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Plant Growth and Development

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Economic yield of vegetables and other food plants is defined as the weight per plant (plant yield in pounds/plant) and weight per unit area (crop yield in tons/acre) of the edible portion of the plant. *Biological yield*, or productivity, refers to the production of biomass, which includes the economic yield plus all remaining supporting structures (roots, leaves, and stems) not used for consumption. The ratio of economic yield to the biological yield constitutes the *harvest index* and is a measure of the inherent efficiency of the plant and the crop systems to accumulate or partition the products of photosynthesis into economic yield. Over the years, the harvest index and crop yield have generally improved for many crops through practices that favor growth and development of the edible part at the expense of the nonedible portions.

Most vegetables crops are fast-growing annuals or biennials or perennials grown as annuals. Maximum yield of the economic portion of vegetables depends on supplying the crop with the correct amount and balance of growth inputs, such as carbon dioxide, water, mineral nutrients, heat (temperature), and light. The balance or relative proportion of growth inputs (growth factors) varies throughout the life of the plant and ultimately determines crop yield.

Any input that is sufficiently out of balance to disrupt or limit the desired pattern of plant growth and development is said to be limiting and generally decreases crop yield. How much crop yield is decreased depends on the level

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of deficiency or the excess of the limiting factor and its duration and when it occurs. The grower's challenge, therefore, is to understand the factors that limit plant growth and development of crop yield and to keep them in desirable amounts and proportions throughout the life of the plant.

GROWTH FACTORS

To grow and produce optimum yields, the vegetable plant must be supplied with chemical (food) energy, heat (optimum temperature), and a balance of water, nutrients, and growth regulators.

Chemical Energy

Photosynthesis. All living cells obtain their energy from oxidizable fuels called foods. These food molecules are chemically very diverse. Complex food substances such as carbohydrates, fats, proteins, and related materials are synthesized from simple manufactured compounds such as glucose, which in turn were formed from the simpler substances CO_2 and water through the process of photosynthesis in living green cells.

Respiration. In contrast to photosynthesis, respiration is essentially an energy-releasing reaction. The potential chemical food energy originating through photosynthesis is transformed into various kinds of kinetic energy as well as being used in all growth and development stages of plants and animals. In this way, the light-energy reserve built up in crop plants through photosynthesis becomes available not only for the growth and development of crops but for all humankind.

Net Photosynthesis. The difference of photosynthesis minus respiration is termed *net photosynthesis*. Net photosynthesis is simply a measure of the total photosynthesis of the plant less any respiration which occurred during its growth. Further, any factors that limit net photosynthesis limit plant productivity; thus, there is considerable interest among crop physiologists to increase plant productivity by either decreasing respiration or increasing photosynthesis.

Since plant productivity (biological yield) can be equated with net photosynthesis, many research workers have attempted to relate biological and economic yields with rates of net photosynthesis when these rates were measured for isolated leaves or leaf sections over a short duration of time (hours). However, generally there is no discernible relationship between yield and these net photosynthetic rates because numerous factors interact throughout the entire growth and development of plants that ultimately influence the final yield.

The banker's statement "what will eventually determine the net worth of an individual is not necessarily the size of his/her net salary, but how much of this money is wisely saved or reinvested into productive enterprises" is equally applicable in the plant's attainment of crop yield. Regardless of the net photosynthetic rates, high yields would only be expected from those plants that utilize the products of photosynthesis in a timely and efficient manner. The grower must therefore supply growth inputs and utilize the best cultivars, planting dates, and production practices to maximize net photosynthetic rates as well as to obtain the optimum pattern of growth and development.

Temperature

The optimum temperature range is defined as the range within which maximum photosynthesis and normal respiration take place throughout the life cycle of the plant and within which the highest marketable yields are obtained. Diurnal temperatures—alternating day and night temperatures—favor increased yields. Higher day-time temperatures followed by lower night-time temperatures are nature's 24-hour diurnal cycle of utilizing the sun's energy for making abundant substances during the day and utilizing them for making new growth and in storage during the night. With all vegetable crops, the optimum day temperature range is higher than the optimum night temperature range, indicating that the optimum temperature range for photosynthesis is higher than the optimum temperature range for cell division and cell elongation.

