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Characterization of Genotype by Planting Date Effects on Runner-Type Peanut Seed Germination and Vigor Response to Temperature

Timothy L. Grey, Charles Y. Chen, Russell Nuti,
Walter Scott Monfort and George Cutts III

Additional information is available at the end of the chapter

Abstract

Experiments evaluated the genotype by environment effects on seed germination and vigor of the peanut runner-type cultivars 'Georgia Green', 'AT3085R0', 'AT271516', 'Georgia 03L', and 'FR458' grown under similar production practices, for three planting dates: April, May, and June in Georgia and Alabama. Objectives were to determine if time of planting and harvest dates would subsequently affect germination and vigor when tested using a thermal gradient devise (temperature range 14 to 35 °C). Runner-type peanut seed grown in Dawson Georgia in 2008 had the strongest seed vigor with $Germ_{80}$ of 22 to 40 growing degree days (GDD), and maximum incidence of germination rate 84.8-95.7% when planted April, May, and June 2008 across 15 seed lots. In contrast, seed harvested from plantings of May 2009 at Dawson Georgia exhibited $Germ_{80}$ of 24 to 40 GDD with maximum incidence of germination rate 79.8-93.6%, but seed from April 2009 plantings had poor vigor of 56.8-72.8% and no amount of GDD could achieve $Germ_{80}$, with similar results for June 2009 plantings for this location. For Headland April, May, and June 2009 plantings of the same cultivars, all seed had poor vigor, ≤75.6% maximum incidence for germination rate, and none obtained a measurable $Germ_{80}$.

Keywords: *Arachis hypogaea*, germination, genotype, phenological development, thermal time

1. Introduction

Runner-type peanut, *Arachis hypogaea* (L.) producers often grow different cultivars in order to take advantage of genetic diversity of this Fabaceae crop. Production often centers on peanut runner-type cultivars (**Figure 1**), which have spreading indeterminate plant

Figure 1. Runner-type peanut -foreground, cotton (*Gossypium hirsutum* L.)middle, and maize (*Zea mays* L.) background.

morphology, can grow to 65 cm in height, and spread to over 1 m in width [1]. While genetic diversity is essential for the production of many crops for pest management, the cultivar 'Florunner' [2] dominated runner-type peanut production for more than 20 years in the Southeastern United States region with planting occurring in April and May [3, 4, 5, 6]. But what usually happens when there is over reliance on a single cultivar for production, a Tospovirus described as Tomato Spotted Wilt Virus (TSWV) increased rapidly across this runner-type peanut production region in the 1990s [7], eventually leading to the replacement of Florunner with tolerant cultivars [7, 8]. Since then, the utilization of newly released cultivars has been a constant factor in runner-type peanut production as many new genotypes have improved disease resistance, yield, quality, and economic value [9–14]. One recommendation for planting to avoid TSWV was to plant peanut after 15 May of each year. Peanut cultivars with tolerance to TSWV exhibited a linear decline in the disease incidence from greater than 50% for April plantings to less than 10% for June plantings [15]. This recommendation was in place for over 20 years and was practiced commonly from 2000 to 2010 (**Figure 2A**). Growers would delay planting until the 2nd–4th week of May with most planting completed by early June. However this created issues as this delayed planting pushed harvest windows into Oct and Nov, resulting in reduced yield and quality [8, 15, 16].

