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Forecasting Bio-economic Effects in the Milk Production based on the Potential of Animals for Productivity and Viability

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A B S T R A C T

The most important biological factors, mainly determining the economic efficiency of milk production, are the productivity potential and the level of viability of cows. The aim of the work is to predict the bio-economic effects in a heterogeneous population of dairy cows taking into account the decrease in the length of productive life with increase in milk productivity. In the considered model situation, with an increase in the productivity of cows, the total profit per cow per year increases, while the profitability of production may decline. The developed algorithms are supposed to be used for solving the problems of optimizing the management of the dairy cow herd and planning technological development in animal husbandry.

1. Introduction

Used abbreviations and terms: PL is length of productive life (the number of consecutive lactations of 305 days each); PP is the potential of productivity, VP is the viability potential, CR is constitutive resistance, dry period is the period from the end of lactation to calving; calving period is lactation period + dry period.

Due to the reduction in the total size of dairy cattle population, the rate of decline in milk production in the Russian Federation is not compensated by a positive trend of increasing the average productivity of cows. The use of imported breeding material on a large scale and the use of intensive industrial technologies in milk production are accompanied by a decrease in the level of biodiversity, an increase in "productivity diseases", a decline in reproduction, a deterioration in the quality and safety of the products obtained. Similar problems in the field of dairy cattle husbandry have arisen in recent decades in other countries, since the high productivity of cows is often associated with an increased frequency of culling. [1, 2]. Therefore, to ensure profitability and overall sustainability of milk production, it is necessary to intensify research in the field of biology of the viability and productive longevity of cows [2 - 4]. It is necessary to search for biological traits and technical tools for the collection and transmission of information for early prediction of the health status of lactating cows at the earliest possible stages of postnatal life [2, 3].

Previously, it was shown that for early assessment and prediction of viability in groups of dairy cows, the trait of constitutive resistance can be used as an integral indicator reflecting the effects of age-related decline in protective forces [5], as well as the reciprocal of the rate of cows culling in first lactation. An analysis of empirical data reveals the presence of heterogeneity in terms of survival parameters in populations of various animal and human species. The data from bio-medical studies show that the patterns of mortality in a population considered as one whole may differ significantly from the mortality frequencies in the constituent subpopulations [6, 7]. There are data indicating the heterogeneity of dairy cattle populations on survival parameters [8, 9]. In the context of the stated approach, the main factors determining the lifetime productivity of cows are PP and VP. Age dynamics of milk production in groups of cows with different PL is determined by a specific combination of these factors.

From the viewpoint of planning the development of the dairy industry, it is important to have methodological tools for a comprehensive assessment and forecasting the influence of the most critical factors in the selection, reproduction and housing condition of dairy livestock. In this paper, as a starting point in this direction, we propose a pilot model for predicting bio-economic effects when varying a set of factors, including milk

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production potential and the rates of disposal of the herd in a heterogeneous population of dairy cows. When setting the initial data, an empirically fact of a decrease in PL with increasing milk production was taken into account, especially pronounced in highly productive cows.

The aim of this work is the systematization of previously identified empirical patterns and the development of a pilot numerical model for predicting the bio-economic effects in a dairy cows population which is non uniform in terms of PP and VP.

2. Determination of The Numerical Values of Parameters using Empirical Data

2.1. Milk Production Potential

To estimate the potential of milk production in the *i*-th homogeneous group, cumulative 305 d milk yield data are used for consecutive lactations, $y_{mi}(t)$, ranging from 4 ($t = 4$) to the last completed lactation t_{imax}. Age dynamics of 305 d milk yield is described by a three-component multiplicative function

$$y_{mi}=A_i \times \exp(-\exp(-bt))\times D^t{}_i \quad (1)$$

in which A_i is a potential maximum lactation yield (productivity potential, PP), the exp(-exp(-bt)) function describes an age-dependent increase in the ability to form milk with a gradual reaching a plateau level, the function D^t (constitutive resistance, CR, D<1) describes an age-related decrease in the ability to maintain lactation activity in the *i*-th group. The maximum yield is always less than *A* by an amount depending on the rate of decline of the CR. At small values of *D*, the peak of milk yield for lactation occurs earlier and the cows drop out of the herd more quickly.

