Chapter 11
Crop Development and Growth

Victor O. Sadras, Francisco J. Villalobos, and Elias Fereres

Abstract Growth of crops, plants or plant parts is defined as the irreversible increase in size whereas development is the continuous change in plant form and function with characteristic transition phases. Growth is primarily associated with capture and allocation of resources whereas development is mostly related to non-resource environmental cues such as temperature, photoperiod and light quality. We separate development and growth conceptually, but both types of processes are closely linked. Thermal time and variations of thermal time corrected to account for photoperiod and vernalization are useful to model crop phenological development. Crop development, in particular the time of flowering, is one of the most important traits for crop adaptation. Breeders, agronomists and growers understand the importance of matching the pattern of phenological development to their particular environments, and use a combination of genetic and agronomic tools to manipulate development. Crop growth depends on the capacity of the canopy to capture CO_2 and radiation, the capacity of the root system to capture water and nutrients from soil, and the efficiency of the crop to transform resources (water, nutrients, radiation, carbon dioxide) into dry matter. Stresses such as water deficits or soil compaction reduce growth by reducing the amount of resources captured by the crop, by reducing the efficiency in the use of resources or both.

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11.1 Introduction

Growth of crops, plants or plant parts is defined as the irreversible increase in size whereas development is the continuous change in plant form and function with characteristic transition phases. The expansion of a leaf or the accumulation of crop biomass are typically growth processes whereas the transition from a vegetative meristem, producing leaves, to a reproductive meristem producing flowers is a characteristic developmental process. We distinguish morphological development (e.g. appearance of successive structures in the plant) from phenological or phasic development which deals with the duration of the different phases of the crop cycle.

The distinction between growth and development is important for two reasons. First, growth is primarily associated with capture and allocation of resources whereas development is mostly related to non-resource environmental clues such as temperature, photoperiod and light quality. Second, the physiological processes involved are different, as discussed in this chapter. Whereas we separate growth and development conceptually, organs, plants and crops grow and develop simultaneously, and for many agronomically important traits the limits between growth and development are blurred. For example, a wheat grain grows, i.e. it expands in volume and gains mass, and also develops, e.g. leaf and root primordia are differentiated in the embryo. Developmental biology (Box 11.1) and crop growth analysis are thus distinct perspectives underpinning the investigation of development and growth. In this chapter, we outline agronomically important aspects of these processes.

Box 11.1 Developmental Biology

The fundamental question of developmental biology is this: how do different cellular phenotypes emerge from cells which share a common set of genes? A typical flowering plant has 30 different cell types, whereas a typical vertebrate has about 120 cell types. All this diversity has to be explained in terms of differential gene expression, as the 30 or so cell types in a plant share the same genome – genetically, the cells of the wheat root endodermis and the mesophyll cells in the flag leaf of the same plant are essentially identical. Likewise, your neurons and liver cells are genetically identical, but their shape and physiology are obviously different. For readers interested in this question, we recommend the book of Mary Jane West-Eberhard: Developmental plasticity and evolution (Oxford University Press, 2003).

Some examples demonstrate the practical implications of understanding the process of cell differentiation. Stem cells, which are undifferentiated cells with potential to generate any cell type, present animal and human health with potential opportunities for new therapies. Short time between generations is one of the cornerstones of successful plant breeding programs. Making use of advanced knowledge of cell differentiation and tissue culture, breeders can

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Box 11.1 (continued)

currently grow up to six generations of chickpeas in a single year. Likewise, tissue culture exploiting the principles of cell differentiation is a rapid, effective and cheap method to generate virus-free seedlings of high value in horticulture.

11.2 Phenological Development

Scales have been devised to characterise phenological development in annual and perennial crops. They are based on the concept of pheno-stage; major pheno-stages in annual crops include

1. Sowing
2. Germination
3. Emergence
4. Juvenile Phase/Initiation of leaves
5. Floral initiation (formation of primordia of reproductive structures)
6. Flowering
7. Physiological maturity
8. Harvest maturity

The case of perennial species is more complex. Trees stay in juvenile phase, thus not flowering, for several years after seed germination. However, most trees of agricultural interest are not propagated by seeds but vegetatively from cuttings that are rooted in nurseries. In this case the cutting may not be juvenile which reduces the time until flowering. In some tree species, the growth of the main stem beyond a certain length accelerates the end of the juvenile period. Once the juvenile phase is over, the tree will follow annual cycles that resemble those of an annual plant, following two possible strategies:

(a) Deciduous species: Most fruit trees and vines belong to this category. All the leaves fall in autumn-winter in response to cold temperatures and/or short photoperiod. Buds stay dormant during winter and usually require low temperatures for an extended period (chilling requirement) until they respond to warm temperature and bud break occurs. After that vegetative and reproductive growth will occur with a degree of overlap that depends on the species. For instance, flowering may occur before leaf growth starts (stone fruits, e.g. peach) or later (pome fruits e.g. apple), while harvest may occur in early to midsummer (several months before leaf fall, e.g. cherry) or in late summer or start of autumn (e.g. apple).

