Reprinted from: Issues in new crops and new uses. 2007. J. Janick
and A. Whipkey (eds.). ASHS Press, Alexandria, VA.

Phenology of Sesame*

D. Ray Langham

This paper describes the development of the sesame (*Sesamum indicum* L., Pedaliaceae) crop from seed to harvest in terms of phases and stages. This description is based on experience over the last 40 years with over 38,000 lines of sesame grown in 88 nurseries and over a quarter million hectares of commercial fields in 9 states in the US and 10 foreign countries. The lines include 2,925 introductions from 67 countries and crosses between those lines. The observations have been made under conditions varying from irrigated to semi-irrigated to rainfed; from rain in all phases to drought; from low to high fertility; from early to late plantings; from 17 to 100 cm row spacing; from sandy to very heavy clay soils; under all levels of weed infestation; from laser leveled fields to sloping hills; from sea level to 1,000 meters elevation; in moderate to very high temperatures (52°C); after very high winds (150 km/hr), dust storms, hurricanes, lightning strikes, light to heavy hail, frosts, hard freezes, and snow.

Sesame is a survivor crop. For 5,000 years it has been planted by subsistence farmers in areas that will not support the growth of other crops or under very difficult conditions with drought and/or high heat. In some countries it is grown after the monsoon on residual moisture with no rains during its production cycle. In some countries it is grown in the monsoon season and subject to daily rains during parts of its cycle. In several countries it is the last crop that can be grown at the edge of deserts, where no crops grow. Very little sesame is grown under high input conditions, although yields improve dramatically as inputs increase. Most current sesame cultivars have been farmer selected or bred to retain the survivor qualities. In the US sesame has been grown in Arizona under high inputs and in Texas/Oklahoma under low inputs with all levels of inputs in between. While there may be exceptions to the following description, the phenology of any crop must start somewhere, and this is the start for sesame.

Sesame germplasm has tremendous variability. The author has identified 412 different characters with wide differences in some of these characters in the world collection. Different genotypes can develop very differently under the same conditions, and the same genotype can develop very differently under different conditions. In general, this description will be centered on the US improved cultivars. Each stage will be described in the following sections: definition, time from planting of the stage, length of time within the stage, description, and factors that shorten and/or lengthen the stage. Table 1 summarizes the phases and stages.

The key factors affecting the length of the various stages are as follows:

- More moisture will shorten germination and seedling stages but will lengthen rest of the stages.
- Higher fertility will shorten seedling stage but will lengthen the rest of the stages. (Effect on germination stage is unknown.)
- Increased degree days over normal will shorten the vegetative and reproductive phases.
- Cool night temperatures will lengthen the ripening phase and full maturity stage.
- Low humidity, wind, and/or heat will shorten all of the drying stages.
- Frost may and hard freeze will terminate the plants at any stage. In a freeze even though plants will be brown in 3–5 days, they will not be dry for 7–10 days.

This paper describes 11 stages which exceeds the number in most other crops. The phenology analysis is intended for 3 uses: for researchers to understand the growth of sesame, for farmers to get visual cues for timing of farming operations, and for plant protection personnel to understand the vulnerable periods of the crop. This paper focuses on the researchers but includes the stages of interest to the farmer. For example, the pre-reproductive appearance of buds is a visual cue for adding fertilizer, setting up the first irrigation, and warning that soon the plants will be too tall to cultivate. Few phenologies include a germination stage, but sesame is a vegetable size seed planted with field crop equipment and conditions. Understanding the germination stage can lead to better strategies to attain a good stand.

---

*Randy Landgren provided a sounding board for the original delineation of the stages and provided some of the names. Amram Ashri (Israel), Malcolm Bennett and Loretta Serafin (Australia),Wasana Wongyai (Thailand), Churl Kang (Korea), and Agustin Calderoni (Argentina) provided helpful comments and editorial work.

There is a tremendous amount of variability in the vegetative, reproductive, ripening, and drying phases of sesame. Sesame is an indeterminate species, and thus there is an overlap between the reproductive, ripening, and drying phases. The seed in the first capsules to form may be mature while the upper part of the plant is still flowering, and there may be dry capsules before the top capsules have matured. The only other known attempt at a sesame phenology was included in a Masters thesis, which divided the phenology into three phases: the establishment phase (0–38 days DAP), the growth phase (38–80 DAP), and the storage phase (56–98 DAP) (Triangtrong 1984). That phenology reflects what is actually happening within the plant, while the phenology in the present paper reflects what can be seen in the field. Table 2 shows the range and mean number of days for each phase for nurseries in Uvalde, Texas, from 2000–2004 using data from 20,281 plots.

Table 3 shows the ranges for lines with commercial potential in the US. The lines in Table 3 have narrower ranges in most phases, and the means are lower than those in Table 2. To date, very early lines do not provide adequate potential yield, and very late lines have a production cycle that extends into a bad harvest window, which can reduce actual yields substantially and degrade the quality of the seed. In Australia these ranges would be vegetative 28–37 days, reproductive 35, ripening 20, and drying 40 (M. Bennett, pers. commun.). Often the cycles are shorter in the tropics.

FACTORS THAT AFFECT PHASES AND STAGES

Populations

In the US, all commercial sesame is planted mechanically and not thinned. The author does not thin the nurseries. The observations in this paper are based on unthinned stands ranging from very high (246 plants/m^2)

Table 1. Phases and stages of sesame.

Stage/Phase	Abbrev	End point of stage	DAP^z	No. weeks
Vegetative	VG			
Germination	GR	Emergence	0–5	1–
Seedling	SD	3rd pair true leaf length = 2nd	6–25	3–
Juvenile	JV	First buds	26–37	2–
Pre–reproductive	PP	50% open flowers	38–44	1–
Reproductive	RP			
Early bloom	EB	5 node pairs of capsules	45–52	1
Mid bloom	MB	Branches/minor plants stop flowering	53–81	4
Late bloom	LB	90% of plants with no open flowers	82–90	1+
Ripening	RI	Physiological maturity (PM)	91–106	2+
Drying	DR			
Full maturity	FM	All seed mature	107–112	1–
Initial drydown	ID	1st dry capsules	113–126	2
Late drydown	LD	Full drydown	127–146	3

^{z}DAP = days after planting. These numbers are based on S26 in 2004 Uvalde, Texas, under irrigation.

Table 2. Range and mean of number of days in phases for all Sesaco germplasm.

	Days from planting		Phase length (days)	
Phase	Range	Mean	Range	Mean
Vegetative	29–59	42	29–59	42
Reproductive	56–116	89	16–70	47
Ripening	77–140	108	(14)^z–54	11
Drying	102–181	150	11–57	38

^{z}In some lines, there are dry capsules above green leaves while the upper part of the plant is still flowering creating a negative range.

to very low populations (1 plant/m^2—in 1989 there was a single plant with over 2,200 capsules that produced 428 grams of seed). In the US, commercial fields are planted with planters ranging from row planters to drills. Farmers have planted from 2 to 9 kg of seed per ha (570,000 to 2,540,000 seeds per ha). Farmers who do a lot of tillage work to prepare a good seed bed, have relatively uniform soils, plant small fields, drive slowly, and continually check/modify the placement of the seed, can get a good stand with low planting rates. These farmers plant about 2 to 3 kg/ha. However, many farmers are reducing tractor passes across the field, do not have uniform soils, plant large fields, drive faster, and do not have time to continually check/modify the placement of the seed. These farmers plant about 3 to 6 kg/ha. Drills are very imprecise (even modern drills with good depth control), and those planters end up planting between 6 to 9 kg/ha. In addition to the land preparation and planting practices, the germinating seedlings must face environmental factors such as rain that will create crusts before emergence, a sudden cold front that will reduce the growth rate before emergence, winds that will blow sand and damage or cover them, insects at the seedling stage, etc. Additional seed is a form of insurance for a good stand, because there is no agronomic practice than can improve a poor stand other than replant. The author has been planting 4+ ha nurseries in mid-May on the same farm in Uvalde since 1988 with the same planter and the same planting rate (about 2 kg/ha). In that time, the populations have averaged from 12.5 to 30.8 plants per linear meter. The environment from the emergence through the juvenile stage is more important for final plant number than the seeding rate.

The population density affects the phenotype and the length of time of the phases and stages. As the plants compete for light, high populations grow taller faster than low populations. However, unless there is considerable moisture and fertility, the final height is usually lower in high populations. Given the same moisture and fertility, high populations will use up the resources sooner and will go through the whole development faster from the mid bloom to the late drydown stage. High populations will lose lower leaves faster since the light will not penetrate the canopy. Since often populations across a field are not uniform, there will be some areas ready to combine sooner than others. In moderate to high populations, there will be dominant plants and minor plants. The dominant plants generally emerged faster and since early growth is a geometric progression, they end up with larger cotyledons leading to larger leaves and deeper roots. These dominant plants will begin shading the other plants which will end up shorter with lower production. Compared to the dominant plants, the minor plants will start flowering later, will stop flowering sooner, and will dry down sooner. Most of the data in this paper is based on the dominant plants.

Some of the observations in this paper will not be seen in research nurseries throughout the world. In most nurseries the plots are planted at specific distances and then thinned to the desired population. The plants are not normally viewed at either high or low populations. In addition, the plants are grown with optimal moisture (irrigations) and fertility. The author plants nurseries under farmer conditions in each area. If it is in a maize area row spacing is 76 cm, in a peanut area 91 cm, in a cotton area 102 cm, etc. The nurseries are either fully irrigated, semi-irrigated, or rainfed, and the fertility matches local farmer practices. Although it has been shown that earlier plantings (once the soil temperatures reach 21°C) have higher yield, if the practice is to plant the cotton first followed by the sesame, the nursery is planted later.

In numerous yield analyses, the author has found little difference in the yields of populations between 10–26 plants/m^2 with lines that adjust to the population, i.e., produce more branches in low populations. When the stands are uniform, even lower populations plants can provide equal yields, and when there is adequate moisture and fertility, much higher populations can still yield well. In Texas, Kinman and Martin (1954) found little difference in yield between 2.5–49 plants/m^2 because of high stand tolerance. In Australia, Bennett (1998)

Table 3. Range and mean of number of days in phases for commercially suitable lines in the US.

	Days from planting		Phase length (days)	
Phase	Range	Mean	Range	Mean
Vegetative	33–53	40	33–53	40
Reproductive	56–114	81	27–52	38
Ripening	86–121	103	9–34	21
Drying	110–163	144	11–57	43

strives for 30–35 plants/m^2 and Sapin et al. (2000) recommend 20–40 plants/m^2. In Venezuela, Avila (1999) found little difference between 30–35 plants/m^2.

Moisture and Fertility

Throughout this paper there will be references to irrigated and rainfed, which are relative terms. Rainfed fields near Oklahoma City have more available moisture than irrigated fields in West Texas where some farmers irrigate but rarely with more than 25–50 mm of water. In the main sesame growing areas in the US, the average rainfall ranges from 480 to 940 mm and little of the rain (0 to 125 mm) is in the 70 days that are critical to sesame in the reproductive and ripening phases. Rain that falls on a full moisture profile does not help; rain that falls in the first 30 days often will set back the plants more than it will help; rain after the seed is filled does not help. In these areas summer rains are often in the form of strong thunderstorms that can have 25 mm of rain in one part of the farm and zero rain 500 meters away. These same storm cells can drop 50 mm per hour and much of the moisture can run off the field instead of penetrating the soil. It is not unusual for storms to rain 200–400 mm in one spot in 24 hours. The number of days in each phase of the phenology depends on the amount of moisture available to the crop.

Sesame is drought tolerant, but as with every crop will do better with more moisture. There have been many cases where sesame has done well in fields with low or no fertility, but in coming back to the same field the following year will not do as well. In analyzing the cropping history of that field it was found the previous crops were shallow rooted and it is hypothesized that the sesame roots went down and found nutrients that had leached lower down into the soil.

There are two types of sesame: those used in dry areas or seasons (US, Venezuela, etc.) and those used in high moisture or seasons (China, Korea, etc.). Many countries such as Thailand and India have sesame for each area or season. Generally, wet sesame does not do well in dry areas but dry sesame may do well in wet areas. The dry lines generally have a strong root that will penetrate deep into the soil to stay in the moisture. The wet lines generally root shallower. There are intermediate lines that are productive in wet or dry but will not do well in the extremes.

Within a line, there are two basic architectures with many gradations in between: high input and low input architectures. The high input architecture occurs when there are good moisture and fertility during the vegetative and reproductive phases. The leaves are larger and the internodes longer resulting in a higher height to the first capsule, more capsule node pairs, and taller plants. The low input architecture occurs when there are low moisture and/or fertility. The leaves are smaller, the internodes shorter, lower height of the first capsule, fewer capsule node pairs, shorter plants, shorter capsules, fewer seeds per capsule, lower hundred seed weight, and lower seed weight per capsule.

If the plants start in high input mode and do not get the appropriate moisture in a timely fashion, the plants will drop the lower leaves and newer leaves will be smaller with shorter internodes, in essence converting to a low input architecture. During this conversion the lower leaves will drop until enough leaf surface has been shed to equalize the evaporation to the available moisture. In some cases applying an irrigation too late after the conversion can actually damage the crop by placing too much stress on the plants. Although a drought can reduce yield considerably, in the US, sesame will survive a drought and make viable seed. If a crop begins in or converts to low input architecture, it will not change to a high input architecture no matter how much moisture and fertility becomes available. However, the plants will continue putting on flowers and capsules despite the small leaves at the top of the plant. The final height of the plant is influenced more by the vegetative phase than the reproductive phase. Some high input crops look like they will be very high yielding because the plants are so luxurious, but the plants may not yield as well if the high inputs are used in the vegetative stage, and there is not enough moisture and nutrients at the end to make good seed fill.

Within lines planted in the same conditions there are two opposite genotypic architectures and all gradations in between. In high input fields the high input genotypes will generally do better, and in low input fields the low input genotypes will generally do better. However, across all fields, the intermediate genotypes will produce higher mean yields.

The interrelationship between moisture and fertility is very evident. If there is adequate moisture and low fertility or if there is little moisture and adequate fertility, the yields will not be good. However, in the intermediate range it is not known whether moisture or fertility is more important.

Phenotypes

There have been several systems for classifying sesame. Hildebrandt (1932) divided sesame into capsule types: bicarpellate and quadricarpellate. Kobayashi (1981) classified sesame by capsules per leaf axil, phyllotaxis (the arrangement of the leaves on the stem), presence of nectaries, and number of carpels in the capsules. Kang (1985) described sesame in terms of branching style, number of capsules per leaf axil, and number of carpels. The author describes sesame phenotypes in terms of branching style, number of capsules per leaf axil, and maturity class. Branching is the first character with the following values: uniculm (1), few (4), or many (7). Capsules per leaf axil is the second character with the following values: single (1) or triple (3). Maturity class is the third character and is in terms of days from planting until physiological maturity. The values are very early (V = fewer than 85 days), early (E = 85 to 94 days), medium (M = 95 to 104 days), late (L = 105 to 114 days) and very late (T = more than 114 days). Table 4 shows the symbols for the various phenotype combinations possible. In parts of this paper the phenotype will be referred to by just the first two characters and preceded by "zx".

Table 5 shows the distribution of released Sesaco cultivars. A large range of phenotypes had been developed because different environments (frost-free days, temperatures, rainfall patterns, farmer equipment, and farmer practices) favor different phenotypes. To date, no lines have been found that would fall into the 71E, 71V, 73E, and 73V phenotypes. It is difficult for an early line to have many branches since flowering is delayed in order to have enough nodes below the capsules to have many branches. It should be possible to have an 11V line, but it probably is not seen because of very low potential yield.

Commercial sesame cultivars worldwide have varied phenotypes. The early, medium, and late cycles are determined by the environment. Late cultivars cannot be used in Korea because of a short growing season. On the other hand in the tropics with mostly late cultivars, certain crop rotations favor early ones. Most of the farmer-selected cultivars have branches with a single capsule since over time these types have survived a multitude of poor conditions and/or weather disasters. In most irrigated or heavy rainfall areas triple capsules are preferred with the Chinese choosing uniculm and the Koreans few branches.

Branching

Branching generally takes place in nodes on the bottom of the plant below the capsule zone. The amount of branching is scored as "few" and "many" based on general behavior of the lines in different populations and row spacing, and by observing the ratio of the number of nodes to the first capsule to the total number of nodes on the main stem. In low populations, "few branch" lines will have 2–4 branches, and "many branch" lines have 6 or more. "Many branch" lines have more nodes below the first capsule, and will have fewer nodes on the main stem. Having defined the difference between few and many, the definition is difficult to apply because

Table 4. Sesaco phenotype combinations.

11T	41T	71T
11L	41L	71L
11M	41M	71M
11E	41E	71E
11V	41V	71V
13T	43T	73T
13L	43L	73L
13M	43M	73M
13E	43E	73E
13V	43V	73V

Table 5. Phenotypic distribution of Sesaco cultivars and germplasm (GP).

Maturity	Uniculm	Few branches	Many branches
		Single capsule/leaf axil	
Very late	GP	GP	S12
Late	S11 S22	GP	S04 S05 S16
Medium	GP	S01 S08 S09 S24 S27	S20 S26 S28
Early	GP	S07 S25 S29	
Very early		GP	
		Triple capsule/leaf axil	
Very late	S06	GP	GP
Late	S15 S50 S51	GP	GP
Medium	S02 S10 S17 S19 S21	S14	GP
Early	S52	S03 S23	
Very early	GP	GP	

the amount of branching varies with different growing conditions. In wide row spacing with intense light a "few branch" line will have 6 or more branches, and under low fertility and moisture, a "many branch" line will have 4 branches or less. From the 1940s through the mid 1980s, it was easy to differentiate between "few" and "many." However, since then there has been so much crossing between the classes that there is a continuum between the two classes. The lines at the edges of the range can be easily identified, but the ones in the middle are difficult to classify. Branching is further complicated by "weak" branches, which appear on uniculm lines in low populations. In most lines all of the nodes below the first flower node have the potential to form branches. With "true" branches, the longest branches are below the first flower nodes, and other branches shorten further down the plant. With "weak" branches, the longest branch is at the base of the plant, and the branches shorten further up the plant. Weak branches get their name because they easily break down and end up below the combine cutter bar. There are some lines with a propensity to form "spontaneous" branches which grow underneath capsules in the middle of the capsule zone. These branches can set several capsules but normally stop flowering by the time that the main stem stops flowering.