Earlier, when analyzing empirical data on cows of the Kholmogor and Black-and-White breeds, a linear positive relationship was found between PL, expressed by the number of last lactations t_{imax}, and the value of D_i in groups [5]. Thus, the value of D has the meaning of viability potential (VP), estimated from the age dynamics of 305 d yields in groups. The value of the parameter b in the second component of formula (1) varies within small limits (0.4–0.5) and for proximate calculations it was assumed to be 0.45.

2.2. Potential of Viability

The presence of a positive relationship between PL and the "initial" value of the CR in the analysis of the age dynamics of milk yield agrees qualitatively with the identified relationship between PL and the viability index estimated from the dynamics of cows leaving the head (culling by sum of reasons). Culling rate is described by the Gompertz function:

$$y_c(t)=\Delta S(t)/(S(t)\times\Delta t)=B\times\exp(ct) \quad (2)$$

where $S(t)$ is the cohort size at the moment of time *t*, $\Delta S(t)$ is the reduction of the cohort size for the period of time Δt. For lactating cows, time is usually expressed as the number of the current lactation and $\Delta t = 1$. Parameters *B* and *c* can be determined not in cohorts (in groups of animals born during the same period of time), but according to the data of age structure of the herd (cross-sectional study).

The mean PL (*T*, the average number of lactations in a cohort) can be estimated from empirical data using an analytical expression [10]:

$$T=\exp(B/c)\times\mathrm{Ei}(B/c)/c \quad (3)$$

where Ei(.) is a special function (integral exponent).

For use in zootechnic practice, we can use the truncated Gompertz distribution, which does not take into account a small number of longevity record holders. Our numerical simulation showed that in the range of values $B = 0.04–0.3$, $c = 0.2–0.8$, the maximum PL value is approximately 2 times larger than the average PL i.e. $t_{max} \approx 2T$ or $T = t_{max}/2$ [8].

The value of the initial rate of disposal y_{c1} in formula (2) means the difference between the number of cows in the first and second lactation divided by their number in the first lactation. When analyzing production data on the age structure of the dairy herd, in particular, on five breeds of the USA and on eight farms of the Leningrad region, the existence of a positive linear dependence of T on the value of $1/y_{c1}$ was revealed [5]. Therefore, the value of $1/y_{c1}$ has the meaning of predictor of longevity, as measured by the dynamics of the disposal of cows from the population, herd or cohort [8].

The function, inverse to the intensity of disposal, is characterized by a decrease in the viability with age ("resistance to mortality" according to Gompertz). Thus, at t = 1, the "initial" disposal intensity $y_{c1} = B\,e^c$ is determined, and the reciprocal, $1/y_{c1} = B^{-1}\,e^{-c}$, has the meaning of the initial viability level.

3. Forecasting Milk Production Efficiency

3.1. Baseline Data for The Forecast

In the model situations under consideration, there are four groups with consecutive values *A* = 24, 20, 16, 12 thousand kg (the average for the lifetime milk yield is 12.4; 11.0; 9.35; 7.64 thousand kg); *T* = 2, 3, 4. 5 (t_{max} = 4, 6, 8, 10 lactations); *D* = 0.95; 0.91; 0.89, 0.88. An additional list of source data may include a large number of indicators. In this case, this list includes the calving period 13 months and the main cost indicators, including feed costs, the price of sold milk and culled cows (delivery at a meat processing plant, utilization of carcasses of sick cows, etc.).

3.2. Intermediate Calculations and Target Forecast

The initial data for each group are calculated:
- the average lifetime cumulative 305 d milk yield over 10 completed lactations (y_m);
- the number of replacements of the culled cow on the heifer for the total number of 10 lactations (*Nr = 10/T*);
- calendar term corresponding to 10 lactations (years);
- revenue from sold milk over 10 lactations with price of 30 rubles per 1 kg of milk, thousand rubles (milk income, *m.inc = 30 × ym*);
- revenue from sold culled cow over 10 lactations, thousand rubles (realization income, *real.inc = cow price × Nr*);
- total revenue, thousand rubles (*income, inc = inc.m+ real.inc*);

- the average price of grown or purchased heifers, thousand rubles (heifer cost, *Hc*);
- the cost of growing or purchasing heifers, thousand rubles (reproduction expenses, *repr.exp.* = *Hc* × *Nr*);
- the cost of maintenance and technological spending per cow for the whole period, thousand rubles (technological expenses, *t.exp.* = *12 × year*);
- feed costs for milk production per 10 lactations, thousand rubles (feed expenses, *f.exp = 0.6 × inc.m*);
- the sum of expenses, thousand rubles (*s.exp = repr.exp + t.exp + f.exp*);
- profit, thousand rubles (income over expenses, *IOE = inc.);*
- profitability (% rentability, *rent*).