(b) Evergreen species: They include citrus spp., olive and tropical fruit trees (e.g. mango). Leaves stay in the tree for long periods (2–3 years). In some cases (e.g. olive) the tree stay dormant (no vegetative growth) during winter and resume growth in the spring.

The period between two phenostages constitutes a phenophase; we can be interested, for example, in the phase sowing-emergence or emergence-flowering. Some of these phases are well-defined biologically, for example the phase between floral initiation and flowering. Other phases are not defined biologically but with agronomic criteria; for example the phase from physiological maturity, when grain reaches its maximum dry matter, to harvest maturity, when grains reach a moisture content suitable for mechanical harvest. Harvest maturity of wine grapes is defined by oenological criteria, including sugar concentration and acidity, and complementary traits such as colour and aromas. Sugar:acid ratio is an important trait for the decision of harvest in most fruit crops.

The duration of the cycle of different crops is shown in Appendix 11.1.

All phenophases are responsive to temperature, which is the main environmental influence on development (Box 11.2). The phase sowing-emergence can also be influenced by the content of water and oxygen in the soil. In some species, photoperiod also affects the duration of some phenophases. Some species and phases are also responsive to low temperature in a process called vernalisation. Here we outline the effects of mean temperature, low temperature (vernalisation) and photoperiod on phenological development.

Box 11.2. Phenology and Global Warming

Phenological shifts are the most conspicuous biological signal of global warming. Using a systematic phenological network data set of more than 125,000 observational series of 542 plant and 19 animal species in 21 - European countries between 1971 and 2000, it was found that 78 % of all leafing, flowering and fruiting records advanced (30 % significantly) and 3 % were significantly delayed.

The consequences of warming for agriculture are many fold and varied. At high latitudes, warming is extending the window for cropping, with overall positive implications for crop production. In China and USA, milder winters are allowing for earlier crop sowing, which combined with new varieties and practices is improving crop production. Climate projections and modelling indicate that Finland's crop productivity by 2050 would be close to the current productivity in Denmark. In 2000, the EU has accepted Denmark as a wine producing country, and the Association of Danish Winegrowers now counts more than 1400 members. In temperate environments like the Pampas, warming over the last few decades has shortened the season of wheat crops, allowing for early sowing and higher yield of soybean in wheat/soybean double cropping. In temperate and subtropical environments, warming is shortening the season of crops, with potential for yield reduction in the absence of adaptive practices. Increasing frequency and incidence of heat

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Box 11.2 (continued)

waves may reduce both yield and quality of crops. Thus, the outcomes of warming are complex and varied, particularly when warming interacts with changes in rainfall, but a good deal of crop responses to warming are related to phenological changes.

Another interesting consequence of warming is the decoupling of processes, from ecosystems to molecules. In the last five decades, the productivity of Northern Sea fisheries has declined. The main reason is that warming has "decoupled" the phenology of the components of the trophic web. This means that for example, predators and preys which were phenologically synchronized before are now out of phase, with direct consequences for the structure and function of the whole ecosystem. In red grapevine varieties, warming is decoupling sugars and anthocyanins. This means that fruit reaches sugar maturity with less pigmentation; growers have therefore two choices. They can wait longer to harvest, hence allowing for color to develop; this leads to undesirably high sugar and alcohol concentration. Or they can harvest at the right sugar level, and deal with lack of color in the winery. The process of decoupling is therefore an agronomically important aspect of warming, which is related to developmental and growth processes.

11.2.1 Effects of Daily Mean Temperature

Figure 11.1 shows the relationship between the daily rate of phenological development (R, unit: day^{-1}) and daily mean temperature (T, unit: °C). The daily rate of development is the inverse of the duration of the phenophase (D, unit: day); for example if it takes 10 days to complete the phase sowing-emergence, the daily rate of development is 0.1 day^{-1}. The rate of development increases linearly with temperature between the base (T_b) and optimum temperature (T_o), and decreases between the optimum and maximum temperature (T_m) for development. These

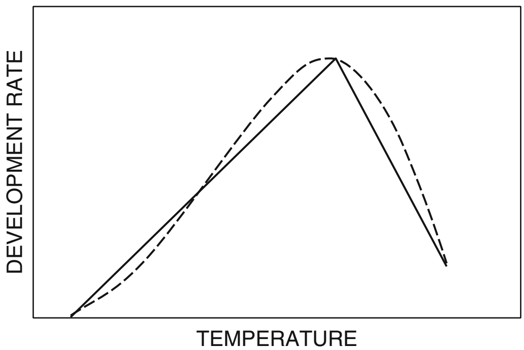


Fig. 11.1 Responses of development rate to temperature. The *dashed line* represents the actual response while the *solid line* is a linear approximation

three parameters, T_b, T_o, and T_m constitute the "cardinal" temperatures for development, and depend on the species and phenological phase.