Most of the cell division and production of protoplasm for vegetable crop plants is made at night. Within the optimum range, the rate of cell division and growth is in general proportional to temperature; comparatively high rates will take place within the upper half, and moderate rates will take place within the lower half. For optimum yields, night temperatures in the upper half of the optimum range are preferred during the vegetative phase of plant growth, while temperatures in the lower half are preferred during the reproductive phase. In addition, the quality of vegetable crops is generally improved when development of the edible part occurs in the lower half of the optimum night temperature range. At relatively low temperatures, this rate of cell division and growth is slow and sugars tend to accumulate, and plants develop less fiber and strong flavors, such as pungency in onions and crucifers. At relatively high temperatures, growth is rapid, and sugars, instead of accumulating, are used in respiration and growth.

When plants are grown at temperatures either above or below the optimum night temperature range, net photosynthesis is decreased, resulting in decreased yields and quality. Flower initiation and fruit set are often affected at non-optimal temperatures.

In addition to influencing yield and quality, temperature can also affect the rate of plant development. For many vegetables, including peas, sweet corn, broccoli, and tomatoes, the concept of *heat units* is used to make predictions of crop maturity. The concept of heat units was introduced in the 1940s as an effort to facilitate harvest scheduling. It is based on the principle that the quantity of heat, not days from planting, determines when a crop will mature.

Heat units (sometimes called degree days) are calculated as the deviation of the daily mean temperature from the base or minimum temperature for growth. The base temperature is usually defined on a physiological basis as the lowest temperature at which plant development will proceed. The standard base temperatures for vegetables varies considerably with crop species, ranging from 35°F for onions to 60°F for eggplants. The minimum temperature for tomatoes is 50°F; thus, on a day with a maximum temperature of 78°F and a minimum of 58°F, the mean temperature would be 68°F, providing 18°F of heat units toward tomato maturity. If the daily mean is lower than the base temperature, no heat units are accumulated. The harvest date can be ascertained by an accounting of cumulated heat units (CHU's).

Commercial growers and processors find the heat-unit system very valuable in handling their crops. In addition to predicting crop maturity, heat units can also be used to schedule planting dates for a desired succession of harvests. For this purpose, the grower uses historical temperature averages to predict the date on which the number of heat units required for a specific cultivar to mature will have accumulated. Precision is gained when temperature records are taken near the planting area.

The use of CHU for determining planting dates has often been criticized since temperature is only one of many factors that influence plant growth and maturity. Some recognized limitations of the heat-unit concept include:

- Soil temperature has a very significant effect on plant growth, especially seed germination and early growth. Organic and plastic mulches tend to influence soil temperature more than air temperatures, thus affecting the CHU needed.
- Differences in day-night (diurnal) shifts, photoperiodic effects, and the differential effects of temperature on various stages of plant growth affect the accuracy of the CHU system.
- Rate of plant growth may not be equally affected by all temperatures above the minimum. To account for different growth-rate responses to temperature, numerous methods of calculating CHU's have been devised, especially when temperatures exceed the maximum for growth.

Nutrients and Water

The supply of nutrients and water influence growth and yield in many ways other than their direct contribution to the photosynthetic processes.

Most mineral absorption by plants occurs near the apexes of young roots. The older roots develop layers impervious to water and are relatively ineffective in the absorption of ions. The absorbing areas of roots have to be in contact with the immobile or adsorbed ions such as K^+ or $H_2PO_4^-$ to absorb them from the soil. Young plants with limited root systems are inefficient absorbers of these ions and usually require high fertility to make optimum growth. A discussion of the sources, functions, and application of the essential nutrients is briefly covered in Chapter 6.

Succulent vegetables are very high in water content, with lettuce having about 95 percent moisture. To maintain succulence and tenderness, the plant usually requires a continuous supply of water throughout its development. Large losses of water occur from plants because of the structure of leaves. They consist essentially of layers of photosynthetically active cells, well supplied with vascular elements and encased in a fairly waterproof but perforated layer, the epidermis. The wet surfaces of the mesophyll cells evaporate large quantities of water into the inter-cellular spaces. Since the open stomates occupy from 1 to 3 percent of the surface of a leaf, they offer little resistance to the diffusion of water to the atmosphere. Under conditions of high humidity and still air, net loss from the leaf is greatly diminished, but with low humidity and turbulent air, water vapor is quickly removed from the leaf surface, greatly increasing the rate of transpiration.

