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Growth stages and developmental patterns of guar

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Abstract

Guar [*Cyamopsis tetragonoloba* (L.) Taub.], also known as clusterbean, is a crop plant grown in semi-arid regions worldwide for the galactomannan gum of its seed, and as a forage, vegetable, and green manure. Despite the importance of guar and its products, uniform growth stage descriptions have not been established for the crop. Such descriptions allow for improved documentation and communication of the growth and phenological development of crops by researchers, producers, and others. Following models of other warm-season, indeterminant-growth legumes, such a system was developed for guar based on visually observable and sequential vegetative (V) and reproductive (R) plant events. The system was evaluated in two locations in dryland and irrigated conditions, using three morphologically contrasting guar varieties. The V stages begin with emergence (VE) and then are determined by counting the nodes on the main stem of the plant, with the cotyledonary node as zero [V0 to V(N)]. The R stages include R1 (First Flower), R2 (First Pod), R3 (First Seed or Full Pod), R4 (Full Seed), R5 (First Maturity), R6 (50% Maturity), and R7 (Harvest Maturity). The V and R stages may be reported alone or concurrently and applied at plant or crop scales. The stage descriptions apply to all growth morphologies of guar (i.e., branched and non-branched) and accommodate the indeterminant growth habit of the plant. Season-long data is reported from field studies on crop V and R stage progression, as well as data on crop growth, including biomass component partitioning, productivity, and canopy development.

1 | INTRODUCTION

Guar [*Cyamopsis tetragonoloba* (L.) Taub] or clusterbean is a leguminous plant that has a long history as a cultivated crop with a diversity of uses. The historical uses of guar were as food, forage, and green manure (Abidi et al., 2015). While the crop is still used in each of these ways today, various uses of the gum derived from guar seeds is the main driver of production (Abidi et al., 2015; Cook & Perrin, 2016; Yadav et al., 2015). In the 1940s and 1950s, "guar gum," which is technically known as galactomannan gum, was used in industrial applications for the first time, as the Institute of Paper Chemistry was seeking a replacement for locust bean (*Parkia biglobosa*) gum as a binder in paper making (BeMiller, 2009). Since that time, raw guar gum has been used in many applications and several processes have been developed in which guar gum is treated to produce various chemical derivatives that widen its applications (Yadav et al., 2015). Guar gum and its derivatives are used in numerous applications in the food, pharmaceutical, textile, cosmetic, explosive, oil and gas, and other industries (Abidi et al., 2015; Mudgil, Barak, & Khatkar, 2014). In these applications, the gum acts as a lubricant, emulsifier, binder, thickener, or hardener, among other functions (Yadav et al., 2015). Both historically and currently, the potential for biological nitrogen fixation by symbiotic association of guar and *Rhizobia* bacteria has also been a primary or secondary motivator for guar production (Arayangkoon, Schomberg, & Weaver, 1990; Hinson & Adams, 2020; Stafford & Lewis, 1980; Thapa, Adams, & Trostle, 2018).

The exact origin of the guar plant is not known, but it is thought to have been domesticated in the region of India and Pakistan where it has been grown for centuries as a food and forage (Whistler & Hymowitz, 1979). Even today, India and Pakistan are the centers of guar production. Estimates of the percentage of the worldwide supply of guar that come from India are about 80%, followed by Pakistan at about 15%, with the remaining 5% coming primarily from the United States, Australia, and parts of Africa (Abidi et al., 2015; Gresta et al., 2014; Yadav et al., 2015). Indian guar production ranged widely from 200,000 to 1,800,000 metric tons of seed per year between 2005 and 2013, whereas worldwide production, including India, was estimated at 250,000 to 2,250,000 metric tons per year over the same timeframe (Yadav et al., 2015). Between 75 and 80% of Indian guar was exported. In 2014, the latest data available (to our knowledge), worldwide guar production was 2,350,000 metric tons (Yadav et al., 2015).

Despite the worldwide importance of guar and its products, growth stage descriptions have not been established for the crop. Such descriptions allow for more accurate documentation and improved communication of the development and phenology of crops by researchers, producers, and others. Growth staging systems are based on discrete, transitional events in the plant life cycle, typically spread across the life cycle, and serve as physiologically relevant growth checkpoints. This allows users of the system to move away from simply time-based agronomic assessments, which cannot easily be compared across sites and years because they are affected by environmental and management factors, such as planting date, soil type, soil nutrient availability, moisture conditions, and many other factors (Hinson & Adams, 2020; Singla, Grover, Angadi, Schutte, & VanLeeuwen, 2016; Stafford & McMichael, 1991; Thapa et al., 2018). Examples of the utility of crop growth staging systems include planning experimental treatment applications, scheduling crop management operations, and tying crop observations to crop development within and across crop seasons and locations. Examples of published growth staging systems for other crops include those for peanut (*Arachis hypogaea* L.), cotton (*Gossypium hirsutum* L.), sorghum (*Sorghum bicolor* L. Moench), maize (*Zea mays* L.), wheat (*Triticum aestivum* L.), soybean (*Glycine max* L. Merr.), and others (Boote, 1982; Elsner, Smith, & Owen, 1979; Fehr, Caviness, Burmood, & Pennington, 1971; Hanway, 1963; Vanderlip & Reeves, 1972; Zadoks, Chang, & Konzak, 1974; respectively). This includes growth staging systems, such as the extended Biologische Bundesanstalt, Bundessortenamt, and Chemische Industrie (BBCH) scale, that have been adapted and applied, as uniformly as possible, to many crops (Lanchashire et al., 1991; Meier et al., 2009). Constraints of the BBCH scale, however, lower its utility when applied to indeterminant crops like guar, because it lacks ability to overlap vegetative and reproductive stages and presents user challenges in assigning onset, ending points, and developmental benchmarks to parameters and processes that experience prolonged change (e.g., pod maturation).