The daily rate of development is assumed to be zero (i.e. the plant does not develop) if the mean temperature is below T_b or above T_m. The concept of "thermal time" (also called degree days or heat units) is useful to predict the duration of a phase for different temperatures. Thermal time (TT, unit: °Cd) is defined as the sum of daily mean temperature (T, °C), above the base temperature, from the beginning to the end of the phase; for example for the phase sowing-emergence:

$$\mathrm{TT} = \sum\nolimits_{sowing}^{emergence} (\mathrm{T} - T_b) \tag{11.1}$$

and the daily rate of development when the daily mean temperature is between T_b and T_o is

$$\mathrm{R} = 1/\mathrm{D} = (\mathrm{T} - \mathrm{T_b})/\mathrm{TT} \tag{11.2a}$$

The duration of a phase can thus be calculated if we know the daily mean temperature, the base temperature and the thermal time required to complete the phase:

$$\mathrm{D} = \mathrm{TT}/(\mathrm{T} - \mathrm{T_b}) \tag{11.2b}$$

Table 16.1 in Chap. 16 shows T_b and TT for the phase sowing-emergence for a number of crops. With adequate supply of water and oxygen, the thermal time required to complete the phase is approximately constant. Thus, we can predict that wheat will take approximately 11 days to emerge at mean temperature of 10 °C [$D = 110/(10 - 0)$] and 7 days if mean temperature is 15 °C [$D = 110/(15 - 0)$].

Base temperatures have physiological and ecological meaning, as they reflect differences between species and stages, and contribute to the coupling of organisms in trophic webs. For example, the base temperature for the sowing-emergence phase is much lower for winter crops than for spring-sown crops (Table 16.1). Base temperatures normally decline from early to late stages in summer crops, e.g. for sunflower and soybean, and increase from early to late stages in winter crops such as wheat. The thermal time model applies not only to plants but also to other organisms including insects which are – like plants – unable to regulate body temperature. The base temperature for the emergence of bollworms after overwintering in the soil is very close to the base temperature for the sowing-emergence phase of cotton; this coincidence of base temperatures ensures that a new generation of bollworm emerges in synchrony with a suitable food source.

The thermal time model (Eq. 11.2a, 11.2b) is a simplification of a more complex response of development to temperature, as it rests on the assumption of a linear relationship between the rate of development and temperature. However, above the optimum temperature, the rate of development declines with increasing temperature, until a maximum temperature (T_m) is reached (Fig. 11.1). For some phenostages, particularly those related with reproduction, development is also responsive to vernalisation and photoperiod. In these cases, the thermal time required to complete the phase is not constant, but influenced by low temperatures and day length.

11.2.2 Vernalisation and Photoperiod

Annual crops have specific windows of development when grain number, the main yield component, is most affected by environmental stresses such as frost, heat and water stress (Fig. 11.2). These windows vary, but are more or less centered on flowering in most crops. For this reason, mechanisms have evolved that reduce the probability of coincidence of extreme stress and the most sensitive developmental stages. These mechanisms are based on two environmental cues: vernalisation and photoperiod. Flowering time is indeed one of the most important traits for crop adaptation to particular environments in agricultural systems. Consider for example wheat in a Mediterranean region. If it flowers too early, a significant frost risk would reduce seed production in a number of seasons. If it flowers too late, frost risk is reduced at the expense of increased risk of heat and water stress. Early wheat varieties introduced to Australia reached flowering at 125 days after sowing, hence exposing the sensitive reproductive window to high frequency of heat and water stress. Recognising this problem, breeders selected for shorter season varieties, which were better adapted to their environments. Where compared under the same conditions, the time from sowing to anthesis was 119 for cultivars released earlier than 1950 and 108 for cultivars developed later. Rainfed sunflower in southern Spain grows on stored soil water that is depleted during the growing season. In these

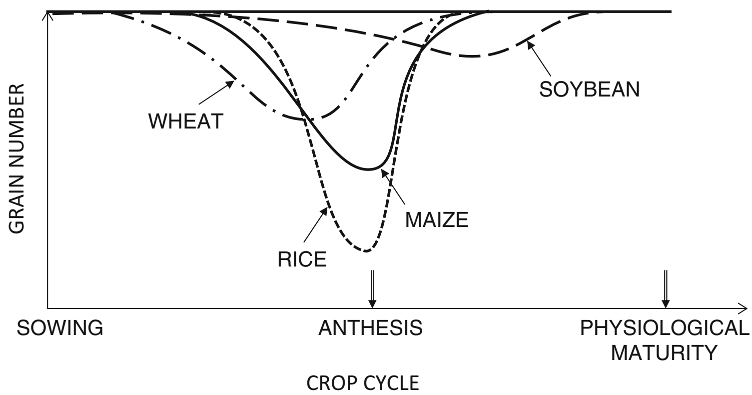


Fig. 11.2 Critical period for grain number determination, the main yield component of annual crops. Grain number is presented in an arbitrary scale where the *vertical line* represents 100 %, of the grain number in unstressed controls. Deviations from this line represent reductions due to stress in different periods of the crop cycle (Source: Calviño and Monzon (2014) in Sadras and Calderini and Hsiao TC 1982. In: Drought resistance of crops with emphasis on rice. IRRI, Los Baños, Manila, Philippines. p 39–52)

environments, hybrids with very long cycle may deplete soil water reserves during a long vegetative stage thus suffering a stronger water deficit during grain filling than short-cycle hybrids. To manipulate the timing of key phenological events, plant breeders make use of fundamental genetic understanding including the manipulation of vernalisation and photoperiod genes in selecting varieties adapted to particular environments. To manipulate the timing of key phenological events, growers combine two practices: cultivar selection and sowing date.

