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CALCULATION OF THE GROWTH RATE AND YIELD OF CROPS UNDER OPTIMUM GROWING CONDITIONS

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In the preceding chapter, the physiological basis of crop growth was discussed. On the basis of these principles and typical values for different plant characters, we will calculate the growth rate of a crop under optimum conditions. From this we derive the yield potential of the crop in the studied area. This contributes to identify and to overcome the physical causes of low yields.

The growth rate of a crop is approximately proportional to the amount of light it absorbs, provided that the crop is well supplied with water and nutrients. Under these conditions about 4×10^{-9} kg (= 0.004 mg) glucose is produced for every Joule of absorbed light. (But note that maize, sorghum, millet and sugar cane have a more efficient photosynthesis: they produce 6×10^{-9} kg glucose per Joule). In the humid tropics, the incoming amount of light is on the average 90×10^{9} Joule/ha/day. Therefore, a closed canopy which intercepts all the incoming light produces about $4 \times 10^{-9} \times 90 \times 10^{9} = 360$ kg glucose/ha/day.

In order to maintain the present biomass, each day an amount of glucose is consumed which is equal to about 1½% of this biomass. So, the maintenance respiration of a crop with a total dry weight (DM) of 4000 kg is $0.015 \times 4000 = 60$ kg glucose/ha/day.

The glucose which remains after substraction of these costs of maintenance is transformed into new plant material (= growth). Respiration in connection with growth is 30% so that 70% of the weight of glucose remains as structural plant dry matter. In our example, the increment in dry weight is $0.70 \times (360 - 60) = 210$ kg/ha/day. This is called the growth rate of the crop.

The preceding calculation shows that the *growth rate* (in kg/ha/day) can be represented as:

$$\text{Growth rate} = 0.7\ (4 \times 10^{-9} \times I - 0.015\ W)$$

where I is the amount of incoming light (Joule/ha/day) and W is the amount of dry weight which is already present (kg DM/ha).

Exercise: Calculate the growth rate of a closed crop of 6000 kg/ha when the incoming amount of light is 100×10^{9} Joule/ha/day. Answer: 217 kg/ha/day.

A rule of thumb for the growth rate of a closed crop under optimum growing conditions is 200 kg DM/ha/day. Usually, however, the actual growth rate is much lower. This is because the crop is not closed so that not all the light is intercepted, or because water supply and fertilization are not what they should be, or because the crop suffers from pests, diseases or weeds. These factors reduce the

Early in the growing period, there is still insufficient leaf area to intercept all the incoming light. Crop assimilation is proportional to the amount of light which is absorbed. Hence, we can re-write the equation for the growth rate as:

Growth rate = $0.7\ (4 \times 10^{-9} \times f_{abs} \times I - 0.015\ W)$

where f_{abs} is the fraction of the incoming light that is absorbed by the canopy. This fraction depends on the leaf area index as follows:

LAI	0	0.25	0.5	1.0	1.5	2.0	2.5	3.0	4.0	5.0
f_{abs}	0	0.16	0.30	0.50	0.65	0.75	0.83	0.88	0.94	1.

(In formula: $f_{abs} = 1-e^{-0.7xLAI}$, where e is the base of the natural logarithm). The leaf area index LAI is expressed in m^2 leaf area per m^2 ground surface.

Exercise: Calculate the light absorption of a crop with LAI = 2 when the incoming light amounts to 100×10^9 Joule/ha/day. How much is the growth rate when the existent biomass is 1110 kg DM/ha? Answer: 75×10^9 Joule/ha/day is absorbed and the growth rate is 198 kg DM/ha/day.

The preceding procedure enables us to calculate the growth rate and yield of a crop which is well supplied with water and nutrients and which is free from pests, diseases and weeds. The yield calculated in this way indicates what is possible with that crop in the studied area and is therefore called the *potential yield*. The *actual yields* are usually much lower because the growing conditions in the field are seldom optimum.

In Table 1, a scheme is given to calculate the crop growth rate for time intervals of 10 days (decades). By adding this dry matter increment each time to the biomass which is already present, we obtain the time course of the biomass production.

The biomass at emergence may be set equal to half of the total weight of the seeds sown. So, when the seed rate is 100 kg/ha, then the crop starts with a biomass of 50 kg/ha.

The leaf area index of the crop is obtained by multiplying its biomass with the ratio leaf area/plant weight. Only that leaf area is considered which is green and so photosynthetically active. The leaf area/plant weight ratio differs from one crop species to the other and decreases as the crop develops. Firstly, because the plant makes not only leaves, but forms more and more other plant organs such as stems, fruits and seeds. Secondly, because leaves turn yellow during their phase of senescence and are then no longer photosynthetically active. In our example, the crop starts with a leaf area/plant weight ratio of 20 m^2 leaf area per kg plant dry matter. With a biomass of 50 kg/ha, this means a LAI of $20 \times 50 \times 10^{-4} = 0.1$ m^2 leaf area/m^2 soil area.

The amount of incoming light varies from day to day: it is larger on sunny days than on cloudy days. As a simplification, we work here with an average value of 90×10^9 Joule/ha/day. This is the average value in the humid tropics.

In its seedling stage, a crop intercepts only a minor part of the incoming light because its leaf area is still small. The relation between LAI and light absorption was given above. From this relation we derive that 7% of the light is absorbed by the crop ($f_{abs} = 0.07$). That means a light absorption of $0.07 \times 90 \times 10^9$ Joule/ha/day.