Core Ideas

- A comprehensive growth staging system was developed for guar.
- The system includes distinct vegetative and reproductive stage components.
- Written stage descriptions and stage-specific images from the field are provided.
- The system is intended to better unify research and production endeavors on guar.
- Data is also reported describing growth and developmental patterns of the crop.

To better unify research and production endeavors of guar, the objective of this work was to develop uniform and accurate growth stage descriptions that apply at single-plant and crop scales to guar of any growth habit (i.e., non-branching, branching) and accommodate its indeterminant nature. We have used an approach similar to that used for other legumes (Boote, 1982; Fehr et al., 1971), separately designating vegetative (V) and reproductive (R) stages, which may be reported alone or together, as they concurrently change. Another objective was to provide data that describe the growth patterns and distribution of major plant parts in different guar varieties and growing conditions over time in relation to the growth stages.

2 | MATERIALS AND METHODS

2.1 | Experimental design and sowing dates

To evaluate the growth stages and developmental patterns of guar, three distinct studies were established at the

Chillicothe Research Station, near Chillicothe, TX in 2019. Each study was arranged in a randomized complete block design. The first two studies, one dryland and one irrigated, were laid out directly adjacent to each other, both including plantings of the guar varieties Kinman (branching) and Monument (non-branching). These studies were planted on 7 June 2019 on an Abilene clay loam soil (Taxonomic class: fine, mixed, superactive, thermic Pachic Argiustolls) with three plot replicates. The third study, which was embedded within a larger ongoing study and managed in dryland conditions, was planted with Lewis guar (finely branched). This study, which was approximately 0.8 km away from the other studies, was planted on 26 June 2019 on a Tipton loam soil (Taxonomic class: fine-loamy, mixed, superactive, thermic Pachic Argiustolls) with four plot replicates. The land used for the first two studies had been fallow for at least 2 yr. The plots used for sampling and observation in the third study had been planted to guar in the previous summer with a fallow period in the winter. The guar varieties used in these studies were chosen for their distinct morphological characters. Monument is a single-stem variety that exhibits minimal branching. Kinman is a highly branching variety. Lewis has a more intermediate, finely branched character.

2.2 | Experimental procedures

Preplant nitrogen was applied as urea and tilled in for the first two studies at a rate of 34 kg N per ha. No fertilizer was applied in the third study and there was no tillage. All plantings were done with a drill on 51-cm row spacing at a rate of 9 kg seed per ha. Meteorological conditions and reference evapotranspiration (ET) were monitored by an on-site weather station. In the irrigated study, subsurface drip irrigation was initiated on 8 July 2019 and ended on 16 Sept. 2019 and managed by ET replacement. The plots were irrigated at a rate equaling 25% reference ET replacement from 8 July to 4 August, and at a rate of 50% ET replacement from 5 August to 16 September. Weeds were managed early in the season by hand hoeing and weed pressure was low in the mid-to-late season.

In-season measurements of crop biomass productivity, including partitioning of biomass to leaf, stem, and reproductive components, were done on a bi-weekly basis in the first two studies. In-season measurement of only crop biomass productivity were made in the third study, also on a bi-weekly schedule. The reproductive fraction included entire clusters (flowers, pods, seeds, and cluster stems). Biomass samples were taken from 1-m sections of representative rows within plots, always excluding border rows, and dried in a forced-air oven at approximately 55 °C for 10 d or until completely dry. Dry biomass was weighed, and the values were converted to crop scale in units of Mg ha^{-1}.

The plots were visited at least weekly to make observations and to take images of reproductive (R) stage transitions. The date of transition for each R stage was noted when 50% of plants in a plot had reached the stage based on non-destructive observations of 10 or more plants per plot. Observations of vegetative (V) stages were made in conjunction with biomass measurements. These observations were made on five representative plants among those clipped for biomass measurements and averaged to give a plot mean. The natural canopy height and width (to the edge of foliage envelope, rather than only growth apex height) were measured with a meter stick at five representative sites within each plot in the first two studies at R stage transitions.

Statistical analysis was performed on the biomass accumulation and seed yield data, separately for the Kinman and Monument dryland and irrigated trials, using the SAS 9.4 software (SAS Institute, Cary, North Carolina). The data were analyzed by analysis of variance (ANOVA; $P \leq .05$) using Proc MIXED, evaluating the main effect of variety. Experimental block was treated as a random factor in the model. The data were checked to ensure they satisfied the assumption of normality and equal variances using histograms, Q-Q Plots, and plots of residuals. Mean separation tests for pairwise comparison of treatments were accomplished using the Tukey method. Standard deviations were added to the canopy height and width values to allow simple statistical comparisons. The field data presented here, collected in several conditions and on several guar varieties, were gathered to provide examples of these parameters for users of the new growth staging system to reference and do not provide any definitive expectations for other conditions.

