Computer Control of Plant Growth by Image Processing

I. Mathematical Representation of Relation between Growth and Pattern Area Taken in Photographs of Plants

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In an attempt to apply the image processing in order to obtain the information about plant growth, relations between the growth and pattern area taken in photographs of cucumber plants were analyzed and represented mathematically. A photographing system was developed, which made it possible to take photographs of plants from various angles. Photographed pattern areas of plants correlated highly with the plant growth. In particular, the correlation coefficients were highest between the total area of patterns taken at various angles, and leaf area, the square roots of plant height, fresh weight and dry weight. The growth elements were given as functions of the pattern area. From Chow's test, it was estimated that the equations represent the normal growth, but do not show the abnormal growth such as succulent growth under higher temperatures. This experiment demonstrates that it is possible to use the image processing for computer control of plant growth.

For advance in computer control of plant growth^{1,2)}, one of the important needs is to develop the instrumentation for obtaining informations about the growth. The image processing of the plant is considered to be applied to non-destructive and intact measurement of the growth for using in an on-line computer system which manipulates the environmental factors on the basis of the growth. However, there remain many problems in hard- and softwares for developing the image processing system in this field.

As the first step toward the image processing of the plant growth, the present study deals with mathematical representation of the relation between the growth and pattern areas taken in photographs of cucumber plants.

MATERIAL AND METHOD

Material plant. *Cucumis sativus* L. "Ao-fushinari" were cultivated under air temperature of 24–26°C and relative humidity of $60 \pm 7\%$ in a phytotron glass room. Three plants were photographed, and at the same time, their plant heights, leaf areas, fresh weights and dry weights were measured at an interval of 4 days during the growth period from 7 to 24 days after germination.

Photographing method. Figure 1 shows the photographing system. Plant was placed on a turn table which revolved from 0 to 360° horizontally, and was photographed with a still camera (Nikon F2 with a motor drive device and a lense of 20 mm focal length). The camera position was vertically moved on a

Fig. 1 Photographing system.

the index of pattern area for the analysis.

RESULTS AND DISCUSSION

Plant shapes appeared in various forms at different view angles, and different patterns were taken in photographs owing to phyllotaxis and other factors, as shown in Fig. 2. So, four pattern areas at horizontal angles of 0, 90, 180 and 270° were summed up, in order to eliminate the differences caused by the view angle. Table 1 lists correlation coefficients between elements of the growth and the total area of patterns taken at the four horizontal angles at respective vertical angles of 0, 45, 90°, and also the total area of patterns taken at all angles. Correlations were linear between these pattern areas, and leaf area, the square roots of plant

Fig. 2 Silhouette patterns photographed at various view angles.

Table 1 Correlation coefficients between pattern area and growth elements

Elements of plant growth	Total areas of patterns taken at 4 horizontal angles at respective vertical angles of 0, 45 and 90°			Total area of patterns taken at all angles
	0°	45°	90°	
Square root of plant height ($\sqrt{Ph}$)	0.977**	0.962**	0.938**	0.971**
Leaf area (La)	0.973**	0.992**	0.981**	0.995**
Square root of fresh weight ($\sqrt{Fw}$)	0.975**	0.987**	0.986**	0.994**
Square root of dry weight ($\sqrt{Dw}$)	0.973**	0.985**	0.985**	0.992**

** Significant at 1% level

height, fresh weight and dry weight. The coefficients were higher than 0.9 with significance at 1% level. Especially, the coefficients were highest between the growth elements and the total area of patterns taken at all angles. Figures 3-6 show relationships between growth elements and the total area of patterns. Mathematical representations of the growth elements by pattern area were given by

$$La = 2.70 p - 3.79, \quad (1)$$

$$Ph = 1.62 \times 10^{-4} p^2 + 2.84 \times 10^{-2} p + 3.86, \quad (2)$$

$$Fw = 1.02 \times 10^{-4} p^2 + 7.12 \times 10^{-2} p + 1.72 \times 10^{-1}, \quad (3)$$

$$Dw = 7.42 \times 10^{-6} p^2 + 7.67 \times 10^{-3} p - 5.81 \times 10^{-2}, \quad (4)$$

where La, Ph, Fw and Dw are leaf area (cm²), plant height (cm), fresh weight (g) and dry weight (g), respectively, and p is the total area (cm²) of patterns in the photographs taken at all angles.

The dotted lines in these figures show confidence limits³⁾ at 5% level for the individual La, Ph, Fw and Dw, at given p . Equations were given by

$$\left. \begin{array}{l} Cla_1 \\ Cla_2 \end{array} \right\} = -3.79 + 2.70 p \pm 8.40 \times 10 \times (1.17 - 1.25 \times 10^{-3} p + 3.82 \times 10^{-6} p^2)^{1/2}, \quad (5)$$

$$\left. \begin{array}{l} Cph_1 \\ Cph_2 \end{array} \right\} = 3.86 + 2.84 \times 10^{-2} p + 1.62 \times 10^{-4} p^2 \pm 9.03 \times (1.34 - 7.32 \times 10^{-3} p + 7.15 \times 10^{-5} p^2 - 2.56 \times 10^{-7} p^3 + 3.08 \times 10^{-10} p^4)^{1/2}, \quad (6)$$