Even with the soil well supplied with moisture, a plant may become deficient during the middle of a bright, warm day. As a result, guard cells of leaves become flaccid and stomates close, restricting CO_2 uptake as well as loss of water and thus decreased photosynthesis. As plants become more deficient in moisture, stomates may remain closed for longer periods during the day. Cell division and enlargement are dependent upon plant turgidity. If a plant loses water, even though not wilted, the rate of growth is reduced, and the products of photosynthesis may accumulate even with reduced photosynthesis.

Water is absorbed by young roots primarily by osmotic forces. The soil forms a reservoir that alternately is filled and depleted. When the soil is filled and the free water removed by percolation, it is held at approximately 0.1 to 0.3 bar water tension and is said to be at *field capacity*. Soil moisture held between field capacity and 1.0 bar is easily removed by roots, but as the soil becomes progressively desiccated, absorption by roots becomes more difficult. Finally, at approximately 15 bars, the rate of absorption by the plant roots will be so slow that the plant will remain wilted and will eventually die if water is not added. The soil water content at this stage is called the *permanent wilting percentage*. Moisture retained in the soil between the field capacity and the permanent wilting percentage is said to be usable by plants and as such is called *available water*. Water held at tensions greater than 15 bars is unavailable to most plants. Soils vary widely in their available water-holding capacity. It is low in coarse-textured soils and relatively high in fine-textured soils. The soil moisture content at both the field capacity and permanent wilting percentage increases as the soil changes from coarse-textured to fine-textured; however, with changes in the soil texture, the moisture content at field capacity increases more rapidly than that at the permanent wilting percentage, thus accounting for the sizeable increase in available soil moisture in the fine-textured soils.

Growth Substances

Growth hormones are known to be involved in many plant responses. They may be classified roughly as auxins, gibberellins, cytokinins, and inhibitors.

The auxin indole-3-acetic acid is generally distributed in plants. It is known as the growth hormone and is vitally involved with cell elongation, proliferation, and differentiation. Many plant responses, such as apical dominance, phototropism, geotropism, and root initiation, can be traced to auxin. Its content in plants is controlled by the enzyme indole acetic acid oxidase. Some of the synthetic auxins, such as 2,4-D, are much more active than the plant auxin primarily because they are not readily metabolized by plant enzymes.

Applied gibberellins have been shown to cause dramatic responses in stem elongation of plants. These growth substances are natural constituents of plants and are known to participate in the endogenous control of growth activities and a variety of developmental activities, including dormancy, flowering, and responses to light and temperature. Dwarfness in some plants has been shown to be due to a deficiency of gibberellin.

The cytokinins include a diverse group of growth substances. Unlike auxins and gibberellins, they are nonacidic and relatively immobile. Cytokinins are apparently necessary for cell growth and differentiation but also have other interesting physiological roles. Detached leaves treated with cytokinins stay green longer and retain their proteins. Constituents tend to accumulate in areas where cytokinins are applied, indicating a mobilizing effect.

In addition to growth-promoting substances, plants also contain inhibitors. These are associated with such plant responses as restricted growth, dormancy, abscission, and senescence. The inhibition of growth during fruiting is an important factor in reproduction. Dormancy is important during periods unfavorable for growth and for storage. Dormant buds of the potato have been found to be high in inhibitors that decrease when dormancy is broken. Abscission seems to be a protective mechanism of plants and is enhanced by abscissic acid and ethylene, both of which are associated with senescence.

The use of chemicals to control certain phases of growth has become important in the production of many crops. The control of fruit setting, fruit ripening, sex ratios, sprouting in storage, dormancy, and weeds are a few of the many uses.