3 | RESULTS AND DISCUSSION

3.1 | Overview

Vegetative (V) and reproductive (R) growth stages were identified for guar as given in Table 1. The stages apply to seed-producing guar at single-plant and population (crop) scales. When applied at the crop scale, the R stages will be noted when 50% of plants in the population have reached a given stage, which may be determined by a representative sampling technique (such as used in this study) or more roughly by visual estimation, whereas V stages are always noted by using a representative sampling technique and averaging the values observed. Guar varieties vary in growth habit from non-branching (single-stem) to highly branching types, with a full spectrum

TABLE 1 Growth stage descriptions for guar

Stage	Stage title	Stage description
Vegetative (V) Stages [a]		
VE	Emergence	Plants are visible at the soil surface.
V0	Cotyledonary Node	The cotyledonary node is developed, with cotyledons flat and open at the soil surface.
V1	First Node	One developed node is present on the main axis of the plant, with associated leaves unfolded and flat.
V(N)	Nth Node	N developed nodes are present on the main axis.
Reproductive (R) Stages [b]		
R1	First Flower	The first flower is visible anywhere on the plant.
R2	First Pod	The first pod is visible and in early development, with a length of approximately 10 to 15 mm.
R3	First Seed or Full Pod	Immature seeds, with a diameter of at least 3 mm, are present within the first pod. This is also the point at which the first pod is full expanded, with a length characteristic to the variety.
R4	Full Seed	The first pod cavity cross-section is apparently filled with seed.
R5	First Maturity	The first pod has naturally desiccated and is fully brown in color.
R6	50% Maturity	50% of pods are desiccated and brown in color.
R7	Harvest Maturity	At least 50% of the plant stem has desiccated, which may be achieved by the natural maturation process, frost, or chemical harvest aids, in addition to achieving at least 75% pod maturity.

[a]V stages are averaged across multiple representative plants within a population or are reported directly on single plants. VE and V0 may be noted when reached by 50% of a population.

[b]R stage transitions are achieved when 50% of plants in a population have reached a given stage or are reported directly on single plants.

of intermediate branching types observed (Gresta, Avola, Cannavo, & Santonoceto, 2018; Morris, 2010; Stafford, 1987), and this system can be applied to all of them. The V and R stages may be reported together or alone, depending on the objective of the work. This system provides several benefits for guar over growth staging systems designed to be applied across many plant species, by accommodating the indeterminant growth habit of the plant in which there is overlap (concurrency) and often prolonged change in vegetative and reproductive development and allowing users to clearly define onset of flowering, pod-set, and seed growth.

3.2 | Vegetative stages

The V stages are based strictly on development of nodes on the main axis of the guar plant, with the exception of the VE stage (Table 1). The VE stage represents plant emergence and is noted when any part of the plant is visible at the soil surface. The timing of emergence of guar in populations is often variable due to the hard and impermeable nature of the guar seed (Iqbal, 2015; Liu, Peffley, Powell, Auld, & Hou, 2007). Because of this, the VE stage should be noted in guar populations when plant emergence is sufficient to clearly observe emergence along planted rows or when 50% of expected plants have emerged. The soil temperature requirement for germination (~22 °C) in guar is high relative to most crops (Abidi et al., 2015), and this can also have a large effect on the timing of the VE stage. Singla et al. (2016) reported emergence to occur between 5 and 16 d in a planting date trial, with longer emergence times associated with earlier, cooler planting times. In the present field trials, VE occurred in 4 to 5 d (Table 2), and the average air temperatures at those times were 21 and 25 °C, depending on the trial.

Following the VE stage, the initial node that will develop is the cotyledonary node, which is denoted node zero, representing vegetative stage V0. The V0 stage is noted when the cotyledons are open and relatively flat along the soil surface. Similar to other plants, the cotyledons of guar are easily recognizable by their rounded and thick appearance without the typical veining patterns observed on true leaves. At later stages of development, it is common for stems to emerge from the cotyledonary node in branching varieties of guar. The next node that develops on the plant, from which true leaves will emerge, is designated as node one, representing vegetative stage V1. All subsequent nodes that develop on the main stem of the plant and corresponding vegetative stages are denoted as V(N). Just like the V0 stage, V(N) stages are noted when the initial leaves emerging from the node are unfolded and leaflets lie flat. Main-stem nodes are used for vegetative growth stage determination, because node scars remain permanently on the plant stem for season-long observation even after leaves may abscise and guar varieties differ in other vegetative growth habits, such as branching. The V stage progression or rate of node development depends on

TABLE 2 The time after planting of vegetative (V) stage progression in three guar varieties. Kinman and Monument were grown at one site in dryland and irrigated conditions, whereas Lewis was grown at a nearby site with a later planting date in dryland conditions only

	Kinman	Monument		Lewis
Time	Vegetative stage		Time	Vegetative stage
d			d	
Dryland				
4	VE	VE	5	VE
7	V0	V0	14	V2
25	V3	V4	26	V6
31	V6	V6	40	V12
46	V14	V14	55	V19
60	V17	V17	71	V19
75	V17	V19	84	V23
84	V19	V20	110	V28
104	V25	V27		
122	V30	V30		
136	V31	V30		
Irrigated				
4	VE	VE		
7	V0	V0		
25	V4	V4		
31	V6	V6		
46	V13	V13		
60	V19	V19		
75	V23	V24		
84	V28	V27		
104	V38	V34		
122	V39	V37		
136	V38	V43		

agronomic management, temperature, and guar variety, which is reflected in the field data presented in Table 2 and in the literature (Meftahizadeh, Ghorbanpour, & Asareh, 2019; Singla et al., 2016; Stafford et al., 1987). For example, the rate of early season V stage progression was faster in the dryland Lewis trial, which was planted when temperatures were warmer, than in the dryland Kinman and Monument trial, and stalling of V stage progression was observed in response to moisture stress later in the season in both trials (Table 2).