$$\left. \begin{array}{l} Cfw_1 \\ Cfw_2 \end{array} \right\} = 1.72 \times 10^{-1} + 7.12 \times 10^{-2} p + 1.02 \times 10^{-4} p^2 \pm 3.50 \times (1.34 - 7.32 \times 10^{-3} p + 7.15 \times 10^{-5} p^2 - 2.56 \times 10^{-7} p^3 + 3.08 \times 10^{-10} p^4)^{1/2}, \quad (7)$$

$$\left. \begin{array}{l} Cdw_1 \\ Cdw_2 \end{array} \right\} = -5.81 \times 10^{-2} + 7.67 \times 10^{-3} p + 7.42 \times 10^{-6} p^2 \pm 4.00 \times 10^{-1} \times (1.34 - 7.32 \times 10^{-3} p + 7.15 \times 10^{-5} p^2 - 2.56 \times 10^{-7} p^3 + 3.08 \times 10^{-10} p^4)^{1/2}, \quad (8)$$

where $Cla_{1,2}$, $Cph_{1,2}$, $Cfw_{1,2}$ and $Cdw_{1,2}$ are upper and lower confidence limits for leaf area, plant height, fresh weight and dry weight, respectively. The confidence intervals were shown as ranges between upper and lower lines of the confidence limit. The deviation of plant height was larger to some extent, but those of other growth elements were small and resulted in the distribution of narrow confidence

Fig. 3 Relation between sum total of pattern areas and plant height.

Fig. 4 Relation between sum total of pattern areas and leaf area.

Fig. 5 Relation between sum total of pattern areas and fresh weight.

Fig. 6 Relation between sum total of pattern areas and dry weight.

Table 2 Measured and calculated values of growth under different temperatures

Cultivating condition of air temperature	Plant height (cm)		Leaf area (cm ²)		Fresh weight (g)		Dry weight (g)	
	calculated value	measured value	calculated value	measured value	calculated value	measured value	calculated value	measured value
19-22°C	7.7	6.3	240.3	238.5	7.27	8.03	0.79	0.72
24-26°C	17.7	19.4	689.9	638.6	25.54	22.11	2.52	2.12
30-34°C	28.8	32.6	843.2	710.8	32.36	23.18	3.26	2.19

intervals. From these statistical analyses, it was estimated that plant growth can be evaluated with reliable resolution on the basis of the mathematical representation.

Thus, pattern area in photographs of plant shapes is an useful index with confidence to evaluate the plant growth. The mathematical representations in this study were given for the cucumber plant grown under air temperature of 24-25°C. When those equations are used to represent the growth of cucumber plant under different environments, the question arises as to whether the same equation is applicable for the two or more groups of plants grown under different environments. Table 2 lists measured and calculated growth elements of cucumber plants grown under different temperatures, which were examined 20 days after germination. The plant grown under higher temperature (30-34°C) showed the succulent growth, and the values of the growth elements (Ph, La, Fw and Dw) calculated from equations (1)~(4), were different from measured ones. From CHOW's test,⁴⁾ it was estimated that the equations (1)-(4) can not fit the growth under higher temperatures. On the other hand, differences between measured and calculated values of plant growth under air temperatures of 19-22°C or 24-26°C were small, and the equations were satisfied for their growth analyses. Therefore these equations represent only normal growth of cucumber plants.

K. TAMAKI and J. DOR⁵⁾ reported a precious work establishing the system of leaf pattern recognition to use in agricultural machinery. In order to obtain the adequate information about the growth, many expedients are necessary for data processing. The result from the present study demonstrates that analysis of plant pattern is available for non-destructive and intact measurement of plant growth and is usable in an on-line system of computer control of plant growth by connecting a vidicon camera.

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<和文抄録>

画像処理による植物生育の電算機制御

I. 植物画像面積と生育との関係の表式化

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本研究では植物生育を非破壊、非接触で計測する方法として植物像の自動撮影をおこない、その画像処理に基づいて生育の電算機制御をおこなうことを目的としている。自動撮影のためには、植物を水平に 360° 回転させ、さらに植物位置を中心とした円周上でカメラを垂直に 0~90° 移動させる装置を開発した。各撮影位置は制御装置によって任意に設定される。この装置によって植物地上部を全角度から撮影することができる。

植物材料としては、キュウリ「青節成」を用い、気温 24~26°C、湿度 60% のファイトロンガラス室で栽培した。発芽後 7 日目から 4 日ごとに、3 個体を用いて撮影した植物の画像面積を測定すると同時に、各植物体の生育解析をおこなった。いうまでもなく植物像は葉序その他の要因で撮影位置によって著しくその様相が異なる。このような撮影位置の変化による画像面積の変動をうち消すために、垂直軸 0°, 45°, 90° において、それぞれ水平軸 0°, 90°, 180°, 270° で 4 回撮影した。水平軸 4 画像を合計することによって葉序による画像面積の変動をうち消すことができた。さらに各垂直軸での画像面積と生育との間には高い相関が見られた。とくに全角度総和面積と各生育要素（草丈、生体重、乾物重についてはそれらの平方根）との間の相関係数は著しく高いことが明らかとなった。

これらの関係式を最小 2 乗法で求めると葉面積に対しては一次、草丈、生体重、乾物重に対しては二次の多項式が適合した。この数式に基づき画像面積から植物生育の状態を評価できることが明らかとなった。また、CHOW の検定法によって、これらの数式は 30~34°C において異常に徒長した植物に対しては適合せず、19~22°C および 24~26°C における植物生育には適合することが判定された。

本実験の結果から、植物生育の電算機制御のための植物情報処理手法として画像処理が応用されることが明らかとなった。