GROWTH INPUTS AND QUALITY

Proper application and timing of growth inputs directly affect the quality of the edible product. Yield and quality often compete for the available plant food energy (products of photosynthesis), and a grower must often choose which component (yield or quality) is most important. In many cases, however, cultivars and grower practices that will provide an acceptable compromise between yield and quality can be selected. Conversely, faulty grower practices may cause severe limitations in one or more growth inputs, resulting in drastic reductions in both yield and quality. Although detailed examples and physiological explanations of this principle are reserved for more advanced texts, three conclusions can be drawn:

1. In general, both the market and the eating quality of vegetables are closely correlated with yield. Recommended cultural practices that permit normal plant growth will generally result in desirable yield and quality. Conversely, serious imbalances in growth inputs often result in poor quality and yield. Water or nitrogen shortages will generally reduce both quality and yield of most vegetables. Excess nitrogen during early plant growth can delay fruit set, which limits fruit size (quality) and yields of many crops because the duration of the yield-producing phase is too short for optimum growth. Weed problems, which limit light and space and may limit water and nutrients, generally result in low yields of non-marketable produce. Excessive infestation of insects and/or diseases can reduce plant growth, resulting in poor yields and quality.
2. Situations may arise or the grower may select cultivars and/or cultural practices that favor high quality (size, protein or sugar content, etc.) at the expense of yield. Cultivars that tend to accumulate high sugar contents and/or practices such as reducing water and nitrogen during the latter part of the yield-producing phase will produce high-quality fruit; however, the yield will be reduced. Wide spacing and/or fruit thinning may give large fruits for specialty markets, but the total yield potential is reduced.
3. Situations may arise or the grower may select cultivars and/or cultural practices that favor high yields at the expense of quality. Abundant water or nitrogen during the yield-producing phase will frequently increase yields; however, the sugar content and other quality characteristics may be reduced. Frequently the quality, especially the size and appearance, of high-yielding cultivars is inferior to that of low- to moderate-yielding cultivars.

PATTERNS OF PLANT GROWTH AND DEVELOPMENT

The growth and development of vegetables can be divided into two distinct, though overlapping, phases—vegetative and reproductive. Although all species have both vegetative and reproductive phases, some vegetables are products of the plant's growth in the vegetative phase (leaves, stems, buds), while others are products of growth occurring predominantly in the reproductive phase (fruit, seed, and storage organs). A basic knowledge of the differences between these two phases as they relate to crop yield and quality is important for the student or farmer involved with vegetable production.

How close the actual yield obtained by a farmer in any given situation approaches the potential yield of a crop under ideal conditions depends on the degree to which the desired patterns of development are achieved. The desired pattern of growth and development for most vegetable crops is (1) uninterrupted, rapid crop growth leading to a predetermined vegetative biomass possessing the structural and productive potential for high crop yields, followed by (2) differentiation (fruit set, tuber or bulb initiation, etc.) and growth of yield-producing organs using the already prepared vegetative plant.

With the vegetative-type species, such as lettuce and spinach, the crop is harvested prior to reproductive growth (flowers and fruit) and major crop losses can result when premature flowering occurs before the crop plant reaches desirable harvest size and quality. The plants should therefore be maintained in an active vegetative state by providing a continuous supply of growth inputs and avoiding any unnecessary stress that could trigger premature onset of flowering and fruiting. With crops in which the edible parts are predominantly developed during the reproductive phase, such as tomatoes and muskmelons, yield and quality depend upon the achievement of a desirable vegetative structure, an adequate growing environment and time (duration) that would allow the plant's yield potential to be realized.

The Vegetative Phase—Carbohydrate Utilization

The vegetative phase includes seed germination and growth of the primary supportive structure. Germination of a seed begins with the imbibition of water. The embryo is stimulated to activity with the radicle beginning to elongate. It pushes through the seed coat weakened by enzymes. Cell division in the apex produces new cells for the developing root and also for the root cap, which prevents injury to the young root as it penetrates the soil. Growth activity in the shoot growing point follows that in the root, the shoot of each kind of seed having its particular method of penetrating the soil. The food reserves in the seed should be sufficient to last until photosynthesis is established.