3.3 | Reproductive stages

The reproductive or R stages are based on the progression of the plants through the reproductive cycle, with stages noted at their first occurrence in the plant or crop (Table 1). The stages include: First Flower (R1), First Pod (R2), First Seed or Full Pod (R3), Full Seed (R4), First Maturity (R5), 50% Maturity (R6), and Harvest Maturity (R7). When any R stage is observed that designation remains until the next stage is reached. In the discussion of the R stages that follows, there are references to the timing of R stage development from the present field trials plus similar data reported in the literature. These observations are helpful in understanding the growth habits and phenological variation of guar but will not provide specific expectations on the timing of developmental progression in any particular system, guar variety, or year. It is important to note that guar has photoperiod sensitivity, and is observed to be a short-day plant (Lubbers, 1987; Teplyakova, Valkov, Dzyubenko, & Potokina, 2019), which will affect reproductive development, depending on the growing environment. The alternative name of guar, clusterbean, is based on the reproductive growth habit of the plant in which pod formation occurs in clusters on reproductive stems. Reproductive clusters are commonly referenced in scientific literature on guar (Gresta et al., 2018; Ramanjaneyulu et al., 2018) and this term is used herein in descriptions of reproductive development.

The R1 stage, or First Flower, is noted when a flower is visible anywhere on the plant if doing a single-plant observation or on 50% of plants in a crop (Figure 1a). This occurred between 27 and 36 d after planting in the present field studies (Table 3). Meftahizadeh et al. (2019) reported flowering initiation to occur in as few as 26 d after planting and as many as 37 d after planting in guar landraces and varieties tested across a variety of planting dates in Iran. In a similar study, Gresta et al. (2013) reported flowering times between 36 and 45 d in Italy. Across two planting dates and eight guar varieties in India, Patil (2014) reported mean times to initiation of flowering of 39 to 49 d. Flowering typically begins on the main stem of the plant toward the base and expands both upward and outward on branches and on reproductive clusters as the plant develops.

The R2 stage, or First Pod, is noted when the first pod on the plant is 10 to 15 mm in length, early in its development. At this length, guar pods have begun to straighten out and are slender (Figure 1b). The R2 stage occurred at 34 d after planting in the dryland and irrigated Kinman and Monument trials and at 44 d after planting in the dryland Lewis trial. The Lewis trial had the most severe drought conditions evaluated here (Table 3) and this is likely the reason for the delay, as R1 was also delayed in this case. Reports of this stage were not found in the literature.

Stage R3, or First Seed or Full Pod, is noted when immature seed in the first pod on the plant are at least 3-mm in diameter. This is also the point at which the first pod is expected to have expanded to the full length characteristic of the variety (Figure 1c), as First Seed and Full Pod

