Ostrinia nubilalis* population dynamics. Since 2014, the surveys also covered fields adjacent to the scientific crop rotation (Scientific Production Association NPO KOS-MAIS), a total area of 500 hectares. Standard meteorological information was received daily from Otrado-Kuban weather station located at the center of the VIR KES crop rotation.

Corn borers were counted annually in 6 maize crop fields on average (minimum 3 fields and maximum 14 fields with a total area of 18.4 to 175.0 ha, where zoned and promising hybrids and their parental forms were grown. The range of cultivated maize genotypes varied according to the State Register of Selection Achievements Allowed to Use [21]. All agricultural techniques adopted in the zone were used (tillage, sowing, application of herbicides, 1-2 inter-row cultivations). Seed sowing time, as a rule, was optimal. The stand density in the fields varied from 2.8 to 7.8 plants per 1 m^2, the insect population density was estimated per 1 m^2 crops. It is this method of calculating the density that seems to be the only possible to describe the full cycle of the insect seasonal dynamics, since the development of individuals of the 2nd generation ends after their hibernation in post-harvest plant debris in the fields.

Periodic counting (21-23 times per season) covered the life cycle of the insect from egg to adult. The counts of overwintered individuals (that is, the 2nd generation of the previous season) were carried out in the fields that were occupied by maize last year. In such areas, the density and mortality of overwintered larvae, pupae, and adults in plant residues were evaluated twice (before pupation and at the end of adult eclosion). The distribution of the overwintered and hibernating larvae was determined at randomly selected 0.7-1.0 m^2 plots (20-25 plots per field). The density of egg masses of the 1st (May-June) and 2nd (July-August) generations was estimated at permanent (during the season) plots, consisting usually of 10 plants, the first and last of which were labeled. The number of such plots per field varied from 9 to 25, depending on the area of the latter. During the flight of adults, plants on the sites were carefully examined every 3-5 days, and the location of each found egg mass was marked, the number of eggs per mass was counted using a handheld magnifier, then the number of eggs from which the larvae hatched out was estimated [22]. The egg density per field was calculated from the total number of eggs during a series of periodic surveys. At the end of the oviposition period, a series of larval counts on plants was carried out, for which plants from randomly selected 0.7-1.5 m^2 plots, 5-10 plants per each, were dissected. The number of such plots varied from 15 to 35, depending on the field size. Weeds found at the plot were also inspected, as they could be infested by pest larvae.

Adult population density was calculated from number of pupal skins. The number of egg-laying females was calculated as the average density of eggs of the next generation divided by 225 [22]. This value characterizes population density of adults normalized to the sex ratio 1♀:1♂ and the average fecundity of the female. According to the results of long-term (1975-2004) counts of eggs laid by moths in labs, the average fecundity of a fertilized female is taken equal to 450 eggs. The average generation density of corn borer eggs, larvae, pupae, adults, and egg-laying females was calculated as weighted average over the surveyed acreage of fields occupied by maize.

Mortality rates of insects for developmental periods (eggs, larvae of I-II and III-V instars, pupae, and adults) were represented as the difference of density logarithms: $K = \log N_1 - \log N_2$, where N_1 and N_2 are the density of insects for relevant accounting periods [23, 24]. Mortality for generation was represented in the form $K = \log N_o - \log N_f$, where N_o and N_f are the density of eggs and ovipositing females of the current generation. Before the logarithm calculation, the density values were recalculated per 1000 m^2 of maize crops in order to avoid the appearance of negative logarithms at a low phytophage density. The breeding index per generation was calculated as $I = N_{t+1}/N_t$, where N_t and N_{t+1} are egg density of the current (t) and next (t + 1) generations [6].

All calculations were performed with Statistica 10.0 software (StatSoft, Inc., USA). The tables show means (*M*), maximum (max) and minimum (min) values, standard deviations (±SD), coefficients of variation (*Cv*) and correlation (*r*). Dependencies between the effects were assessed using correlation and regression analyzes, the reliability of correlations at a $p < 0.05$ significance level was evaluated using the Student's *t*-test and Fisher's *F*-test.

