Introducing Viewpoints of Mechanics into Basic Growth Analysis (3) : Applying Growth Force and Leaf-Light Complex to Production and Digestion, Analyses of Forages

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Introducing Viewpoints of Mechanics into Basic Growth Analysis – (Ⅲ) Applying Growth Force and Leaf–Light Complex to Production and Digestion Analyses of Forages –

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The present study was designed to give new equations by applying growth force and leaf–light complex to production and digestion analyses of forages. The results obtained were as follows. The traditional equation for forage AGR (absolute growth rate) given by the product of NAR (net assimilation rate) and LAI (leaf area index) was modified as follows: (1) AGR was replaced by growth force that was given by the product of weight and growth acceleration, (2) LAI was replaced by MLA (mean leaf area weighted with relative light intensity) suggesting a kind of leaf–light complex. Inserting growth force and MLA into the traditional description of AGR led to a new equation, where growth process of forages was analyzed more deeply. The application of growth force to indigestible materials in forages gave a new equation that analyzed the indigestibility increase with forage growth more deeply compared with the former equation. It was suggested that growth force and leaf–light complex were useful tools in the production and digestion analyses of forages.

INTRODUCTION

In a paper (Shimojo *et al*., 2006) we suggested three aspects of growth mechanics that were compared with three laws of motion (Kawabe, 2006), where relationships among weight, absolute growth rate and growth acceleration gave a concept of growth force that might resemble Newton's equation of motion in appearance. However, it does not seem that growth force has been applied to basic growth analysis. The dry matter productivity by plant leaves (Watson, 1952; Radford, 1967; Hunt, 1990) based on light environment in plant canopy (Monsi und Saeki, 1953; Monteith, 1965) is a factor of importance to forage production. Shimojo *et al*. (1995a, 1998e, 2004) gave an equation suggesting a kind of leaf–light complex in plant canopy, an index that might be related to light receiving performance of canopy leaves.

The present study was designed to apply growth force and leaf–light complex to production and digestion analyses of forages in order to modify traditional analytic equations.

APPLYING GROWTH FORCE AND LEAF–LIGHT COMPLEX TO PRODUCTION AND DIGESTION ANALYSES OF FORAGES

Modifying basic growth analysis of forages

(A) Traditional equation

As shown by some reports (Watson, 1952; Radford, 1967; Hunt, 1990), absolute growth rate (AGR) of forages described using leaf area index (LAI) and net assimilation rate (NAR) is given by

$$\frac{dW}{dt}=\left(\frac{1}{A}\cdot\frac{dW}{dt}\right)\cdot A, \tag{1}$$

where W＝forage weight, t＝time, A＝LAI, dW/dt＝AGR, $(1/A)\cdot(dW/dt)$＝NAR.

(B) Newly suggested equation

(B–1) Concept of growth force

Shimojo *et al*. (2006) obtained a concept of growth force by a series of calculations (2)～(8).

$$W=W_0\cdot\exp(\mathrm{RGR}\cdot t), \tag{2}$$

where RGR＝relative growth rate, W_0＝the weight at t＝0.

$$\mathrm{AGR}=\frac{dW}{dt}=W_0\cdot\mathrm{RGR}\cdot\exp(\mathrm{RGR}\cdot t). \tag{3}$$

$$\mathrm{GA}=\frac{d^2W}{dt^2}=\frac{d(\mathrm{AGR})}{dt}=W_0\cdot(\mathrm{RGR})^2\cdot\exp(\mathrm{RGR}\cdot t), \tag{4}$$

where GA＝growth acceleration.

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Relating equations (2)～(4) gives

$$\frac{\mathrm{AGR}}{W}=\frac{\mathrm{GA}}{\mathrm{AGR}}=\mathrm{RGR}. \quad (5)$$

Relating the first and second terms in (5) leads to a series of calculations as follows:

$$(\mathrm{AGR})^2=W\cdot\mathrm{GA}. \ (6) \ \rightarrow \ \mathrm{AGR}=\sqrt{W\cdot\mathrm{GA}}\ . \ (7)$$

$$\rightarrow \ \mathrm{AGR}=\sqrt{W\cdot\frac{d^2W}{dt^2}}\ . \ (8)$$

Equations (6)～(8) are a newly suggested form of AGR that might look like Newton's equation of motion (Shimojo *et al.*, 2006), namely growth force in growth mechanics compared with force in motion. Thus, there occurs the following replacement in AGR:

$$\mathrm{AGR}=\frac{dW}{dt} \quad \text{replaced by} \quad \mathrm{AGR}=\sqrt{W\cdot\frac{d^2W}{dt^2}}. \quad (9)$$