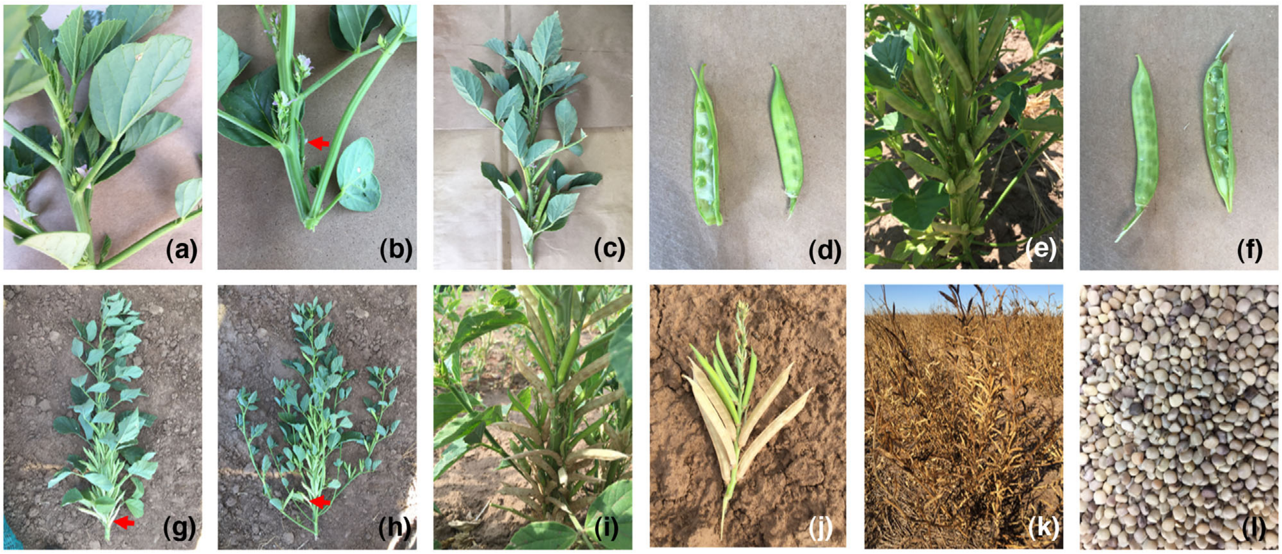

FIGURE 1 Images of the reproductive stages and traits of guar. (a) R1 or First Flower; (b) R2 or First Pod, with the pod identified by a red arrow (the image also includes a cotyledon and a stem emerged from the V0 node); (c) R3 or First Seed or Full Pod; (d) closed and open pods in R3; (e) a plant advanced within R4 or Full Seed; (f) closed and open pods at R4 or Full Seed; (g) R5 or First Maturity in a non-branching variety, with the first mature pod identified by a red arrow; (h) R5 or First Maturity in a branching variety, with the first mature pod identified by a red arrow; (i) a plant advanced within R5, exhibiting mature and immature pods; (j) a reproductive cluster with mature and immature pods and flowers; (k) R7 or Harvest Maturity, following a frost; and (l) mature guar seeds

TABLE 3 The timing of reproductive (R) stage progression in three guar varieties. Kinman and Monument were grown at one site in dryland and irrigated conditions, whereas Lewis was grown in a nearby site with a later planting date in dryland conditions only

Reproductive stage	Kinman	Monument	Lewis
	Time after planting		
	d		
Dryland			
R1	27	27	36
R2	34	34	44
R3	47	47	54
R4	55	54	60
R5	68	67	70
R6	–	–	–
R7	145	145	127
Irrigated			
R1	27	27	
R2	34	34	
R3	46	46	
R4	52	52	
R5	65	65	
R6	–	–	
R7	145	145	

seem to occur concurrently or in rapid succession in guar. Because the seed is immature, the pod has a characteristic flat appearance (Figure 1d). Observation of First Seed requires opening pods and measuring seed diameter, but seed size provides a more universal indicator of this stage than full pod length, which varies by guar variety and can be difficult to ascertain without prior knowledge. All three guar varieties evaluated in the present studies had fully expanded pod lengths of about 55 mm and R3 was noted at 47 to 54 d after planting (Table 3). In a characterization of 73 varieties from the USDA guar collection, Morris (2010) reported pod lengths ranging from 30 to 110 mm, with an average of 61 mm. Morris (2010) noted that 59 of the 73 accessions (81%) averaged a pod length of 58 mm. Rai, Dharmatti, Shashidhar, Patil, and Patil (2012) reported pod lengths ranging from 44 to 103 mm, averaging 56 mm, across 31 varieties.

The R4 stage, or Full Seed, is characterized by the first pods on the plant or 50% of plants in a population having their first pods apparently physically filled with fresh seed (Figure 1e). Please note this stage is based on physical and visual characteristics of the pod and nothing is implied about seed mass or the seed filling process. This can be a somewhat subjective evaluation, but a pod meeting the description of Full Seed will be firm and the walls of the pod will be tightly wrapped around the seed, which can be best recognized by feeling the smooth texture of the pod surface and visually observing bulging of the pod at the sites of seed. The pod and the seeds within will be fully green, with seed less than half of the final mature weight, and not yet beginning to desiccate. For comparison, Boote (1982) found that weight per seed at the Full Seed stage for peanut was less than half of the final mature weight per seed. Figure 1f shows both open and closed pods in the Full Seed stage. Stage R4 occurred between 54 and 60 d after planting in the present field trials (Table 3).

Stage R5, or First Maturity, occurs when the first pod on a plant is mature or when 50% of plants have reached this condition in a crop setting. This occurred between 65 and 70 d after planting in the present trials (Table 3) and is shown in both non-branching and branching guar types in Figures 1g and 1h, respectively. At this stage, a mature guar pod has naturally desiccated and is fully brown in color. Congruent with the pattern of flowering and pod development across the plant, the first mature pod typically occurs near the base of the main axis of the plant, then proceeds on a pod-by-pod basis, moving from proximal to distal positions within reproductive clusters and branches (Figure 1i). A guar cluster can simultaneously contain flowers, newly formed and maturing pods, and fully mature pods at the same node position (Figure 1j). Because of the indeterminate growth habit of guar, First Maturity occurs long before 50% Maturity or Harvest Maturity and is not used as an indicator of such. Because of the potentially broad timeframe between R5 and R6 and R7, simultaneous collection and reporting of V stages will be particularly useful in the R5 stage.

Stage R6, or 50% Maturity, occurs when at least 50% of pods have desiccated and are fully brown in color. Determining R6 will be more subjective than most reproductive stages. Any particular level of maturity in guar can be a moving target due to its indeterminant growth habit, which typically allows for continued growth and productivity as long as environmental conditions are suitable to sustain it. For example, in the present study, at least 50% of pods were mature in stressful dryland conditions in the mid-season, but late-season rains promoted rapid pod addition and growth, much of which was harvestable, reducing the percent pod maturity for a time (Figure 2).