Results. A long-term trend was a gradual but steady increase in the degree of host plant resistance of new maize hybrids to the pest during development of first generation [21]. So, if in 1994-1997, the average estimation of leaf feeding damage by the pest on a scale of 1-9 scores [25] for maize entries grown on 18 fields varied within 3-7 scores, with an average value of 5.4 score and 27.1% *Cv*, then in 2014-2018 in 14 entries it ranged from 2 to 5 scores, 3.2 score on average with a *Cv* of 34.9%.

1. Density of corn borer (*Ostrinia nubilalis* Hbn.) individuals of the first and second generations during observations (neighborhood of the village Botanika, Krasnodar Territory, 1994-2017)

Periods	Density		
	per 1 m^2		Per plant, M±SD
	M±SD	min-max	
	First generation		
O	32.81±30.70	2.87-133.60	6.31±5.95
L1	20.14±16.81	1.94-67.35	3.87±3.25
L2	4.24±4.00	0.09-17.07	0.82±0.78
P	2.52±2.66	0.05-12.22	0.48±0.52
A	1.62±1.62	0.04-6.90	0.31±0.33
FO	0.55±0.50	0.02-1.82	0.11±0.12
	Second generation		
O	108.77±107.22	4.92-408.45	20.92±20.66
L1	47.02±43.77	2.32-163.20	9.04±8.48
L2	17.56±16.13	1.17-57.77	3.38±3.12
P[a]	1.52±1.41	0.13-5.11	–
A[a]	0.97±1.08	0.10-4.11	–
FO[a]	0.17±0.15	0.01-0.59	–

N o t e. O — eggs, L1 and L2 — larvae emerged from eggs and larvae of III-V instars feeding on plants, respectively, P — pupae, A — imago, FO — ovipositing females, [a] — the next season after overwintering. Dashes mean that there were no corresponding plants on the field.

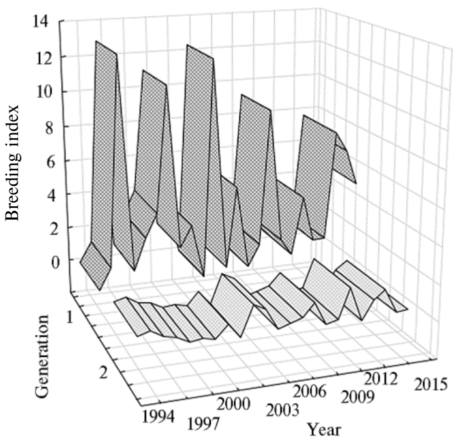

Fig. 1. Breeding index (I) of the corn borer (*Ostrinia nubilalis* Hbn.) of the first and second generations during observations (neighborhood of the village Botanika, Krasnodar Territory, 1994-2017).

Observations during 1994-2017 indicated a wide variation in the number of corn borers on maize, also fluctuations in the density of insects of the first and second generation significantly varied (Table 1). So, in the first generations, the density of eggs and larvae feeding on plants, as a rule, was significantly lower than in the second generations, while the densities of overwintered pupae, adults and egg-laying females were significantly higher, which was due to the additional mortality of insects of the second generations during harvesting, autumn and spring tillage, and overwintering (see Table 1). The insect breeding index also varied widely (Fig. 1): from 0.34 to 13.04 (an average of 4.24) for the first generation and from 0.02 to 1.85 (an average of 0.65) for the second generation. In other words, if in the first generation the corn borer usually increased in counts, then in the second generation it decreased.

Although the number of adult larvae (the harmful stages of corn borers) in the first generation is usually lower than in the second, the damage caused to plants by individuals of the first generation is usually significantly higher [26-28]. Thence the practical interest arises to analyze the dynamics of the pest abundance precisely for the first pest generation, when the abundance is subject to sharp fluctuations and the impact of meteorological factors on insect development during critical periods is quite expected [20].