The adopted forecasting scheme assumes a certain method of combining in the same algorithm two heterogeneous data, i.e. the age dynamics of productivity and the longevity of cows. In the literature, there is no description of such an algorithm, and there are also no systematic empirical data necessary for detailed analysis. The simplified calculation method used in this work for ten 305 d lactations at one value of calving interval is as follows. Since the average daily milk yield values are used in groups, to obtain a forecast of the calendar period for 10 lactations per cow place, you can use the above ratio $T = t_{max}/2$. For example, at $T = 5$ it is necessary to have two periods, i.e. 2 cows with 5 lactations and 4 dry periods (100 months of lactation, 24 months of dry period). At the same time, in the case of culling, a new primiparous cow is transferred to this place, one period of dry period is missed, and the total calendar period for which the cost of one cow per year is calculated for this group is 10.3 years. For the next three groups, these values are 10, 9.9, 9.5.

4. Results and discussion

The results of calculating the profitability of milk production for 4 model groups (subpopulations) with different values of the productivity potential, the average PL, the cost of raising or importing young stock and the main technological costs with an interval of 13 months are given in Table 1 and Figure 1 and Figure 2.

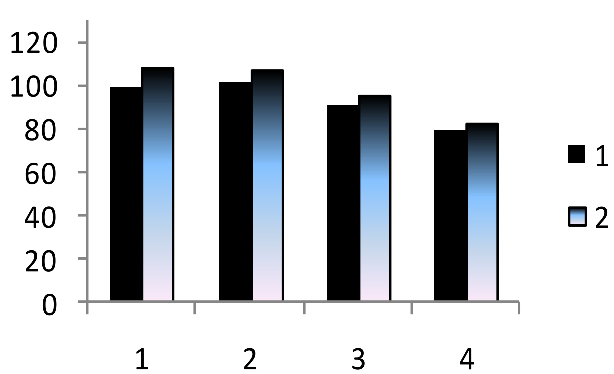

Figure. 1. Total profit per cow per year in the production of milk in four groups of cows with the values of the parameters listed in Table. In groups 1, 2, 3, 4, the average milk yield per life is 12.4; 11.0 9, 35, 7.64 thousand kg.; the calving period is 13 months. The average price of a culled cow sold in option 1 is 10, in option 2 it is 30 thousand rubles.

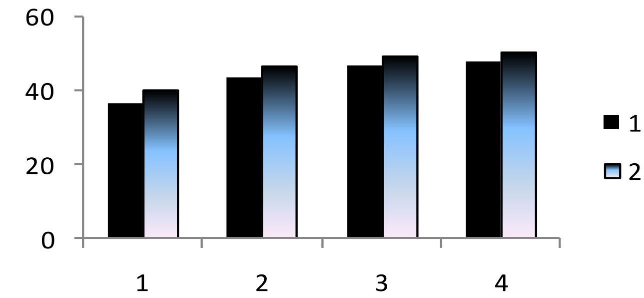

Figure. 2. Profitability of dairy raw materials production (revenue per milk and from sale of culled cows / sum of expenses) in four groups of cows with the values of the parameters listed in Table. In groups 1, 2, 3, 4, the average milk yield per life is 12.4; 11.0; 9.35; 7.64 thousand kg.; the calving period is 13 months. The average price of a culled cow sold in option 1 is 10, in option 2 it is 30 thousand rubles.

In the considered model situation, with an increase in the productivity of cows, the total profit per cow per year increases, while the rentability of production decreases.

To predict bio-economic effects in real conditions (including in terms of long-term planning), it is necessary to take into account the variability of interrelations and a wide range of possible values of parameters. In this work, seven factors were considered, the numerical value of which can vary widely, which is the case for different regions of the Russian Federation. At the same time, four gradations of two factors (level of productivity and viability index) were taken into account with two levels of one additional factor. At this stage of the study, the operability of the formulated concept and the pilot prediction model were tested. With a positive assessment of the results of the first stage, the expansion of the empirical base becomes urgent, i.e. obtaining a sufficient amount of production data while improving the calculation algorithm.