Growth in the vegetative phase is associated with three important processes: cell division, cell enlargement, and initial stages of cell differentiation. Large quantities of carbohydrates are required for all three processes. Thus, the plant utilizes carbohydrates for growth in the vegetative phase, and the rate of plant growth and ultimately the size of the edible part (lettuce head, celery stalk, etc.) are dependent upon the daily availability of carbohydrates (net photosynthetic rate) as well as the inherent plant growth potential—i.e., the plant's capacity to divert or reinvest its net photosynthetic gain into new photosynthetically useful plant parts (leaves and supporting structures). Although a continuous source of carbohydrates through photosynthesis is obviously essential for optimum yields, the plant growth potential generally determines plant productivity (plant size) more than the rate of net photosynthesis.

The eating quality of the vegetative types is also influenced by plant growth rate. A relatively rapid, steady growth in which nearly all the available carbohydrates are used for new growth results in succulent, tender, crisp produce. Conversely, a relatively slow, non-uniform, stressed growth, in which some of the available carbohydrates are used to thicken and mature existing tissues, results in woody, hard, off-flavor produce.

Factors limiting the development of plant growth potential may be genetic or environmental. Thus, vegetable growers should select cultivars that have high growth potentials and are well adapted to local climates. Growers can maximize the chance of obtaining the inherent high plant growth potential and marketable crop yield potential of these cultivars by (1) planting at the proper time to allow growth during a period when the environment is most favorable for photosynthesis and net assimilation rate; (2) establishing the crop at the proper spacing and density to assure maximum development of marketable edible parts per acre (marketable crop yield); (3) selecting and preparing soils that are well drained and friable to optimize root growth and nutrient uptake; (4) supplying adequate, but not excessive levels of water and nutrients throughout the life of the crop; (5) maintaining healthy, photosynthetically efficient plants through the judicious use of recommended pest-control systems; and (6) using mulches and row covers to alter soil temperature, conserve water and nutrients, and control weeds.

The Reproductive Phase—Accumulation or Storage of Carbohydrates

Relatively little cell division occurs during the reproductive phase. Several important processes are associated with the reproductive phase: (1) the maturation and thickening of tissues and fibers laid down during the vegetative phase; (2) production of plant growth regulators necessary for the development of flower-bud primordia; and (3) development of flower buds, flowers, fruit, and seed, or the development of storage organs (bulbs, storage roots, tubers, etc.). Although some of the available carbohydrates are used for continued growth and thickening of the vegetative structures, most are accumulated in the fruit, seed, or storage organs.

With the reproductive-phase crops, there is a gradual transition from the vegetative to the reproductive phases; however, the plant processes are never totally reproductive and a vegetative-reproductive balance occurs with every crop. The reproductive-phase vegetables can be divided into two distinct groups: (1) those that have dominance of the vegetative phase during the first part of the growing season and dominance of the reproductive phase during the latter part and (2) those that have dominance of the vegetative phase during their first period and a relatively equal balance of vegetative and reproductive during the second period. The first group includes determinate fruit crops (main axis terminates in a flower bud), such as sweet corn and certain cultivars of tomatoes, and beans and crops grown for their storage organs (bulbs, storage roots, tubers, and fleshy roots). The second group includes the indeterminate fruit crops (main axis remains vegetative and flowers form on auxiliary buds), such as bell peppers, cucurbits, eggplants, and certain cultivars of tomatoes and beans.

The vegetative and reproductive phases can be altered by environmental conditions and cultural practices. Temperature and light are two important environmental factors that affect the duration and pattern of crop development.

Temperature and Vernalization. The yield potential of a reproductive-type vegetable crop is dependent upon the size of the vegetative structure and the level to which the vegetative parts have been conditioned for reproduction. Plants grown under optimum diurnal temperatures will develop a large, rigid plant structure that is physiologically prepared (conditioned) for optimum utilization of the products of photosynthesis to set, develop, and mature high yields of fruit and storage organs.

