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## Plant Growth Analysis

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The **plant development** from a single cell to the mature plant consists of pattern formation, morphogenesis, growth and differentiation. The capacity for growth and development originates from the embryonic tissue regions concerned with the formation of new cells. These regions are called meristems and are composed of stem cells. The stem cells are undifferentiated and have the ability for cell division indefinitely. The single cell zygote undergoes changes from single cell to 2 cell, 4 cell, 8 cell, 16 cell leading to globular stage. After which further cell division, pattern formation and morphogenesis leads to a mature embryo. The axial patterning leads to formation of apical parts (cotyledons, shoot apex, hypocotyl), central part (hypocotyl) and basal part (root apex). The radial patterning provides base for formation of protoderm, ground meristem (cortex and endodermis) and procambium (pericycle and vascular tissues). The root and shoot apical meristems formed during embryogenesis are called primary meristems. Whereas, the meristems developed during post embryonic development e.g. axillary meristems, inflorescence, intercalary meristem, lateral meristems etc. are called secondary meristems.

**Growth** refers to the irreversible changes in the size of a cell, organ or whole plant. It involves both the cell division and enlargement. The plant growth can be visualized in terms of increase in length or plant height, stem diameter, volume of tissue, increase in cell numbers, increase in fresh weight and dry weight, increase in leaf area, leaf weight etc. At plant constituents level also increase in total proteins and total DNA is directly associated with the plant growth. The plant cells can increase in size in two ways. The tip growth involves increase in the growth only in the tip region such as in root hairs and pollen

tubes. Whereas, the diffuse growth involves overall growth and is observed in subapical parts of stems, roots, grass coleoptile. At the organ level, the growth and differentiation can be visualized from three different zones i) cell division zone, ii) cell elongation and differentiation zone and iii) cell differentiation and maturation zone with some overlap. The growth in the cell elongation zone is governed by the rate of water uptake by cell and the cell growth rate. These are dependent on the water potential gradient, surface area of cell membrane, permeability of membrane, cell wall extensibility and yield threshold or the minimum turgor required for growth, cell wall modifying proteins/enzymes for loosening of cell wall, nutrients, carbohydrates, ATP, hormones etc.

### Plant Growth Analysis

Cell division can't cause an increase in size and therefore does not drive growth itself. It provides the structural framework for subsequent cell expansion. The increment in volume or mass requires deposition of mass in the cytoplasm and cell walls. However, increment in dry mass may not coincide with the changes in size. For example, during starch accumulation a potato tuber may gain dry weight without concomitant change in volume. Thus, increase in dry matter is the most important parameter for quantitative analysis of plant growth. Plant growth analysis is required to explain the differences in plant growth in terms of differences between species growing under same environmental condition or differences within a species growing in different environments.

The simplest expression of plant growth is presented as **average growth rate (AGR)**. It is defined as increase in dry weight per unit time. The calculation of average growth rate assumes a linear increase in

plant growth. However, the plants show a sigmoidal pattern of growth where the initial plant growth (e.g. in terms of weight) is exponential which later becomes reduced and reaches a maximum level finally. This pattern is applicable to the growth of plant organs in terms of size, volume, weight, length etc. also. Based on the plant growth studies, Blackman (1919) mentioned that ..... “The rate of production of new material would be proportional to the size of plant, i.e. the increase in plant weight would follow the **compound interest law**”. The proportional rate of increase was termed as **efficiency index** by Blackman (1919) and he further stated that ..... “clearly the efficiency of the plant is greatest at first and then falls somewhat but the fall is only slight until the formation of the inflorescence when there is a marked diminution of the efficiency index”. Briggs, Kidd and West (1920) also argued that the efficiency index is not constant and named it as **relative growth rate**.

The growth of plant based on compound interest law can be expressed as -

$$W = W_0 e^{rt}$$

Where, W = Weight of plant after time t

$W_0$  = Initial weight of plant

r = Relative growth rate and

e = exponential coefficient (=2.7182)

The formula for calculation of mean RGR between two time intervals was given by Fischer (1921) as follows -

$$RGR = (\ln W_2 - \ln W_1) / (t_2 - t_1)$$

Where,  $W_1$  = Initial dry weight of plant at time  $t_1$

$W_2$  = Final dry weight of plant at time  $t_2$

Suppose, there are three plants A, B and C of initial weight 5, 10 and 20 g each and after 10 days they attain dry weight of 10, 20 and 40g respectively. A **comparison of the AGR and RGR** of the these plants A, B, C discussed earlier shows that the AGR of plant A, B and C will be 0.5, 1 and 2 g/day whereas the RGR of all these plants will be equal (0.069 g/g/

day). Actually, all these plants have doubled in dry weight during the 10 days period. Thus the AGR values are size dependent and difficult to compare while RGR values are independent of plant size and can be compared.