2. Importance

Seed quality issues occurred for some TSWV-resistant runner-type peanut cultivars in the 2000s [17]. Specifically, Georgia-01R [18] and York [19] cultivars had germination and stand establishment failures when planted for production. When tested and evaluated in field settings, advanced breeding lines of these cultivars did not have stand establishment and germination issues, but when planted in producer fields, some cultivars did not perform as expected with respect to stand establishment. This led to some TSWV resistant cultivars not to be accepted by growers. While peanut seeds were certified via individual state's standard
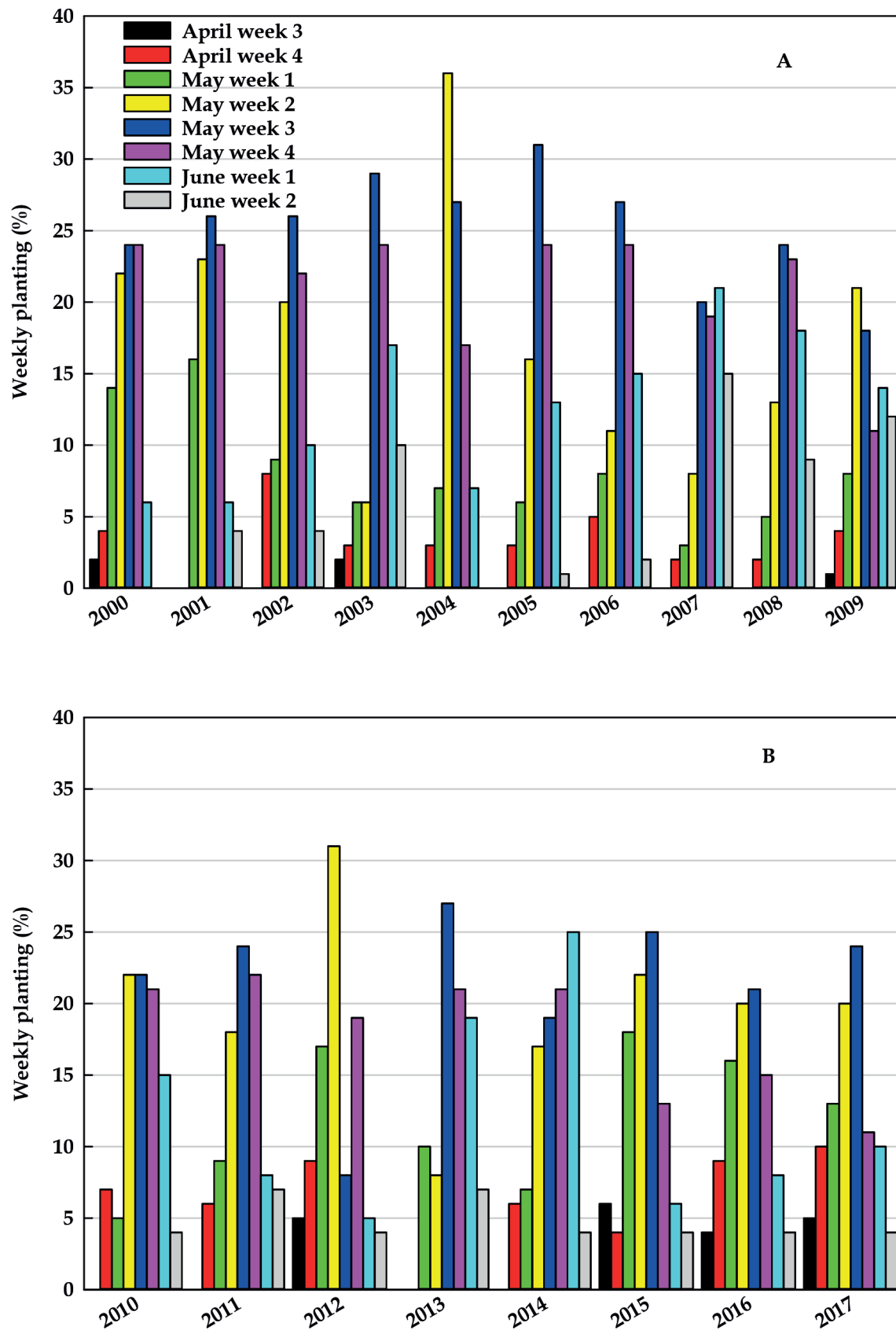
Figure 2. Weekly planting of runner-type peanut from 2000 to 2009 (A) and 2010 to 2017. (B) in Georgia, United States (National Agricultural Statistics Service, USDA. Data available at https://www.Nass.Usda.Gov).

seed germination testing, this did not always guarantee adequate stand establishment in the field. Seeds can be a substantial cost of growing peanuts due to its large size, often requiring greater than 170 kg ha^{-1}. When there is poor stand establishment, replanting can be expensive due to additional seed expenditures and trips through the field, and can reduce yield due to planting outside optimum time for peanut production. This can result in difficulty in determining optimum maturity, can promote weed escapes due to soil disturbance, incur greater disease opportunities, and can potentially incur additional pesticide costs. Therefore, planting cultivars with high germination and vigor to maximize net returns on input costs is essential.

3. Background information on peanut seed

It has been noted that runner-type peanut has an indeterminate growth habit which hampers the identification of an optimum harvest date [20, 21]. Due to this indeterminate growth, just prior to harvest there will be a range of pods with different maturities present on the same plant. When harvested all pods that have reached a given size and weight, regardless of maturity, are collected. This can result in high levels of immature pods in the harvested product. After shelling, this mix of seed maturities has critical implications for overall seed quality. Seed germination is often the trait that is commonly utilized to establish seed quality; but this presents significant limitations because there is often a difference between germination and overall seed vigor [20]. The maturity pattern of runner-type peanuts will vary by cultivar and one from one year to another. For virginia-type peanut, it has been demonstrated that seed maturity impacted not only germination capacity, but overall seed vigor [21]. However information about the effect on maturity for runner-type peanut germination and vigor has not reported.