We also know that 4×10^{-9} kg glucose is formed for each Joule. Hence, crop assimilation is $4 \times 10^{-9} \times 0.07 \times 90 \times 10^9 = 25$ kg glucose/ha/day. For a period of 10 days, this means 250 kg glucose/ha. The costs of maintenance are $0.015 \times 50 = 0.7$ kg glucose/ha/day and thus 7 kg for a 10-day period. An amount of $250 - 7 = 243$ kg glucose remains and this is converted into biomass. In this conversion process, 30% of the plant mass is lost so that in this decade the dry weight increment is $0.7 \times 243 = 170$ kg/ha. The biomass at the end of this decade is $50 + 170 = 220$ kg/ha.

In Table 1, this series of calculations was repeated for each 10-day period. That resulted in a total biomass of 11441 kg/ha at the end of the growing period of the crop. However, only a certain part of the biomass produced is of interest to the farmer. With cereals it is the grain yield which matters. The ratio between the yield of the desired plant parts and the total biomass is called the *harvest index* of the crop. We assume the harvest index to be 40%. In the case of a cereal crop, this means that 40% of the total biomass is found in the grains. The calculated grain yield becomes $0.40 \times 11441 = 4576$ kg/ha.

Up till now, we have assumed the biomass to be dry (dry weights are obtained by drying for 24 hours at a temperature of about 80°C). However, the harvest product contains also a certain amount of water. The *moisture content* of ripe grains is about 15%. Hence, our freshly harvested product weighs $4576/(1-0.15) = 5384$ kg/ha or 5.4 tons/ha.

The usefulness of such calculations of the *potential yield* is that it demonstrates the possibilities of the crop in the studied area. It also shows how the crop yield is realised in course of the growing period and which factors play a role in this. Moreover, it gives us an idea about the magnitude of the different growth processes.

This approach contributes to discover the causes of low yields and then to improve cultural practices. But realise that there are also many socio-economical factors why crop yields are lower than they could be.

Exercise

Try to calculate for yourself the growth pattern of a crop in your area. Calculate also the potential yield of this crop.

In order to do this, it is necessary to collect some characteristics of this crop, either from literature or from experimentation on the spot: the leaf area/-

plant weight ratio in course of time, the harvest index, and the moisture content of the harvested product.

Also the available amount of light has to be known. Calculations are most accurate when the radiation measured at a meteorological station in the neighbourhood is used (e.g. the radiation for 10-day periods). These stations normally measure total global radiation. Plants only utilize the visible part of the radiation in their photosynthesis. Because this is only half of the total radiation , the radiation data of meteo stations must be halved in order to obtain the amounts of visible light.

When the crop has not yet closed, its growth rate increases sharply with time. It is therefore more accurate to work with periods shorter than 10 days early in the growing period, e.g. up till $f_{abs} = 0.50$ with periods of 5 days.

In the ripening phase, plant activities decrease and so does the maintenance respiration. For simplicity however, we keep computing with 0.015 W. If, however, the maintenance respiration surpasses crop assimilation, then we do not fill in this negative value for crop growth, but we assume it to be zero (see the last decade of Table 1).

Questions: How much differ actual crop yields in the area from the calculated potential yield? What could be the causes of these differences (consider the different reduction factors mentioned for the crop growth rate)? How could actual yields be brought closer to the potential yield?

Note, however, that the calculation procedures given in this chapter provide only a rough indication of yield potentials. Their main aim was to illustrate quantitatively how crop yields come about.

Table 1. Example of the calculation of growth rate and potential yield of an annual crop growing under optimum conditions.

Data: amount of seed sown: 100 kg/ha
incoming light: 90×10^9 Joule/ha/day
harvest index: 0.40
moisture content of harvest product: 0.15

days after emergence	5	15	25	35	45	55	65	75	85	95
m^2 green leaf area/kg plant dry weight	20	18	18	17	14	12	9	4	1	0

Equation for the growth rate over a 10-day period:

$$\text{Growth rate} = 0.7\ (10 \times 4 \times 10^{-9} \times f_{abs} \times I - 10 \times 0.015\ W) \quad \text{kg/ha/decade}$$

Days after emergence	At start of decade: Biomass W kg/ha	At start of decade: LAI m^2 leaf/m^2 soil	Fraction abs. light f_{abs}	Assimilation kg DM/ha/ decade	Maintenance kg glucose/ha/ decade	Growth rate kg DM/ha/ decade	At end of decade: Biomass W kg/ha
0- 10	50	0.1	0.07	250	7	170	220
10- 20	220	0.4	0.24	864	33	582	802
20- 30	802	1.4	0.62	2232	120	1478	2280
30- 40	2280	3.9	0.93	3348	342	2104	4384
40- 50	4384	6.6	1.0	3600	658	2060	6444
50- 60	6444	7.7	1.0	3600	967	1843	8287
60- 70	8287	7.5	1.0	3600	1243	1650	9937
70- 80	9937	4.0	0.94	3384	1491	1325	11262
80- 90	11262	1.1	0.54	1944	1689	179	11441
90-100	11441	0	0	0	(1716)	0	11441

Yield (dry weight) = 0.40 x 11441 = 4576 kg/ha
Fresh yield = 4576/(1-0.15) = 5384 kg/ha