Further, **precaution** in the calculation of RGR is needed for replication data. For example if the dry matter data ( $W_1$  at time  $t_1$  and  $W_2$  at time  $t_2$ ) with three replications ( $r_1, r_2$  and  $r_3$ ) is as follows-

Plant weights of three replications (at time $t_1$ )	Plant weights of three replications (at time $t_2$ )	logarithm of plant weights of three replications (at time $t_1$ )	logarithm of plant weights of three replications (at time $t_2$ )
$W_{1r_1}$	$W_{2r_1}$	$\ln(W_{1r_1})$	$\ln(W_{2r_1})$
$W_{1r_2}$	$W_{2r_2}$	$\ln(W_{1r_2})$	$\ln(W_{2r_2})$
$W_{1r_3}$	$W_{2r_3}$	$\ln(W_{1r_3})$	$\ln(W_{2r_3})$

Then the two estimates of RGR for replicated data will be as follows -

$$R_1 = [ \ln[(W_{2r_1} + W_{2r_2} + W_{2r_3})/3] - \ln[(W_{1r_1} + W_{1r_2} + W_{1r_3})/3] ] / (t_2 - t_1)$$

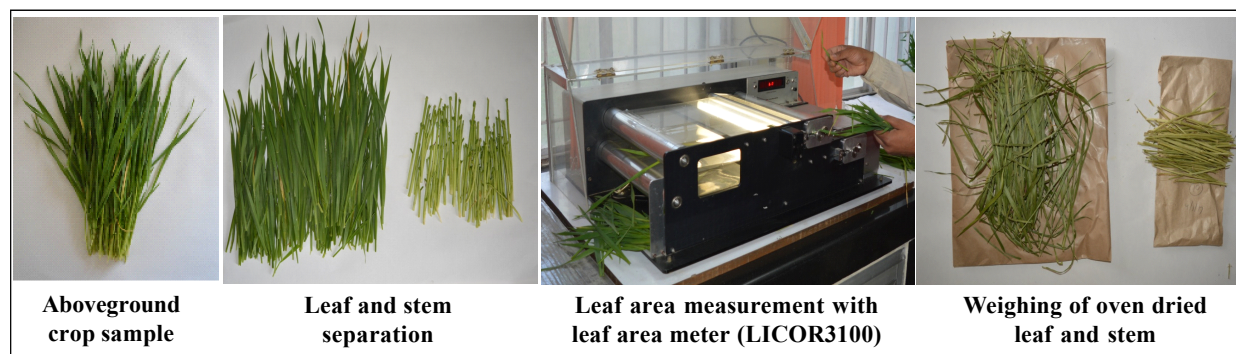
$$R_2 = [(\ln(W_{2r_1}) + \ln(W_{2r_2}) + \ln(W_{2r_3}))/3 - ((\ln W_{1r_1}) + \ln(W_{1r_2}) + \ln(W_{1r_3}))/3] / (t_2 - t_1)$$

Hoffmann and Poorter (2002) reported that the estimate  $R_2$  is the correct method for RGR calculation as it does not give any bias in terms of standard deviation, time between harvests or sample size. Thus the better approach for replication data is to take the mean of logarithms of replications rather than the logarithms of the mean of replications.

For analyzing the plant growth there are two major plant measures required. These are (1) the plant material dry weight (W) and (2) the leaf area or assimilatory system (LA). Besides, these the leaf dry weight (LW) is also useful. The plant growth analysis parameters based on W, LA and LW have been expressed as rates and ratios. All the rates and ratios have been defined at an instant of time. A list of these growth analysis parameters with their definition, unit and significance is listed in Table 1 and their instantaneous and mean values are given in Table 2.

**Table 1:** Plant growth analysis parameters

Growth analysis parameters	Definition	Unit	Significance
Relative Growth Rate (RGR)	Rate of increase in dry matter per unit dry matter	$g\ g^{-1}\ day^{-1}$	Indicates the proportionate growth of plant independent of their size
Net Assimilation Rate (NAR)	Rate of increase in dry matter per unit leaf area	$g\ cm^{-2}\ day^{-1}$	Indicates the assimilatory capacity of plant
Crop Growth Rate (CGR)	Rate of increase in dry matter per unit ground area	$g\ cm^{-2}\ day^{-1}$	Indicates the dry matter production capacity per unit area and also indicates net primary productivity
Average Growth Rate (AGR)	Rate of increase in dry matter	$g\ day^{-1}$	Indicates the growth of plants
Leaf Area Index (LAI)	Ratio of leaf area to the ground area	-	Proportion of ground area covered by leaves
Leaf Area Ratio (LAR)	Ratio of leaf area to the plant dry weight	$cm^2\ g^{-1}$	Indicates leafiness of plant
Leaf Weight Ratio (LWR)	Ratio of leaf weight to the plant dry weight	$g\ g^{-1}$	Partitioning to leaf or proportion of dry weight involved in assimilation
Specific Leaf Area (SLA)	Ratio of leaf area to leaf weight	$cm^2\ g^{-1}$	Higher SLA indicates less thick and or less density of leaf
Specific Leaf Weight (SLW)	Ratio of leaf weight to the leaf area	$g\ cm^{-2}$	Higher SLW indicates more leaf thickness and or density
Leaf Area Duration (LAD)	Product of leaf area and the time period which leaf area is maintained	$cm^2\ day$	Duration of greenness of crop
Biomass Duration (BMD)	Product of biomass and the time period in which biomass is maintained	$g\ day$	Indicates the biomass persistence and useful for calculation of maintenance respiration over times