3.1. Runner-type cultivars

One distinct aspect of runner-type peanut is that almost all cultivars are releases from public institutions from the Southeast region including the University of Georgia, University of Florida, Auburn University, and United States Department of Agriculture Research Service (USDA-ARS) [14]. These institutions have maintained constant releases over the past 25 years, and as previously noted, some cultivars have not been successful due to poor stand establishment [17], leading to their rapid demise from production even though they had desirable traits for disease resistance and improved quality [22]. In contrast, some cultivars have been rapidly adapted and garnered greater than 80% of field planting in some years. For example, 'Georgia Green' [23] was released in 1996 and from then to the mid-2000s was widely adapted and in some growing seasons, planted to greater than 90% of production hectares in the Southeast [24]. 'Georgia-06G' [25] replaced Georgia Green with plantings of greater than 75% (estimated) of the Southeast hectares. One advantage to using the aforementioned cultivars is their demonstrated resistance to TSWV. This has prompted the recommendation that growers begin planting peanut again in late April and early May [26].

This change has occurred as over the past few years as noted by a shift to late April-early May peanut planting (**Figure 2B**). For example, comparing the May week 1 in 2007–2012 and 2015 there is a clear indication that producers made that shift to planting earlier after Georgia-06G and other more TSWV cultivars were released. In contrast, for the May week 4 planting in the early 2000's, over 20% of the crop was planted the last week of May [27]. As prior noted, planting in late May and early June often reduces yield and quality of runner-type peanut due to maturity issues [8, 15, 16]. By 2015 and 2016, 15% or less was planted in late May and less than 10% in June. These changes and rapid acceptance of new cultivars has led to a need to ensure high quality seed and prevent any future stand establishment issues.

3.2. Seed quality

In reviews of factors that contribute to seed deterioration over time during storage, it has been noted that seed moisture content, mechanical and insect damage, pathogen attack, seed maturity, relative humidity, and temperature can have negative impacts [17]. These impacts have been quantified by previous research [14, 28]. Vigor testing can be utilized to evaluate seed for successful field establishment under different environmental conditions [29]. Strong primary seedling development in standard germination testing is regarded as an indicator of strong vigor [30], but this does not always translate into adequate field performance.

3.3. Seed testing

One method of testing seed quality, germination, and vigor is the use of a thermal gradient device [31–34]. This method has been used for weed and other crop seed evaluations [35, 36] to determine germination speed and vigor. A thermogradient allows investigators to examine a single seed lot, or multiple seed lots, at different temperatures simultaneously without the use of growth media, such as soil or growth chambers. Previous research using this process has demonstrated grower stock-dependent differences in seed vigor [22]. Quantifying genotypic by phenotypic differences in vigor have also been evaluated where site-specific differences in environmental factors during seed development kept all management variables equal (irrigation, pesticides, fertility) in order to minimize environmental variation [37]. Data indicated that eight runner-type cultivars exhibited phenotypic vigor variation by year, over the course of six years during the experiment, with genotype consistency across years.

4. Research

In order to quantify if phenotypic differences in peanut cultivar seed production could occur over different planting dates in the same year, multiple cultivars were planted over a 40-day planting window. After harvest and processing, evaluations of runner-type peanut

seed germination and vigor were conducted from one location in 2008 (Dawson Georgia) and two locations in 2009 (Dawson Georgia and Headland Alabama). Initial data from this research was used to quantify TSWV effects on pod yield and quality [15], but seeds were also saved. Thus, the objectives of this research were to evaluate the same seed for different peanut cultivars grown using the same management practices each year to determine if there were differences in seed vigor when planted at different times in the same field. Multiple cultivars were evaluated for seed viability and vigor for two consecutive growing seasons using a thermal gradient device (**Figure 3**).

4.1. Field trials

Field experiments were conducted near Dawson Georgia in 2008 and 2009 and repeated near Headland Alabama in 2009. Soils were a Tifton, Fine-loamy, kaolinitic, thermic Plinthic Kandiudults at Dawson and a Dothan, Fine-loamy, kaolinitic, thermic plinthic kandiudults at Headland. Five peanut cultivars were planted and included Georgia Green, as the agronomic standard because of its tolerance to TSW. Other cultivars included Georgia-03 L [38], AT 3085RO and AT271516 [39] were considered to have greater field tolerance to TSW compared to Georgia Green. Cultivar Flavor Runner 458 was also included as a susceptible check [40]. For runner-type peanut seed production for eventual evaluation, seeds were planted at three different dates each year starting in April. The earliest planting date in each year and location was determined when the 10-cm soil temperature reached 18.3°C for 3 consecutive days after 10 April. Once the initial planting date was determined, planting was repeated in 20-day intervals two times for three in total (**Table 1**).