Vernalisation is a response to low temperatures necessary for some plants to become competent for the transition to the reproductive phase. The plant apex may sense vernalising temperatures from seed imbibition, throughout the vegetative phase. Vernalisation requirements are characteristic of temperate crops such as wheat, barley, Brassicas and field pea. In many of these species, 'winter' types require vernalisation whereas, 'spring' types have little or no vernalisation requirements. For instance, for winter wheat, temperatures between 0 and 8 °C are the most effective, although vernalisation happens with temperatures up to 15 °C. Vernalisation may be reversed by high temperatures (usually >20 °C), in a process known as 'devernalization'. In some species, vernalization combines with photoperiod to modulate time of flowering.

Vernalization is also important in horticultural crops. In biennial plants such as sugar beet and carrot, vernalisation modulates the development of flower buds in the second year of growth. In proteranthous perennials (i.e. those that flower before leafing) vernalisation modulates flowering time. In horticulture, the vernalisation requirement is also known as "chilling hours", which is the time below a species-specific base temperature. Understanding vernalisation requirements is important to determine the geographical limits and risks of growing particular crops. Apple trees for example, have a high vernalisation requirement, hence they cannot be grown successfully in warm-winter environments where these requirements are not met. Almond trees have a relatively low vernalisation requirement, and this implies the risk of early flowering with subsequent yield losses due to frost. Breeders have selected horticultural perennials with a broad range of vernalisation requirements to extend their cropping areas and reduce risks of crop failure.

Virtually in all plant species photoperiod sensitive genotypes can be found, or rather, genotypes sensitive to the duration of the night. Gardner and Allard classified annual species into two categories: long-day plants and short-day plants. The short-day plants accelerate their development (shorten the time to flowering) when the days are short, while long-day plants develop faster if the days are long.

Small grains (wheat, barley, oats and rye) are long-day species, while maize, rice, sorghum and soybeans are short-day species. However, within each species there is often a great variability in sensitivity to photoperiod. In general photoperiod response is quantitative, i.e. development rate increases or decreases with the photoperiod but never becomes zero, which would be a qualitative response. By manipulating photoperiod genes in soybean, varieties have been developed that can be grown between high latitudes in the northern hemisphere to the tropics; a classification system of maturity types, with 00 the shortest (90 days) and VIII the longest season (190 days) shows the wide range of phenological patterns in soybean.

11.3 Morphological Development

The architecture of the plant is under genetic control, and is modulated by environmental factors including temperature, photoperiod, and light-quality. Agronomically, the architecture of the crop is important because it influences traits such as lodging, harvestability, competition with weeds, responses to herbivory and distribution of light and chemicals in the canopy profile. The introduction of semi-dwarf genes in rice and wheat has lead to significant improvements in crop production, and part of the success of these semi-dwarf crops is related to their improved architecture, which allows for higher nutrient inputs with reduced lodging risk. The node where the first pod is set is an important trait of grain legumes, as genotypes with pods too close to the ground cannot be harvested effectively.

Plants have numerous meristems (buds) which can follow one of three fates: they can remain dormant, they can activate to produce vegetative structures, or they can become reproductive structures. Different species combine different strategies of meristem allocation, and these strategies involve trade-offs. For example, the adaptation of grasses to browsing, and their exploitation in agriculture, is directly related to their underground, dormant meristems that allow re-growth after grazing. Plants with profuse branching or tillering are more able to fill gaps originated, for example, from failures in sowing or damage by pests or diseases. As an example of trade-off, strong apical dominance, whereby most lateral buds are dormant, favours growth in height, competition for light, and capacity to recover after herbivory, at the expense of limited capacity for growth and reproduction, and constrains to expand into neighbouring gaps.

Interactions between neighbouring plants influence the morphology of individual plants, and the final architecture of the crop. Part of these interactions are mediated by the ability of plants to sense changes in the quantity, quality and direction of light, which in turn trigger developmental responses called photomorphogenesis. The main groups of photoreceptors involved in plant photomorphogenesis are the red (R)/far-red (FR) light-absorbing phytochromes and the blue/UV-A light-absorbing cryptochromes and phototropins. As the green tissue of plants differentially reflects and absorbs light of different wavelengths, plants are able to detect the presence of neighbours by detecting changes in the spectral composition of light, and in particular, reductions in the R/FR ratio. Typically, a shade-avoidant plant responds to neighbours by extending internodes, increasing stem:leaf ratio, reducing activation of lateral buds, producing more erect shoots and in some cases advancing the time of flowering. In some weeds, germination can be triggered by changes in the R/FR ratio associated with soil cultivation. Light signals interacting with the central circadian oscillator, enable plants to monitor photoperiod and adjust the timing of the transition from vegetative to reproductive development (Sect. 11.2.2).

The successive appearance of plant leaves is an important component of morphological development. In general, the thermal time between the appearance of two consecutive leaves, known as phyllochron, is constant. For example, wheat has a phyllochron around 100 °C d with a base temperature of 0 °C. In sunflower the phyllochron is around 20 °C d with a base temperature of 4 °C.

