Theory of the Growth of Silkworm Larvae and Its Application

By SATORU UEDA

Sericulture Division, Sericultural Experiment Station
(Yatabe, Ibaraki, 305 Japan)

In the past, when the cause for unstable cocoon production was not known, the silkworm rearing technique was that centered on foods, with less relationship to growth of silkworm. However, after cytoplasmic polyhedrosis and infectious flacherie were discovered in 1952 and 1960, respectively, and method of controlling flacherie, the greatest cause of unstable cocoon production, was established in 1957–1962, the silkworm rearing technique has undergone a great change from the food-centered system of rearing technique to the new system based on the growth of silkworm used as an index, resulting in a marked progress in labor-saving.

Needless to say, the growth expresses a composite result of various physiological activities of organisms, and is the basis of matter production and hence agricultural production. Growth is the accumulation of the matter, as a result of balance between assimilation and dissimilation, and in which complicated physiological phenomena are involved.

Recent remarkable progress in silkworm physiology, especially nutrition physiology by the use of artificial diets, and insect hormone studies, has gradually clarified factors pertaining to the growth. However, physiological knowledges so far obtained have succeeded in clarifying only fragmental aspects of growth, by analysis of growth mechanism, but are not sufficient to make prediction how much growth can be attained with given conditions. In other words, there are difficulties, still now, in directly linking physiological facts to agricultural production. An immediate need for agricultural scientists is not individual physiological phenomena but rules governing matter accumulation.

Growth of silkworm

Although it is said that there are more than 200 different growth curves of organism, a representative growth curve for multi-cellular organisms is the Robertson curve[9]:

$$\log \frac{x}{A-x} = k\,(t-t_o) \quad \cdots\cdots (1)$$

where x: growth quantity
A: maximum growth quantity
t: time
t_o: time at $A/2$
k: constant

This curve, which originally expresses monomolecular autocatalysis in chemical reaction, is known to fit the growth of silkworm body weight and silkgland weight. However, this curve has been applied to silkworm only by rote, without any biological implications. On the basis of the fact that growth is the accumulation of matter resulted from the balance of accounts between assimilation and dissimilation, Ueda and Suzuki (1967)[4] derived a logistic curve[8], by giving biological and mathematical considerations, as shown below:

$$w = \frac{A}{1+C\,\exp(-kt)} = \frac{A}{1+\exp\{-(\lambda+kt)\}} \quad \cdots\cdots (2)$$

where w: growth quantity
t: time
C, λ, k: constants

In this equation, the parameters A and k have a meaning as shown in Fig. 1. The above two equations, (1) and (2), are different in the formulation, but they are same mathematically each other.

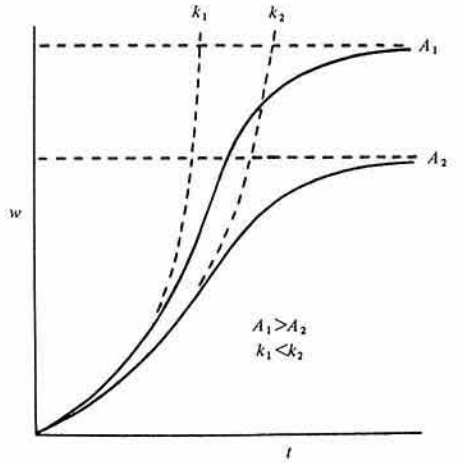

Fig. 1. Logistic curve expressing growth of silkworm.
A_1, A_2, k_1, k_2, t, and w: see the quation (2) in the text.

Growth curve is an expression of final product, but how is the process reaching the final product, i.e., relation between growth and food ingestion and digestibility, will be shown below:

Digestibility is influenced by accumulative amount of food ingested at each instar: the greater the latter, the lower is the former. Namely, at a given instar, the digestibility becomes lower at the later period of the instar when accumulative amount of ingested food increases. Similarly, the digestibility is decreased at an advanced instar which shows greater accumulative amount of ingested food.

Rate of digested food remained in the larval body was lowest, about 40%, at the 1st instar, and it increased with the advance of instar, showing the highest rate, about 65% at the 5th instar. This difference in the rate is caused by the fact that a part of digested food is consumed as energy required for maintenance and movement, and the younger the instar the higher is the rate of consumption.

Relative growth[6] in body weight and silkgland weight at the 5th instar is hardly effected by silkworm varieties and rearing conditions, and can be expressed as follows, irrespective of percentage of cocoon shell weight:

$$y=bx^{2.0} \quad \cdots\cdots (3)$$

where x: body weight (dry weight)
y: silkgland weight (dry weight)
b: constant

Namely, the silkgland weight increases in proportion to square of body weight. Accordingly, to increase weight and percentage of cocoon shell, it is necessary to get a heavy body weight at the 5th instar by increasing ingested food. A longer duration of the 5th instar may also be a contributing factor.