There is further confusion with branching due to regrowth. Certain lines have a propensity for restarting growth after the main stem has stopped growing. Regrowth usually occurs in areas where conditions are such that the plants have run out of moisture and/or fertility. If there is rain, some lines will form branches at the bottom of the plant and these will flower and set capsules while the main stem and the older branches will not start flowering again. Regrowth is considered an anomaly and is not considered as part of the typical phenology. However, it can cause confusion in that the end of mid bloom is defined as no flowers on the branches. Regrowth and the destruction of the apical meristem (insects or hail) are the only cases where the flowering on the branches extends beyond than the flowering on the main stem.

Direct sunlight has a tremendous effect on the amount of branching. In order for a branch to form, light needs to strike the leaf axil. In some uniculm lines there is no branching at all under all circumstances. However, most uniculm and branched lines have the potential to branch in every leaf axil. Some lines have the potential to form secondary branches on the branches, and a few have the potential for tertiary branches. In some lines, if there is sunshine at the second pair of leaf axils of a branch, another branch will form, but in lower light, a capsule will form. In order for a branch to continue growing, it needs light at the tip. The amount of light that reaches the branches is dependent on population and/or leaf area. Higher populations and more leaf area shade the leaf axils. True branches have the longest branches below the capsule zone because those branches have more light and grow faster than the lower branches. Weak branches appear to form from the bottom of the stem because as the lower leaves drop the light hits the lower leaf axils and the branch tip.

There are branches that are light seeking. In a high population they will grow out horizontally towards the furrows and once they reach the direct sunlight will bend up and grow close to vertical. Other branches will grow at the same angle regardless of sunlight. In high populations the leaf axil closest to the light may develop a branch whereas the axil inside the canopy may not form a branch. There are some rare lines where the branch on the inside of the canopy will grow around the stem and head towards the furrow parallel to the branch on the opposite side of the plant. North of Uvalde, there is normally a cloud cover that clears between 10:00 and 11:00 AM. When a crop is planted in north/south rows, there are more branches on the west side that receives more direct sunlight. Further north in the US there is more sunlight on the south rows planted east/west resulting in more branching on the south side of the row. There are lines that will bend over in the wind and not bend back up. On these lines, there are more branches on the upper part of the plant. Just as some branches are light seeking, there are plants that are light seeking—the tips of these plants will bend out of the canopy to reach the light and then grow vertically. On these types after defoliation, uniculm lines can appear as branched from a distance. Other lines will only grow vertically to try to reach light.

Elevation, latitude, and row spacing can affect branching. With wider row spacing, more light gets to the lower part of the plant. Elevation increases light intensity, and in northern latitudes there are longer days in the summers providing more light. In the US, areas like Lubbock, Texas, with high elevation, northern latitude, and wider row spacing have the most branching. Areas with less clouding have more branching as direct sunlight has more effect than weak sunlight.

The International Plant Genetic Resources Institute (IPGRI), classifies branching as non branching, basal branching, top branching, and other (Anon 2004b). The top branching character has been eliminated from US cultivars because they are prone to breaking over in high winds; the thick woody stem required to support the plant can break the teeth on the cutter bars of the combine; and the plants are too tall for the combine auger to feed the material into the combine—they bridge the header.

The width of the canopy is dependent on the branching habit, the angles of the branches, and the number of branches. As mentioned there are branches that grow vertical after they reach the light creating narrower rows than the lines where the branches continue growing at the same angle. There is variation on the angle between the main stem and the branch. With more acute angles, the row is narrower. The angle varies from the top branch to the bottom with each lower pair of branches having a wider angle. Thus, with more branches the row is wider.

Capsules Per Leaf Axil

Capsules form from flowers in the leaf axil from about 4–6 node pairs to the top of the plant. IGPRI (Anon 2004b) classifies capsule arrangement as monocapsular or multicapsular. The author uses single (1) and triple (3) capsules. The character is governed by a single gene, and the recessive allele produces triple capsules. The IGPRI classification accounts for the fact that most triple capsule lines have single capsules at the bottom and top of the plant, and rarely have three capsules in every node. There are germplasm lines primarily from China, that can have 5 capsules per leaf axil in many nodes, and two lines have been found that can have 7 capsules per leaf axil. Weiss (2000) reported up to 8 capsules. On triple capsule lines, on any given node there may be 1, 2, 3, 4, 5, 6, or 7 capsules. Nodes with greater than 3 capsules normally occur only in very low populations or at the edge of a field. On the other hand, single capsule lines under high light intensity may have as many as six node pairs with triple capsules. The author uses single and triple capsule classification to reflect the genetic makeup of the line instead of the number of capsules per node on any one plant, which depends on the environment.

In the early 1940s D.G. Langham received germplasm from China that had triple capsules. Since his Venezuelan cultivars had single capsules, he felt that he could triple the yield just by passing the character to the Venezuelan germplasm. In the same year he received some germplasm with 4 carpels in the capsules translating to 8 rows of seed instead of his 4 rows. He then felt it might be possible to increase the yield six fold. Obviously there were source/sink issues, but a breeder must be allowed to dream. Axillary capsules on triple capsule lines are rarely the size of the central capsules and have fewer seeds with lower 100 seed weight, resulting in lower seed weight per capsule. In a 1999 Sesaco study, the axillary capsules averaged 79.4% of the weight of the central capsule with a range of 69.9% to 87.3%. To date, in converting lines from 2 carpels to 4 carpels, the seed weight per 4 carpel capsules is greater, but not double, and lower total capsules are formed on the plant.

As with branching, light has an effect on the formation of the capsules. On the single capsule lines, there is a single capsule in the leaf axil flanked by two nectaries. In a triple capsule line, the central flower forms first and opens 3–5 days before the axillary flowers. In high populations the central open flowers are in the sunlight whereas as the plants keep growing, the leaves may shade the axillary flowers. Although there is a very strong correlation between the lack of light and a low number of axillary capsules, it is not known at what point the light affects the development of a capsule. It may even be the result of another condition such as higher humidity in the microclimate inside the canopy.

In low moisture and/or fertility conditions, the plants may not even form the axillary flowers. In 1987 in Arizona part of a field of a triple capsule line did not get irrigated the first time and as a result did not form any of the axillary capsules. The whole field had water on the second irrigation, and the plants then put on axillary capsules on most of the nodes. This particular line put on small flowers (without a lip) where there was a missing axillary capsule and formed a capsule. At the end of the crop, it was difficult to find the demarcation line between the two conditions without looking at the size of the axillary capsules within the missing irrigation part being smaller. These no lip flowers have been seen on many lines, and appear to be genetically controlled. Other lines will not go back and put on missing axillary capsules under any conditions. Some triple capsule lines will vary with the conditions: have single capsules in low moisture/fertility; then switch to triple capsules under good conditions; and can go back to single capsules in poor conditions; other lines have started with triple, gone to single, and back to triple. Lines with 4 changes in capsule number have not been observed.

Two studies have been done on the number of capsules on the plants. A 1998 Sesaco study looked at 51 lines studying the theoretical number of capsules that should have been formed on the capsule nodes with one capsule per node for single capsule lines and three capsules per node for triple capsule lines. Kang et al. (1985) counted the number of flowers and then the number of capsules. The results are shown in Table 6. The percentages for triple capsules for Kang were higher because normally triple capsule lines put on single flowers at the bottom and top of the plant which the author was counting as potentially three capsules.

Maturity Class

Prior to 1988, the third character of the phenotype was plant height class. In those years the growing conditions were similar and the height repeated each year. In 1988 due to planting in different locations in Texas, plant heights varied considerably. There was an attempt to adjust the height to a standard, but there was still a lot of variation with lines moving back and forth between classes. There was a general positive correlation between plant height and maturity class, and there was less movement between maturity classes. Therefore, the third character became maturity class. Since maturity depends so much on growing conditions, the lines still need to be adjusted to a standard. S24 has been chosen as the standard (95 days to physiological maturity). If there is more rain and higher fertility, S24 will mature later, and if rainfall and fertility are lower, S24 will mature earlier. To standardize the cycle the 95 days is subtracted from the S24 maturity in a certain environment, and this difference is used to adjust the maturities of all the other lines in that environment.

The maturity class is the sum of the first three phases: vegetative, reproductive, and ripening. The drying phase is not used because it is the one that is affected the most by the environment and in certain harvest strategies, the plants are harvested at the end of the ripening phase. The effects of moisture, fertility, temperatures, and other weather conditions will be discussed in each stage.

Leaves

The author has debated using leaf area as part of the phenotype. The leaves are generally opposite low and alternate above, but can be opposite or alternate on the whole plant. In some lines plants have 3 opposite leaves for part of the plant. In the opposite pattern the leaves rotate 90° each node pair; however, in low moisture conditions, the opposite leaves will appear to spiral up the plant because the stem twists. The alternate leaves have a slow spiral at the bottom of the plant and then will have a tighter spiral nearer the top. The lower leaves are generally ovate to elliptic and then become lanceolate with narrower leaves in each node after the 6th node. The top leaves can become linear in some lines. The lower leaves can be entire, lobed, cleft, parted, or divided. The lowest leaves are entire with the first non-entire leaf from the 3rd to 6th node (cultivar and population related). After a few lobed leaves, the shape will revert to entire. The base of the leaf is rounded or obtuse on the lower leaves and can reach attenuate in the upper leaves. The tip can vary from obtuse to acute to attenuate. The edge of the leaves range from smooth to serrate to toothed.

Visually there are major differences within the germplasm. However, it is very difficult to quantify leaf area. The number of leaves has an effect with some branched lines with smaller leaves having higher leaf areas than uniculm lines with larger leaves. A short internode length has an effect in compacting the leaves and giving the impression of more leaf area than longer internodes with more space. The timing of the data collection is also important because the differences in rates of decrease in leaf sizes may end up with lower ratings on some lines just by taking the data ten days later.

Table 6. Percentage of actual capsules per plant versus theoretical number of capsules.

Branching	Capsule	Sesaco capsules based on number of nodes	Kang capsules based on number of flowers
Single stem	Single	91.6	80.0
Few branches	Single	89.3	82.8
Many branches	Single	89.4	-
Single stem	Triple	59.2	77.1
Few branches	Triple	51.6	61.4

Measuring leaves can be difficult. Bar-tel and Goldberg (1985) felt that using a specific leaf for measuring was "impossible." Despite the difficulties in data collection leaves are very important and some form of data collection is necessary, and the author measures one leaf at the 5th, 10th, and 15th pair of nodes. The size of the leaves is determined from the seedling stage through the early-bloom stage of the reproductive phase. The overall size of the leaves does not determine ultimate yield. There are very small leaf lines and very large leaf lines that do not yield as high as the medium leaf lines. Fig. 1 shows the length and width of the leaf blades of the current US commercial cultivars (Sesaco 25, D.R. Langham 2004a; Sesaco 26, D.R. Langham 2004b; Sesaco 28, D.R. Langham 2006a; and Sesaco 29, D.R. Langham 2006b) plus the smallest and largest leaves being carried in the Sesaco germplasm. In some lines, the leaf blade length may continue getting larger further up the plant through the 10th pair of nodes, but the width will always be narrower leading to a lower area. The width of the 5th leaf can be dramatically larger in lobed leaves, but these leaves may not exceed the area of the entire leaves. The figure is included to show the dramatic drop in leaf width between the 5th and 10th pair of nodes. It should be noted that most lines have the capsules from the 5th to 6th pair of nodes.

The shape and the size of the leaves are controlled genetically. Lines with small leaves, lines with medium leaves, and lines with large leaves planted side-by-side in multiple locations and environments will have the same relative sizes within one place even though the leaves on the small leafed lines in one location can be larger than the large leafed lines in another location. While it is clear that moisture and fertility increase leaf size, the effects of population density, light, and degree days is not as clear. End plants of a row have larger leaves than plants within the row, but is this due to wider space or greater moisture and fertility available to end plants? Leaves in the shade inside the canopy of a row are smaller than the leaves in light on the opposite side of the plant implying that light increases leaf size. It is assumed that low degree days decrease leaf size, but no known experiment has proved it. In very sparse populations the lower leaves of the plants are larger than the lower leaves of plants in crowded populations. In some lines in high sunlight, additional leaflets form in the leaf axil, and in many lines there are appendages along the petiole.

The sizes of the leaves will vary within the same cultivar based on the availability of moisture and fertility. Fig. 2 shows the variation within S26 grown under 6 environments with sample 1 having the least water and nutrients and sample 6 the most, with the others in between. The petioles vary in length from the bottom to the top of the plant parallel to the leaf width. However, there are some notable exceptions. There are lines whose petioles lengthen to keep the leaf blade in direct sunlight. At the edge of a field with no shading from

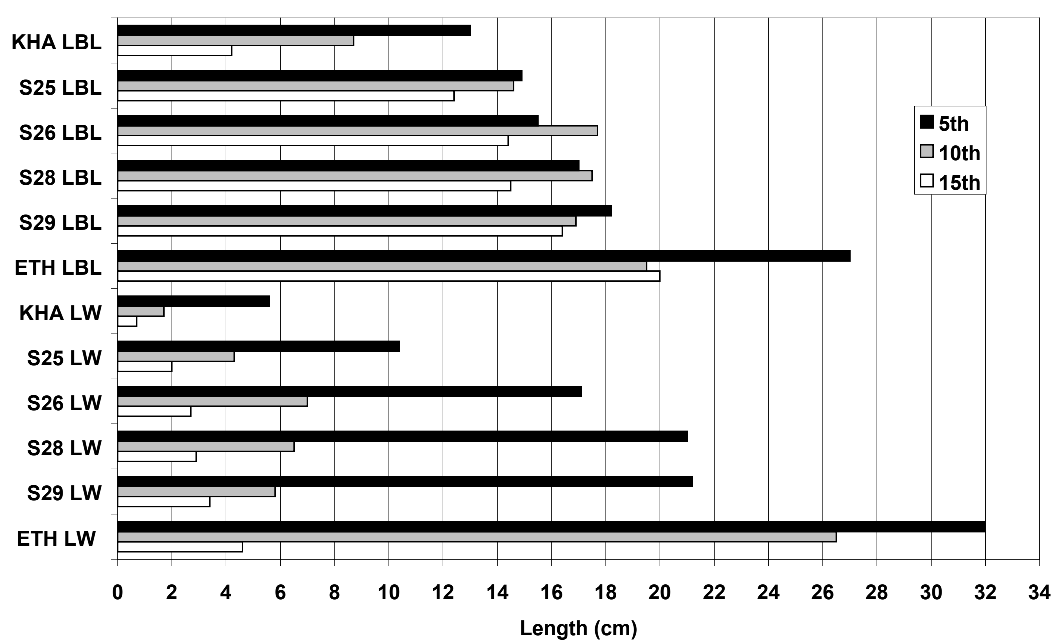

Fig. 1. Leaf dimensions of current Sesaco cultivars and other germplasm on the 5th, 10th, and 15th node pair (LBL= leaf blade length and LW = leaf width).

adjacent rows, on some lines it is possible to pick 50 leaves from the third pair of nodes from plants of equal height, and all 50 leaves will have close to the same length and width, but the petiole length can have threefold difference. In other lines the petiole lengths are all close. In opening the canopy, leaves on opposite sides of the plant at the same node pair can have a different petiole length. In some lines, the petioles bend around the stem allowing the leaf blade to reach the light.

Lines have different shades of leaf color throughout the growing cycle. During the vegetative and reproductive phases the color is usually a shade of green, and then as the plants mature and begin to drop their leaves, the color will turn to many shades of yellow/green, and rarely purple. There are many lines that have purple on the upper surface of the petioles. The purple on the leaves, stems, and capsules can appear anywhere from late bloom stage until the drying phase. There are sesame growing areas where researchers and farmers have a narrow range of colors, and thus base phases and stages of growth on the shade of color. The color is controlled genetically, and decisions made based on color on one continent can be wrong on another. The color of the leaves usually matches the color of the stem and capsules. Within a line the shade of color is an indication of what is happening with the plant.

- Generally, when the plant is in normal growth it will be one shade of green. In two side-by-side fields, the darker green will generally indicate better fertility.
- If that field starts getting a very dark green with almost a bluish hue, it is running out of moisture. When there is a rain or irrigation, there will be a growth spurt leading to a lighter green.
- If there has been a lot of rain the field may turn yellowish green indicating that the roots are not getting adequate oxygen. With aeration from cultivation, the leaves can green up within a matter of 6 hours. The greening up from the soil drying out, without a cultivation, takes a longer time.
- When the plants start to drop their leaves and turn yellow, the shades of yellow are an indication of the late history of the plant. If the leaves turn a pale yellow and stay on the plant, it is an indication that the plants ran out of nutrients. If the leaves turn a darker yellow and most of the leaves drop earlier than normal, it is an indication that the plants ran out of moisture.