11.4 Growth

Box 11.3 outlines the methods used to quantify crop growth. Crop growth depends on the capacity of the canopy to capture CO_2 and radiation, the capacity of the root system to capture water and nutrients from soil, and the efficiency of the crop to transform resources (water, nutrients, radiation, carbon dioxide) into biomass (Fig. 11.3). The right half in Fig. 11.3 highlight how environmental factors, such as ambient temperature or soil salinity, modulate the rate of capture of resources and the efficiency in the transformation of resources in plant biomass. Other chapters deal in detail with the capture and efficiency in the use of radiation (Chap. 13), water (Chap. 14) and nutrients (Chaps. 24, 25, and 26).

The capture and efficiency in the use of resources changes with the stage of phenological development. The growth of a typical annual crop is characterised with a sigmoid curve (Fig. 11.4) with three phases. First, in a lag-phase, plants grow slowly, as they mostly depend on seed reserves, whereas small root and canopy systems constrain their capacity to capture resources. Many practices (e.g. sowing date, fertiliser) seek to reduce the duration of this lag-phase, also known as "period lost to growth". Second, the growth increases rapidly to reach a linear phase when sufficiently large canopy and root system allow for a high capacity to capture resources. Third, crop growth slows down as both canopy and root systems age, entering a senescence phase in parallel to the accumulation of carbon and nitrogen in reproductive organs. The senescence of leaves and roots is genetically driven in a

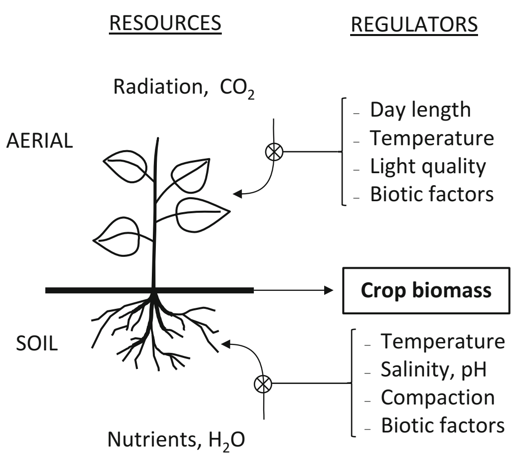


Fig. 11.3 Crop growth depends on the ability of crops to capture above-ground and soil resources, and on the capacity of crops to transform these resources into biomass (Adapted from Sadras and McDonald 2012)

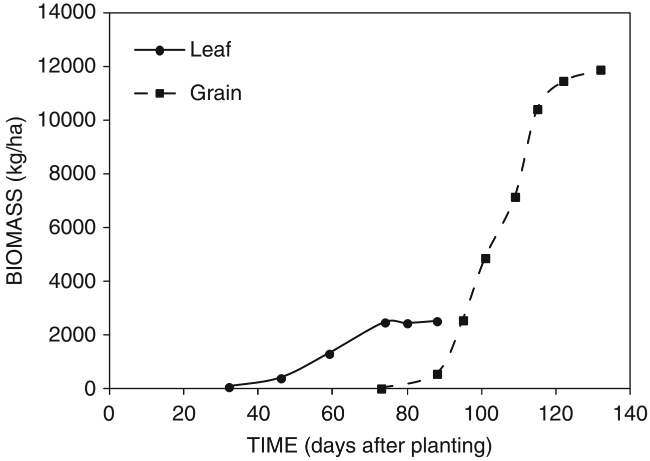
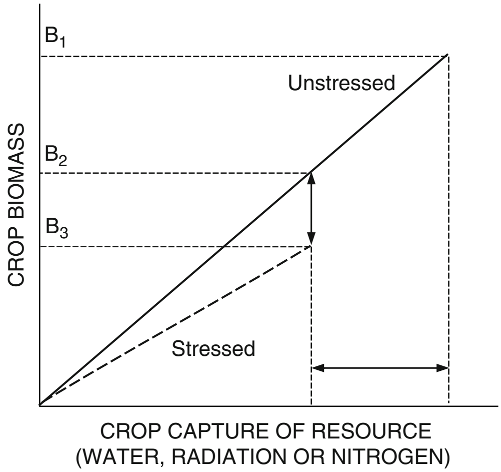


Fig. 11.4 Time course of biomass of leaves and grain of a maize crop in Florida (Data taken from DSSAT 4.6, experiment UFGA8201MZ)

Fig. 11.5 Crop biomass increases with increasing capture of resources, primarily water, radiation and nitrogen. Maximum crop biomass is shown as B_1. Stress reduces crop growth by reducing capture of resources (*horizontal arrow*) resulting in B_2, reducing production per unit resource (*vertical arrow*) or both, which leads to B_3



process known as monocarpic senescence, whereas stresses such as shortage of water or nutrients may accelerate the process.

Figure 11.5 illustrates the relationship between crop growth and capture of resources in crops with favorable and stressful conditions. As the season progresses and roots and canopies expand, the crop captures more soil and above-ground resources. A straight line represents increasing growth with increasing resource capture. Stresses such as deficit of nutrients or soil compaction reduce growth through two processes: reducing the amount of resources captured by the crop (horizontal arrow in Fig. 11.5, and b) reducing the efficiency in the use of resources.