Many of the vegetative-type crops may be induced to prematurely flower when the young plants are exposed to temperatures below the optimum night temperature range. The biennials and some annuals are subject to this low-temperature induction of flowering, termed *vernalization* (Table 3.1). The premature appearance of a flower stalk in vegetables, called *bolting*, can cause substantial yield loss, particularly in crops such as celery that require little cold exposure. Bolting is a problem that occurs frequently in winter production areas and occasionally in the North. Under favorable temperatures, the normal edible parts of the quantitative annuals (lettuce, sprouting broccoli, cauliflower, spinach, Chinese cabbage, etc.) and the biennials (cabbage, carrots, celery, onions, etc.) are harvested for consumption prior to flower initiation. These same plants, however, will prematurely bolt and flower before they

Table 3.1. Flowering Response of Vegetable Crops to Exposure to Low Temperature (Vernalization)

Classification[a]	Vegetable Crop
No exposure needed to induce flowering . . .	Snap beans, lima beans, sweet corn, Irish potatoes, tomatoes, peppers, cucumbers, muskmelons, watermelons, pumpkins, squashes, sweet potatoes, eggplants, garden peas (Ecvs),[b] asparagus
Quantitative (preferential)	Cauliflower, sprouting broccoli, lettuce, radishes, spinach, Chinese cabbage, kohlrabi, turnips, garden peas (Lcvs),[b] endive (Ecvs), chicory (Ecvs)
Obligate (qualitative)	Beets, cabbage, carrots, celery, Swiss chard, collards, kale, leeks, onions, parsley, parsnips, rutabagas, brussels sprouts, overwintering cauliflower (heading broccoli),[b] endive (Lcvs), chicory (Lcvs)

Vegetable crops flower during periods of moderate to warm weather. However, with many vegetable species, flower initiation requires (obligate) or is hastened by (quantitative) exposure of the plant to a period of cool weather. With most of these crops, flower initiation does not occur during the chilling period, but only after the plants are exposed to higher temperatures following chilling. Normally, to be effective the vegetable plants that respond to chilling should be partly developed (physiologically mature) before they receive the cold period. Most of them are not greatly affected by the cold if they are too small. The chilling period should average below 45°F (7°C) and continue for two to eight weeks. The cooler the temperature, the shorter the period of exposure.

[a] *Obligate*—Absolute requirement for vernalization and will not flower without the crops' minimum chilling needs. *Quantitative*—Optional requirement for low temperature treatment. Hence, flowering is hastened or promoted by a cool weather period but will occur in unvernalized plants (i.e., plants not exposed to cool weather).

[b] Ecvs—Early-maturing cultivars. Lcvs—Late-maturing cultivars.

reach marketable size when the seedling plants are subjected to temperatures somewhat below the optimum range, i.e., between 40° and 50°F for 4 to 8 weeks, depending on the species and cultivar.

Light and Photoperiod. The intensity of light and the relative length of the light and dark periods can dramatically affect the pattern of crop development and yield. The light intensity available to a leaf varies considerably and is influenced by (1) the season of the year, (2) latitude, (3) elevation, and (4) shading (clouds, humidity, plant density, etc.). As with temperature, light has an optimum range for growth, and this favorable light range varies with the crop species. Within this range, assuming there are no other limiting factors, the rate of net photosynthesis is high and there are abundant carbohydrates available for growth. Outside the optimum light range, net photosynthesis is reduced and growth and yield decline.

The length of the light and dark period affects plant growth and development in two ways: (1) determines the relative amount of carbohydrates or net photosynthetic products made by all crops and (2) regulates the time of flower bud formation of many crops and the time of initiation of storage organs of such crops as onions, garlic, Irish potatoes, and sweet potatoes. Long daylengths result in high rates of net photosynthesis, favoring high growth and yield potentials. This explains, at least partially, why high marketable yields of many vegetable crops are achieved in the northern latitudes during the summer months. The importance of daylengths to net photosynthesis means that vegetable growers should plant early to benefit from the long days of June.