In the extended version of the model, additional indicators may be introduced into the calculations, including the reproduction parameters of the dairy herd. Since, at high levels of milk production, there is a shortage of the young animals number, to preserve the livestock population size the complex methods are developed (separation of bull-sires semen, induction of superovulation, *in vitro* fertilization, transplantation and embryo cloning), which increase the cost of reproduction of the dairy herd. To provide enhanced herds reproduction, the choice of the most appropriate method depends largely on the conditions of the territorial distribution of specific farms, as the initial data in the forecasting can vary greatly for small farms in the regions and for large industrial complexes with intensive technologies located near large urban agglomerations. Therefore, in order to rationalize management decisions, multivariate model calculations are required.

Researchers working in the field of studying the dynamics of human populations have identified the need to identify subpopulations in order to correctly predict demographic processes [11, 12]. In the process of breeding work in animal husbandry, similar problems arise, since an early assessment of the breeding value of parents for productive longevity of offspring is important. For bull-sires, one of the options for such an assessment may be

Table. Baseline data and results of the prediction of the bioeconomic efficiency of milk production in groups that differ in productivity potential (A) and viability (D).

D	*T*	*A*	*ym*	*Nr*	*Hc*	*years*	*repr.*	*t.exp.*	*inc.m*	*s.exp./year*	*inc./year*	*rent.*
0,95	2	24	124	5	80	10,3	400	124	969,2	268	98,9	37
0,91	3	20	110	3,3	65	10	214	120	980,7	231	101,4	44
0,89	4	16	93,5	2,5	50	9,9	125	119	878,2	195	91,2	47
0,88	5	12	76,4	2	35	9,5	70	114	732,8	164	79,2	48

Notes: notations are given in the section 3.2.

the inverse of the rate of disposal in first lactation, measured in a group of daughters [13]. When using the latest genomic, bioinformatics and telecommunication technologies, there are ample opportunities for solving such problems. The use of microelectronic sensors and wireless communication allows to increase the amount of information captured during screening surveys throughout the animal's life, which can dramatically increase the possibilities for monitoring and forecasting multifactorial bio-economic effects.

At this stage, it is important to compare the initial prerequisites of our calculations with known ideas and concepts related to the problems of populations viability. The concept of constitutive resistance as the main determinant of productive animal longevity, used in this work, is in many ways consistent with the concepts of creod according to Waddington [14] and primal health of Odent [15]. There is evidence that metabolic diseases occurring in later life may arise *in utero* as a result of suboptimal intrauterine conditions. The process by which prenatal defects lead to permanent changes in tissue structure and function, and finally to low birthweight, is known as developmental programming; i.e. placental insufficiency invariably affects embryonic development and health in later life [16]. So, the level of viability in heifers is being formed epigenetically in the prenatal and postnatal periods when exposed to internal and external factors. Our data indicate that the value of cow PL depends on the “initial” level of viability indicators (at the beginning of the reproductive period). The existence of this dependence is indicated by empirical data and, as carried out by calculations, a similar relationship follows from the general properties of the Gompertz function, traditionally used in analyzing the survival of populations.

5. Conclusion

The most important biological factors, mainly determining the economic efficiency of milk production in dairy farms, are the productivity potential and the level of cow viability formed to the age of reproductive activity. The length of the productive life of cows largely depends on the initial level of viability indicators. Currently, the average group potential levels of productivity and viability can be determined from indirect information – the data of age dynamics of 305 d milk yields and intensity of cows culling in first lactation.

From the viewpoint of planning the development of the dairy industry, it is important to have methodological tools to predict the influence of the most critical factors in the selection, reproduction and housing condition of dairy livestock. In this paper, we tested the operability of the general approach and the algorithm of numerical simulation using discrete scales and data approximation by the Gompertz function. The results showed that in the considered model situation, with the increase of the average of lifetime milk yield, the total profit per cow per year increases, while the profitability may decline. According to the authors, there is reason to assume that the identified consistent patterns reflect a general trend, at least in a qualitative sense, since empirically established facts and regularities are taken into account in the set of initial data.

After expanding the volume of empirical data, setting parameters and modification of algorithm taking into account the features of real objects, the proposed forecasting model is supposed to be used to optimize the herd management and forecast scientific and technological development in dairy cattle husbandry.

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