Depending on the weather conditions of the year, the timing of certain stages of corn borers development shifted significantly. So, the time of the beginning of pupation among larvae from overwintered generation varied over a very wide range (from the first dates to the end of April). Oviposition by overwintered females, the beginning of which on mid-season maize genotypes (FAO 350-400) is confined to the phase of the middle leaf whorl (5-6 leaves), as a rule, began from decades I-III of May and ended in the middle June—early July with a peak in decade III of May—decade I of June. The development of the first generation larvae usually ended by the beginning of August, pupation of the main part of the population covered the period from early July to mid-August, the mass flight of the first generation adults occurred from mid-July to mid-August. Egg laying by first-generation females began on maize plants from the second half of July to mid-August with a peak in late July—early August. Almost every year, some of the second generation larvae (usually within 0-5%, up to a maximum of 30%) pupated, giving rise to individuals of the third generation. These larvae mostly died because of feed shortage and cold weather, therefore in the total mass of larvae ready for wintering, individuals of the third generation usually amounted to no more than 2.0% of those of the second generation with seasonal variations from 0 to 7.6%.

2. Statistically significant ($p < 0.05$) **correlations** (*r*) **between mortality of the first corn borer (*Ostrinia nubilalis* Hbn.) generation** (K effects) **and meteorological factors** (neighborhood of the village Botanika, Krasnodar Territory, 1994-2017)

Period	Mortality, K		
	eggs	I-II instar larvae	generation from egg to adult
	Air temperature, °C		
May, decade III	0.634		0.564
	Air humidity, %		
May, decade III	–0.568		–0.462
June, decade I	–0.542	–0.437	–0.590
	Precipitation, mm		
June, decade I	–0.435		–0.618

For 1994-2017, a correlation was analyzed of insect mortality (K effects) with average decadal values of air temperature, humidity and total precipitation for two periods (March—end of June and decade II of July—decade II of August) (Table 2).

3. Main statistical parameters of corn borer (*Ostrinia nubilalis* Hbn.) mortality (K effects) **during different stage of development as correlated to the mortality of a generation** (neighborhood of the village Botanika, Krasnodar Territory, 1994-2017)

Indicator	Mortality effects (K) during periods of development					
	generation from egg to adult	eggs	larvae		pupae	adults
			I-II instars	III-V instars		
M±SD	1.862±0.436	0.207±0.229	0.726±0.367	0.268±0.184	0.199±0.138	0,463±0,412
min-max	1.225-2.815	0.035-0.876	0.039-1.366	0.053-0.703	0.007-0.466	–0,173-1,505
Cv, %	23.42	110.96	50.55	68.64	69.39	89,08
r (correlation with mortality over generation)		0.70*	0.23	0.23	–0.09	0.39

* The value of the correlation coefficient is statistically significant ($p < 0.05$).

Significant correlations of the insect demography parameters with meteorological factors were found only in the interval from decade III of May to decade I of June, that is, when mass egg laying and larval hatching of the first generation occurred (see Table 2). Moreover, most often, a reliable relationship between meteorological factors and demographic indicators was found during egg development period. Correlation analysis indicates a significant negative effect of elevated air temperatures and the positive effect of moisture, both drop-liquid and water vapor, on egg survival (see Table 2). The effect of air humidity on the survival of younger larvae was less pronounced, and there was no statistically significant correlation at all between variation of meteorological factors and the survival rate of older larvae, pupae or adults.

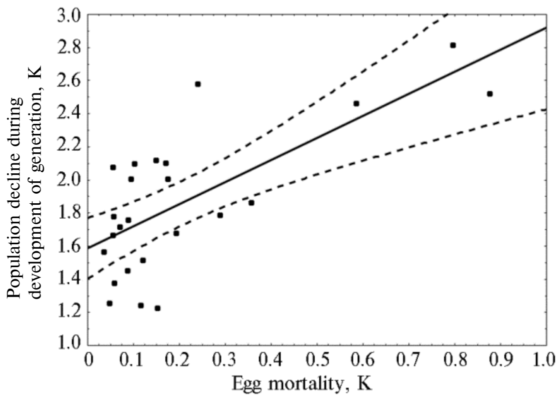

Fig. 2. The relationship between mortality (K effects) during egg development and from egg to adult of the first generations of corn borer (*Ostrinia nubilalis* Hbn.) per season (neighborhood of the village Botanika, Krasnodar Territory, 1994-2017).