**Figure 1:** Steps of plant growth analysis

**Sampling procedure for growth analysis** involves plant biomass sample cutting at different intervals of time (in days), leaf separation immediately after sample cutting, leaf area measurement, oven drying of plant biomass and weighing of dry matter.

The steps are as follows -

- i) Aboveground crop sample is selected from a uniform plant population.
- ii) Cut a segment of crop row (eg. 50 cm of wheat row) from the ground level.

**Table 2:** Instantaneous and mean values of plant growth analysis parameters

Growth analysis parameters	Instantaneous value	Mean value over internal ( $t_2 - t_1$ )
Relative Growth Rate (RGR)	$\frac{1}{W} \times \frac{dw}{dt}$	$\frac{\ln W_2 - \ln W_1}{t_2 - t_1}$
Net Assimilation Rate (NAR)	$\frac{1}{L} \times \frac{dw}{dt}$	$\frac{(W_2 - W_1) \times \ln(LA_2 - \ln LA_1)}{(t_2 - t_1) \times (LA_2 - LA_1)}$
Crop Growth Rate (CGR)	$\frac{1}{GA} \times \frac{dw}{dt}$	$\frac{1}{GA} \times \left[ \frac{W_2 - W_1}{t_2 - t_1} \right]$
Average Growth Rate (AGR)	$\frac{dw}{dt}$	$\left[ \frac{W_2 - W_1}{t_2 - t_1} \right]$
Leaf Area Index (LAI)	$\frac{LA}{GA}$	$\left[ \frac{LA_2 + LA_1}{2} \right] \times \frac{1}{GA}$
Leaf Area Ratio (LAR)	$\frac{LA}{W}$	$\left[ \frac{LA_2}{W_2} + \frac{LA_1}{W_1} \right] / 2$
Leaf Weight Ratio (LWR)	$\frac{LW}{W}$	$\left[ \frac{LW_2}{W_2} + \frac{LW_1}{W_1} \right] / 2$
Specific Leaf Area (SLA)	$\frac{LA}{LW}$	$\left[ \frac{LA_2}{LW_2} + \frac{LA_1}{LW_1} \right] / 2$
Specific Leaf Weight (SLW)	$\frac{LW}{LA}$	$\left[ \frac{LW_2}{LA_2} + \frac{LW_1}{LA_1} \right] / 2$
Leaf Area Duration (LAD)	-	$\left[ \frac{LA_2 + LA_1}{2} \right] \times (t_2 - t_1)$
Biomass Duration (BMD)	-	$\left[ \frac{W_2 + W_1}{2} \right] \times (t_2 - t_1)$

- |                                                                                                                                                                                                                        |                                                                                                                                                                                                                          |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <p>iii) Place the sample in polythene bag and sprinkle water drops if necessary to maintain leaf turgidity and to avoid leaf shriveling.</p> <p>iv) Detach the leaves from the base of leaves without leaf sheath.</p> | <p>v) Take leaf area of the leaves with the help of a <b>Leaf area meter</b> (e.g. LICOR3100 automatic leaf area meter).</p> <p>vi) Keep the leaves and the shoot devoid of leaves in separate brown paper envelops.</p> |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|

- vii) Immediately put these samples in an oven at 65°C for 2-3 days or until they are completely dry. Delay in keeping in oven leads to loss of dry matter due to respiration.
- viii) Take dry weight of leaf samples and remaining shoot samples. Add them to get total plant dry matter.
- ix) After 7-10 days again take samples as described earlier.

**Calculations:** The ground area can be calculated based on the row spacing and length of crop row harvested. For example, if 50 cm wheat row was harvested where the row spacing was 22.5 cm, then the ground area of the sample will be  $22.5 \times 50 = 1125 \text{ cm}^2$ . Further, if the initial dry matter is  $W_1$ , initial leaf area is  $LA_1$  and initial leaf weight is  $LW_1$  and the corresponding parameters in the second harvest after some time interval are  $W_2$ ,  $LA_2$  and  $LW_2$ , then

the mean values of different growth analysis parameters can be calculated as given in Table 2.

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