(B–2) Concept of leaf–light complex

Reports of light environment in plant canopy (Shimojo *et al.*, 1995a, 1998e, 2004) suggested that mean leaf area weighted with relative light intensity (MLA) gave a kind of leaf–light complex because of including both LAI and K (light extinction coefficient of plant canopy) as follows:

$$\mathrm{MLA}=\left\{\int_0^A F\cdot 100\cdot\exp(-K\cdot F)dF\right\}\Big/\left\{\int_0^A 100\cdot\exp(-K\cdot F)dF\right\}$$
$$=\frac{1}{K}\cdot\left\{1-\frac{K\cdot A}{\exp(K\cdot A)-1}\right\}, \quad (10)$$

where F=cumulative leaf area index from the top layer to the jth layer of canopy leaves, A=LAI of the canopy, K=light extinction coefficient of the canopy.
Equation (10) shows that MLA is affected by not only A but also K. This viewpoint suggests that leaf–light complex is preferable for the description of light receiving performance of canopy leaves compared with the traditional treatment of leaf and light.
Thus, there occurs the following replacement in LAI:

$$\mathrm{LAI}=A \quad \text{replaced by} \quad \mathrm{MLA}=\frac{1}{K}\cdot\left\{1-\frac{K\cdot A}{\exp(K\cdot A)-1}\right\}. (11)$$

(B–3) Combining growth forth and MLA

Combining equations (9) and (11) gives the following replacement:

$$\frac{dW}{dt}=\left(\frac{1}{A}\cdot\frac{dW}{dt}\right)\cdot A, \quad (1)$$

$$\text{replaced by}\sqrt{W\cdot\frac{d^2W}{dt^2}}$$

$$=\left\{\frac{1}{\frac{1}{K}\cdot\left(1-\frac{K\cdot A}{\exp(K\cdot A)-1}\right)}\cdot\sqrt{W\cdot\frac{d^2W}{dt^2}}\right\}$$
$$\cdot\left\{\frac{1}{K}\cdot\left(1-\frac{K\cdot A}{\exp(K\cdot A)-1}\right)\right\}. \quad (12)$$

There are more pieces of information on forage growth analysis in new equation (12) than in traditional equation (1). Equation (12) shows a close relationship between growth force of forages and leaf–light complex, a new viewpoint that modifies basic growth analysis to give a deeper interpretation to growth process of forages. This is why we have made the present attempt.

Modifying digestion analysis of forages

(A) Former equation

A series of studies by Shimojo *et al.* (1995b, 1997, 1998a, 1998b, 1998c, 1998d, 1998f, 1998g, 1998h, 1999a, 1999b, 1999c) reported digestion analysis of forages with growth of them. In those reports indigestion analysis was taken up frequently, because this is easier to treat than digestion analysis due to a continuous formation of indigestible materials with growth of forages. The increase in indigestibility is described as follows:

$$\frac{I_2}{W_2}-\frac{I_1}{W_1}=\left(1-\frac{W_1}{W_2}\right)\cdot\left(\frac{\overline{\mathrm{FRI}}}{\overline{\mathrm{RGR}}}-\frac{I_1}{W_1}\right), \quad (13)$$

where W= forage dry weight, RGR= forage relative growth rate, I= dry weight of indigestible materials, FRI=formation rate of indigestible materials.
In equation (13), $\overline{\mathrm{RGR}}$ and $\overline{\mathrm{FRI}}$ show mean RGR and mean FRI over the interval t_1 to t_2, respectively. The instantaneous expression of them is given by

$$\mathrm{RGR}=\frac{1}{W}\cdot\frac{dW}{dt}, \ (14) \qquad \mathrm{FRI}=\frac{1}{W}\cdot\frac{dI}{dt}, \ (15)$$

(B) Newly suggested equation

Equations (14) and (15) are modified under the concept of growth mechanics. Thus,

$$\text{modified RGR}=\frac{1}{W}\cdot\sqrt{W\cdot\frac{d^2W}{dt^2}}\left(=\sqrt{\frac{1}{W}\cdot\frac{d^2W}{dt^2}}\right), \quad (16)$$

$$\text{modified FRI}=\frac{1}{W}\cdot\sqrt{I\cdot\frac{d^2I}{dt^2}}\left(=\frac{I}{W}\sqrt{\frac{1}{I}\cdot\frac{d^2I}{dt^2}}\right), \quad (17)$$

