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Survival rate as a parameter of sustainability of the honey bee population and bee colonies

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Abstract. The results of studying the number of honey bees in colonies and the results determining and the evaluation the age-stage specific survival rates of bee colonies have been presented. The survival rate depends on the egg-laying of the queen bee, the period of the season, the level of development of bee colonies and reaches a minimum in all colonies in the period after the main honey collection S = 0.3-0.5. In the spring and autumn periods, there is a high negative correlation dependence (r=–0.7÷(–0.9), between the egg-laying of the queen bee (number of brood) and survival. The average survival rate in the spring and summer periods for strong families is 20-30% lower than in weak and medium families. The values of the survival rate in the spring and autumn periods for all types of bee colonies are more than one. This result is typical for bee colonies and is associated with the presence of wintering bees with a high life expectancy (up to 9 months) in colonies. A decrease in the survival rate in the period after the main honey flow to S<0.5-0.6 may be one of the factors in the colony collapse disorder (CCD) due to a violation of the gene expression mechanism in bees during the transition from hive activity to forager or to the autumn-winter period. A high survival rate determines the sustainability of the honey bee population, increasing the survival rate to one allows you to manage the vital activity of bee colonies, reduce the impact of various adverse factors on bees, reduce the risk of CCD, and manage the population of honey bees in ecosystems.

1. Introduction

Food security, sustainable agricultural development, restoration, conservation and protection of biodiversity are among the priority goals (purposes 2,15) of the 2030 Agenda for Sustainable Development [1], which, to a certain extent, can be achieved by the use of the ecological opportunities of pollinating insects and beekeeping. Intensive anthropogenic activity, violation of biodiversity, deterioration of environmental conditions leads to a decrease in the number of pollinating insects and especially honey bees (bee colonies), as a result of the colony collapse disorder (CCD). These factors lead to a decrease in the quality of ecosystem services as well as economic losses of agricultural producers [2-4]. The reduction in the number of pollinating insects and honey bees has a negative impact on the productivity of entomophilic plants, on the production of a significant amount of

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agricultural products, as well as on the biodiversity and sustainability of natural and agricultural biocenoses [2-5].

Changes in the number of honey bees (bee colonies), of sustainability its population largely depend on the conditions of their vital activity, which are determined by the production conditions of the apiary and the experience of the beekeeper [6], as well as environmental conditions within the bee colonies and biological, population characteristics of honey bees. One of the methods to determine the population sustainability is based on determining the survival rate. This indicator reveals the change in the population, including the insect population, throughout the life cycle of the species in their natural environment [7-8]. Understanding the systemic connections and factors that determine the vital activity of bee colonies and its survival, requires careful study of this issue. Accordingly, this study is important for understanding the mechanisms of resistance of the bee colonies depending on various factors.

2. Materials and methods

Assessment of changes in the number of honey bees in colonies is based on a logistic model of changes in the number of brood of hive and flight bees (forager), as well as the egg-laying of the queen bee. The data estimates the number of honey bees are given in many works, in particular [8-10]. The survival rate of insect populations, taking into account the various stages of their development - larvae, pupae, imago, is used to assess the dynamics and sustainability of the population. At the same time, an important element is the calculation of population survival tables based on the Leslie model. [7;11]. These models of population dynamics change were used in this work as a basis for determining and the evaluation of survival rate of honey bees in colonies.

The objects of research were bee colonies without swarming, which were divided into three groups according to the level of development: on "medium ", the number of bees in which is 1.5 kg by April 1 and May 1, 3 kg by July 1, 2 kg by September 1. On "strong" and "weak" bee colonies, the number of bees in which is significantly more or less compared to bee colonies with an average level of development. In bee colonies, the number of bees (excluding drones) and egg-laying of the queen bee (based on the calculation of the number of brood in colonies) were periodically determined.

It was taken into account that worker bees sequentially go through 4 stages of metamorphosis: egg and larva stages - 9 days, brood - 12 days, imago stage - up to 48 days. The life activity of bees in the imago stage is divided into two approximately equal periods. The first period is the stage of hive bees (perform intra-hive work). The second period is the stage of forager bees (collection of nectar, pollen, water) [8]. If we consider a bee colony at time t, then the total number of bees in the colony $N(t)$ is a set of individuals of different ages τ_1, τ_2, τ_3 ..., τ_n in various stages of metamorphosis j (τ depends linearly on t). At the same time, the number of individuals can be determined by individuals of a certain age x_n or by the stage of metamorphosis x_j. Considering that the number of individuals of the bee colonies at any given time depends on the egg-laying of the queen bee and for any previous period of time t-1, then the number of the first age class x_1 of the eggs stage (j=1) is completely determined by the egg-laying of the queen bee b_τ (egg/day) for the corresponding period of time (equation (1)):