Growth and silkworm rearing technique

As to the method of assessing food value of mulberry leaves, many attempts have been made by the use of physical and chemical procedures. At present, the bioassay, in which mulberry leaves are actually ingested and resultant growth is assessed, is regarded to be most reliable. There are two typical methods, the one which utilizes molting ratio[3] as a criterion, and the other which measures growth of silkworm fed with artificial diet[1]. In the former, food intake is limited only for 1–2 hr every day or for 60–70% of food intake period of each instar, and such limited supply of food induces molting without further supply of food. Attainment to the critical point of molting varies with quality of mulberry leaves supplied. Use of newly hatched larvae for this test gives most stable results. In the latter method of bioassay, mulberry leaves dried, pulverized, and added to artificial diet are used, and differences in feeding value of the leaves cause differences in growth, development and survival of test larvae.

Effect of nutrition and rearing environment[5] at larval stage on quantitative characters of silkworm is expressed most remarkably for silk substance production, followed by body weight growth and number of eggs laid in that order, while it is hardly expressed for weight of individual eggs, ratio of normal eggs per moth, and rate of survival, especially the latter two. In other words, allowable range of rearing condition is wide for survival, relatively narrow for growth and further narrow for silk poduction.

Of microclimatic factors, temperature is most effective on growth. Body temperature changes with air temperature of rearing room, and is influenced by air current and humidity. As shown in Fig. 2, body temperature is

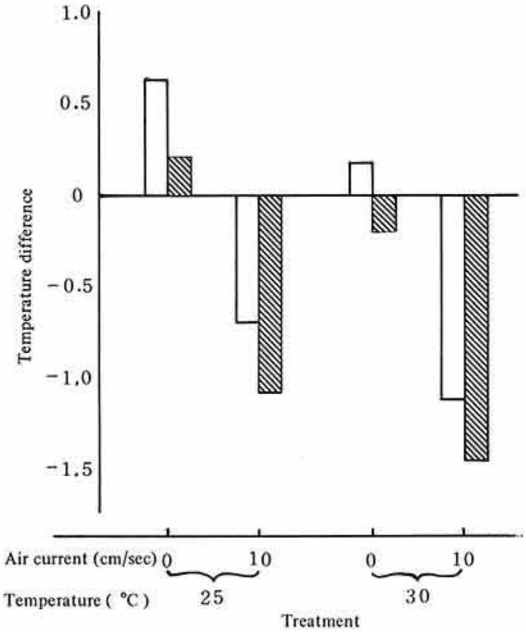

Fig. 2. Effects of room temperature and air current upon the temperature of rearing seat or of larval-body.
Temperature difference: Difference between room temperature and rearing seat or larval-body temperature (°C)
□ : Larval body (fifth instar)
▨ : Rearing seat

higher than air temperature by less than 1.0°C without air current, but it lowers below air temperature with air current[2]: about 1°C lower than air temperature even with an air current of about 10 cm/sec. Effect of humidity is small as compared to that of air current, but body temperature increases, though slightly, when humidity is high. These phenomena can be applied to the rearing technique. Temperature higher than 30°C inhibits silkworm growth, especially at the 5th instar, as the optimum temperature of rearing is 20–28°C. At that temperature, effect of air current in lowering body temperature gives a large influence on the growth, so that supply of air current at a rate not causing serious wilting of mulberry leaves is very effective. On the other hand, temperature lower than 20°C causes delayed growth. As the countermeasures for that, the rearing seat is covered with damp-proof paper, etc., to raise body temperature by natural heat generated from the rearing seat, and also by the effect of no air current, though its effect is only small. However, the covering for a whole day causes adverse effects due to accumulated carbondioxide, etc. so that it is desirable to remove the covering for 1 hr prior to the supply of mulberry leaves.

Changes in body water content associated with growth[4], given in Fig. 3, show characteristic patterns at the 1st and 5th instars. The lowest water content in the newly hatched larvae continues to increase after feeding, up to the first molting stage. At the 2nd to 4th instar, the water content remains almost constant, but at the 5th instar it decreases from the highest content in newly exuviated larvae to the lowest content in mature larvae. In other words, the 1st instar larva requires physiologically much water, and accumulates water at a higher content than water content of ingested mulberry leaves. On the contrary, the 5th instar is a stage which requires to release water to a level lower than the water content of mulberry leaves. High humidity for the 1st instar and low humidity with air current for the 5th instar are regarded suitable for the rearing, because mulberry leaves supplied at the early instar are apt to wilt, while large quantities of food ingested and of silkworm feces at the 5th instar spoil the air. In addition, such humidity management is quite reasonable from the physiological water requirement of silkworm.