The final reproductive stage is R7, or Harvest Maturity, which is defined as the point at which at least 50% of the plant stem has desiccated and is brown in color, in addition to having at least 75% mature pods. The focal point of this stage is achieving at least 50% desiccation of the stem, rather than the condition of the seed—such as seed weight or moisture content, as used in other crops—because drydown of the stem is required for successful mechanical harvest of guar and seed maturity occurs in a continuum in this indeterminant-growth crop. Immature pods and seed will typically be present at harvest, which will be discarded by a properly set combine. Desiccating the guar stem for mechanical harvest can occur by the natural maturation process or by the first fall frost, which are common producer practices, depending on the growing environment, though the process can be hastened by application of chemical harvest aids (Abidi et al., 2015). Figure 1k shows guar fully mature and ready to harvest, following a frost. There appear to be few drawbacks to late guar harvesting. There is some evidence that seed coat degradation occurs when harvest timing is delayed for extended timeframes, especially when environmental conditions are wet, resulting in black seed (Liu et al., 2007). But black seed does not seem to have lower galactomannan gum quantity or quality than lighter colored seed and black seed actually imbibes water more effectively and has higher germination than lighter colored seed (Liu et al., 2007). The typical spectrum of guar seed colors is shown in Figure 1l, including a few black seed.

The time to reach Harvest Maturity will vary greatly by growing and/or environmental conditions, and to some extent, by variety. In a comparison of 68 guar varieties in the relatively long-season Mediterranean environment of southern Italy, Gresta et al. (2018) reported crop cycles lasting between 155 and 195 d, with an average of 182 d and a median of 190 d. In the U.S. Southern Great Plains region, guar varieties are selected and managed to achieve Harvest Maturity in as few as 100 to 130 d (Abidi et al., 2015), though the regional growing season may allow up to 170 d of production. In the present field trial on Kinman and Monument varieties, the crop cycle lasted 145 d (Table 3) and was truncated by frost. In contrast to the 145-d cycle of these trials, Gresta et al. (2018) tested Kinman and Monument in southern Italy and reported much longer crop cycles of 188 to 195 and 163 to 175 d, respectively, reflecting the indeterminant flexibility of the plant to respond to its growing conditions.

3.4 | Plant growth and additional field observations

The indeterminant growth and branching habits of guar are among the most important traits of the plant from an agronomic perspective, though varieties differ in many other traits of interest to breeders and producers. Guar varieties will produce pubescent leaves, glabrous leaves, or a mixture of these types (Morris, 2010). Varieties differ in height, stem diameter, leaf morphologies, yield components and reproductive characters (e.g., clusters per plant, pods per plant, etc.), seed protein and galactomannan content, pod shattering, drought tolerance, and other traits (Garg, Burman, & Kathju, 2005; Gresta et al., 2018; Kapoor, 2014; Morris, 2010; Patil et al., 2014; Rai et al., 2012). Branching characteristics, growth habits, and other field observations are discussed further below.