All plantings were on single rows on 0.9 m centers, with planting date at each location arranged as a randomized complete block design in a separate block [41]. All treatments were replicated four times in each planting date block. Agronomic management inputs and irrigation were

Figure 3. Thermal gradient table (left) and peanut seed after evaluation for germination (right).

Dawson Georgia								Headland Alabama			
2008				2009				2009			
Month	R[b]	SR	GDD	Month	R	SR	GDD	Month	R	SR	GDD
	mm	MJ m^{-2}			mm	MJ m^{-2}			mm	MJ m^{-2}	
April	20	227	44	April	0	239	62	April	0	205	8
May	30	686	250	May	188	526	235	May	233	455	281
June	114	685	360	June	39	688	377	June	53	620	416
July	228	662	373	July	100	639	352	July	223	540	391
Aug	409	533	346	Aug	352	568	261	Aug	190	523	382
Sept	59.9	541	279	Sept	44	490	292	Sept	89	397	334
Oct	0.0	51	15	Oct	41	98	58	___			
Total by planting date											
21 Apr	802	2824	1398	21 Apr	681	2724	1322	20 Apr	736	2394	1518
12 May	841	2907	1533	11 May	708	2811	1464	11 May	702	2437	1619
2 June	799	2452	1361	1 June	577	2484	1340	1 June	555	2384	1523

[a]Rainfall, solar radiation, and GDD are reported from initial planting to digging. For Dawson, in 2008 digging dates were 2 Sept, 10 Sept, and 3 Oct, respectively; 2009 digging dates were 4 Sept, 23 Sept, and 8 Oct, respectively. For Headland, in 2009 digging dates were 4 Sept, 22 Sept, and 1 Oct.
[b]R, rainfall; SR, solar radiation; GDD, growing degree days.

Table 1. Monthly and total rainfall, solar radiation, and total growing degree days for various peanut planting dates up to time of digging from University of Georgia and Auburn University weather stations 1 km from experiments[a].

applied according to University of Georgia [42] and Auburn University recommendations. All cultivars were considered to have similar maturity requirements, thus digging date was determined separately by location and planting date according to the hull scrape method [43] of Georgia Green in each respective planting date block. Border rows were planted to Georgia Green to use for maturity determination. Plots were 6.1 m by two rows in 2008 and 6.1 m by four rows in 2009. Peanut vines were threshed with a stationary harvester (Kingaroy Engineering Works, Kingaroy, Australia) after sufficient field drying, since all pods and seeds can be cleaned-out between plots to prevent mixtures and maintain cultivar purity with this machine. A uniform sample was obtained with divider, then this was graded and these seed were saved for germination and vigor testing.

4.2. Seed screening

After threshing, peanut pods were dried with forced 30–40°C warm air to 7% moisture. All samples of pods were then hand-cleaned over a screen table. For each cultivar and planting date sample, grades were determined according to Federal State Inspection Service procedures [44] for runner-type peanut. Pods were mechanically shelled on a small scale unit and seeds were sized according to diameter via round holed screens with selection based on what

passed through a size 8.3 mm (Screen No. 21) but retained over 7.1 mm (Screen 18). Further screening was then conducted and sound mature seeds retained over a 7.1 by 19.1 mm slotted screen from each plot (four plots for each cultivar and planting date combination each year) were then evaluated for seed size based on Georgia Federal-State Inspection Service regulations [44]. Seeds were then stored at 16–18°C at approximately 30% humidity for up to 7 months prior to testing. Seed response to temperature and time for all seed to germinate were then evaluated on a thermal gradient table [31, 37].