$$x_1(t) = \sum_{\tau=1}^{\tau} b_\tau(t; N(t)) \tag{1}$$

At the next time point, during the observation period $t+1$, the dynamics of changes in the number of all subsequent age classes x_τ will be determined by the survival rate S_τ of individuals of the previous age class and the total number of the bee colony $N(t)$ and for all subsequent age groups (equation (2)):

$$x_\tau(t) = x_{\tau-1}(t) * S_\tau(t, N(t)) \tag{2}$$

The indicator S_τ (equation (2)) is the age-stage specific survival rate, which is determined by the age survival l_x of individuals in different stages of metamorphosis or the number of individuals of age τ in the j-th stage of metamorphosis that survived to the next stage of metamorphosis $j + 1$ and the corresponding age $\tau + 1$ (equation (3)):

$$S_\tau(t,x_j)=\frac{l(\tau+1;t+1;x_{j+1})}{l(\tau;t;x_j)} \tag{3}$$

It should be noted that the survival rate (equation (3)) is essentially a probability value that shows the chance of surviving an individual in a bee colony to a certain age. The obtained equations (1-3) characterize the spring-autumn period of life of a bee colony in the absence of diseases and swarming. During the winter period, the survival rate S_τ will be determined as the ratio of the number of bees of age τ that survived to the age of $\tau+\varphi$ until the spring of the next year. In this case, the survival rate corresponds to the empirical indicator of winter hardiness of bee colonies, determining the initial conditions of the system of equations (1) and the initial state of the bee colonies after wintering in the current year (equation (4)):

$$N(0,t)=x(0,t)=x_\tau(t-1)*S_{\tau+\varphi} \tag{4}$$

The initial state and the total number of the bee colonies in the current year $N(t)$ will be determined as the number of individuals of the age τ before wintering in the previous year t-1, who lived up to until time t (survived during wintering).

3. Results

The determining and the evaluation of survival rate the honey bee in the colonies according to the equations (1-4) based on the primary data on the egg-laying of the queen bee and the number of bees in colonies of different levels of development was performed with a step of one day (t=220 days). Table 1 presents egg-laying of the queen bee and age-stage specific survival rate data for selected discrete time periods. Table 2 presents the average values of the age-stage specific survival rate calculated for the entire sampled population (statistically) for a period of April-November, and for some periods of the season, as the average of a part of the sampling for the corresponding period.

Table 1. Egg-laying queen bees and age-stage specific survival rate the honey bees in colonies with different levels of development.

	"Weak" bee colonies		"Medium" bee colonies		"Strong" bee colonies	
	Egg-laying (b_t, egg/day)	Survival rate (S_τ)	Egg-laying (b_t, egg/day)	Survival rate (S_τ)	Egg-laying (b_t , egg/day)	Survival rate (S_τ)
24.04	83	8.09	571	8.58	1133	6.09
06.05	250	2.99	762	2.35	1286	2.73
18.05	750	1.78	1048	1.24	1638	1.78
12.06	1083	1.44	1157	0.93	2076	1.05
24.06	1143	1.09	1571	0.87	2204	0.86
06.07	1428	0.85	1714	0.88	2068	0.76
18.07	1142	0.71	1428	0.82	1724	0.72
12.08	643	0.61	333	0.51	516	0.54
24.08	357	0.40	286	0.39	439	0.47
06.09	143	0.34	238	0.39	367	0.49
18.09	71	0.37	95	0.43	145	0.56
12.10	0	0.60	0	1.01	0	0.93
24.10	0	0.91	0	1.88	0	1.43

The study of the survival rate for the honey bees in colonies based on empirical observations of changes in the number of colonies, in different periods of the season showed that the survival of a bee colony is an important indicator of its vital activity. It varies significantly and depends on many factors, including the number, age of individuals of the bee colonies and the time of the season. Thus, survival in the first stages of metamorphosis (eggs, larva and brood) depends on the number of bees and their ability to maintain optimal conditions for brood development (temperature, humidity, nest volume, feeding conditions, etc.), as well as on the presence of infectious and invasive brood diseases. At the next stage of metamorphosis – imago, when worker bees are engaged in hive activity work, the survival rate of steadily developing bee colonies (without swarming) weakly depends on internal and external factors, despite the presence of bee diseases. The survival rate of brood and hive bees has a maximum value, approaching unity. The survival rate of worker bees-foragers, occupied mainly by collecting nectar and pollen, is determined by the lifespan of forager and external conditions, primarily honey harvest conditions, the amount of collected nectar and pollen. Therefore, the last stage of the life of the honey bee will determine the overall survival rate for all stages of metamorphosis bees.