The relative length of day and night influences the initiation of flowers and storage organs with many vegetable crops. Plant development reactions to daylength are called *photoperiodism* or photoperiod responses. Vegetative species vary considerably with regard to their photoperiodic response to flowering or formation of storage organs (Tables 3.2 and 3.3). For example, spinach flowers and onions initiate a bulb only when a critical or threshold daylength is reached. At the threshold daylength or longer, spinach plants flower and onion plants bulb; such species are called *obligate* long-day plants. For each obligate long-day species, the plant remains vegetative and fails to flower or set storage organs until its threshold photoperiod is reached. The length of the threshold photoperiod may vary considerably among cultivars within a given species such as onions. Other species such as carrots flower more profusely under relatively long photoperiods than short days. Such spe-

Table 3.2. Flowering Response of Vegetable Crops to Photoperiod

Classification[a]	Vegetable Crop
Day neutral	Asparagus, cucumbers, muskmelons, watermelons, squashes, pumpkins, tomatoes, peppers, eggplants, cabbage, broccoli, cauliflower, brussels sprouts, kohlrabi, potatoes, garden peas (Ecvs)[b], snap beans, lima beans, lettuce ("Great Lakes" types), onions
Long day[c] (short night)	Spinach (O)[d], endive (O), chicory (O), beets, radishes, parsnips, carrots, celery, garden peas (Lcvs)[b], lettuce ("Grand Rapids" types), Swiss chard, Chinese cabbage, turnips
Short day (long night)	Sweet potatoes (O), sweet corn

[a] Day neutral—No preferential photoperiod for flowering. Long day—Flower only if photoperiod is equal to or exceeds threshold (obligate), or flower best under relatively long days (quantitative, or preferential). Short day—Flower only if photoperiod is equal to or less than threshold (obligate), or flower best under relatively short days (quantitative, or preferential). Obligate plants will not flower without being exposed to their critical or threshold daylength. With quantitative plants, flowering is hastened or promoted by exposure to their preferential photoperiod (either short or long days), but flowering will occur in nonpreferential photoperiods (either long or short days).

[b] Ecvs—Early-maturing cultivars. Lcvs—Late-maturing cultivars.

[c] Some species such as many of the *Brassica* crops (cabbage, broccoli, cauliflower, brussels sprouts, and kohlrabi) are preferential long day with plants that have not been exposed to a low-temperature treatment (unvernalized plants). Thus, with these unvernalized *Brassica* plants, bolting and flowering tends to occur more readily under long days than short days. After these plants are vernalized, photoperiod has no effect on flowering.

[d] With the long-day and short-day plants, all species listed are quantitative except for those marked with an "O" (obligate).

Table 3.3. Formation of Underground Storage Organs of Vegetables in Response to Photoperiod

Classification[a]	Vegetable Crop
Day neutral	Carrots, beets, turnips, radishes
Long day (short night)	Onions (O)[b], Garlic (O)
Short day (long night)	Potatoes, sweet potatoes, yams, cassavas

[a] Day neutral—No preferential photoperiod for storage organ formation. Long day—Develop storage organs only if photoperiod is equal to or exceeds threshold (obligate) or develop storage organs best under relatively long days (quantitative or preferential). Short day—Develop storage organs only if photoperiod is equal to or less than threshold (obligate), or develop storage organs best under relatively short days (quantitative, or preferential).

[b] O—Obligate photoperiodic requirement. All species listed as short day are quantitative.

cies are referred to as *quantitative* (preferential) long-day plants, since flowering is not prevented under short photoperiods. Sweet potato cultivars only flower at a specific daylength or shorter and are referred to as *obligate* short-day plants. Sweet corn flowers and Irish potato sets tubers best under relatively short photoperiods and thus are considered to be quantitative (preferential) short-day plants with regard to these responses.

The majority of vegetable crops are classified as day-neutral. These crops will flower or form storage organs under either long- or short-day photoperiods (Tables 3.2 and 3.3).

The yield of photoperiodic plants (plants in which formation of flowers or storage organs is affected by the relative length of day) can be profoundly influenced by daylength. Photoperiodic response also varies among cultivars of the same crop species. Thus, for photoperiodic crops, daylength must be considered an essential growth input, and regional and local adaptation of species and cultivars is required.

Since the relative rate and duration of growth in each phase of plant development directly affect crop yield, the grower can adjust cultural practices and manipulate the environment and thus alter the pattern of plant growth and development to favor increased yield and/or quality. Methods of manipulating crop growth and development are briefly discussed under the heading "The Vegetative Phase" and are discussed in more detail throughout the remainder of this text.

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