The vertical arrow in Fig. 11.5 indicates the reduction in growth for the same amount of resource captured; this means lower efficiency.

In general shortage of resources (water or nutrient deficits) and soil constraints (compaction, salinity) reduce crop growth by reducing capture of resources, rather than affecting the efficiency in the use of resources.

Ambient temperature influences growth directly, by changing the rate of processes such as cell division, leaf expansion and crop photosynthesis, and indirectly by affecting phenological development and the duration of key phenophases, as discussed before. Within agronomically sensible ranges, the main effect of temperature on crop production is related to the modulation of phenological development. In temperate environments, late sowing shifts the crop cycle to warmer conditions, development proceeds faster, the period available to capture resources and growth is reduced, and biomass at maturity is normally lower. Figure 11.6 illustrates the interplay between development and growth in faba bean crops sown between October (autumn) and early May (spring) in Lugo, Spain. As the sowing is delayed, both temperature and photoperiod increase. This shortens the phenophases of the crop, resulting in a reduction of crop cycle from 209 to 87 days. With shorter cycle duration, the peak leaf area is reduced, the amount of radiation captured by the crop is reduced and the final production of biomass is also reduced. Hence, the effects of temperature and photoperiod on development (cycle length) have a dominant role in seasonal growth. Of interest, the first sowing date does not conform to this pattern. For the earliest sowing, the crop has the longest cycle duration and the highest capture of radiation as expected; therefore it should also have the highest biomass. However, it has the lowest biomass. The explanation is that the extremely

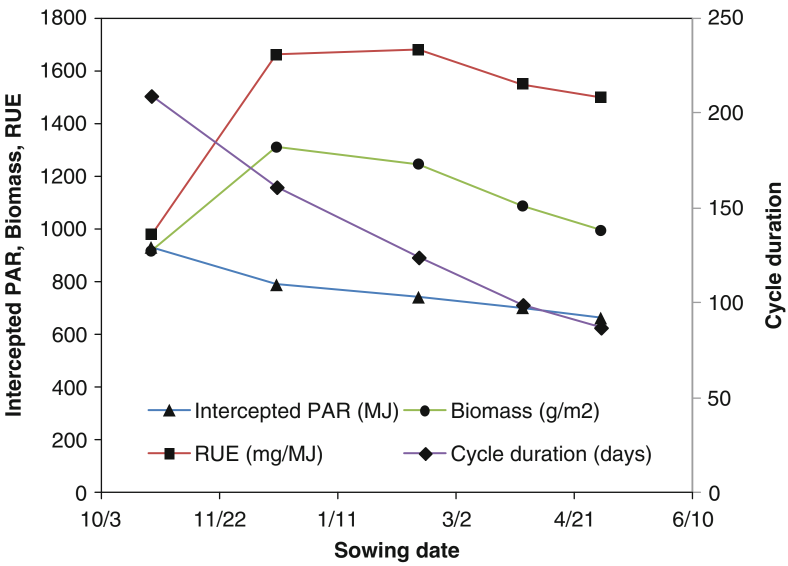


Fig. 11.6 Effect of sowing date on crop duration (time sowing maturity), intercepted PAR, RUE and biomass production of Vicia faba (Adapted from Confalone et al. (2010) Field Crops Res 115, 140–148)

low temperature in the earliest sowing reduced the photosynthetic efficiency of the crop. In this case, the physiological response (photosynthesis) was stronger than the developmental response.

Box 11.3 Quantification of Crop Growth

Depending on the objectives of measurements, we could be interested in describing growth in terms of crop height, leaf surface area, fruit volume, or grain mass. As crop growth depends on capture of resources, and this is in turn related to the size of the canopy and root system, we often use the leaf area index (LAI, m^2 leaf/m^2 ground) to measure the size of the canopy and the rooting depth and density characterized as Root Length Density (L_v, m root/m^3 soil) to quantify the size of the root system. LAI is the ratio of leaf area (assuming single-sided leaves) and ground area, and L_v is the length of roots per unit of soil volume. For many agronomic applications, shoot mass is measured by taking crop samples (e.g. 1 m^2 of crop cut to ground level), which are dried to constant weight to express the dry matter in g/m^2 or kg/ha; this measure of dry matter is also called biomass. Periodic sampling of biomass combined with periodic measurements of radiation interception, nutrient uptake and evapotranspiration allows calculating the efficiency in the use of radiation, nutrients and water as illustrated in Fig. 11.5.

Indirect methods are also used for quantifying biomass or LAI. For trees empirical relationships between biomass and trunk diameter have been widely used. Transmittance of PAR or reflectance of radiation in different wavelengths (e.g. red and far red) (see Chap. 3) may be related to LAI and are the base of most indirect methods for non-destructive measurement of LAI.