Reelability of cocoons is effected by vari-

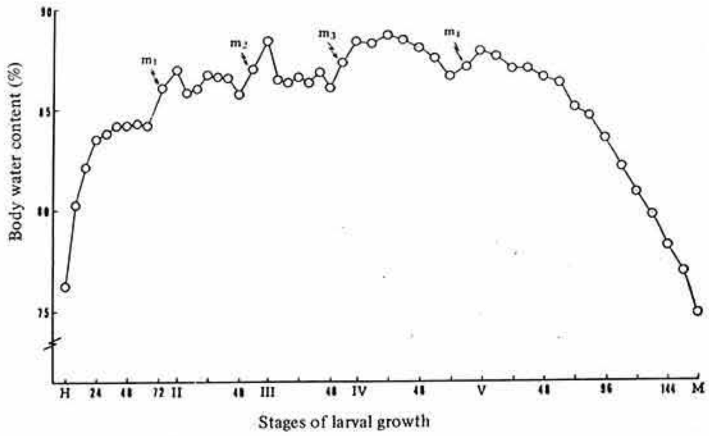

Fig. 3. Changes in body water content as related to growth stages
Roman numerals indicate instars
Arabic numerals indicate time (in hr) in each instar.
H: Newly hatched larva
M: Mature larva
m_1, m_2, m_3 and m_4: molting stages
Water contents in mulberry leaves supplied were always about 78%

ous conditions during cocooning, especially humidity is most influencial. Amount of water released during 3 days before the end of silk spinning of silkworm is 2.6–2.7 g and 2.3–2.4 g for one female and male respectively.[2] Of this large quantity of water, about 30% is excreted by urine and feces, and the balance is released by hardening of liquid silk. As the latter is evolved in the form of vapor, it makes mounting room wet.

Larval density in rearing was relatively low in the past food-centered rearing system with emphasis on silkworm nutrition. However, the larval density has been re-examined[7] on the basis of larval growth used as a criterion, in view of the need for increasing efficiency of investments which are required for modernization of rearing facilities, and for increasing labor-productivity. Thus, it was found that the larval density higher than the traditional one, as shown in Table 1, can be adopted under the full prevention of silkworm epidemics. The larval density which allows normal growth of larvae at each instar is that the "body length × body width" occupies 70–72% of the rearing seat area. Beyond that density, larval growth is retarded. The high density results in a reduced amount of supply of mulberry leaves, and hence it is economical.

Table 1. Maximum rearing density in each instar, in the shelf rearing

Instar	Max. rearing density (A)	Usual rearing density (B)	(A)/(B)
1	12200	2500	4.9
2	3200	1250	2.6
3	1250	625	2.0
4	400	160	2.5
5	110	80	1.4

(Number of larvae per 0.1 m^2 of rearing seat)

References

1) Ito, T. & Arai, N.: Food values of mulberry leaves for the silkworm, *Bombyx mori* L., determind by means of artificial diets. I. Relationship between kinds of mulberry leaves and larval growth. *Bull. Seric. Exp. Sta.*, 18, 209–229 (1963) [In Japanese with English summary].
2) Takahashi, S.: Chronological change in the content of body water in the fifth inster larvae of silkworm, *Bombyx mori* L. *Sansi-Kenkyu*, 117, *J. Seric. Sci. Japan*, 50, 453–

456 (1981) [In Japanese].
3) Takeuchi, Y.: Studies on the effect of nutrition on the molting in the silkworm (*Bombyx mori* L.). II. Analysis of various factors concerning the judgement of nutritive value of mulberry leaf by the means of molting ratio of silkworm fed with the leaf concerned. *Bull. Seric. Exp. Sta.*, 17, 53–89 (1961) [In Japanese with English summary].
4) Ueda, S. & Suzuki, K.: Studies on the silkworm, *Bombyx mori* L. I. Chronological change of the amount of food ingested, body weight and water content of body, and their mutual relationships. *Bull. Seric. Exp. Sta.*, 22, 33–74 (1967) [In Japanese with English summary].
5) Ueda, S., Kimura, R. & Suzuki, K.: Studies on the growth of the silkworm, *Bombyx mori* L. II. The influence of the rearing condition upon larval growth, productivity of silk substance and eggs, and boil-off loss in the cocoon shell. *Bull. Seric. Exp. Sta.*, 23, 255–293 (1969) [In Japanese with English summary].
6) Ueda, S., Kimura, R. & Suzuki, K.: Studies on the growth of the silkworm, *Bombyx mori* L. III. Relative increase in body weight and silkgland weight in the fifth instar larvae. *Bull. Seric. Exp. Sta.*, 25, 1–20 (1971) [In Japanese with English summary].
7) Ueda, S. & Suzuki, K.: Estimation of the maximum rearing density which has no bad influence on the growth of silkworm larvae, *Bombyx mori* L. *J. Seric. Sci. Japan*, 44, 259–266 (1975) [In Japanese].
8) Ueda, S.: Fitting of the growth curve. In "Ôyô Tokei Handbook (Handbook for applied statistics)" (ed. by Okuno, C.), Yokendo Ltd., Tokyo, 736–742 (1978) [In Japanese].
9) Yagi, N.: Analysis of the growth curve of the insect larvae. *Mem. Coll. Agric. Kyoto Imp. Univ.*, 1, 1–35 (1926).

(Received for publication, March 23, 1981)