Roots

Very little research has been done on sesame roots, but they are very important to the phenology. Generally, sesame plants have a strong tap root component and some fibrous roots. However, under differing conditions,

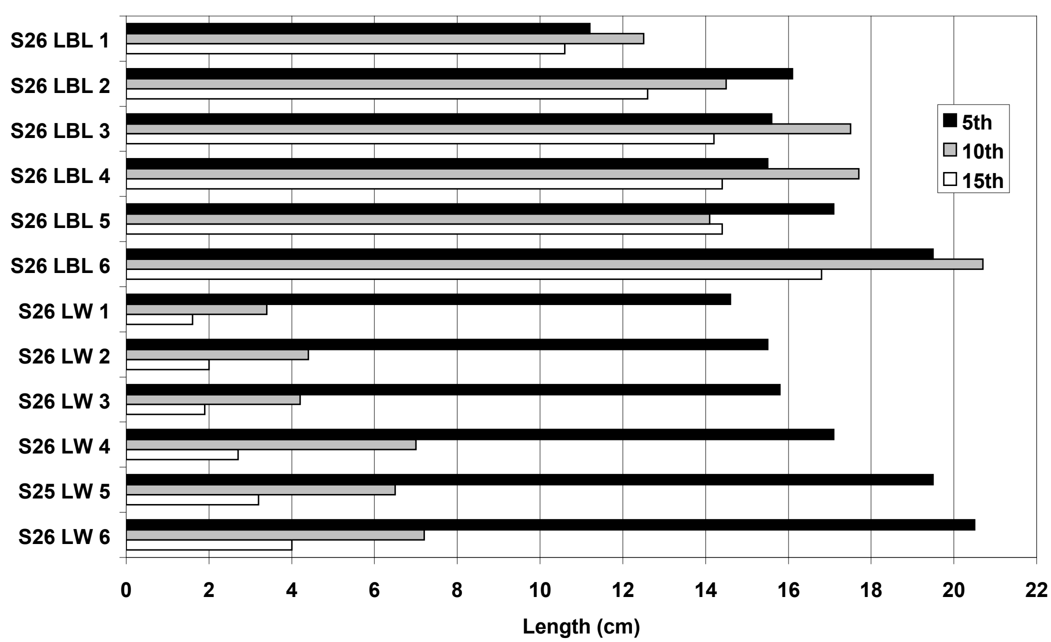

Fig. 2. Variation of leaf sizes in S26 based on the environment on the 5th, 10th, and 15th node pair (LBL= leaf blade length and LW = leaf width).

the plants may have a stronger tap root or a stronger group of fibrous roots. Sesame is considered a drought resistant species because the root will penetrate the deeper into the soil and find moisture. However, every crop needs moisture, and in a year with little deep moisture, sesame will not do as well. In the US the optimum situation is to plant sesame into moisture and have no added moisture for about 30 days. Under these conditions the roots will follow the moisture down, and sesame can withstand a lack of rain for the rest of the cycle. In Venezuela, sesame is planted after the monsoon and will produce a crop with zero rain. If there are rains or irrigations soon after planting, there will be more fibrous root development in the upper 30 cm of soil with shorter tap roots. If this condition is followed by a drought, the plants can be in trouble as the moisture in the top 30 cm is depleted, or a heavy rain can waterlog the plants and kill them.

Weiss (2000) cites Lea (1961) that in clay soils of Sudan, roots penetrate 25 cm in 10 days, 50 cm in 24 days, and 75 cm in 50 days. Weiss states that roots will penetrate faster in sandy soils and grow more profusely; late flowering lines have deeper roots. Root growth is inhibited by relatively low salt concentrations. The author has found a rough correlation between uniculm stems and single tap roots, and between branched stems and branched tap roots. However, there are many exceptions in both directions.

Generally, the roots are as deep as the plants are tall. By the end of the reproductive phase, most of the moisture is being drawn out of the 90–120 cm layer of soil. In Yuma, Arizona, in 1983, the Soil Conservation Service placed neutron probes in sesame fields and found the deep moisture depleted while the surface of the soil was almost muddy.

There is a condition known as wrinkled leaf (D.G. Langham 1945) where the blade in the leaves do not fill in as the veins grow. Many have tried to isolate a virus, however it has been shown that when the roots of certain lines hit a rock or a hard pan, the condition develops. Once that root finds a route down or a rain/irrigation softens the hardpan, the condition disappears and is difficult to find later in the cycle. The wrinkled leaf is controlled genetically and can be carried further for many generations until the right conditions exist to manifest itself. As will be discussed later, the root mass and leaf area need to be in balance, and the ways the leaves adjust can be seen, but no research has shown how the roots adjust.

Time of Planting

The time of planting can have a major effect on the final size of the plants and the yield. Mulkey et al. (1987) and the author have carried out four time of planting studies in Uvalde as shown in Fig. 3. However, as will be shown later, the soil temperature must be sufficiently high at planting to germinate the seeds. Planting in April is risky because the soil temperatures may be too low, and the one farmer that was able to get a stand in March had a very poor yield. The data clearly shows that the yields decrease the later the crop is planted. The previous assumption has been that degree days are critical for yield. However, in comparing the decrease in yield to degree days there is no clear correlation. Fig. 4 shows the accumulated degree days through 100 days after planting when the seeds have filled and are at physiological maturity. Degree days are in centigrade and represent the sum of the mean daily temperatures for 100 days using a base of 0°C.

The degree day data for the years of the experiments in Fig. 3 was not available on the internet, but the patterns in terms of peak units can be extracted to have a similar curve. In the four years in Fig. 4, there are considerable differences for early planted sesame, but by the middle of May the accumulated degree days do not vary as much. The temperatures in April are more erratic than the later temperatures. The correlation between the yields in Fig. 3 and the accumulated degree days in Fig. 4 is $R=0.613$. Beech (1985) cites Kostrinski (1955) who determined that 2,700 accumulated degree days (DD) is necessary to produce maximum yields in sesame. He also cites Ding (1983) that 2,300 DD together with 750 to 770 hr of sunshine are necessary. Beech (1995) states that although the Australian objective had been 2,700 DD, most of the areas in Australia do not meet this requirement. Having grown sesame successfully in areas without 2,700, Beech felt that the optimum number of DD could be lowered significantly by breeding lines with lower heat requirements. He found lines from Japan and Korea that needed lower DD, but for lines from Mexico such as Yori, he determined the DD required was 2,900. The author agrees with the Beech theory because in the US yields of 1,500 kg/ha have been obtained in northern Texas with 2,400 DD using germplasm that is more suited to lower temperatures.

In order to relate the yields shown in Fig. 3 to the accumulated daylight hours for 100 days from date of planting in Uvalde, Fig. 5 was derived. The correlation between the yields in Fig. 3 and the daylength hours in

Fig. 5 is R=0.864. The accumulated daylight hours have a higher correlation to the higher yields in Fig. 3 than the accumulated degree days. In northern Texas the accumulated daylight hours are even longer than in Uvalde (with a max of 1403 daylight hours), and higher daylight hours may make up for some of the lower degree days in that area.

As shown in Table 7, in time of planting studies in the Sudan, Tanzania, India, and Korea (Weiss 2000), Korea with two systems of planting (Lee 1986), and Ciudad Obregon, Mexico (G. Musa 1988, pers. commun.), the earlier the sesame is planted, the higher the yield. The data from all the environments in similar latitudes as the growing areas in the US (Mexico and Korea) shows the same pattern as the Uvalde data in that yields of crops planted in April are lower than the yields of those planted in May and then there is sharp drop-off.

Rate of Growth of Irrigated Sesame

Fig. 6 shows the rate of growth of three cultivars under irrigation in 2004 in Uvalde. Generally, the plants are about 30 cm in the first 35 days, and then almost double in height in the next 7 days and continue this rapid growth until 70 days when the plants begin to shut down. Note that 'S29' has a faster rate of growth and yet it shuts down before 'S26'. The rate of growth is not related to physiological maturity. In rainfed conditions, the final plant heights are lower, but the pattern of very slow growth followed by fast growth during the reproductive phase exists under all conditions. In order to compare the rate of growth diagram to the phases, Table 8 shows the phases of the 3 cultivars in Fig. 6. Sesame grows slowly in the beginning because it is using its resources to put down the root that is following the moisture. In seeing that the internodes shorten from bottom to top, there has been a misconception that once flowering begins, the rate of growth slows down. As can be seen in Fig 6, the rate is fairly constant from the start to end of flowering.

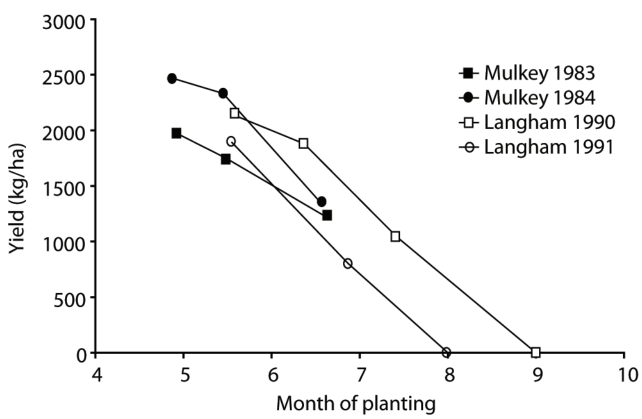

Fig. 3. Effects of dates of planting on yield in Uvalde, Texas.

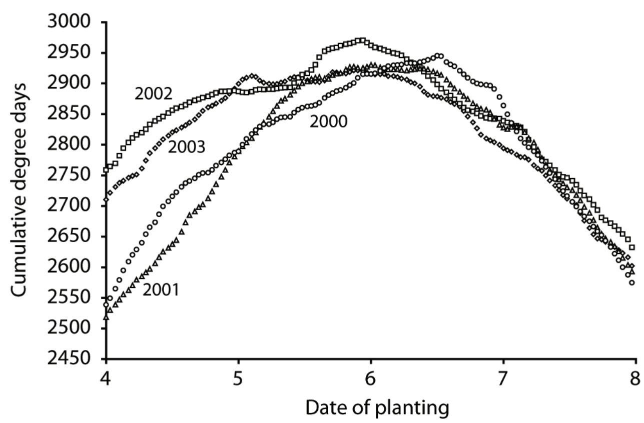

Fig. 4. Accumulated degree days (C°) for 100 days from different dates of planting in Uvalde, Texas.

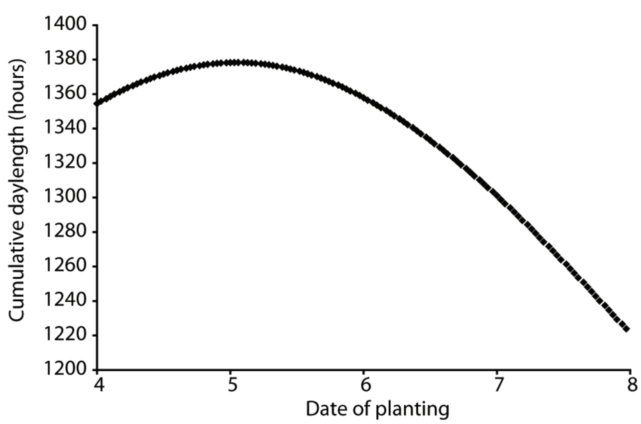

Fig. 5. Accumulated daylight hours for 100 days from different dates of planting in Uvalde, Texas.

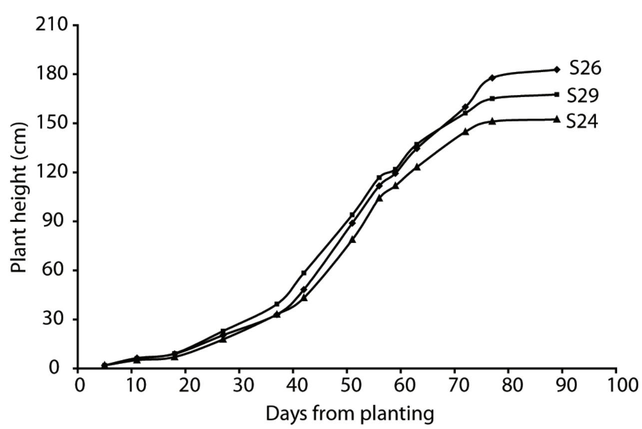

Fig. 6. Rate of growth of 3 US cultivars in adjacent plots.

Basis for Number of Days to and Within Phases/Stages

The description of each phase and stage provides the number of days for that phase or stage. In the phases, the number of days will be in terms of all Sesaco lines and 'S26' between 2000 and 2005, while in the stages the number of days will be in terms of 'S26' planted in Uvalde in 2004. 'S26' is used as the example because it has been the major cultivar planted in this time period, and thus there is much more commercial experience. Table 9 shows data on 'S26' from 2000 to 2005. The 2003 nursery is not included because it was damaged by hail in the juvenile stage and by the eye of a hurricane in the mid bloom stage. The hail destroyed 30% of the leaf surface, and the hurricane leaned the crop over but did not lodge it.

Any one cultivar will be different depending on the growing conditions for that field and the weather for that year. The timing of the rains can have as much an effect as the quantity of the rains. For example, a rain at 30 days from planting for one field can help that field while an adjacent field just planted may get crusted in and not be able to germinate. As can be seen there are wide variations in total days to direct harvest, ranging from 114 to 154 days. In 2000, there was a rain substituting for the first post-plant irrigation that prevented adding the application of the post-plant nitrogen. The lack of nitrogen terminated the crop earlier. Then, there was no rain from the end of flowering to drydown, which accelerated complete drydown. In 2001 and 2002 there were rains in the reproductive phase eliminating the need for the third irrigation. In 2001 through 2005, there were rains between maturity and drydown lengthening this period.

Table 7. Effects on time of planting on yield in diverse environments.

Author	Country	Planting date	Yield (kg/ha)
Weiss	Sudan	Mid-June	1096
		Mid-July	346
		Mid-August	293
	Tanzania	Mid-Jan	973
		Mid-Feb	835
		Mid-Mar	521
	India (Bengal)	Mid-May	325
		Mid-June	101
		Mid-July	45
	Korea	Mid-Apr	677
		Mid-May	764
		Mid-June	437
Musa	Mexico	10-Apr	765
		20-Apr	885
		10-May	985
		30-May	766
		20-Jun	408
		10-Jul	285
Lee	Korea (Conventional)	1-May	670
		15-May	540
		25-May	480
		15-Jun	370
		25-Jul	50
	(Vinyl mulch[z])	1-May	1270
		15-May	1110
		25-May	670
		15-Jun	500
		25-Jul	101

[z]In Korea most farmers plant under a vinyl cover to increase soil temperatures and reduce weeds.

VEGETATIVE PHASE

The vegetative phase is divided into four stages: germination, seedling, juvenile, and pre-reproductive.

Definition: From the time the seeds imbibe the moisture to 50% of the plants with open flowers. The 50% point is somewhat subjective because it is difficult to differentiate in terms of percentages, i.e., there is little visual difference between 40%, 50%, or 60%.

In the same location, with different planting dates, lines will flower at about the same time. In a 1990 time of planting Sesaco study in Uvalde, 80 lines began flowering an average of 40 days in the May 19 planting, 42 days in the June 12 planting, and 41 days in the July 14 planting. In 2006 some fields were planted in late August, and 'S26' started flowering much earlier—at the 4th pair of nodes at 30 days instead of the 6th pair at 40 days. This anomaly needs further study. Some lines from the tropics are photosensitive and will only begin flowering at a certain number of hours of sunlight. No photosensitive lines were included in the 1990 data above.

In a 1998–1999 Sesaco study in Uvalde, the number of days within the vegetative phase were grouped by phenotype, and there were no significant differences as shown in Table 10. The differences between phenotypes are more pronounced in the next phase.

Time to End of Phase from Planting: 29–59 days for all lines, 40–44 days for 'S26'.

Length of Time within Phase: 29–59 days for all lines, 40–44 days for 'S26'.

Table 8. Number of days from planting and within phases for cultivars in the plots in Fig. 6.

	Days from planting			Days within phase		
Phase	S24	S26	S29	S24	S26	S29
Vegetative	42	44	40	42	44	40
Reproductive	87	90	82	45	46	42
Ripening	103	105	102	16	15	20
Drying	135	145	147	32	40	45

Table 9. Data on S26 between 2000 and 2005 planted in research nurseries in Uvalde, Texas.

		Planting date				
		2000	2001	2002	2004	2005
Variable		05/28	06/06	06/09	05/17	05/20
Previous crop		Wheat	Wheat	Wheat	Fallow	Fallow
Pre-plant nitrogen (kg/ha)		33.6	33.6	33.6	33.6	33.6
No. pre-plant irrigations		1	1	1	1	1
Post-plant nitrogen (kg/ha)		0	33.6	33.6	33.6	33.6
No. post-plant irrigations		2	2	2	3	3
Yield sampling (kg/ha)		1,421	1,696	1,642	1,692	1,808
Branching style		Many	Many	Many	Many	Many
No. capsules/leaf axil		1	1	1	1	1
Days to flowering		41	40	42	44	43
Days to flower termination		79	75	81	90	89
Days to physiological maturity		96	103	102	106	106
Days to direct harvest		114	154	145	146	141
Plant height (cm)		128	143	165	174	162
First capsule height (cm)		52	49	61	64	55
Capsule zone length (cm)		76	94	104	110	107
No. capsule node pairs on main stem		23	29	29	31	30
Leaf length (cm) at designated node pair	5th		30	25	29	
	10th		20	19	27	
	15th		19	15	18	
Leaf blade length (cm) at designated node pair	5th		17	16	15	
	10th		14	14	18	
	15th		14	13	14	
Leaf width (cm) at designated node pair	5th		20	15	17	
	10th		7	4	7	
	15th		3	2	3	
Capsule length (cm)		2.2	2.3	2.3	2.4	2.3
Seed wt/capsule (g)		0.219	0.254	0.234	0.280	0.239
Hundred seed wt (g)		0.326	0.328	0.337	0.352	0.344

Factors that Shorten the Phase: Lower fertility and moisture and higher temperatures.