4.3. Thermal gradient testing

The thermal gradient table was constructed from solid aluminum block measuring 2.4 m long by 0.9 m wide by 7.6 cm thick with a mass of 470 kg (**Figure 3**). On each end of the aluminum block, a 1.0 cm hole was drilled across the side section to allow fluid to be pumped into the table. On each end of the table, ethylene glycol plus water (1:10 mixture) at 14 or 35°C were pumped at 3.8 L per min to generate the thermogradient. Approximately 1.0°C increments occurred every 10 cm along the length of the thermogradient with a constant temperature across the width. This produced 24 increments across the length to obtain different temperatures, with nine increments across the width at each temperature. Thermocouples made from duplex insulated wire (PR-T-24 wire, Omega Engineering, Inc. Stamford, CT) were mounted to the underside of the table from the hot to cold ends. These were inserted vertically into a hole on the bottom of the table. Holes measuring 8 mm wide by 7 cm deep were drilled to allow the thermocouple to be placed within 5 mm of the upper table surface, at 10 cm intervals along the length of the table. This created a continuous temperature gradient ranging from 14 to 35°C along the length of the table. Temperatures were monitored continuously for each thermocouple and recorded at 30 minute intervals with a Graphtec midi data logger (MicroDAQ,com Ltd., Contoocook, NH).Temperature data for each thermocouple was recorded daily.

4.4. Seed testing

Peanut seeds for the appropriate plot of each cultivar by planting date were evenly distributed on germination paper (SDB 86 mm, Anchor Paper Co., St. Paul, MN), which was placed in a 100 by 15 mm sterile plastic Petri dish (Fisher Scientific Education, Hanover Park, IL). Twenty seeds were placed in each Petri dish followed by 10 ml of distilled water. A single Petri dish was then placed at each 1.0°C increment every 10 cm along the length of the table for a total of 24 dishes per plot (**Figure 3**). Beginning within 68–72 hours after seeding, peanut seed germination was counted when the radicle extended more than 5 mm beyond the seed, and then the seed was removed from the dish. Peanut seed with radicles longer than 2 mm from the seed coat are considered germinated [45] but 5 mm was chosen as it has been used in previous research [46]. Distilled water in 5 ml increments was added as needed to maintain adequate moisture in each Petri dish, and varied by temperature increment. Tests were run for 7 days with counts taken daily. All counts were taken in less than one hour each day at approximately the same time, depending upon when an experiment was started

on day zero. Counts were conducted from the cold end working toward the warm end. Seeds availability were limited each year, so individual field plots were considered replications with 24 Petri dishes for each replication (n = 480 seed per field replication, n = 1920 seed per cultivar by planting date each year). Germination data was converted to a percentage by day, and cumulative germination was determined for each Petri dish over the duration of that assay. Temperature data was recorded by the data loggers for each experiment. Data included temperature maximum and minimum (±0.5°C for each thermocouple) by individual Petri dish. Maximum and minimum temperatures were the highest and lowest measures, respectively taken during one germination experiment for a specific Petri dish.

4.5. Data analysis

Maximum and minimum temperatures were then used to determine the thermal time [30, 31] or growing degree day (GDD) accumulation for the following equation.

$$t_n = \sum_{i=1}^{n} \left[\frac{Ti_{\max} + Ti_{\min}}{2} - T_b \right] \tag{1}$$

where t_n is the sum of GDD for n days, $Ti_{\max}$ and $Ti_{\min}$ are the daily maximum and minimum temperature (°C) of Day i [47], and T_b is the base temperature for peanut, in this model T_b was set at 15°C [48].

For all measurements, analysis of variance (ANOVA) was applied to the data combined across cultivar, planting date, experiment replication in time, and year to test for the differences among group means of variables and interactions. Years were regarded as random factors while cultivars (seed lot cultivar within a year) and seed germination thermal times were considered fixed effects. Interactions between cultivar and these factors were used as error terms.

Nonlinear regression using the logistics growth curve with three parameters was used to model data [49]. The equation

$$Y = \frac{a}{1 + [((a - b1)/b1)^* \, e^{(-b2x)}]} \tag{2}$$

with the parameters a being the height of the horizontal asymptote at a very large X, $b1$ the expected value of Y at time $X = 0$, $b2$ is the measure of growth rate, and Y is the predicted seed germination. One indicator of seed vigor is the number of GDD required to reach the 80% germination rate (Germ$_{80}$). Germ$_{80}$ was then determined by solving the logistic growth curve equation using the parameter estimates for each seed lot cultivar setting $Y = 80\%$. Data for cultivar by planting date equations were subjected to ANOVA using the general linear models procedures with mean separation using 95% asymptotic confidence intervals. The 95% confidence limits of three parameters in the equations were used to compare the significant differences for Eq. (2). Nonlinear regressions were graphed using SigmaPlot 13.0 (SigmaPlot 13.0. SPSS Inc. 233 S. Wacker Dr., Chicago, Illinois).