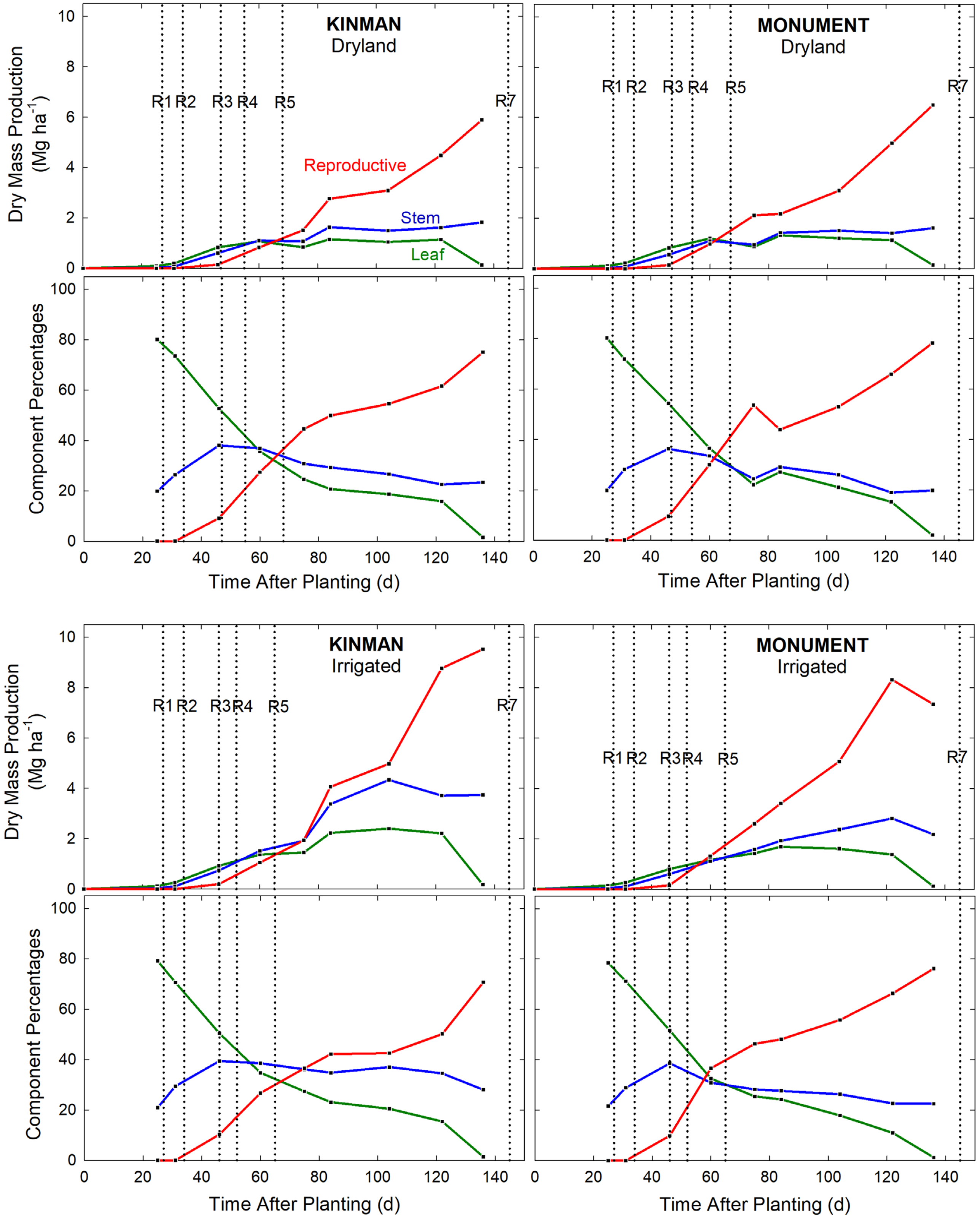

FIGURE 2 Season-long crop data. Biomass accumulation, including partitioning and percentages among leaf, stem, and reproductive components, over time for Kinman and Monument guar in dryland and irrigated conditions. The reproductive fraction includes entire clusters (flowers, pods, seeds, and cluster stems)

TABLE 4 Season-long canopy heights and widths at given R stages and times after planting for Kinman and Monument guar in both dryland and irrigated conditions. The error term is the standard deviation

Reproductive stage	Kinman			Monument		
	Time	Canopy width	Canopy height	Time	Canopy width	Canopy height
	d	cm		d	cm	
Dryland						
R1	27	13.2 ± 1.1	13.3 ± 1.4	27	13.4 ± 1.4	13.8 ± 1.5
R2	34	21.6 ± 2.5	23.4 ± 2.8	34	24.1 ± 2.3	22.8 ± 2.3
R3	47	32.3 ± 2.4	33.2 ± 1.7	47	27.2 ± 2.5	35.4 ± 2.6
R4	55	33.2 ± 2.8	38.5 ± 2.3	55	25.9 ± 3.4	43.0 ± 2.9
R5	68	32.2 ± 2.9	37.9 ± 3.0	67	24.2 ± 2.5	41.4 ± 3.9
R6	–	–		–	–	–
R7	145	–	60.3 ± 4.3	145	–	64.5 ± 6.5
Irrigated						
R1	27	13.5 ± 1.1	13.5 ± 1.3	27	13.0 ± 1.2	12.9 ± 1.2
R2	34	22.7 ± 2.2	22.4 ± 2.2	34	23.2 ± 2.3	22.9 ± 2.2
R3	46	33.1 ± 3.5	34.1 ± 3.0	46	27.2 ± 2.4	34.1 ± 2.1
R4	52	41.4 ± 4.1	49.7 ± 2.6	52	27.5 ± 2.0	52.4 ± 3.5
R5	65	41.5 ± 2.9	59.0 ± 2.9	65	27.0 ± 2.7	62.8 ± 4.2
R6	–	–	–	–	–	–
R7	145	–	84.5 ± 3.7	145	–	86.3 ± 3.6

The branching characteristics of guar vary greatly among varieties, including non-branching varieties. In a comparison of 68 guar varieties selected by Gresta et al. (2018), 17 were non-branching and 51 were branching and the number of branches per plant ranged from zero to about 12. In the process of regenerating guar accessions from the USDA germplasm collection, 73 guar varieties were evaluated by Morris (2010) and only three were non-branching. It has been noted that non-branching guar types have the benefit of better elevating pods from the soil surface for more efficient harvest and also provide more uniformity in pod maturation than many branching varieties, making the non-branching morphology a common target in guar breeding efforts (Abidi et al., 2015; Gresta et al., 2018). Differences in canopy architecture among guar varieties will also affect their management. For example, non-branching varieties may require higher sowing densities and/or narrower row spacing to optimize productivity, while branching varieties may create better ground coverage for weed suppression and preservation of soil moisture. In the primary field trial, non-branching (Monument) and branching (Kinman) guar varieties were compared. The canopy height was similar between varieties, though the canopy was narrower in the non-branching Monument, especially in irrigated conditions (Table 4). Aerial biomass productivities never differed between varieties in dryland conditions, but diverged around 84 d after planting in irrigated conditions such that the branching Kinman produced more biomass than the non-branching Monument (Figure 2; Table 5).