Factors that Lengthen the Phase: Higher fertility and moisture and cooler temperatures.

Germination Stage

Definition: From the time the seed meets moisture until most of the seedlings emerge from the soil. In the US most sesame is planted into the moisture, but there are a few cases where the seed is planted dry soil and then watered up.

Time from Planting: 3–5 days. For seed planted about 2.5 cm deep in good moisture, in South Texas, the low end is usually 4–5 days in late April and 3–4 days planted in mid May. In northern Texas and Oklahoma, the low end is 4–5 when days planted in late May and 3–4 days if planted in late June.

Length of Time: 3–5 days.

Description: Germination is one of the most important stages because if there is a poor stand, no subsequent farmer action or weather condition can produce a high yield. The threshold temperature for sesame is 15.9°C (Angus et al. 1980). In the early years of US commercial production the recommended minimum planting temperature was 23.9°C (Kinman 1955). Weiss (1971) states that should temperatures fall below 20°C for any length of time, germination may be inhibited and will certainly be delayed. In planting hundreds of thousands of hectares of sesame since the 1980s, the current recommended minimum temperature is 21°C (Langham et al. 2006). This does not mean that sesame will not germinate at a lower temperature. The recommended temperature is based on a reasonable probability of achieving a full stand. Higher temperatures increase the rate of germination and increase the probability of achieving a full stand.

Temperatures between 25–27°C encourage a rapid germination, initial growth, and flower formation (Weiss 1971). The present author has found that with soil temperatures around 25°C, the seed imbibes enough moisture that it is soft within 24 hr, and the seed can be pushed out of the seed coat with a bulge at the tip of the seed. Between 24 and 48 hr, the radicle emerges and within 12 hr of emerging, the root will push down and start following the moisture. Between 36 and 60 hr the seedling will start pushing up through the soil. Between 3 and 5 days, the seedling emerges from the soil.

Fig. 7–9 show the importance of temperature in germination. The 1967 author study was done in Petri dishes in a growth chamber with light plus the higher temperature for 14 hr and darkness and the lower temperature for 10 hr. Fig. 7 shows the number of days from the time that the seeds meet the moisture until the radicle pushes out of the tip of the seed. The effect of temperature is very pronounced. The seeds where the temperature dipped below 21°C had radicle emergence, but nowhere near as high as the higher temperatures in terms of percentage of seeds that reached emergence or the emergence speed.

Fig. 8 shows the number of days until the root has developed secondary hairs and the seedling started push-

Table 10. Vegetative phase length by phenotype.

		Vegetative phase length (days)			
		1998		1999	
Branching	Capsule	Mean	Range	Mean	Range
Uniculm	Single	41	39–48	42	40–45
	Triple	40	36–50	43	41–46
Few branches	Single	39	36–44	42	38–46
	Triple	41	38–50	42	39–45
Many branches	Single	40	36–49	43	41–47
All		40	36–50	42	38–47

ing up. At 18.3–21°C most of the seeds whose radicles emerged also had secondary roots develop on the main root and the seedling starts pushing up, but at 12.8–15.6°C, none of the seeds reached that point even though 37% had emerged radicles. Many did develop some hairs but the plants did not push up. At higher temperatures most of the seedlings had root hairs but at 23.9–26.7°C it took longer than at 29.4–32.2°C.

Fig. 9 shows the number of days until the seedlings flip over and the cotyledons open up. At the 18.3–21.1°C and 12.8–15.6°C treatments after 14 days very few seeds had open cotyledons. In several sets, the materials were left in the chamber until 21 days without any further change. In this third stage of development, the temperatures lead to a wider gap between the two high temperature curves.

The above study shows the sensitivity to temperature, but the 14/10 hr split with a 2.8°C temperature swing does not approximate the temperature fluctuation over several days as shown in Fig. 10 (uvalde.tamu.edu/weather, accessed 5 April 2005). Depending on the amount of sunlight the differences between the low and the high soil temperatures can be as much as 13°C in one day in Uvalde soils.

Different genotypes react differently to the low temperatures with some emerging faster than others at low temperatures but all emerging at about the same time at high temperatures (Bennett et al. 1997). They also showed that the type and depth of soil made a difference on speed of emergence by genotypes. The present author plants plots by volume instead of seed count, and thus there are fewer seeds planted in a large seeded line. In most environments the stands are comparable regardless of seed size. However, in marginal germination conditions there are differences. In compacted soils, soils with a thin crust from a rain, or seeds planted at deeper depths, there is a positive correlation between large seed and stand. If the moisture is marginal or at

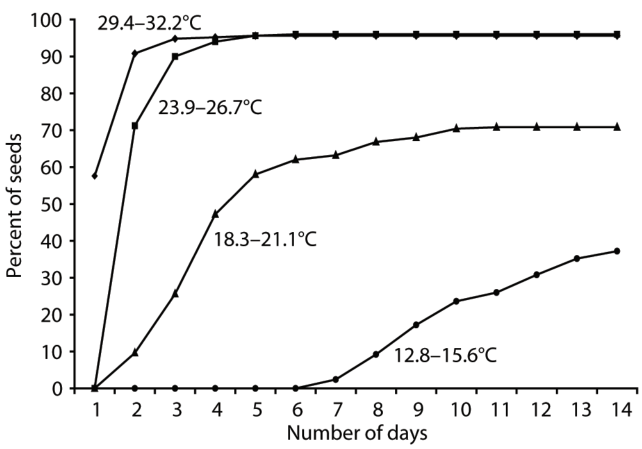

Fig. 7. Rate of emergence of the radicle from the tip of the seed under different temperature conditions.

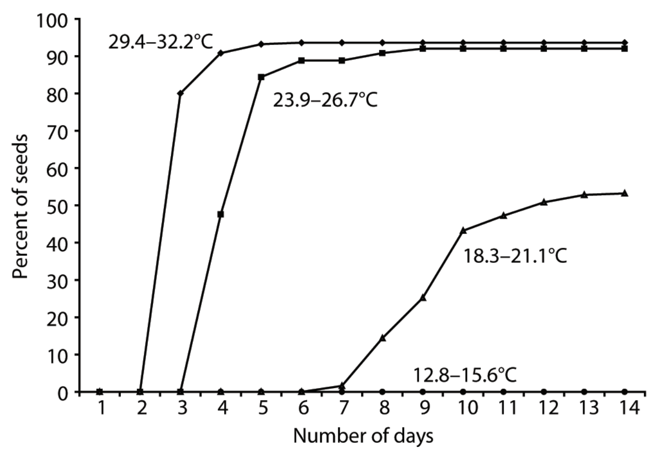

Fig. 8. Rate of development of secondary hairs and seedlings pushing up under different temperature conditions.

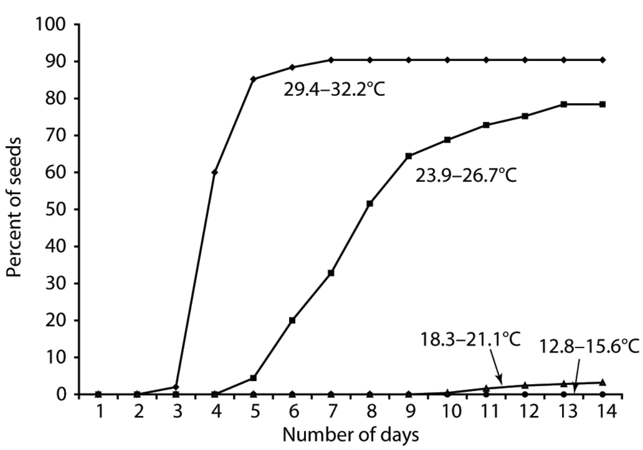

Fig. 9. Rate of cotyledons opening under different temperature conditions.

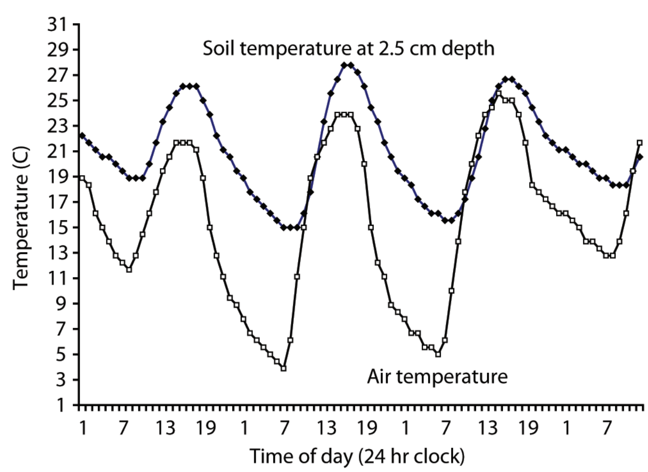

Fig. 10. Air and soil temperature at Batesville, Texas, 1–4 April, 2005.

shallow planting depths, there is a positive correlation between small seed and stand. In marginal moisture, the seeds may imbibe water and swell, but if there is not enough water, they will dry out and germinate with a later rain or irrigation. However, if the seed swells to the point that the radicle pushes through the seed coat before not having enough moisture to continue, the seed will rot and will not germinate.

The germination stage is very vulnerable to rain, which can create a crust in the soil over the sesame. If the seedlings are caught in the crust, there is no hope and the sesame should be replanted. If the seedlings are below the crust, there is a possibility that the crust will crack and allow the seedlings to emerge. If the soil types are such that there is no cracking, the ability to break through is dependent on the thickness of the crust. Once the seedlings have pushed against the crust for several days, they will not have the resources to push to the surface.

Factors that Shorten Stage:

- Shallower planting (however if too shallow, may lose moisture and not germinate).
- Reduced soil compaction (however, some soil types lose moisture quickly under no compaction).
- Higher seeding rates (sesame has small seeds, and more seeds together have more push).
- Higher temperatures.

Factors that Lengthen Stage:

- The inverse of the above: deeper planting, increased soil compaction, lower seeding rates, and lower temperatures.
- There are some root pruning herbicides such as pendimethalin and trifluralin that also lengthen the stage.

Seedling Stage

Definition: From the seedling emergence point until the point where the third set of true leaves is the same length as the second set of true leaves.

Time from Planting: From about 6 days to 25 days.

Length of Time: About three weeks.

Description: In 2003, about 600 ha were planted between 2 and 29 May in Batesville, Texas, under pivots. Fig. 11 is based on observations from those fields. Zero denotes cotyledons with no visible true leaves. A leaf pair is counted when it exceeds the length of the previous pair. Up to that point, decimals are used, e.g., 2.5 indicates that the third pair of leaves is 50% the length of the second pair. This system can be used to estimate the number of days since planting in a field.

When the seedlings first emerge, the cotyledons are yellow and inverted in a crook. Within several hours, the cotyledons straighten up, open and the shoot primordia start growing. Within several days, the 1st set of true leaves will be visible, but will not equal the size of the cotyledons until about 11 days after planting. From the 1st through the 5th or 6th leaves, the leaf area will get larger and then after that the leaves will generally get smaller all the way to the top of the plant. The 2nd set of true leaves is visible about 13 days after planting, and it exceeds the length of the 1st leaves in about 18 days. The 3rd set of true leaves becomes

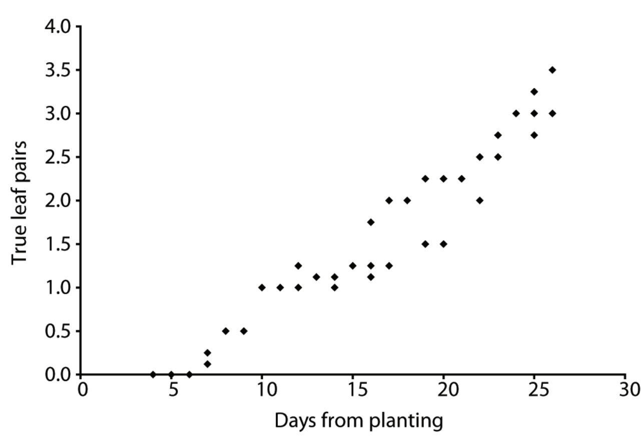

Fig. 11. Rate of development of true leaves on commercial sesame in 2003 in Batesville, Texas.

visible at about the same time and exceeds the length of the 2nd about 25 days after planting. At this point the plants are about 15 cm tall. By the time the 3rd leaves equal the 2nd leaves, the 4th set is visible, and then before the 4th set equals the 3rd, the 5th and 6th sets are visible.

The seedling stage is the most vulnerable stage to perils. At the beginning of the stage, leaf eating insects can destroy the plants, but towards the end, the plants can usually overcome the damage. High winds with blowing sand can sandblast the plants or cover the seedlings. Rains with running water can cover the seedlings. With no weed control, most weeds will outgrow the sesame plants and cover them.

This is the stage where the plants will start differentiating in size. The first seedlings that emerge will normally have the largest cotyledons and will accelerate their growth the fastest. This will lead to larger leaves and to longer roots. The plants with longer roots will compete against the later emerged plants by pulling more moisture and fertility. The larger leaves have an effect in a high stand in that they will begin to shade the later emerged plants and reduce the amount of light they receive. The larger plants will become dominant plants and will form the canopy. The minor plants will be below the canopy. Depending on cultivar, some minor plants will turn to the weaker light in the furrows and when they emerge into the sunlight will turn vertical. They will still be minor plants, but they can be productive. In other cultivars, the minor plants will stay within the canopy and will produce few capsules and may die. This later phenomenon is known as self-thinning. In some cases when there is a weather phenomenon that damages the dominant plants (e.g., hail or lodging), the minor plants will emerge and become the dominant plants. In some cases with limited moisture, all of the plants will exhaust the available moisture and the plants will be very short and have few capsules.

There are some occasions when all of the seedlings emerge at relatively the same time. In this case, no one seedling has a clear advantage, and this can lead to abnormal growth. This group of plants will compete equally for light, resulting in much taller plants. Similarly, roots will compete equally, but will end up shallower than normal as the plants shift their resources to making stems and leaves. This group of plants will eventually be shorter than the rest in the field as the resources are divided equally with less water and nutrients to each plant. This group will also mature and dry down sooner than the rest of the field.

The time of day that the seedlings emerge can be a factor. Seedlings that emerge in the evening just before dark do not have an advantage over seedlings that emerge 12 hr later the next morning. However, because of the sunlight these morning seedlings will have a clear advantage over the seedlings that emerge 12 hr later. There are some soils that crack allowing light to the seedling before it reaches the surface. These seedlings may turn green and if given enough of a crack the cotyledons may invert before reaching the surface. These will generally emerge unless they are covered by rain (closing the crack) or by blowing sand.

Factors that Shorten Stage:

- Larger cotyledon size. Within a cultivar with the same size seeds, the faster the seedlings emerge, the larger the cotyledons because there has been less expenditure of stored materials to emerge. Between cultivars, larger seeds have larger cotyledons.
- Higher temperatures.

Factors that Lengthen Stage:

- Rain or irrigation that reduces the oxygen available to the roots and compacts the soil. Sesame does better when there is no rain or irrigation until about 30 days after planting as long as there is sufficient moisture (see below).
- Lack of fertility. This is particularly evident in fields that have been planted after a disced in crop where there has been no additional fertilizer, and the plant matter is tying up the nutrients.

Juvenile Stage

Definition: From third true leaves until the first floral buds are visible. The growing shoot can be pulled apart showing buds earlier, but this stage ends when the buds are visible without touching the plants.

Time from Planting: From about 26 days to 37 days.

Length of Time: 1.5 weeks.

Description: The juvenile stage is short and could have been combined with the seedling stage; however, this is an important 1.5 weeks to the farmer because this is the time the plants are tall enough for directed spraying with herbicides. It is also the first time that a farmer should consider moisture conditions for the first irrigation.

From the start of this stage multiple leaf sets are visible, and the number of days between leaf sets equaling the previous set decreases. High moisture, fertility, and temperatures increase the plant height and the size of the leaves at this stage, but the length of the stage remains basically the same.

As mentioned before, this stage is very dramatic because it is in stark contrast to the seedling stage where after 26 days from planting, the plants are only 15 cm tall. Within this stage in the next 11 days the plants can double in size to be 30 cm tall; and then double again in the next stage.

This is the last stage where a low level of stress will not hurt final production. By holding back irrigations, the roots will continue to follow the moisture deeper into the soil, and the stems and leaves will not be as large. The deeper roots give the plants more flexibility in withstanding late irrigations, and the smaller stems and leaves reduce the potential to lodge and allow more photosynthates to go to the reproductive stage. However, the plants should not be stressed to the point that they will shed leaves and convert to a rainfed architecture.

Factors that Shorten Stage: Drought. There have been many examples in flood or furrow irrigation where the irrigation water does not reach the end of the field. That dry end will start producing buds earlier than the irrigated part of the field.

Factors that Lengthen Stage:

- Rain or irrigation that cuts off oxygen to the roots. Sesame does better when there is no rain or irrigation until after this stage as long as there is sufficient moisture in the soil.
- Cool night temperatures.
- Low soil fertility. As in the seedling stage, this is particularly evident in fields that have been planted after a disced in crop where there has been no additional fertilizer, and the plant material is tying up the minerals.

Pre-reproductive Stage

Definition: From first floral buds until 50% of the plants have open flowers.

Time from Planting: From about 38 days to 44 days.

Length of Time: About 1 week.

Description: The first floral buds appear in the leaf axils from the 4th to the 6th set of true leaves, depending on cultivar. Although it is possible earlier than 38 days to pull the leaves down and look closely at a bud forming, first floral buds are considered when the buds are visible without touching the plants. The buds start out greenish yellow and as they get closer to the day they will open, they will turn more cream-yellow. On the evening before they open, they will turn a whiter color, pick up purple hue, and will double in size from then until the next morning when they open.