5. Research

There were differences for environmental measures taken during the course of each experiment. All experiments were conducted at times when runner-type peanut seed production could normally occur and are thus representative of producer practices. Cumulative rainfall ranged from 555 to 841 mm between the times of the first and last planting (**Table 1**), which are representative for the region. Irrigation was applied as recommended when required (data not shown). Maximum solar radiation (MJ m^{-2}) and total GDD occurred each year with the May, as opposed to April or June, planting dates for all three site-year locations. Significant cultivar-by-year interactions prevented the data from being combined by cultivar across tests. Therefore, data for the Dawson 2008 and 2009, and Headland 2009 seed experiments were analyzed separately and presented by seed location and planting date for each cultivar (**Table 1**).

There are three primary requirements for seed germination: heat, water, and oxygen. Temperature was the only variable evaluated for the runner-type peanut seed in this research. It is an important factor influencing germination in the field [48, 50]. Germination patterns by day against temperature under thermal times were consistent from year to year (Data not shown). Patterns were nonlinear in progression with germination beginning slowly at low temperatures, followed by a rapid growth phase from 20 to 32°C and then remained constant. The optimum temperatures for experiments were >25°C for all intervals greater than 48 hours. Variation in radicle development occurred with respect to temperature, and therefore variation in vigor detected (**Figure 4**).

Figure 4. Runner-type peanut seed radicle length 144 hours after initiation for temperatures of 18, 22, 26 and 30°C. Photograph curiosity of Sidney Cromer.

Germination varied by year and planting date for each experiment. For Dawson 2008 runner-type peanut seed germination was 79–93% across all planting dates and cultivars when averaged over all temperatures (**Table 2**). While these differences are noted, they do not relate to seed vigor. For non-linear regression, the seed produced from all cultivars had a greater germination rate (parameter *a*) of 89–93% for the 12 May 2008 planting date, as opposed to the 21 April or 1 June plantings at 79–86%. Using 95% confidence intervals, the three parameters in the logistics growth curves were compared within cultivars over planting dates [51]. Maximum germination rate (parameter *a*) were different dependent on the cultivar and time of planting (**Table 2**). Overall runner-type peanut seed produced from 21 April, 12 May, and 2 June 2008 plantings maintained a high level of vigor when exposed to gradient temperatures ranging from 14 to 35°C. Overlap existed in parameters *b1* and *b2* in most cultivars, indicating that the initial germination rate and growth speed were similar (**Figure 5**), although some significant differences did occur (**Table 2**). Runner-type

Cultivar	Planting date[a]	Germination[a]	Parameter *a*[c]			Parameter *b1*[c]			Parameter *b2*[c]			Germ$_{80}$
			Maximum rate	95% CL	Estimate	95% CL	Estimate	95% CL				
		%										GDD
GA Green	21 April	85	90.5	±1.2	b[d]	0.74	±0.21	a[d]	0.20	±0.01	a[d]	34
	12 May	93	95.7	±1.2	a	0.93	±0.31	a	0.28	±0.02	b	22
	2 June	86	88.0	±0.9	b	0.20	±0.07	b	0.32	±0.02	b	26
AT3085R0	21 April	80	88.0	±1.2	b	0.80	±0.23	a	0.20	±0.01	a	35
	12 May	91	94.0	±1.2	a	1.2	±0.35	a	0.25	±0.02	b	24
	2 June	86	89.5	±1.0	b	0.40	±0.11	b	0.30	±0.02	c	25
AT271516	21 April	83	86.1	±1.0	b	0.50	±0.14	b	0.22	±0.01	a	35
	12 May	92	93.7	±1.2	a	1.3	±0.40	a	0.24	±0.02	a	25
	2 June	90	92.3	±0.8	a	0.17	±0.06	c	0.34	±0.02	b	24
GA-03 L	21 April	84	90.1	±1.2	a	0.74	±0.22	b	0.20	±0.01	a	34
	12 May	90	93.2	±1.4	a	2.0	±0.53	a	0.21	±0.02	a	27
	2 June	84	86.3	±1.0	b	0.34	±0.11	c	0.29	±0.02	b	28
FR458	21 April	79	85.5	±1.3	b	0.90	±0.25	a	0.18	±0.01	a	40
	12 May	89	94.0	±1.1	a	1.1	±0.30	a	0.22	±0.01	b	28
	2 June	81	84.8	±1.3	b	0.38	±0.15	b	0.30	±0.02	c	27

[a]Year seed were grown, tested the following year after processing; n = 1920 seed.

[b]CL, confidence limit; Germ$_{80}$, cumulative growing degree day value at 80% germination; NA, not applicable as the seed lot of that cultivar did not achieve 80% germination over the duration of the assay; GDD, growing degree day.