Appendix 11.1

Durations of phases of growth cycle (FAO method) for different crop species and climatic areas. A: sowing to 20 % ground cover, B: 20 % to 80 % ground cover, C: 80 % ground cover to start of leaf senescence, D: start of senescence to harvest

Crop species	Climate	Sowing date	Duration of crop stage (days)				
			A	B	C	D	Total
Horticultural crops							
Artichoke (year 1)	M	April	40	40	250	30	360
Artichoke (year 2)	M	May	20	25	250	30	325
Asparagus	M-warm winter	Feb	50	30	100	50	230
Asparagus	M	Feb	90	30	200	45	365
Beets (table)	M	Apr/May	15	25	20	10	70

(continued)

Crop species	Climate	Sowing date	Duration of crop stage (days)				
			A	B	C	D	Total
Broccoli	A	Sept	35	45	40	15	135
Brussel sprouts	M	Feb/April	20–25	30–35	20–25	10	80–95
Cabbage	A, M	Sept	40	60	50	15	165
Cabagge	M	Feb/April	20–25	30–35	20–25	10	80–95
Melon (Cantaloupe)	M-warm winter	Jan	30	45	35	10	120
Melon (Cantaloupe)	M	Aug	10	60	25	25	120
Carrots	A	Oct/Jan	20	30	40	20	110
Carrots	M	Feb/Mar	30	40	60	20	150
Carrots	A	Oct	30	50	90	30	200
Cauliflower	A	Sept	35	50	40	15	140
Celery	SA	Oct/Jan	25–30	40–55	95–105	20	180–210
Celery	M	April	25	40	45	15	125
Cucumber	A	May–August	20	30	40	15	105
Cucumber	A-warm winter	Nov/Feb	25	35	50	20	130
Egg plant	A	October	30	40	40	20	130
Egg plant	M	May/June	30	45	40	25	40
Lettuce	M	April	20	30	15	10	75
Lettuce	M	Nov/Jan	30	40	25	10	105
Lettuce	A	Oct/Nov	25	35	30	10	100
Lettuce	M	Feb	35	50	45	10	140
Melon	M	March/May	25–30	30–35	40–50	20–30	120–140
Melon	A	Aug	15	40	65	15	135
Melon	A	Dec/Jan	30	45	65	20	160
Onion (dry harvest)	M	April	15	25	70	40	150
Onion (dry harvest)	A	Oct/Jan	20	35	110	45	210
Onion (green harvest)	M	April/May	25	30	10	5	70
Onion (green harvest)	A	October	20	45	20	10	95
Pepper	T & M	April/June	30	35	40	20	125
Pepper	A	October	30	40	110	30	210
Pumpkin, Winter squash	M	Mar, Aug	20	30	30	20	100
Pumpkin, Winter squash	T	June	25	35	35	25	120
Radish	M, T	Mar/Apr	5	10	15	5	35
Radish	A	Winter	10	10	15	5	40
Spinach	M	Apr; Sep/Oct	20	20	20	5	65
Spinach	A	November	20	30	40	10	100

(continued)

Crop species	Climate	Sowing date	Duration of crop stage (days)				
			A	B	C	D	Total
Squash, Zucchini	M, A	Apr; Dec.	25	35	25	15	100
Squash, Zucchini	M,T	May/June	20	30	25	15	90
Tomato	A	January	25–30	40	40–70	30	135–155
Tomato	M	Apr/May	35	40	50	30	155
Tomato	A	Oct/Nov	35	45	70	30	180
Water melon	M	April	20	30	30	30	110
Water melon	A	May/Aug	10	20	20	30	80
Roots, tubers and bulbs							
Cassava (year 1)	T	Rainy season	20	40	90	60	210
Cassava (year 2)	T		150	40	110	60	360
Potato	SA	Jan/Nov	25	30	40	30	125
Potato	C	April/May	25–30	30–35	45–50	30	130–145
Potato	C	Apr/May	45	30	70	20	165
Potato	A	Dec	30	35	50	25	140
Sweet potato	M	April	20	30	60	40	150
Sweet potato	T	Rainy seas.	15	30	50	30	125
Sugarbeet	M	March/April	25–30	35–45	50–80	20–50	160–180
Sugarbeet	M	Oct/Nov	45	75	80	30	230
Sugarbeet	A	Sept/Nov	25–35	60–65	70–100	40–65	205–255
Sugarbeet	C	April	50	40	50	40	180
Legumes							
Beans (Phaseoulus) (green)	M	Feb/Mar	20	30	30	10	90
Beans (Phaseoulus) (green)	M, A	Aug/Sep	15	25	25	10	75
Beans (Phaseoulus) (dry seed)	C	May/June	20–25	25–30	30–40	20	100–110
Beans (Phaseoulus) (dry seed)	M	June	15	25	35	20	95
Faba bean, broad bean (green)	C, M	Mar/May	15–20	25–30	35	15	90–100
Faba bean, broad bean (green)	C, M	Oct	90	45	40	0	175
Faba bean, broad bean (dry seed)	C, M	Nov	90	45	40	60	235
Green gram, cowpeas	M	March	20	30	30	20	110
Groundnut (peanut)	T	Dry season	25	35	45	25	130
Groundnut (peanut)	C, high latitude	Spring	35	35	35	35	140

(continued)