This is the most important farming stage to optimize production because it coincides with the last time that a tractor can enter a field to cultivate and/or apply fertilizer. It also signals the latest time for the first irrigation unless there have been adequate rains.

From this stage until the late bloom stage it is important not to stress the crop. Although the plants stress when they do not get adequate moisture, sesame is well adapted to going into a drought. It will drop the lower leaves in order to equalize the amount of transpiration with the amount of available moisture. If the crop is stressed to this point, irrigations will not bring back the leaves and depending how long the plants have been stressed, an irrigation may be counter-productive. It may set the plants back, may cause shedding of flowers, and may kill the plants.

Factors that Shorten or Lengthen Stage: There are no known factors that will shorten or lengthen the stage.

Factors that Accelerate the Onset of the Stage:
- Dry portions of the field will bud first.
- High degree days will accelerate the start of first buds.
- By this stage within a field there can be considerable variation in the number of days until floral buds. Dominant plants will bud first.

Factors that Delay the Onset of the Stage:
- High moisture and fertility.
- Hail can damage plants and set them back delaying the start of buds.
- Cool night temperatures.

REPRODUCTIVE PHASE

The reproductive phase is divided into three stages: early bloom, mid bloom, and late bloom.

Definition: From 50% of the plants flowering to 90% flower termination. As in flowering, the flower termination measure is subjective in that it is difficult to distinguish between 85% and 95%. At the end of the flowering period, the rate that plant puts out open flowers is reduced. Thus, there can be more than 30% of plants with buds and still have reached this measure since there will not be more than 10% flowering any one day. Another problem is that under low moisture conditions a field noted as terminated may restart flowering if there is sufficient rain.

Within the same location with different planting dates, the later the planting the earlier most lines will stop flowering. In a 1990 time of planting Sesaco study in Uvalde, 80 lines stopped flowering an average of 97 days after planting in the May 19 planting, 86 days in the June 12 planting, and 84 days in the July 14 planting. There are lines that stop flowering earlier than expected in northern latitudes, and this early termination must be controlled genetically since certain parents and their progeny exhibit the same pattern. However, it is not known if this is due to photoperiod or cool temperatures.

In a 1998 and 1999 Sesaco study in Uvalde, the number of days within the reproductive phase was broken out by phenotype, as shown in Table 11. Within each phenotype with more moisture and higher fertility in 1998, there were more days in the reproductive phase than the 1999 nursery. For each branching style, the triple capsules had fewer days in the reproductive phase. For the number of capsules, in the uniculm and few branch phenotypes there were fewer days in the few branch phenotypes, but the pattern was not the same for the many branch types. In isogenic lines, the zx43 version had 6 flowering days fewer than the zx41 version, and a zx13 version had 5 flowering days fewer than the zx11 version. Similar patterns have been seen in F_2 segregating populations.

Time to Start of Phase from Planting: 29–59 days for all lines, 40–44 days for ‘S26’.

Table 11. Reproductive phase length by phenotype.

		Reproductive phase length (days)			
		1998		1999	
Branching	Capsule	Mean	Range	Mean	Range
Uniculm	Single	50	38–56	39	27–44
	Triple	47	38–53	35	30–46
Few branches	Single	46	38–63	34	25–41
	Triple	42	36–49	32	26–38
Many branches	Single	47	39–56	37	28–43
All		46	36–63	35	25–46

Time to End of Phase from Planting: 56–116 days for all lines, and 75–90 days for 'S26'.

Length of Time within Phase: 27–52 days for all commercial lines, and 35–46 days for 'S26'. For 'S26' the short flowering period was in 2000 with lower fertility, fewer irrigations, and no rain; the long flowering period was in 2004 with more water from rains.

Factors that Shorten the Phase: Lower fertility and moisture and higher temperatures.

Factors that Lengthen the Phase: Higher fertility and moisture and lower temperatures.

Early Bloom Stage

Definition: From 50% flowering until capsules have formed in 5 node pairs.

Time from Planting: From about 45 days to 52 days.

Length of Time: About 1 week.

Factors that Shorten or Lengthen Stage: There are no known factors that significantly shorten or lengthen the stage.

Description: Sesame flowers have five petals with the lower petal being longer, and forming what is known as the lip. The lip is folded over the top of the flower keeping it closed to around dawn when it opens and forms a landing strip for bees. Sesame is self-pollinating, but differing rates of cross pollination have been reported. D.G. Langham (1944) reported 4.6 cross pollination in Venezuela. Yermanos (1980) cited the following cross pollination rates: 1–17% by Ali and Alam (1933) and Sikka and Gupta (1949) in India, 3–15% by Martinez and Quilantan (1963) in Mexico, and 3–6% by Khidir (1973) in Sudan. In his own experience in the US, Yermanos found less than 1% when the sesame was surrounded by cotton and other crops. In Moreno, California, he found 68% in a field where the sesame was the only blooming plant in a semi-arid area. Ashri (2007) cited Van Rheenen who had rates between 2.7 and 51.7% in Nigeria. The present author found considerable cross pollination in the Arizona nurseries where many farmers maintained bees for pollinating other seed crops, but little cross pollination in the Texas nurseries. Recent research has indicated an increase in yield with high populations of bees (Mazzani 1999; Sarker 2004).

Pollination normally takes place around the time the flowers open. Flowers open later in cool and/or overcast days. In the afternoon the corolla tubes drop off the flower, but the ovary that will form the capsule, stays on the plant. There are cultivar differences when the corolla will drop, and there are some lines where it does not drop and stays attached as the capsule forms. Within 3 days the capsule will be visible and will lengthen to about 2.5 cm within a week. There are varietal differences in the rate of elongation. The seeds form inside the capsules.

In watching the crop during this stage, the first flowers rarely make capsules, but often in looking at the plants later, there are capsules in these nodes. Given the right conditions, the plants will put on another flower at that leaf axil and form a capsule. In this stage, and in the late bloom stage there are many nodes with missing capsules. In crops under no stress, there are fewer gaps. Often a gap will indicate a stress such as heavy rains that cut down the oxygen to the roots, winds that blows flowers off the stem, or a cold spell that prevents fertilization. In a drought, the flowers have a weaker attachment to the stem, and can blow off even in a mild wind. 'S26' is a branched single capsule line and on the whole plant it would be expected that there would be a failure of 1 out of every 10 flowers. The distribution of missing capsules is not even, with most of the missing capsules at the lower main stem and the branches. In the 1998 Sesaco study on the 5 lines similar to 'S26', the lower main stem segment had 84% actual capsules versus potential capsules; the middle main stem had 97%; the upper main stem had 100%; the lower branches had 86%; and the upper branches had 84%.

In the Western Hemisphere, most lines have a phyllotaxis of opposite leaves: each leaf of a pair is on opposite sides of the stem forming a pair of nodes. Each subsequent pair of nodes rotates 90° and is on the opposite side of the stem. The opposite rotation is essential to allow the capsules from the lower leaves to rest in between the leaf axils of the leaves above thus allowing longer capsules with shorter internodes. In some lines the leaves are offset in an alternate pattern and generally have longer internodes.

In a high population, from this stage forward the plants may drop the lower leaves that are not receiving light. This is not considered stress. Those leaves are transpiring moisture and without light, not performing optimum photosynthesis. If leaves in daylight are dropping, it is an indication of insufficient moisture and/or fertility. However, in the dry areas of Texas, it is expected that late in the day there will be a certain amount of wilting with the plants fully recovered by morning.

Mid Bloom Stage

Definition: From 5 node pairs of capsules until the branches and minor plants (plants of lower stature, growing in part under the canopy of the taller plants) stop flowering.

Time from Planting: From about 53 to 81 days.

Length of Time: About 4 weeks.

Description: The beginning of this stage normally coincides with the branches starting to flower. However, the 5 node indicator is used because the start of flowering on the branches depends on population. In order for a branch to grow and become productive sunlight must shine on the branch. In very dense populations, the plants at the center of the canopy and the minor plants may not have any branches. In thin populations, the branches will start putting on flowers and capsules before the 5 pairs of capsule nodes indicator. In lines with no branches and triple capsules, the expression of triple capsules is usually stronger after the 4th node pair. The 5th node is not as significant in lines with no branches and single capsules.

This stage is the most productive stage because both the main stem and branches are putting on flowers/capsules. In a study in Thailand Suddhiyam et al. (2001, pers. commun. 2005) counted the number of flowers every day on two lines. UB1 has many branches and a single capsule while UB2 is a uniculm with single capsule. The study on UB1 is the average of 4 seasons, and the study on UB2 is the average of 2 seasons. The results in Fig. 12 show that on UB1 80% of the flowers occur in the first three weeks of mid bloom (4 weeks after flowering commences), and in UB2 83% of the flowers occur in the same three weeks. Therefore, even though flowering can drag out for as many as 10 weeks, most of the production (90%) is put on the plant in the first 4 weeks of flowering.

Kang et al. (1985) in Korea did a similar study for four phenotypes as shown in Fig. 13. The branched single capsule phenotype had 79% of the flowers in the first three weeks after flowering.

As stated before, the mid bloom stage is the worst time to stress the crop by untimely irrigations. Delaying too long will force the crop to try to adjust to a perceived drought, but irrigating back too soon is almost as bad. Sesame prefers not to have too much water at any time, and standing water even for a short time can kill sesame. Over-irrigation can reduce yields more than under-irrigation.

If there is an unavoidable delay in irrigation, it may be better to stop irrigating. When the plants are stressed for moisture, the lower leaves will wilt more each day and the top of the plant may also droop. Within 7–10 days of severe wilting, the plant will drop its lower leaves thereby reducing the transpiration rates. Depending on multiple factors, the plants will drop enough leaves that the moisture in the soil can support the plant,

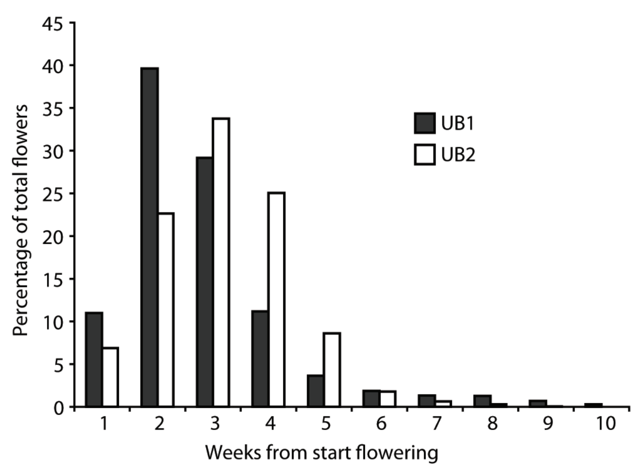

Fig. 12. Percentage of flowers produced for each week in study of two lines in Thailand.

and the plants will wilt less each day. The plants may also stop flowering and will accelerate the filling of the seeds. If the plants in this state are irrigated, there is more stress than before in that the leaves cannot transpire enough moisture out of the soil to get oxygen to the roots, and the plants can die.

One sign that the plants are running out of moisture is the number of flowers that are open in a day. In single capsule lines in mid bloom each flowering head (the main stem and each branch) will have 2 flowers open per day. There are instances where the main stem may have 3 flowers open. It is not unusual to have branches with less than 2 flowers in dense populations. However, when a large percentage of the main stems are down to a single or no open flower, the plants are running out of moisture and/or nutrients. After a rain or irrigation, the number of flowers per flowering head will increase, but it takes time for the plants to restart. On triple capsule lines, the main stem will normally have 6 open flowers per day—two central flowers and 2–4 nodes down four axillary flowers. There can be as many as 9 flowers open on a main stem. There are generally fewer open flowers on the branches.

At the end of the cycle, it is possible to know the moisture history of the plants by looking at the internode lengths. The lengths get progressively shorter from bottom to top of the plant, but they reduce at a discernable rate. If there is an abrupt shortening of the internodes, the plants went into moisture stress at that time. When the plants do get the water, the lengths can remain about the same for several node pairs or can actually increase. Similarly, the capsule length will decrease going into a drought and increase coming out of the drought.

Factors that Shorten and Lengthen Stage: This stage is almost totally dependent on the availability of moisture and fertility. The greater the amount, the longer the flowering period. However, too long a stage can be counterproductive. Sesame is an indeterminate species that will continue putting on flowers as long as there is moisture, fertility, and sufficient heat. In 27 years of growing commercial sesame in the US, Sesaco has only encountered three occasions when the crop continued flowering while the lower capsules began to dry. In all cases, there was a tremendous amount of residual fertility in the ground from previous crops, and the farmers continued adding water. Although very high fertility and moisture adds more potential yield, it generally will lead to lower actual yield for one or more of the following reasons:

- The capsules at the bottom of the plant will mature and dry while the plant is still flowering, and by the time the plant is dry enough for harvest, some of the seed in the bottom of the plant is lost due to shattering. The amount of shattering is cultivar related with most cultivars in the world losing considerable seed while the US improved cultivars have minimal losses.
- Longer growing periods mean taller plants that are more susceptible to lodging and more difficult to combine.
- In the fall, the drying weather deteriorates. There are fewer hours of sunshine for drying, and in most of the sesame growing areas there is more rainfall in the fall. These rains lead to dews in the morning and evening. In some areas with natural high humidity such as Uvalde, the window for combining in late September is about 8 hr and can be as low as 4 hr by mid-November. This window problem does not apply to areas such as West Texas with very low humidity and constant winds where on good days the crop can be combined for most of the day even in late fall.
- Although the present cultivars are more shatter resistant than older cultivars, they do shatter more the longer they remain in the field.
- The top capsules produce lower seed weight per capsule and the quality is not as high, and thus the additional production has more damaged seed with lower test weight, which can lead to discounts.

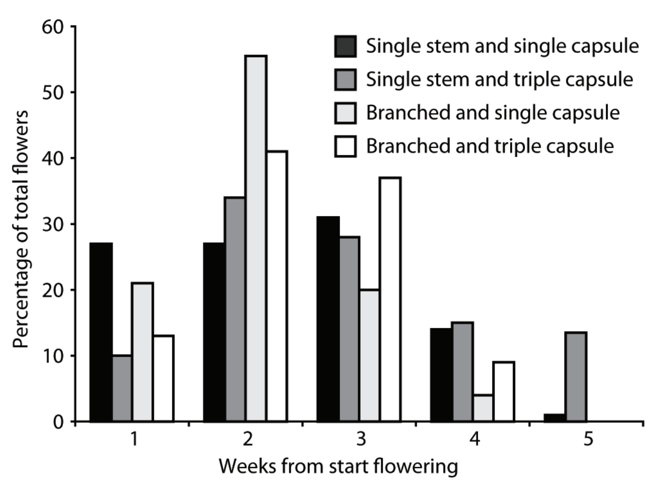

Fig. 13. Percentage of flowers produced for each week in study of four phenotypes in Korea.

Late Bloom Stage

Definition: From branches/minor plants not flowering until 90% of the plants in a stand have no open flowers.

Time from Planting: About 82 to 90 days.

Length of Time: A little over 1 week.

Description: The beginning of this stage on branched lines is when the branches stop flowering. In uniculm lines, the minor plants will stop flowering. The onset of this stage generally coincides with the plants running out of moisture and/or nutrients. As in mid bloom, there will be progressively fewer and fewer open flowers per day.

This is a very difficult stage to determine because at times it is very abrupt and clear and under other conditions, it stretches out over a long time. With a given line in different years, one year it appears the stage has just commenced, and the next week it has ended. In another year, it appears that the stage has commenced, and the next week the field still has the same level of open flowers because of a rain. In Texas and Oklahoma, the rainfall is generally accompanied by lightning, and thus the moisture will often bring down nitrogen from the atmosphere slightly increasing fertility and the available moisture and nutrients keep flowering at a reduced rate for as much as two weeks.

The end of the stage is when 90% of the main stems do not have an open flower. In some cases, there may be as many as 30% of the plants that still have unopened buds, and a third of those will have open flowers on any given day appearing as 90% no open flowers. In most cases there will be fewer and fewer plants each day with buds and/or open flowers, but in rare cases the 30% can keep going for several weeks as do the Thailand cultivars in Fig. 12 above. It is very important that flower termination be determined in the mornings before the corollas have fallen. There are lines that drop their corollas as early as 1:00 PM and then appear to be no longer flowering.

At this stage, many plants will start having yellow leaves at the bottom, and they will drop the lower leaves without the leaves wilting. This is the start of natural self-defoliation to be discussed in the ripening phase below.

At the top of the plants there is a higher percentage of flowers that do not become capsules than on the lower parts of the plants. The amount is both genetic and environmental. There are lines that never produce capsules at the top, and lines that may or may not produce them, depending on moisture and fertility. The level of temperatures that begin to affect growth in the final stages as yet has not been determined because no two years are alike. In some years, there are cold fronts that come through and then temperatures return to normal levels and there is little effect. In other years, the weather is generally cooler, and the night temperatures appear to be more important than the day temperatures. The sesame plants will indicate cooler nights by the flowers containing more anthocyanins; they are deeper purple. The rule of thumb is that sesame is affected by night temperatures of 4–10°C. Genotypes react differently to cold: some will stop flowering; some will flower but will not set capsules and/or seeds; some will flower and set capsules and seeds.

There are several patterns of termination: indeterminate, determinate due to lack of moisture/fertility, and determinate. For many years almost all of the sesame introduced from Asia was indeterminate, but recent introductions are not. On indeterminate lines, the tops of the plants are still flowering while the lower capsules are drying down. In some of these lines, the plants drop the leaves before the capsules dry down, but in others, the dry capsules can be in the leaf axil of a very green leaf. In Asia there are many cultivars where the farmers cut the plants that are still in mid bloom stage because they want to place the plants in shocks before the capsules dry and the seed falls out. In this type of harvest there is a continuum of mature seed to immature seed. Even though it is easy to separate the very immature, there is a point where semi-mature seed is included in the final product.