[c]Parameter estimates calculated by nonlinear regression equation (2) for seed germination with respect to time based on GDD accumulation: *a* is the height of the horizontal asymptote at a very large X, *b1* is expected value of Y (cumulative germination) at time X = 0, and *b2* is a measure of growth rate.

[d]Values for each parameter within a column for each cultivar followed by the same letter are not significantly different at the 5% probability level. General linear models procedures were used with mean separation using 95% asymptotic confidence intervals. To obtain the equation for the respective regression line in **Figure 1**, the parameters from this table are used.

Table 2. Standard germination[a], logistic growth parameter estimates, 95% confidence limits (CL[b]), and vigor indices (Germ$_{80}$[b]) for germination of seed lots of runner-type peanut planted over 40-day period in 2008[a] at Dawson Georgia using a thermogradient germination assay.

peanut seed produced for all planting dates and cultivars in 2008 Dawson $Germ_{80}$ were 22–40 GDD. This was similar to other research comparing runner-type breeder seed over a 6-year period with $Germ_{80}$s of 24–42 GDD [37].

Data from 2009 varied by location, planting date, and cultivar. Germination was 59–75% for runner-type seed produced at Dawson (**Table 3**). Runner-type peanut seed produced from the Dawson 11 May 2009 plantings had the most consistent maximum germination rates
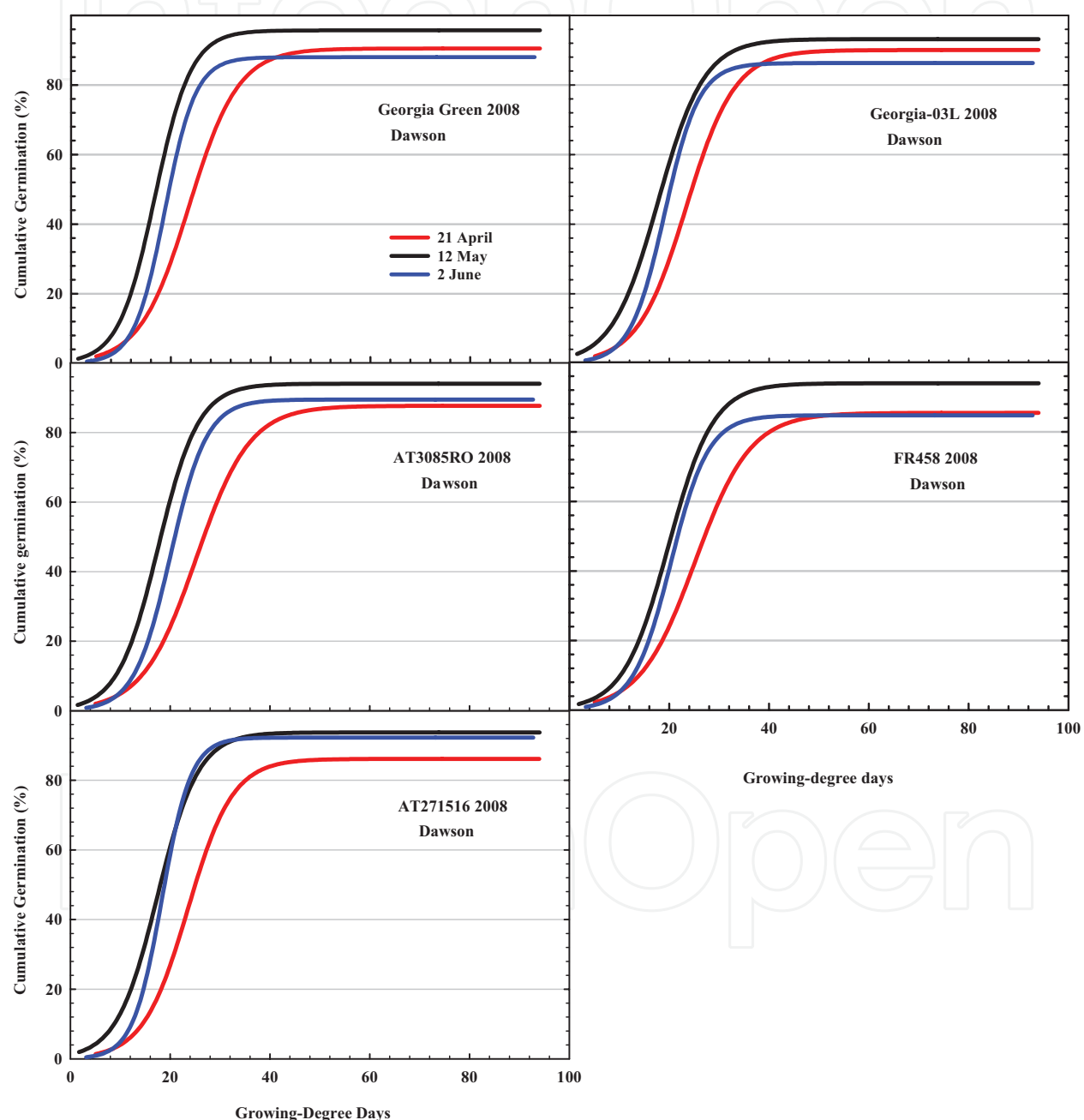