Table 2. Average survival rate the honey bees in colonies with different levels of development.

	Average age-stage specific survival rate bee colonies (S_τ)		
	"Weak" bee colonies	"Medium" bee colonies	"Strong" bee colonies
April-November	0.60	0.70	0.69
Spring period (until 01.06)	6.39	7.29	4.30
Summer period (until 01.09)	0.79	0.71	0.70
Autumn period (until 18.11)	1.97	2.89	2.04

An analysis of the survival rate for different (by level of development) bee colonies shows that for the active spring-autumn period, the highest survival rate was observed in bee colonies of average development (the difference is significant $p<0.001$). Medium colonies had the highest survival rate in spring, and in weak colonies it was higher than in strong colonies in this period (the difference is significant $p<0.001$). In spring period, the value of the survival rate of more than one indicates that the colonies have overwintered bees, whose life expectancy can reach 9 months. Analysis of the relationship between the number of brood in the colony and the survival rate in spring period shows a close negative correlation. For all colonies, it was within $r = -0.7 \div (-0.93)$, and the maximum was in strong colonies $r = -0.93$.

The value of the survival rate in summer period has a high positive correlation dependence on the amount of brood and is in the range $r = 0.79 \div 0.89$, that is, for families with any degree of development, an increase in the number of brood also increases the survival rate. But during this period, the value of the survival rate in weak colonies was significantly higher ($p<0.001$) then in medium and strong colonies, which did not differ. In all likelihood, this is due to the fact that in the middle of the summer period, weak colonies begin a period of intensive growth, while medium and strong colonies are in a period of accumulation of an excess of hive bees and partly in the phase of preparation for wintering. The minimum value of the survival rate in summer period for weak, medium and strong bee colonies of 0.34, 0.37 and 0.46 falls respectively on average in the third decade of August. The decrease in the survival rate to a minimum actually coincides with the death of bees wear and tear out during the collection and processing of nectar during the main honey flow.

In autumn period, before wintering, the survival rate is increased quite natural and, in principle, determines the survival rate of bee colonies during wintering. At this time, the survival rate has a close negative correlation with the number of brood, for all colonies about $r = -0.86$, which shows the negative impact of a large number of brood in autumn on the survival of bee colonies during wintering. In the autumn period, the survival rate in colonies with an average level of development was significantly higher ($p<0.001$) than in weak and strong colonies, which did not differ ($p<0.001$).

The results evaluation of the survival rate of bee colonies, the value of this indicator in different periods of the season, the relationship with the number of brood in colonies actually corresponds to the data of empirical observations of the vital activity of bee colonies in experimental apiaries and allows us to speak about the adequacy of the estimates obtained survival rate.

4. Discussion

The general processes of changes in survival rates and dynamics of the number of individuals in a bee colony, obtained on the basis of primary observations, showed that honey bees demonstrate survival of the second type with the actual absence of mortality of larvae, pupae and young bees and high mortality at older ages, which is consistent with the results obtained in [12]. The values of the survival rate in the spring, early summer and autumn periods turn out to be more than one, that is, conditionally, the number of adults turns out to be more than those born. This result, quite unique, is characteristic specifically of bee colonies: in spring period, the survival rate of more than one is observed in colonies during the alternation of generations and the gradual death of overwintered bees, the number of which does not depend on the egg-laying of the queen bee in the current spring period; in the autumn period before wintering, survival more than one is observed in colonies when both the egg-laying of the queen bee and the mortality of bees in the colony are close to zero, and there are bees in colonies that remain during wintering and whose age is significantly exceeds the average age of bees of earlier age groups. From the point of view of population ecology, the population of honey bees should be attributed to an intermediate special variety - a population of mixed type. In the spring and autumn period, honey bees have structure and the signs of a mixed-age population with overlapping generations. However, if we consider the life of a bee colony as a separate unit, then due to the fact that during the diapause of the queen bee, when the bee colony loses its structure of different ages, it fully corresponds to a seasonally breeding population with non-overlapping generations, for which survival will be determined by the results of wintering.