The intra-stem lifestyle of the pest is undoubtedly one of the factors mitigating the weather impact on the viability of the insect. In the second critical period, that is, during the end of the development of the first generation and the beginning of the second one, we did not reveal reliable relationship of meteorological factors with the demographic indicators of the insect, probably, due to powerful stands with a microclimate favorable for insect reproduction, which maize plants form by this time [29]. In addition, in the second half of season, a pest population often is experiencing powerful press of parasitic insects [30], which could smooth the effects of meteorological factors. The results indicate that decade III of May—decade I of June can be deemed the only critical period in the development of the pest in the eastern part of the Krasnodar Territory. During this critical period, weather conditions had a strong effect on the development of eggs and, to a lesser extent, on the viability of hatched larvae. Correlation (Table 3) and regression (Fig. 2) analyzes indicate that egg mortality the most significantly contributes to the overall mortality of the first generation. This conclusion is quite obvious, since the role of a factor in the population dynamics is determined not so much by the factor intensity as by variability of its effect [24].

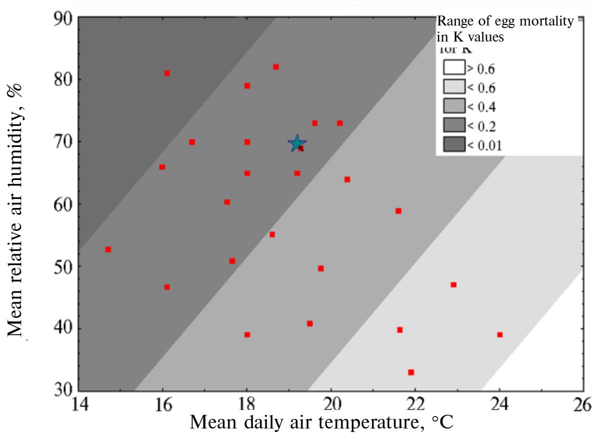

Fig. 3. 3D contour linear diagram of the relationship between egg mortality (K effects) **of the first generation of corn borer (*Ostrinia nubilalis* Hbn.) and meteorological conditions of decade III of May.** The actual air temperatures and humidity used to construct the diagram are indicated by red dots. An asterisk indicates a combination of the average daily air temperature of 19.3 °C and 70% relative humidity at which K = 0.093 (neighborhood of the village Botanika, Krasnodar Territory, 1994-2018).

The development of eggs during the first generation is important in terms of the dynamics of insect abundance. Thence a constructing 3D-contour linear model of K effects of pest mortality plotted vs. meteorological factors (average daily temperature and relative humidity in decade III of May) is of interest from the point of view of developing refined models for predicting the pest population. The provisional verification of the model with the use meteorological data and the demographic indicators of the pest for 2018 gave a positive result (Fig. 3).

In detail, the long-term dynamics of corn borer abundance was studied in North

America in Minnesota (USA) in 1948-1970 and in the Ontario province (Canada) in 1957-1965. The key factors in the dynamics of insect abundance in these regions were the portion of larvae pupating in summer (Minnesota) and capacity of females to realize their egg production (Ontario) [6]. Importantly, in both cases, a strict relationship was revealed between dynamics of the pest abundance and meteorological factors during critical periods of insect development. As for corn borer populations living in Europe, the dynamics of their abundance also significantly depends on abiotic factors, primarily temperature [31, 32]. It is known that temperature has a decisive effect on insect phenology, and this allows expectation of developing mathematical models to predict the timing of control measures against pests [33]. In addition, based on temperature dependences, models are developed that predict changes in the range and zones of damage of the corn borer, as well as its abundance under conditions of global climate warming [34]. In this context, our findings reveal additional aspects of causal relationships between fluctuations of weather and climate factors and the dynamics of insect abundance. The compilation of life tables allows researchers and practitioners to identify characteristic variation of pest abundance and the factors most significantly affecting pest population. Understanding how and why the number of living organisms changes in time and space is one of the most important tasks of theoretical and applied ecology [35, 36].

Thus, the key factors of corn borer population dynamics vary significantly depending on environmental conditions. In the eastern part of the Krasnodar Territory, the only biological factors affecting abundance of this pest, showing statistically confirmed relationship with meteorological factors, are the egg mortality and, to a lesser extent, the mortality of hatching larvae in the first generations of the season. The constructed contour diagram of first-generation corn borer egg mortality vs. average daily air temperature and relative air humidity over the last decade of May is of interest for improving technologies for short-term prediction of the pest reproduction in the Krasnodar Territory.

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