Since the 1940s many cultivars have been developed where the plants stop flowering on their own when they run out of moisture and/or nutrients. All US commercial cultivars fall into this category. However, two cultivars were developed that in two different environments flowered much longer, and there were dry capsules while the plants were still flowering. In those cases, the soil was unusually fertile from previous vegetable crops, and the roots found the water table 180 to 300 cm deep. In strips adjacent to the commercial fields, the 18 other lines stopped flowering before there were dry capsules. It is not known if the roots of these lines did not reach the water table, or if there is another mechanism that stopped flowering, or if there was another mechanism that delayed dry capsules.

An indeterminate crop has both advantages and disadvantages (Beech 1985). The main advantage is sesame's ability to continue to grow and produce harvestable yields as long as soil water supply and temperature are adequate. The main disadvantage is asynchrony of maturity. In conditions in the US, sesame's indeterminate nature has a great advantage in that the reproductive stage (average 38 days, ranging from 27–52 days) can overcome many environmental conditions that reduce yields substantially in other crops were the flowering stage is short.

Ashri (1985) discovered a botanic determinate mutant controlled by a single recessive gene. The last node at the top of the main stem was a flower which became a capsule. The flower had six fused lobes instead of the normal 5 with no lip and six stamens and jutted vertically upwards. Ashri distributed the gene throughout the world and thousands of crosses were made with germplasm in many countries. However, the mutant produced only 3–5 pairs of nodes before terminating and then would produce branches that in turn would terminate in a flower. This process would continue and the final effect was that the capsules on the main stem would dry down while the outer branches were still flowering. Several breeders developed lines that would stop flowering before dry capsules and several developed uniculm lines that would not branch. However, no line was developed with a higher yield than local cultivars (Day et al. 2002). R. Brigham had one plant that had 7 pairs of nodes (pers. obser.) but his breeding program ended before the seed from the plant could be planted to see if the character would repeat. The present author did hundreds of crosses without being able to increase the number of nodes. The determinate mutation continues to be worked on because it produces an intriguing phenotype: a tremendous number of branches with a short capsule zone resembling the final architecture of safflower. Ashri's original mutant is a parent in several cultivars released in Korea by C.W. Kang.

In 2003, the author found a line where some of the plants terminated in a capsule and by 2005 there was a pure line. In 2006, more attention was placed on the late bloom stage and a similar flower to Ashri's was found on the final node. The main difference in this line was that there were 20–25 node pairs on the main stem, no branches, no dry capsules at the end of flowering, and a reasonable yield. The line has been crossed with the Ashri mutant to determine if both have the same gene.

As with any crop, there will be areas of the field that have stopped flowering while others are still in midbloom. In sandier soils, the plants will generally stop flowering sooner. In low areas, in some years there will be too much moisture which will damage the plants and that will be the first area to stop flowering while in other years, the same area may have the optimum amount of moisture and will be the last to stop flowering. Areas with high populations will stop flowering first.

Factors that Shorten Stage: Very hot period with low humidity.

Factors that Lengthen Stage: Cool weather with high humidity and rain.

RIPENING PHASE

The ripening phase is not divided into stages. Technically, the ripening process begins in the reproductive phase.

Definition: From 90% flower termination until physiological maturity. Physiological maturity (PM) is the date at which 3/4 of the capsules on the main stem have seed with final color and a dark tip. In many lines, the seed will also have a dark seed line on one side.

The concept of physiological maturity (PM) in sesame was developed by M.L. Kinman in the 1950s (pers. commun.) in order to determine the earliest date that the plants could be cut and still harvest over 95% of the potential yield. When the seed has final color, the seed can germinate. If the plant is cut at physiological maturity, most of the seed above the 3/4 mark will continue maturing sufficient for germination, but may be lighter. Since even in a fully mature plant, the seed weight produced at the top of the plant is low, this loss of seed weight does not seriously affect the potential seed yield of the plant. PM is important in northern US crops where there is a potential for an early frost or freeze. After PM the majority of the yield can be harvested even if the plants were terminated by cold.

In Uvalde, the rule of thumb is that physiological maturity will move up 6–7 node pairs per week below the 75% PM level, and 4–5 node pairs per week above the 75% level. In West Texas at higher elevations with cooler nights, the weekly rate has not been determined, but in 2003, with limited data, it appeared that just below the 75% level, the progress was about 3–4 node pairs per week, and above it, 1–2 node pairs per week. More data is necessary to quantify the rates in both locations, but from additional observations made in 2004 through 2006, there is no doubt that ripening is slower in cooler temperatures.

In a 1990 time of planting Sesaco study in Uvalde, 80 lines had a mean of 120 days to PM in the May 19 planting, 107 days in the June 12 planting, and 102 days in the July 14 planting. In a 1998 and 1999 Sesaco studies in Uvalde, the number of days within the ripening phase were analyzed by phenotype, as shown in Table 12. Within each phenotype with more moisture and fertility in 1998, the ripening phase was longer in the 1998 nursery. Although there were patterns in the reproductive phase, there are no clear patterns between the phenotypes in the ripening phase. In isogenic lines, even though the zx43 version matured 8 days earlier it only had 3 fewer ripening days than the zx41 version. A zx13 version had 1 fewer ripening day than the zx11 version.

Time to Start of Phase from Planting: 56–116 days for all lines, 75–90 days for 'S26'.

Time to End of Phase from Planting: 77–140 days for all lines, and 96-106 days for 'S26'.

Length of Time within Phase: (14)–54 days for all, 15–28 days for S26. There are negative values in the low end because lines from Asia which have mature (and dry) capsules before the plants stop flowering.

Description: Technically, sesame is in the ripening phase from the mid-bloom stage through the early late drydown stage. To date, there is no universal definition of mature seed. Some define the seed as mature when it can germinate. Others define the seed as mature when it reaches its maximum dry weight. Within a capsule, the seed matures within 25 to 63 days (P. Suddhiyam, pers. commun., 2005) from the day the flowers open. The seeds in the lower capsules take longer to mature than those in the upper capsules—51.0 versus 29.4 days (Day et al. 2002). There has been little research to determine how much difference there is between cultivars. Both of these definitions require tagging flowers and then sequentially harvesting them and processing them.

For farming, Sesaco defines the seed as mature when the placenta attachment between the seed and the capsule dries, and the seed coat gets its final color (turns from milky white to a buff color) (Langham et al. 2006). In US lines on one side of the seed, there is a visible seed line from the tip to the middle arc. There are lines from Korea and China without this line at maturity. The Sesaco system is conservative; capsules at the top of the plant whose seeds have not put on the final color have viable seeds that have germinated in laboratory tests. Generally, the seeds get their color first at the lower capsules and maturity progresses up the stem. There are a few exceptions where the lowest capsules do not get their color first. There are lines that put on the lowest capsule later in the cycle. However, it is not important because the seed in these lower capsules always put on color before physiological maturity.

Table 12. Ripening phase length by phenotype.

		Ripening phase length (days)			
		1998		1999	
Branching	Capsule	Mean	Range	Mean	Range
Uniculm	Single	16	7–24	13	9–22
	Triple	18	14–23	14	3–19
Few branches	Single	20	7–32	16	8–28
	Triple	19	14–21	15	8–19
Many branches	Single	19	14–28	13	8–19
All		18	7–32	14	3–28

In a 1998 Sesaco study, it was shown that the dry weight of the seed in different parts of the plant differs as shown in Table 13. The number of node pairs on the main stem was counted and divided by 3 to divide the main stem into lower, middle, and upper segments. The branches were pushed to the main stem and the branch segment to the top of the lower main stem segment were designated as the lower branch segment. The rest of the branches segments above this point were designated as the upper branch segment. There were only two lines that had node pairs on the branches above the middle main stem segment. There can be as much as 13% difference between the smallest and largest seed on the plants when it is divided by large segments. The seed in the very top capsules is usually considerably smaller than the seed in the middle stem.

During this phase, most of the leaves fall off the plants. Sesame starts self-defoliation in late bloom stage and ends in the initial drydown stage. Generally, leaves will turn yellowish green (some lines go to a pale yellow or a deep yellow) before dropping. In many lines the lowest leaves turn yellowish when the canopy blocks the light, and they will drop even while the plants are in full bloom. As mentioned above the leaves may drop due to drought. Dropping of leaves because of shade or drought is not considered the maturity self-defoliation. As the plant stops flowering and matures, the leaves will drop from the bottom of the plant to the top. There are a few US lines where the plants hang on to a few node pairs of lower leaves while dropping the leaves in the middle node pairs. However, in these lines, the lower leaves drop as the plants enter the drying phase. In some fields, the upper leaves can hang on longer providing some photosynthesis for seed fill in the upper capsules. These will also drop long before the combine. If the plant is killed prematurely by insects or disease, the leaves will dry on the plant and will generally only fall after considerable rain and wind.

There are many defoliation patterns in the world sesame germplasm. W. Wongyai from Thailand has developed a series of lines that defoliate while green. Her objective is to reduce the amount of transpiration after the leaves have provided the nutrients for the capsules at that level. This character has been confirmed to occur in both the US and Thai growing conditions. This is a good trait for crops that are cut at maturity, but in the US where the crop is not cut until the plants are dry, early drop of leaves allows more light to the ground and can bring on weeds. There are lines that do not drop the leaves even when the lower capsules have dried. These can cause problems in drying in that farmers cut the plants to avoid losing the seed, and yet the leaves force a longer drydown in a shock, or push up the moisture in the threshed seed.

In the US, the leaf below the capsule will drop before the capsule matures and the capsule and plant will turn a yellowish green. At PM certain genotypes have a shade of yellowish green with some with a lot more green and others with a lot more yellow. In order to use the color as a cue to look for PM, the researcher needs to be familiar with the color of that cultivar. For example, ‘S27’ is more green than yellow; ‘S29’ is more pale yellow; ‘S25’ is a deeper yellow; and ‘S24’/‘S26’/‘S28’ a balanced yellow green. There are lines that are dark green capsules with mature seed and lines that are very light yellow with immature seeds.

After the plants have stopped flowering, there is a danger that the plants will have regrowth, and the plants will start flowering again. Regrowth occurs primarily when the plants have stopped flowering earlier than normal because the plants ran out of moisture and/or nutrients. Fields that go to normal termination rarely will restart. There are three types of regrowth, top (restarts at the tops of the main stems), middle (branches emerge from the middle of the main stem), and bottom (branches start in the axils of other branches or below the branches). There are lines that show spontaneous branching whereby branches start in the middle of the capsule zone under

Table 13. Hundred seed weight in different plant segments by phenotype.

		Hundred seed wt (g)					
Branching	Capsule	All[z]	LMS	MMS	UMS	LBR	UBR
Uniculm	Single	0.298	0.296	0.305	0.290		
Few branches	Single	0.286	0.290	0.295	0.283	0.271	0.269
Many branches	Single	0.305	0.322	0.322	0.306	0.286	0.284
Uniculm	Triple	0.271	0.276	0.270	0.264		
Few branches	Triple	0.245	0.241	0.246	0.246	0.237	0.252

[z]All = average of whole plant, LMS = lower main stem, MMS=middle main stem, UMS=upper middle stem, LBR=lower branches, UBR=upper branches.

capsules. However, this is not considered regrowth because spontaneous branches start during flowering and stop flowering before the top of the main stem stops flowering. In regrowth, the plants look indeterminate in that the lower capsules dry while the plants are still flowering.

The onset of regrowth needs further study because there are conflicting patterns. In 1991 there was a drought from planting time, which stopped flowering in all but a few lines. With a rain, all the lines that had stopped went into regrowth. In 2006 there was a drought resulting in no flowers on most lines, and yet after a rain, the plants started flowering again without going to regrowth. The lines flowered longer than normal, but the lower capsules did not dry down while the plants were flowering. There is a positive correlation between tendency to go to regrowth and the lines that have the longest delayed shattering (discussed in full maturity stage). In some years lines with a tendency to go to regrowth will be the only lines to go to regrowth and yet under similar conditions none may go to regrowth. To date no line has been found that will not go to regrowth under the proper conditions. Fields will rarely go to regrowth in cooler night temperatures.

Factors that Shorten Phase: Lower moisture and/or fertility and higher temperatures.

Factors that Lengthen Phase: Higher moisture and/or fertility and lower temperatures.

DRYING PHASE

The drying phase is divided into three stages: full maturity, initial drydown, and late drydown.

Definition: From physiological maturity until complete drydown when 99% of the plants are dry above where the cutter bar would hit the plants. This is a difficult date to determine because there are few fields that have uniform soils and some parts of the field will always be dry ahead of others.

One of the problems with a freeze is a false indication of the extent of the drydown. With natural drydown, as the stems dry down, they will turn brown, and lose most of the moisture. After a freeze, the plants will turn brown within days, but will still have too much moisture to combine. Green plants will take 7–10 days to dry down after a freeze.

With the exception of the lines mentioned before with dry capsules during flowering, all harvest scenarios are done in the drying phase. The first four options below are usually done in the full maturity stage, while the last option is cut after the late drydown stage.

- In the majority of the world, sesame plants are cut manually and shocked. Although the ideal is to cut the plants before the first dry capsules, in large fields it is not possible to cut all the plants when they are mature without dry capsules. In many areas, farmers will cut plants that are ready and plants that are not will be cut later. In parts of Africa, the plant bundles are tied to a fence. In parts of India and Turkey, the cut plants are taken to a drying floor where less seed is lost during drying. When the shocks are dry, the plants are turned upside down over plastic or a blanket and the seed falls out. In Mexico, the shocks are fed into a combine.
- In Korea and Thailand, some farmers cut the plants with a rice cutter and place them into shocks. When dry the plants are fed into stationary threshers.
- In Venezuela, the plants are cut with a binder after PM and are manually shocked. When dry the shocks are fed into a combine by a hydraulic attachment to the front of the combine.
- In the US, for many years the plants were cut with a swather and left in a windrow. Upon drying they were combined with pickup attachment.
- Currently in the US and Australia, the plants are cut after the late drydown stage when the plants are completely dry. Desiccants have been used in the full maturity or initial drydown stages to accelerate the drying.

Time to Start of Phase from Planting: 79–140 days for all lines, 96–105 days for ‘S26’.

Time to End of Phase from Planting: 102–181 days for all lines, and 114–154 days for ‘S26’.

Length of Time within Phase: 11–57 days for all lines, 18–51 days for ‘S26’.

Factors that Shorten the Phase:

- Lower fertility and moisture.
- Higher temperatures.
- Lower humidity.
- Sunshine.
- Constant winds.
- A frost may accelerate drydown, but often depends on the stage of the plant and the length of time the plants are subjected to the low temperature. A frost in the early stages will not accelerate drydown as much as the same frost in the late stages.
- A hard freeze will kill the plants and they will start drying down quickly.

Factors that Lengthen the Phase:

- Higher fertility and moisture.
- Lower temperatures.
- High humidity.
- Cloudy days, fogs, and dews.
- Later planting leads to later drydown as the days are getting shorter providing fewer drying hours.

Full Maturity Stage

Definition: From physiological maturity until 90% of all the plants have all seeds mature. Sesaco does not take data on days to all seeds mature and thus the following range is an estimate based on one year of data.

Time from Planting: From about 107 to 112 days.

Length of Time: About 1 week.

Description: With direct harvest without desiccation, this stage is not important. With swathing or desiccation, the plants will be killed and the seeds will no longer fill. At the end of this stage, the plants will have the highest potential yield and can be terminated to accelerate drydown. However, since the capsules in the top 2–3 node pairs contribute little seed, the practical time may be at some point between PM and all seeds mature. In essence the purpose of swathing and desiccation is to harvest sooner, and thus the practical time may be better.

Tables 14 and 15 show the relative importance of the parts of the plant as they relate to yield. These are from the same 1998 Sesaco study as in the 100 seed weight in Table 13. Table 14 shows that the capsules in the upper third of the plant produce lower seed per capsule and that the capsules in the branches produce even less. However, it is still yield.

In experimental fields where there is thinning, the seed weight per capsule would be expected to be fairly uniform, but in unthinned fields, there is a lot of variation between dominant plants and minor plants. In a 2004 Sesaco study, two capsules were harvested from the middle of the capsule zone on 50 consecutive plants of the same cultivar in a row. As can be seen in Fig. 14, there is considerable variation between dominant and minor plants.

Table 15 shows the percentage of seed weight in each plant part from the 1998 Sesaco study. In the upper portion of the main stem there is lower percentage of seed than would be implied from the seed weight per capsule in Table 13 because there are fewer capsules in the upper portion of the plant. Although this significant lower seed weight per capsule in the branches, there are enough branches and capsules resulting in a significant amount of seed in the branches (an average of 36.4%), and even more in lower populations.

The ratio of seed in the main stem versus the branches changes considerably with population with less seed in the branches in high populations and more seed in the branches in low populations.

Under some conditions there is vivipary in sesame—the seeds will germinate in the capsules. Not only are the germinated seeds lost, but the root of the seedling binds the rest of the seed. Many researchers have felt that the opening of the capsules allows water to enter and germinate the seed. Actually, the opposite occurs. Seeds in open capsules do not germinate because the moisture will evaporate out of the capsule before the seed can germinate. The vivipary occurs in closed capsules. It is believed that this is a dispersal mechanism to open the capsule and allow the seed to fall out. Vivipary is controlled genetically with some lines having a greater propensity than others. Vivipary is rare in the US because normally at harvest the temperatures are below 21°C—the minimum germination temperature. Vivipary is more common in tropical temperatures, particularly Ashri's determinate mutant. There are lines such as Cola de Borrego from Mexico (Ashri 1985) and UB1 from Thailand (Suddhiyam et al. 2001) whose seeds are dormant after maturity for several months after harvest.

Factors that Shorten Phase:

- At this point it is not known if lower moisture and/or fertility shortens the phase. There is not enough data.
- High temperatures.