As a percentage of total biomass over time, the leaf, stem, and reproductive components of Kinman and Monument followed similar trends across the growing season, in both irrigated and dryland conditions (Figure 2). The crop was initially about 80% leaf and the percentage leaf declined in an exponential pattern over time, with an abrupt decline at the end of the season due to natural defoliation that preceded the first frost (Figure 2). Percent stem was relatively consistent across the growing season in both dryland and irrigated conditions (Figure 2). These temporal trends in percentage leaf and stem resemble those reported by Stafford (1987). The initial rate of aboveground growth of guar is quite slow, postulated to be a time when the plant is devoting most of its resources to development of the root system, though studies confirming this were not found in the literature. Aboveground growth in this study was only 0.1 to 0.4 Mg ha^{-1} by 30 d after planting and the rate of growth accelerated after that point (Table 5; Figure 2). The R1 stage, First Flower, occurred around 30 d after planting (Table 3) and there was relatively little reproductive biomass accumulation between 30 and 50 d after planting (Figure 2). The temporal trend in percent reproductive biomass in this study differed from that reported by Stafford (1987), likely due to differences in rainfall patterns. Percent reproductive biomass rose and plateaued in the study of Stafford (1987), whereas late-season rains in the

TABLE 5 Total biomass accumulation over time and final seed yields for three guar varieties. Kinman and Monument were grown at one site in dryland and irrigated conditions, whereas Lewis was grown at another site with a later planting date in dryland conditions only

	Kinman	Monument		Lewis
Time	Total crop biomass		Time	Total crop biomass
d	———Mg ha^{-1}———		d	Mg ha^{-1}
Dryland				
0	0	0	0	0
25	0.116	0.147	15	0.0121
31	0.265	0.314	27	0.158
46	1.59	1.54	41	0.840
60	3.00	3.30	56	1.79
75	3.42	3.95	72	2.34
84	5.55	4.93	85	2.04
104	5.63	5.82	99	2.90
122	7.24	7.54	111	4.50
136	7.84	8.27		
Seed yield	3.44	3.66	Seed yield	0.60
Irrigated				
0	0	0		
25	0.145	0.180		
31	0.367	0.369		
46	1.85	1.55		
60	3.93	3.59		
75	5.30	5.60		
84	9.64a[a]	7.01b		
104	11.7a	9.05b		
122	16.8a	12.5b		
136	13.4a	9.63b		
Seed yield	5.29a	4.01b		

[a] For each date, values followed by different lowercase letters were significantly different ($P < .05$).

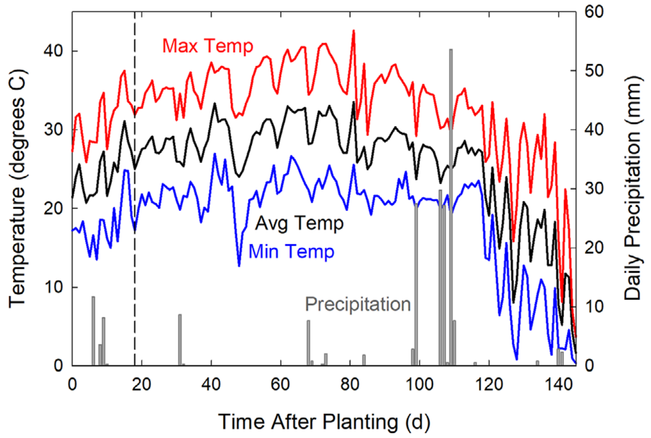

FIGURE 3 Weather data. Minimum, maximum, and average daily temperatures, and daily precipitation during the study period. The time after planting scale has been set for the Kinman and Monument studies. The Lewis study began at the time indicated by the vertical dotted line

current study drove a large increase in reproductive growth on both existing and new clusters beginning at about 100 d after planting (Figures 2, 3).

Seed yield was measured in the three field studies, which included dryland and irrigated conditions, two planting dates, and three varieties. The only statistical yield comparisons that could be made were between varieties in the Kinman and Monument dryland and irrigated trials, showing that Kinman (branching variety) yielded more than Monument (non-branching) in irrigated conditions, while the varieties did not differ in dryland conditions (Table 5). The dryland yield of Monument was 8.7% less than the irrigated yield of the same variety and the dryland yield of Kinman was 34% less than the irrigated yield of that variety. Dryland yields were relatively close to the irrigated yields despite minimal rainfall during the first 100 d of the growing season (Figure 3). The yield of Lewis, which was planted 18 d later than the other varieties, was poor (Table 5). Developmental effects of the late planting date, as well as environmental conditions (Figure 3), likely contributed to the slow season-long growth of Lewis shown in Table 5. The rate of crop growth and pod set (data not shown) in Lewis did increase at about 100 d after planting when a substantial amount of late-season rain fell (Figure 3), though this resulted in a minimal amount of additional harvestable yield, unlike what occurred in the different cultural circumstances of the dryland and irrigated Kinman and Monument study where yield did improve. The difference in yield responses may reflect the physiological condition of the plants at the time the late-season rainfall was received, as the newly set pods rapidly matured in the Kinman and Monument study but remained green in the Lewis study.

4 | CONCLUSIONS

Growth stage descriptions were developed and are herein proposed for guar. The proposed growth staging system is based on discrete vegetative (V) and reproductive (R) developmental benchmarks that can be objectively observed and applied to guar of any growth morphology and that accommodate its indeterminant growth habit. This system provides several benefits over growth staging systems designed to be applied across plant species. We anticipate this system will allow for more accurate documentation and improved communication of the development and phenology of guar by researchers, producers, and others.

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