Analysis of changes in the survival rate of bee colonies reveals certain inconsistency. For example, the average survival rate of weak colonies in some periods of the active season is comparable to the survival rate of strong and middle colonies, and in the spring period is even higher than that of strong families. The survival rate of middle colonies is always higher than the survival rate of strong colonies. The high negative correlation is observed between the egg-laying of the queen bee (the number of brood) and survival rate in spring and autumn periods (r=–0.7÷(–0.9)) and is shows that the more brood in the bee colony in spring and autumn, the lower its survival rate. Accordingly, the low average survival rate for strong colonies in spring period is associated with a large number of brood, which was 2-5 times more than in weak colonies. At the same time, in weak bee colonies, with a low number of brood in spring, the survival rate was relatively high. A natural question arises, why is the survival rate of strong colonies in the spring and summer periods 20-30% lower than in weak colonies? Strong colonies in terms of the level of development, the number of bees in which can reach 5-6 kg, as a rule, is a product of the impact of modern technological methods in the apiary. Strong bee colonies are beneficial in terms of getting more honey, from the point of view of beekeeping technology, but, in terms of the obtained data, strong colonies have a lower survival potential as an object of the population compared to medium and weak colonies at certain periods of life.

In summer, already a high positive correlation is observed between the egg-lying of the queen bee (the number of brood) and survival rate. However, in the period after the main honey harvest, when there is a decrease in the number of bees in bee colonies as a result of the death of older age groups of forager bees wear and tear out during the collection and processing of nectar, there is a sharp decrease in survival to the level of S_τ=0.3-0.4. The survival rate of strong colonies was higher than that of middle and weak ones in the period from the end of August to the beginning of September. But the survival rate of colonies with different levels of development in the period after the main honey flow was 30-40% less than in the spring and early summer periods (before the main honey flow).

Specific lifestyle changes after the main honey flow occur in the vital activity of honey bees. They are accompanied by changes in the work of genes (gene expression), which are characterized by changes in the physiology of bees and, in particular, an increase in fat content, a decrease in the amount of water in the body of bees and an increase in overall life expectancy [12,13]. Accordingly, if the mechanism of gene expression fails in the bee colony due to any external environmental factors or internal genetic or biotic factors against the background of a decrease in the survival rate, and individuals of the bee colony for some reason are unable to switch to a new way of life - to the autumn-winter dormant period, perhaps even more ancient evolutionary survival mechanism is activated - the colony collapse disorder occurs - majority of worker bees disappear from the nest (hive). For example, a fall in the population of a hive below the threshold of viability and a rapid disintegration of the colony is possible with an increase in the proportion of diseased bees in the colony [14]. Another example is the Alli effect, which determines the critical minimum size of the number of imago bees, below which mortality exceeds replenishment, which leads to a loss of viability of the colony and to CCD [15].

A sharp decrease in the survival rate in the summer period, and especially after the main honey flow to the value of S_τ<0.5-0.6 is one of the probable reasons of CCD. The obtained results are in good consistency and confirm data obtained and the data of the Alli effect [14,15]. Quite a few factors can be identified that have an impact on the decrease in the survival rate of bee colonies and can lead to a disruption in the process of gene expression, in particular, to CCD. A decrease in the number of forager bees as a result of diseases, including the invasion of the *Varroa destructor* mite, viral diseases [15], or pesticide poisoning [14] include these factors. At that, hive bees must rebuild their way of life – from hive activity to outside hive activity, to the autumn-winter dormancy period, but with a drop in the survival rate and a violation of the mechanisms of gene expression, it leads to CCD. A high level of survival rate close to one characterizes a relatively high resistance of honey bees to various external and internal factors, and to increase the survival rate requires the creation of favorable living conditions for colonies – absence of drastic decline numbers in honey bees in colonies as a result of diseases, absence of poisoning of bees with pesticides, absence of wear and tear of bees on the collection of nectar and pollen in August-early September. the data obtained and the data of the Alli effect confirm this

5. Conclusion

The study and evaluation of the survival rate of honey bees in colonies showed that the survival rate is largely determined by the period of the season, the egg-laying of the queen bee and the level of development of bee colonies, which have the signs of both of the mixed-age population with overlapping generations and of the seasonally reproducing population with non-overlapping generations. A high negative correlation between the egg-laying of the queen bee (number of brood) and the survival of colonies in spring and autumn periods determines the lower potential for survival in these periods for strong colonies. During the active season, there are significant fluctuations in the survival rate, which reaches a minimum in the period after the main honey flow. The low values of the survival rate during this period may be one of the factors that disrupt the mechanism of gene expression in bees during the transition from of bees hive to outside hive activity or to the autumn-winter dormant period, and the colony collapse disorder. A high level of survival rate close to one characterizes the relatively high resistance of honey bees to various external and internal factors, and requires the creation of favorable conditions for the life of colonies, without a sharp fluctuation in numbers. Respectively, an increase in the survival rate allows us to strengthen the of sustainability of the honey bee population, the vital activity of bee colonies, reduce the risks of CCD, manage the population of honey bees in ecosystems.

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