Table 14. Seed weight per capsule in different plant segments by phenotype.

		Seed weight/capsule (g)					
Branching	Capsule	All[z]	LMS	MMS	UMS	LBR	UBR
Uniculm	Single	0.206	0.196	0.220	0.203		
Few branches	Single	0.195	0.194	0.215	0.203	0.148	0.158
Many branches	Single	0.204	0.215	0.242	0.225	0.168	0.187
Uniculm	Triple	0.156	0.157	0.163	0.140		
Few branches	Triple	0.131	0.140	0.141	0.122	0.114	0.116

[z]All = average of whole plant, LMS = lower main stem, MMS=middle main stem, UMS=upper middle stem, LBR=lower branches, UBR=upper branches.

Table 15. Percent of total seed yield in different plant segments by phenotype.

		Percent of total seed yield						
Branching	Capsule	LMS[z]	MMS	UMS	MS	LBR	UBR	BR
Uniculm	Single	31.2	37.1	31.7	100.0			
Few branches	Single	27.1	28.8	23.7	79.6	9.9	10.5	20.4
Many branches	Single	22.4	23.5	17.7	63.6	15.9	20.5	36.4
Uniculm	Triple	25.5	41.8	32.7	100.0			
Few branches	Triple	19.1	32.5	26.9	78.5	10.6	10.9	21.5

[z]LMS = lower main stem, MMS=middle main stem, UMS=upper middle stem, MS=total in main stem, LBR=lower branches, UBR=upper branches, BR=total in branches

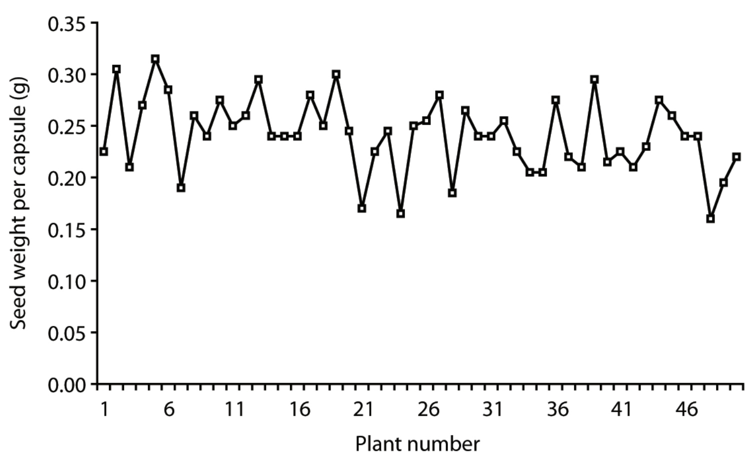

Fig. 14. Seed weight per middle main stem capsule from 50 consecutive plants.

Factors that Lengthen Phase: Low temperatures—see description of ripening phase.

Initial Drydown Stage

Definition: From all seeds mature until 10% of the plants have one dry capsule. The plants used should be green plants that have natural drydown excluding plants that have died from a disease. In windy areas, the plants may rub against each other and break down capsules. These will become dry, but these are not considered as dry capsules.

Time from Planting: from 113 to 126 days.

Length of Time: About 2 weeks.

Description: Earlier, lines were described that have dry capsules at the bottom of the plant while the plant is still flowering. Since the 1940s lines have been selected that do not have open until the plants are past PM (D.G. Langham and Rodriguez 1945). The time between PM and first dry capsule is known as the harvest window and US cultivars have been developed with as much as 21 days of harvest window. A wide window is important when the crop is cut at maturity to decrease the amount of seed lost from the dry capsules. However, if the crop is going to harvest at complete drydown, a long harvest window is a disadvantage in that it will delay harvest.

The main stem will generally have dry capsules before the branches, but the branches will generally dry down before the main stem. The lower capsules dry first with the top capsules drying last. Parts of the stems will dry before all of the capsules are dry. The pattern of stem drydown differs in that in some cases the middle of the stem dries first and then goes in both directions, in others the top stem dries first and goes down, and in others the bottom stem just below the capsules dries first and goes up and down. In any sequence the lowest part of the plant between the lowest capsules and the root is the last to dry.

The only exception to the lowest part drying last is when the plant succumbs to root rot, then the drying will be from the very bottom of the plant up, and the drydown will be much faster. There are three root rots (*Fusarium*, *Phytophtora*, and *Macrophomina*) that affect US sesame. The newest cultivars have much greater tolerance than cultivars developed in the mid 1990s, but there are still plants that die earlier than the rest. Plants are more susceptible to the root rots when there is stress: low soil moisture at the seedling stage when the root is racing to keep up with the moisture; the use of some root pruning herbicides which will not kill the plant but will offer a point of entry for the root rot; moisture stress in both directions—too little or standing water. Plants that die should not be counted in the 10% of plants with dry capsules.

Factors that Shorten the Phase: The same as described in the drying phase paragraph above—lower fertility and moisture, higher degree days, lower humidity, sunshine, constant winds, frost, and freeze.

Factors that Lengthen the Phase: The same as described in the drying phase paragraph above—higher fertility and moisture, lower degree days, high humidity, cloudy days, fogs, dews, and later planting.

Late Drydown Stage

Definition: From first capsule drydown until enough drydown for a combine to produce 6% moisture seed.

Time from Planting: From 127–146 days.

Length of Time: About 3 weeks.

Description: Of all of the phases, the final drydown phase is the most variable in terms of length of time in the phase. If the reproductive phase is shorter because of lack of fertility, this phase will have a shorter time from planting but will not necessarily change in terms of length of time in the phase. However, if the reproductive phase is shorter because of lack of moisture, this phase will have shorter time from planting and length of time in the phase. On the other hand, the fall has more rain than the summer in Texas and Oklahoma, and the reproductive phase can be shortened, but sufficient, late rains will keep the length within the drydown phase the same. Table 16 is an extract of Table 9 and it shows how one cultivar ('S26') can have radically different starting and end points for each phase. In 2000 rains prevented the second fertilizer application and there were no rains during the drydown phase. As a result there was 40 days difference in total drydown compared to 2001 where there were rains throughout drydown.

When the capsules are dry, they open at the tip allowing the seed to fall out. For 5,000 years sesame has been harvested manually. The farmers cut the plants when green and shock the plants to dry. The sesame is then inverted and struck to shake out the seed. Farmers have thrown out any mutations that keep the seed from just falling out when the capsules are inverted. Two closed capsule mutants have been found: the indehiscent allele *id* was discovered by D.G. Langham in 1943 (D.G. Langham 1946) and the seamless allele *gs* was discovered by D.R. Langham and D.G. Langham in 1986 (D.R. Langham 2001). Although initially these were thought to be the solution for mechanization, the combines damaged the seed too much. The indehiscent gene was distributed throughout the world with hundreds of breeders trying to reduce the damage. In the 1950s there was hope in combining the indehiscent allele with a character known as "papershell" capsules (Culp 1960). However, when they were combined in Sesaco 01, it was still not enough. In combining closed capsules, the concaves must be closed and the cylinder speed increased. Many operators have added rasp bars to increase the threshing surface. Essentially, each capsule must have opposing forces on each side and some seed in each capsule is damaged. In addition, the cutting action often crimps the opening created on the capsule and the seed cannot flow out. Sesame seeds have a thin seed coat and contain over 50% oil and can be damaged easily. Even if the seeds are not broken, they can be bruised, which will create free fatty acids that will turn the seed rancid.

Sesaco bred non-dehiscent sesame (D.R. Langham 2000, 2001; D.R. Langham and T. Wiemers 2002) by joining 6 characters so that the seed is held in the capsules until in the combine and then most of the seed is threshed out of the capsules in the feeder housing of the combine. The concaves can be opened and the cylinder speed slowed down. The key was the development of a stronger placenta attachment by accumulating genes to improve the original placenta attachment discovered by D.G. Langham (Langham et al. 1956). In addition, there were genes with minimal opening and a gene that held the two halves of the capsule together until the combine. There is an adhesion that is similar to a post-it note that holds the halves but not too much. There are lines that have better shatter resistance than the present cultivars, but they hold the seed in the capsules in the combines. Capsules with tips that are more closed also are susceptible to forming mold in the capsules. Non-dehiscent sesame is a balance between the capsules holding the seed until the combine cuts the plants but then releasing the seed inside the combine with minimal force.

Non-dehiscence is controlled by multiple genes and is difficult to move over to shattering lines requiring many crosses and large segregating populations in the F_2. There are some shattering lines from China and Russia that have yet to produce a progeny with non-dehiscence despite viewing tens of thousands of F_2 plants. Crossing between two non-dehiscent lines usually results in non-dehiscence in the F_1, but in other pairs the shatter resistance mechanisms break down. Through the 2006 season, non-dehiscence has been incorporated into over 1,000 lines with varied genotypes and phenotypes.

Many researchers continue to try to close up the capsule at drydown. However, there is tremendous advantage in opening the capsule in terms of accelerating harvest. The seed at maturity has about 60% moisture and for combining it has to reach 6%. With a closed capsule, all of this moisture must travel from the seed through the capsule wall whereas with open capsules, the moisture can escape out the top. In Yuma, in 1982 two lines

Table 16. Cycle dates that delineate phases in 'S26' planted between 2000 and 2004 in research nurseries in Uvalde, TX.

Stage	2000	2001	2002	2004	2005	Max–Min
Days to flowering	41	40	42	44	43	4
Days to flower termination	79	75	81	90	89	15
Days to physiological maturity (PM)	96	103	102	106	106	10
Days to direct harvest	114	154	145	146	141	40
Direct harvest—PM	18	51	43	40	35	33

were swathed the same day—one with a closed capsule (indehiscent) and the other with an open capsule. There were rains on both windrows, which delayed harvest. When the open capsule windrow was ready to combine, the closed capsule windrow had too much moisture in the seed. Additional rains kept the combines out of the indehiscent field for 6 weeks. At that point there were weeds growing through the windrow further complicating harvest. When combining direct in subsequent years, if the combines were operating in the field before a rain, the combines could re-enter the open capsule lines 3–5 days earlier than the closed capsule lines. The capsule walls absorb moisture and it is easier to dry out from both sides of the capsule than just from the outside. The longer that a crop is left in the field, the longer that it is in danger.

In US sesame with combine harvest, the consistency of the stem has many effects on the phenology. In many US field crops, the harvesting equipment does not take the stem into the machine (corn and cotton) or only takes the top part of the plant (wheat, sunflowers, safflower, and sorghum). In these crops, strong stems can be bred to prevent lodging. In crops such as sesame, soybeans, other types of beans, and guar, the majority of the plant enters the combine. In order to breed for lodging resistance in sesame, there has to be a balance between creating a stem that will reduce lodging and still cut without damaging the cutter bars, be pliable enough to move through augers, and break up in the combine. Woodier stems take longer in the vegetative and early reproductive stages because the plants are using resources to produce more lignins. These woodier stems hold their moisture longer and take longer to dry down in the drydown stage.

Factors that Shorten the Phase: The same as described in the drying phase paragraph above—lower fertility and moisture, higher degree days, lower humidity, sunshine, constant winds, frost, and freeze.

Factors that Lengthen the Phase: The same as described in the drying phase paragraph above—higher fertility and moisture, lower degree days, high humidity, cloudy days, fogs, dews, and later planting. At the end of a day the sesame may be below 6%, but the seed will rehydrate during the night. With a dew, the capsule can be hydrated and close up. It will take time in the morning for the sesame to dry out again.

ABIOTIC EFFECTS ON PHENOLOGY

Light

As explained before, light is essential in branch and capsule development. In Uvalde time of planting studies there is a high positive correlation between yield and total light units in the vegetative and reproductive phases. In planting the same cultivar at the same latitude in Oklahoma and Korea, the plants are taller in Korea under similar moisture and fertility inputs (pers. obser.). One possible explanation is that in Korea there is less sunshine in the Suweon area due to smog and cloudy days. In planting the seed 20 miles apart in Uvalde under similar moisture and fertility inputs, the plants to the south are usually shorter. One possible explanation is that in the north the fields are near the hills, and the sun usually breaks out of the overcast 2–3 hours later in the morning. It appears that weak light promotes stem elongation and strong sunshine reduces it; however, it does not appear to change the number of days in the stages.

Daylength

There is photoperiodism in sesame where short-day sesame cultivars grown in long-day conditions will start flowering much later and produce larger plants and conversely long-day cultivars grown in short-day conditions will have accelerated flowering and produce shorter plants (Joshi 1961). In the US, most introductions from Africa and South America will not start flowering for 50–70 days depending on the planting date, and the plants can be as tall as 245 cm (D.R. Langham and Wiemers 2002). One of the major cultivars in Venezuela was Aceitera which in Venezuela was 65 cm tall and matured in 92 days (Mazzani 1962). In Arizona, Aceitera in 1990 was 215 cm tall and matured in 137 days. In 1967 the author took the best US lines and planted them in two nurseries in South India. The plants were very short, started and ended flowering earlier, and had significant lower yield compared to the local lines.

As discussed above, in the 1990 date of planting Sesaco study the number of days to flowering of US lines does not vary considerably with daylength in plantings from May through July. However, daylength appears to have a shortening effect on flower termination and maturity. It is difficult to compare the length of phases between South Texas and West Texas because the amount of moisture is usually so different. However, in terms of flowering, the order between cultivars will remain the same, i.e., lines that flower first in South Texas, flower first in West Texas. The same is generally true for flower termination, maturity, and drying. However, there are some genotypes with a common ancestor that will stop flowering earlier in West Texas and out of sequence.

Rain

As stated in most of the phases and stages, the amount of moisture has an effect on the length of time. The ideal rain pattern is enough rain prior to planting the crop to fill the soil profile; a planting rain that will provide enough moisture to plant; 30 days of dry weather (in a dry area so the root goes deep—not as important in a wet area); rains about every week for the next 50 days, and then no rain until the crop is harvested. The rains should be light enough so that the moisture percolates into the soil into the root zone. Continual rains saturate the soil and keep oxygen out, yellowing the plants, and delaying the vegetative phase. The actual rain has the following effects on the stages:

- In the germination stage, a rain will often move the seed deeper in the soil, delaying emergence. In certain types of soils, a rain can create a crust, delaying or preventing emergence. A rain will also lower the temperature of the soil.
- At the seedling stage, rain can splatter mud up on to the cotyledons and first few leaves reducing the photosynthetic surface and delaying growth. In some cases, a rain can cause erosion and cover seedlings with mud. Once the cotyledons have inverted, the seedling has little push. If the seedlings are totally covered, they will die. If part of the seedling is exposed, it can recover, but the stage will be delayed.
- In the ripening phase, if there has been a drought, a rain can lead to regrowth which was discussed in that phase.
- In the drying phase, rain can reduce shatter resistance.
- In 2000 in Oklahoma there was a period of rain, drizzle, rain, and overcast conditions that lasted over 3 weeks. With high temperatures a mold formed over all of the crops, gardens, and forests that ruined the sesame, soybeans, sorghum, and cotton.
- Rain can germinate seeds that were in dry soil at planting. The greater the difference between the initial germination and this late germination, the greater the farming problems due to differing maturity dates. In manual harvest, the ripe plants can be cut first and the rest left for later cutting, but in combining, the green plants will cause problems with moisture and seed quality.
- Sesame plants suffer from standing water and will usually die if the water is on the stem for a period of time. Excessive rain that leads to water logging in low spots can kill sesame in any phase.
- In trying to predict production in an area it is more important to know the timing of the rains compared to the phases than to know the total amount of rain.

Drought

As stated earlier sesame is drought tolerant, but as with every crop will do better with more moisture. In US crops there is a weather phenomenon in the summer known as a “Texas high” when a high pressure area sets up over Texas and southern Oklahoma. During this time it will not rain for about 6 weeks with the drought starting sometime in June—coincident with the vegetative and reproductive phases. Even without this high there is little rain during the summer (usually lower than 250 mm) during the growing phases. Sesame persists in these conditions, and in extreme conditions, *Amaranthus* species have died while the sesame plants have survived. The indeterminate nature of sesame allows it to bridge these drought periods.

In 2006 there was an extended drought throughout the US growing area resulting in virtually no subsoil moisture prior to planting. In Uvalde there was only 70 mm of rain in 12 months through PM in an area that averages 560 mm. There were no planting rains for the rainfed crops, and the only fields that performed close to average were those where there were good pre-plant irrigations. Once the sesame germinated, there was a dry line below the roots that prevented deep penetration. Trying to get the dry soil below wet, the irrigations hurt the sesame more than they helped. Fields with fewer irrigations of around 25 mm per irrigation had higher yields than fields with more irrigations of around 38 mm per irrigation.

Wind

In any breeding programs wind should be taken into account because of the potential of lodging. In the last 10 years of the US sesame program through constant selective pressure, lodging has been a rare problem that usually occurs only when winds exceed 60 km/h. In the 2006 northern Texas Sesaco nursery, less than 1% of the plants lodged with two days of winds between 50 and 90 km/h.