Crop species	Climate	Sowing date	Duration of crop stage (days)				
			A	B	C	D	Total
Groundnut (peanut)	M	May/June	35	45	35	25	140
Lentil	C	April	20	30	60	40	150
Lentil	A	Oct/Nov	25	35	70	40	170
Peas	C	May	15	25	35	15	90
Peas	C, M	Nov, Mar–Apr	20–35	25–30	30–35	15–20	100–110
Soybeans	T	Dec	15	15	40	15	85
Soybeans	C, high latitude	May	20	25–35	60–75	25–30	140–150
Sugar, oil and fiber crops							
Castor beans	SA	March	25	40	65	50	180
Castor beans	T	Nov.	20	40	50	25	135
Cotton	M, A	Mar–May (M), Sept. (A)	30	50	50–65	45–55	180–195
Cotton	A	Mar	45	90	45	45	225
Flax	C	April	25	35	50	40	150
Flax	A	October	30	40	100	50	220
Hops	C	April	25	40	80	10	155
Safflower	M, A, SA	March/April	20–25	35	45–55	25–40	125–145
Safflower	A	Oct/Nov	35	55	60	40	190
Sesame	C	June	20	30	40	20	100
Sugarcane, virgin	T, low latitude		35	60	190	120	405
Sugarcane, virgin	T		50	70	220	140	480
Sugarcane, virgin	Pacific		75	105	330	210	720
Sugarcane, ratoon	T, low latitude		25	70	135	50	280
Sugarcane, ratoon	T		30	50	180	60	320
Sugarcane, ratoon	Pacific		35	105	210	70	420
Sunflower	M	April/May	25	35	45	25	130
Sunflower	M warm winter	Feb	45	40	60	25	170
Cereals and pseudocereals							
Barley, oats, wheat (spring types)	Central India	November	15	25	50	30	120
Barley, oats, wheat (spring types)	Mid latitude	March/Apr	20–40	25–30	40–60	20–30	130–135
Barley, oats, wheat (spring types)	East Africa	July	15	30	65	40	150

(continued)

Crop species	Climate	Sowing date	Duration of crop stage (days)				
			A	B	C	D	Total
Barley, oats, wheat (spring types)	C	Nov	40	60	60	40	200
Barley, oats, wheat (spring types)	M	Dec	20	50	60	30	160
Winter wheat	M warm winter	December	20	60	70	30	180
Winter wheat	M	November	30	140	40	30	240
Winter wheat	C	October	160	75	75	25	335
Grains (small)	M	March–April	20	30	60	40	150
Grains (small)	A	Oct/Nov	25	35	65	40	165
Maize (grain)	A	Dec/Jan	25	40	45	30	140
Maize (grain)	T	June	20	35	40	30	125
Maize (grain)	C (dry, cool)	October	20	35	40	30	125
Maize (grain)	M, C	March–April	30	40	50	30–50	150–170
Maize (sweet)	T	March	20	20	30	10	80
Maize (sweet)	M	May/June	20	25	25	10	80
Maize (sweet)	A	Oct/Dec	20	30	40	10	100
Maize (sweet)	C	April	30	30	30	103	110
Maize (sweet)	M warm winter	Jan	20	40	70	10	140
Millet	A	June	15	25	40	25	105
Millet	C	April	20	30	55	35	140
Sorghum (grain)	C, M	May/June	20	35	40	30	130
Sorghum (grain)	A	Mar/April	20	35	45	30	140
Rice	T, M	Dec; May	30	30	60	30	150
Rice	T	May	30	30	80	40	180
Forages							
Alfalfa*	frost free period		10	30	–	–	Variable
Alfalfa*	M	Mar	5	10	10	5	30
Alfalfa*	C	Jun	5	20	10	10	45
Bermuda (for seed)	A	March	10	25	35	35	105
Bermuda (for hay)	A	–	10	15	75	35	135
Grass Pasture	Frost free period		10	20	–	–	Variable
Sudangrass (first cutting cycle)	A	Apr	25	25	15	10	75
Sudangrass (other cutting cycles)	A	June	3	15	12	7	37

(continued)

Crop species	Climate	Sowing date	Duration of crop stage (days)				
			A	B	C	D	Total
Fruit trees, vines and shrubs							
Banana (year 1)	M	Mar	120	90	120	60	390
Banana (year 2)	M	Feb	120	60	180	5	365
Citrus	M	Jan	60	90	120	95	365
Deciduous orchard	C high latitude	March	20	70	90	30	210
Deciduous orchard	M,C low latitude	March	20–30	50–70	120–130	30	240–270
Grapes	Low latitude	April	20	40	120	60	240
Grapes	M, C mid latitude	Mar/April	20–30	50–60	40–75	60–80	205–210
Grapes	High latitude	May	20	50	90	20	180
Olives	M	March	30	90	60	95	365
Pineapple	T		60	120	600	10	790
Pistachios	M	Feb	20	60	30	40	150
Walnut	C high lat	April	20	10	130	30	190

Adapted from Doorenbos and Pruitt (1977) and Allen et al. (1998). This Table should be used with caution as the actual duration of phases may change for different regions, cultivars and weather conditions of each year

*For the first cut cycle use durations twice the values shown

Cimates: *M* Mediterranean, *A* arid, *SA* semi-arid, *C* continental, *T* tropical

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