Equation (17) is derived from a series of calculations as shown below.

$$\frac{1}{I}\cdot\frac{dI}{dt}=\mathrm{RGR_I}, \ (18) \ \rightarrow \ I=I_0\cdot\exp(\mathrm{RGR_I}\cdot t), \ (19)$$

$$\rightarrow \ \frac{dI}{dt}=I_0\cdot\mathrm{RGR_I}\cdot\exp(\mathrm{RGR_I}\cdot t), \ (20)$$

$$\rightarrow \ \frac{d^2I}{dt^2}=I_0\cdot(\mathrm{RGR_I})^2\cdot\exp(\mathrm{RGR_I}\cdot t), \ (21)$$

$$\rightarrow \ \frac{dI}{dt}\Big/I=\frac{d^2I}{dt^2}\Big/\frac{dI}{dt}=\mathrm{RGR_I}, \ (22)$$

$$\rightarrow \ \left(\frac{dI}{dt}\right)^2=I\cdot\frac{d^2I}{dt^2}, \ (23)$$

$$\rightarrow \ \frac{dI}{dt}=\sqrt{I\cdot\frac{d^2I}{dt^2}}\left(=I\cdot\sqrt{\frac{1}{I}\cdot\frac{d^2I}{dt^2}}\right). \ (24)$$

where I= dry weight of indigestible materials, I_0= dry

weight of indigestible materials at $t=0$, RGR_I=RGR of I, dI/dt=growth rate of I (GRI), d^2I/dt^2=growth acceleration of I (GAI), $I\cdot(d^2I/dt^2)$=growth force of I, $(1/I)\cdot(d^2I/dt^2)$=GAI per unit of I.
Thus, equation (24) gives

modified FRI=

$$\frac{1}{W}\cdot\frac{dI}{dt}=\frac{1}{W}\cdot\sqrt{I\cdot\frac{d^2I}{dt^2}}\left(=\frac{I}{W}\sqrt{\frac{1}{I}\cdot\frac{d^2I}{dt^2}}\right). \quad (17)$$

Therefore, there occurs the following replacement in both RGR and FRI:

$$\mathrm{RGR}=\frac{1}{W}\cdot\frac{dW}{dt}, \ (14) \qquad \text{replaced by}$$

$$\text{modified RGR}=\frac{1}{W}\cdot\sqrt{W\cdot\frac{d^2W}{dt^2}}\left(=\sqrt{\frac{1}{W}\cdot\frac{d^2W}{dt^2}}\right), \quad (16)$$

$$\mathrm{FRI}=\frac{1}{W}\cdot\frac{dI}{dt}, \ (15) \qquad \text{replaced by}$$

$$\text{modified FRI}=\frac{1}{W}\cdot\sqrt{I\cdot\frac{d^2I}{dt^2}}\left(=\frac{I}{W}\sqrt{\frac{1}{I}\cdot\frac{d^2I}{dt^2}}\right). \quad (17)$$

These result in the following replacement:

$$\frac{I_2}{W_2}-\frac{I_1}{W_1}=\left(1-\frac{W_1}{W_2}\right)\cdot\left(\frac{\overline{\mathrm{FRI}}}{\overline{\mathrm{RGR}}}-\frac{I_1}{W_1}\right), \quad (13)$$

replaced by
$$\frac{I_2}{W_2}-\frac{I_1}{W_1}=\left(1-\frac{W_1}{W_2}\right)\cdot\left(\frac{\text{modified }\overline{\mathrm{FRI}}}{\text{modified }\overline{\mathrm{RGR}}}-\frac{I_1}{W_1}\right). \quad (25)$$

Modified RGR [equation (16)] shows that there are two descriptions for RGR: (1) growth force per unit of W, (2) growth acceleration per unit of W. These two kinds of expressions suggest a deeper interpretation of RGR, an improvement that is given by introducing the growth force of weight.

Modified FRI [equation (17)] shows that there are two descriptions for FRI: (1) growth force of I per unit of W, (2) the product of I/W and growth acceleration of I per unit of I. These two kinds of expressions suggest a deeper interpretation of FRI, an improvement that is given by introducing the growth force of indigestible materials.

Therefore, there are more pieces of information on digestion analysis of forages in new equation (25) than in former equation (13). This is why we have made the present attempt.

Conclusions

The present study suggested that the application of growth forth and leaf–light complex to basic growth analysis gave new equations analyzaing production and digestion characteristics of forages more deeply compared with traditional equations.

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