- During the germination stage, wind is rarely a problem except for hot continual winds that can pull the moisture out of some soil types. If the farmer does not plant deep enough, the moisture around the seed can evaporate and prevent germination. However, planting deeper to prevent this problem will take the seedling longer to emerge.
- In the seedling stage the wind can cover the seedlings with blowing dirt and sand. While seedlings covered by rain carrying silt will seldom push through, the silt from wind is looser and occasionally, the seedlings can push through and survive. Normally, the seedlings are low enough to have a low profile to the wind and there is no lodging at this point. However, in windy areas such as northern Oklahoma and Southern Kansas, the winds can whip the seedling around and the stems will form a cone into the soil. There has been no apparent damage from this, and in fact, this may help the stem develop more wind resistance.
- In the vegetative phase in many areas of the West Texas where the soils are sandy, farmers need to "sandfight" on all of their crops. Rains create the problem in sandy soils by slicking the ground. Winds can then carry sand that blasts the tender seedlings and depending on the intensity can just shred the leaves and set the seedlings back or can "sandpaper" the plants to just stems. As soon as farmers can get a tractor into the field they will till the soil with an implement to trap the sand. Normally, one month after planting, the plants are tall enough to not require sandfighting.
- During the reproductive phase, although it is rare, wind can blow a set of whole flowers off the plant. This tendency to blow off is genetic in terms of the strength of the pedicel.
- Generally, the leaves act as shock absorbers and branches and plants rubbing against each other in the wind, do not lose their capsules, but in the ripening phase as the plants lose their leaves, the capsules come into contact, and the capsules can rub off. Triple capsules rub off more easily than single capsules.
- In the drying phase, the capsules will open and winds can cause the seed to shake out of the capsules. Although the amount of shatter resistance is the largest determinant of the amount of seed lost, plant architecture of the plant can make a difference. The tips of branches whip the most and are more apt to lose seed.
- Winds can be beneficial in the drying phase in that they pull moisture out of the plants faster. Once the plants are dry, the wind in conjunction with low humidity can increase the number of harvest hours per day.
- After the seedling stage, the main peril from wind is lodging. In understanding lodging, it is important to realize that the stage and plant architecture can create different amounts of wind resistance. The following characters present more resistance: tall plants, large leaves, branches, wide angle branches, and three capsules per leaf axil. The weight of the plant also makes a difference once the winds start bending the plants. Wet plants from rain tend to lodge more than dry plants.

There are three types of lodging: where the plants break at the stem, where the plants bend over but do not break, and where the plants uproot and bend over. When a plant breaks over, it will rarely produce any new seed, and the existing seed may or may not mature. If there is a total break, there is no hope, but if there is still some active stem translocation through the break, there can be some yield recovery. The main causes for uprooting of plants are shallow root systems and fields that have just been irrigated, creating a soft layer of soil. When a plant bends over early in development, some lines adapt better than others in terms of having the main stems turn up and continue flowering. The tips of the branches are usually matted under the canopy and will rarely turn up, but new branches can develop. As the plants go to drydown and the weight of the moisture is lost, many of the bent plants will straighten up making the crop easier to combine.

Temperature

The rule of thumb is that 150 frost free days are needed for sesame (Kinman and Martin 1954). Work has been done in the greenhouse on optimum temperatures, but the conditions cannot approximate the interactions between temperature, sunshine, and wind in the field. Many publications have repeated that temperatures above 40°C affect fertilization and seed set (Weiss 1971) implying that sesame crops should not be grown in hot areas; however, excellent crops have been grown in Arizona where the day temperatures during the reproductive phase are rarely below 40°C and often reach 50°C. In Yuma in 2006, there was a three day period when the temperatures were never below 43°C at dawn at a nursery with thousands of lines, and the capsules set seed. However, the temperatures around the flowers may have been cooler from air movement, evaporation of water from the soil, and transpiration from the plants.

On the cold side, as stated earlier low temperatures can prevent or inhibit germination; will lead to slower growth; and will slow down ripening. In the US there can be frosts at the end of the cycle. Planting on time will normally keep the crop from frosts through the full maturity stage, but after that point, frosts are possible and are an advantage. Frosts can accelerate the drying phase, which moves harvest into a better weather window.

In learning the latest time to plant, there were many commercial fields that had a frost or even a hard freeze. In the 1950s a crop in Kansas had a hard freeze near maturity and the plants dried down quickly. The seed was harvested and appeared to be fine; however, within a week the seed was rancid. M. Kinman (pers. commun.) watched the harvest, tested the seed, and found extremely high acid values. He speculated that the freeze created ice within the seed. The temperatures and length of time below freezing were not recorded. Since that time, there have been several hard freezes around minus 5°C for as much as 6 hours during the drying phase. There was an accelerated drydown, but the harvested seed was not damaged. However, there has not been a freeze when the seed contains high moisture (60% at physiological maturity). Dry seed placed in the freezer for weeks have germinated.

The effects of frost are difficult to determine because conditions vary too much to compare frosts. In general, a frost may accelerate a drydown, and it appears that at the same temperatures, crops further along on drying will be affected more than crops that are still green. In one extreme case, a line from Paraguay that was still flowering continued flowering after a frost that dried down the other 1,100 lines that were still green.

In 1998 there was an extreme abnormal frost that hit Oklahoma and north Texas in mid September—seven weeks before normal early frosts. Most of the fields were still flowering, but there were no general patterns—some fields stopped flowering and others continued flowering. One interesting effect was that in most fields the leaves on the side of the wind dried down. This was a repeat of the observation in a late planted field in 1990 where the temperatures were above freezing, but below freezing with the wind chill factor.

Hail

The sesame growing areas in the US are prone to hail storms. As with any crop, if the hail is severe, it can destroy the crop. However, the present US cultivars of sesame have good recovery traits. There is sesame germplasm that will not branch under any circumstance including losing the growing tip on the main stem. This type of germplasm has been eliminated from the US program because of the problems with hail. Within branching lines there are differences in the amount of branching in terms of the number of branches and the percentage production of seed on the branches. Branches are important in hail damage because the growing shoot of the main stem is tender and a direct hit will often break the tip off. Unless branches start, the production of that particular plant is stopped at the point of the hail strike.

The effect of hail on the phenology depends on development stage of the plant. In the vegetative phase the hail may lengthen the phase as much as a week, whereas in the later phases it will shorten the phase. Given a hail of equal intensity, the earlier the damage, the higher probability of recovering from the damage.

- In the seedling stage, if there are no first leaves and the head of the seedling is severed, the plant will die. If the first true leaves are severed, the plants will form branches from where the cotyledons meet the stem. Above the first set of leaves there will be branches commensurate with the amount of light and the number of node pairs available to form branches.

- In the rest of the vegetative and early reproductive phase, in moderate to high populations, the dominant plants will get the hail hits and damage, and often the minor plants will grow through the canopy and become the dominant plants. If the hail hits the primary meristem, the optimum situation is to have it break off entirely. Often the top is broken over and hangs on the plants. The tip will bend up and will flower and set capsules, but with the reduced flow of nutrients there will not be much seed produced. However, the worst effect is that the primary meristem appears to suppress the secondary meristems and these plants will not have substantial branches. In some years, the severity of the damage is not seen until harvest when there is lower yield. In extreme cases, the leaves have been torn apart, but the plants have gone on to branch and produce flowers and capsules, but the reproductive phase is delayed.
- Sesame leaves are soft and hail will easily go through leaving minor holes. A single hail stone can damage multiple leaves. If there are enough hail stones, the hail can reduce the leaf surface area. Hail hitting the stems will leave "bruises"—darkened areas.
- In the reproductive phase, hail can damage the leaves enough to reduce the rate of flowering but will actually extend the date to flower termination. However, if the leaves are severely shredded, the plants may stop flowering. Although the stem and capsules are green, they do not produce enough photosynthesis to fill the seeds. The plants will delay going to physiological maturity.
- In the ripening phase, there are fewer leaves and the capsules are more exposed. The hail can have a direct hit on a capsule and open it taking it to drydown ahead of capsules below it. The hit can break the capsule down, but it will often stay attached to the plant and dry down. A severe hail will denude stems of the capsules and may break off parts of the main stems or branches.
- In the drying phase, dry capsules are open and have a brittle attachment to the stem. Direct hits can detach the capsule or shatter out the seed.

Salinity

Sesame is more sensitive to salt than most crops including cotton and alfalfa. At some point the salinity will prevent germination, but this subject has not been studied sufficiently. Salinity slows down growth and makes the plants more yellow. In Arizona there were irrigated fields where the sesame would thrive near the head of the ditch but would not grow near the tailwater. In these areas, the water was from the Colorado River, which was fairly salty. In 1987, different lines were planted in 8 row strips in a field where cotton and alfalfa would not grow in the west fifth of the field due to salinity. There was as much as 30 meters difference in how far out into the salty area some sesame lines would grow indicating genetic variability.

Effects of Weather Perils

The paragraphs above detail many of the perils from weather, but sesame withstands weather very well. The Risk Management Agency of the US Department of Agriculture funded a study of sesame, which provided the information shown in Table 17 (Anon 2004a). The author provided the raw data for the study.

As can be seen sesame is a survivor crop even in modern agriculture as it has been over the past 5,000 years in subsistence farming in many areas of the world.

REFERENCES

Angus, J.F., R.B. Cuningham, M.W. Moncur, and D.H. Mackenzie. 1980. Phasic development in field crops I. Thermal response in the seedling phase. Field Crops Res. 3:365–378.

Anon. 2004a. Research report on hybrid sunflower, sesame, and spelt crop insurance programs. p. 1–96. Watts and Associates, Billings, MT.

Anon. 2004b. Descriptors for sesame. Int. Plant Genetic Res. Inst., Rome, Italy.

Ashri, A. 1985. Sesame improvement by large scale cultivars intercrossing and by crosses with indehiscent and determinate lines. p. 177–181. In: A. Ashri (ed.), Sesame and safflower status and potentials. FAO Plant Production and Protection Paper 66, Rome, Italy.

Ashri, A. 2007. Sesame (*Sesamum indicum* L.). p. 231–289. In R.J. Singh, (ed.), Genetic resources, chromosome engineering, and crop improvement. Vol 4. Oilseed crops. CRC Press, Boca Raton, FL.

Table 17. Weather perils affecting sesame (1987–2003).

					Crop lost (%)	
Peril	Distribution	Frequency	Extreme	Stage(s) affected	Typical year	Extreme year
Drought	Localized	Most years	2000–2002	Any	1-5	30 affected but not lost
Prevented planting (due to lack of rain on non-irrigated crops	Localized	Most years	1996, 1997	Germination	<1 to 3	15–25
Excessive heat	General	Annually		All stages	≅ 0	
Heavy rain (at planting)	Scattered	Annually		Germination, seedling	1–3	5
Excessive rains (causing lakes)	Localized	Annually	1989, 2003	Any	<1	3
Rain at harvest	General	Most years	2000	All of the drying phase	0-5	30 in 2000 only[z]
Unseasonably cold	Localized	Some years	1998	Late bloom	<1	2–4
Frost	Localized	Annually	1998	Late bloom	1–2	15 affected but not lost
Hail	Isolated	Annually	2003	Any, more affected the later the stage	<1	2
Wind	Scattered	Annually		Before juvenile	<1	1–2
	Scattered	Annually		After juvenile	<1	1–3
	Localized	Annually	2003	Drying	<1	1–3

[z]In 2000 there was a period of 3 weeks with heavy dews, fogs, cloud cover, and little sunshine. All of the crops, gardens, lawns, and forests developed a fungus that covered the vegetation. Up until that point the sesame and other crops were harvested, but after that point all crops were abandoned. Oklahoma State extension personnel said that there had been no previous record of this phenomenon, and it has not repeated.

Avila M., J.M. 1999. Cultivo del ajonjoli, *Sesamum indicum* L. Fondo Nacional de Investigaciones Agropecuarias, Maracay, Venezuela.

Bar-tel, B. and Z. Goldberg. 1985. Descriptors for sesame: A modified approach. p. 191–197. In: A. Ashri (ed.), Sesame and safflower status and potentials. FAO Plant Production & Protection Paper 66. Rome, Italy.

Beech, D.F. 1985. Sesame: Research possibilities for yield improvement. p. 96–106. In: A. Ashri (ed.), Sesame and safflower status and potentials. FAO Plant Production and Protection Paper 66. Rome, Italy.

Beech, D.F. 1995. Australian sesame industry: An overview. p. 19–33. In: M.R. Bennett and I.M. Wood (eds.), Proc. First Australian Sesame Workshop, Darwin – Katherine, 21–23 March 1995.

Bennett, M., D. L'Estrange, and G. Routley. 1997. Sesame research report, 1996–1997 wet season. Katherine, Australia.

Bennett, M. 1998. Sesame seed. The new rural industries, a handbook for farmers and investors. www.ridc.gov.au/pub/handbook/sesame.html.

Culp, T. 1960. Inheritance of papershell capsules, capsule number, and plant color in sesame. J. Hered. 51(3):101–103.

Day, J.S., D.R. Langham, and W. Wongyai. 2002. Potential selection criteria for the development of high-yielding determinate sesame cultivars. p. 29–35. Sesame and Safflower Newsletter, Inst. Sustainable Agr., Cordoba, Spain.

Hiltebrandt, V.M. 1932. Sesame (*Sesamum indicum* L). Bul. Appl. Bot. Genet. Plant Breed. 9:109–114.

Joshi, A.B. 1961. Sesamum. The Indian Central Oilseeds Committee, New Delhi, India. p. 109.

Kang, C.W. 1985. Studies on flowering, capsule bearing habit and maturity by different plant types in sesame. Ph.D. Thesis Korea Univ., Suweon.

Kang, C.W., J.I. Lee, and E.R. Son. 1985. Studies on the flowering and maturity in sesame (*Sesamum indicum* L.) III. Growth of capsule and grain by different plant types. Korean J. Crop Sci. 30(2):158–164.

Kinman, M.L. 1955. Sesame production. Texas Agr. Expt. Sta. Bul., College Station.

Kinman, M.L. and J.A. Martin. 1954. Present status of sesame breeding in the United States. Agron. J. 46(1):22–27.

Kobayashi, T. 1981. The type classification of cultivated sesame based on genetic characters. p. 86–89. In: A. Ashri (ed.), Sesame: Status and improvement, proceedings of expert consultation. FAO Plant Production & Protection Paper 29. Rome, Italy, 8–12 Dec. 1980.

Langham, D.G. 1944. Natural and controlled pollination in sesame. J. Hered. 35:254–256.

Langham, D.G. 1945. Genetics of sesame. J. Hered. 36:245–253.

Langham, D.G. and M. Rodriguez. 1945. El ajonjoli (*Sesamum indicum* L.): Su cultivo, explotacion, y mejoramiento. Bol. 2, Publ. Ministerio de Agricultura y Cria, Maracay, Venezuela.

Langham, D.G. 1946. Genetics of sesame III: "Open sesame" and mottled leaf. J. Hered. 37:149–152.

Langham, D.G., M. Rodriguez, and E. Reveron. 1956. Dehiscencia, y otras caracteristicas del ajonjoli *Sesamum indicum*, L., en relacion con el problema de la cosecha. Genesa, Publ. Tecnica 1, Maracay, Venezuela.

Langham, D.R. 2000. Method for making non-dehiscent sesame. United States patent 6,100,452.

Langham, D.R. 2001. Shatter resistance in sesame. p. 51–61. In: L. Van Zanten (ed.), Sesame improvements by induced mutations. Proc. Final FAO/IAEA Co-ord. Res. Mtng, IAEA, Vienna, TECDOC-1195.

Langham, D.R. and T. Wiemers. 2002. Progress in mechanizing sesame in the US through breeding. p. 157–173. In: J. Janick and A. Whipkey (eds.), Trends in new crops and new uses. ASHS Press, Alexandria, VA.

Langham, D.R. 2004a. Non-dehiscent sesame variety S25. United States patent 6,781,031.

Langham, D.R. 2004b. Non-dehiscent sesame variety S26. United States patent 6,815,576.

Langham, D.R. 2006a. Non-dehiscent sesame variety S28. United States patent 7,148,403.

Langham, D.R. 2006b. Non-dehiscent sesame variety Sesaco 29. United States patent application 2006/0230472.

Langham, D.R., G. Smith, T. Wiemers, and J. Riney. 2006. Southwest sesame grower's pamphlet. Sesaco Corporation, San Antonio, Texas.

Lee, J.I. 1986. Sesame breeding and agronomy in Korea. Crop Expt. Sta., Rural Development Administration, Suweon, Korea.

Mazzani, B. 1962. Mejoramiento del Ajonjoli en Venezuela. Ministerio de Agricultura y Cria, Centro de Investigaciones Agronomicas, Maracay, Venezuela, Monographia 3.

Mazzani, B. 1999. Investigacion y tecnologia del cultivo del ajonjoli en Venezuela. Ediciones del Consejo Nacional de Investigaciones Cientificos y Tecnologicas (CONICIT), Caracas, Venezuela.

Mulkey Jr., J.R., H.J. Drawe, and R.E. Elledge, Jr. 1987. Planting date effects on plant growth and development in sesame. Agron. J. 79:701–703.

Sapin, V., G. Mills, D. Schmidt, and P. O'Shanesy. 2000. Growing sesame in South Burnett. Department of Primary Industries, Queensland Government. www.dpi.qld.gov.au/fieldcrops/2888.html.

Sarker, A.M. 2004. Effect of honeybee pollination on the yield of rapeseed, mustard and sesame. Geobios-(Jodhpur) 31(1):49–51.

Suddhiyam, P., S. Chatcharoenthong, and S. Kritjanarat. 2001. Seed development of red seeded sesame cultivar Ubon Ratchathani. In: W. Wongyai (ed.), Proc. Second Natl. Conf. Sesame, Sunflower, Castor, and Safflower, Nakhon Nayok, Thailand, 16–17 August 2001.

Triangtrong, A. 1984. The effect of environmental factors on growth, development, and yield of sesame (*Sesamum indicum* L.) in south-eastern Queensland. Master thesis, Univ. Queensland, Brisbane, Australia.

Weiss, E.A. 1971. Castor, sesame and safflower. Leonard Hill Books, London. p. 311–525.

Weiss, E.A. 2000. Oilseed crops. 2nd ed. Blackwell Science., Malden, MA

Yermanos, D.M. 1980. Sesame. p. 549–563. In: H. Fehr and H. Hadley (eds.), Hybridization of crop plants. Agronomy-Crop Science Society of America, Madison, WI.