Figure 5. Cumulative germination patterns for runner-type peanut seed produced in 2008 at Dawson Georgia, based on nonlinear regression using growing-degree day (GDD) accumulation with a base temperature 15°C. To calculate the regression equation for the respective seed lot, the parameter estimates shown in **Table 2** for the Eq. (2) were used. Germination was measured on a thermal gradient.

Cultivar	Planting date[a]	Germination[a]	Parameter a[c]			Parameter $b1$[c]			Parameter $b2$[c]			$Germ_{80}$
			Maximum rate	95% CL		Estimate	95% CL		Estimate	95% CL		
		%										GDD
GA Green	21 April	70	67.3	±2.7	b[d]	6.9	±3.1	a[d]	0.21	±0.05	a[d]	NA
	11 May	75	83.0	±2.3	a	1.9	±1.0	b	0.28	±0.04	a	25
	1 June	73	69.9	±2.7	b	7.5	±3.2	a	0.22	±0.05	a	NA
AT3085R0	21 April	59	54.3	±3.0	b	10.3	±4.1	a	0.16	±0.05	b	NA
	11 May	68	93.6	±1.1	a	1.2	±0.3	b	0.26	±0.01	a	24
	1 June	60	58.2	±3.0	b	7.9	±3.5	a	0.17	±0.06	b	NA
AT271516	21 April	62	59.1	±3.1	b	10.6	±4.1	a	0.2	±0.04	a	NA
	11 May	66	81.6	±2.5	a	4.0	±1.5	b	0.2	±0.02	a	33
	1 June	69	77.7	±2.4	a	3.0	±1.3	b	0.21	±0.03	a	NA
GA-03 L	21 April	62	72.8	±2.6	c	3.2	±1.3	a	0.18	±0.03	a	NA
	11 May	72	79.8	±2.4	b	3.6	±1.4	a	0.22	±0.03	a	40
	1 June	67	97.1	±1.5	a	3.4	±0.47	a	0.14	±0.01	b	35
FR458	21 April	61	56.8	±3.1	b	9.5	±3.9	a	0.16	±0.04	a	NA
	11 May	68	93.1	±1.3	a	1.1	±0.27	b	0.25	±0.06	a	25
	1 June	62	57.3	±2.6	b	7.6	±3.4	a	0.2	±0.05	a	NA

[a]Year seed were grown, tested the following year after processing; n = 1920 seed.

[b]CL, confidence limit; $Germ_{80}$, cumulative growing degree day value at 80% germination; NA, not applicable as the seed lot of that cultivar did not achieve 80% germination over the duration of the assay; GDD, growing degree day.

[c]Parameter estimates calculated by nonlinear regression equation (2) for seed germination with respect to time based on GDD accumulation: a is the height of the horizontal asymptote at a very large X, $b1$ is expected value of Y (cumulative germination) at time X = 0, and $b2$ is a measure of growth rate.

[d]Values for each parameter within a column for each cultivar followed by the same letter are not significantly different at the 5% probability level. General linear models procedures were used with mean separation using 95% asymptotic confidence intervals. To obtain the equation for the respective regression line in **Figure 1**, the parameters from this table are used.

Table 3. Standard germination[a], logistic growth parameter estimates, 95% confidence limits (CL[b]), and vigor indices ($Germ_{80}$[b]) for germination of seed lots of runner-type peanut planted over 40-day period in 2009[a] at Dawson Georgia using a thermogradient germination assay.

(parameter *a*) of 79.8–93.6%, as compared to 21 April at 54.3–72.8%, and 1 June at 57.3–97.1% (**Table 3**). Vigor differences were noted as none of the seed produced from 21 April plantings achieved 80% maximum rate of germination. Similarly, all seed produced from 1 June planting at Dawson in 2009, except GA-03 L at 97.1%, had low vigor as determined by maximum rate of germination (**Figure 6**). The Germ$_{80}$ for Dawson 2009 seed were 25–40 GDD for the 11 May
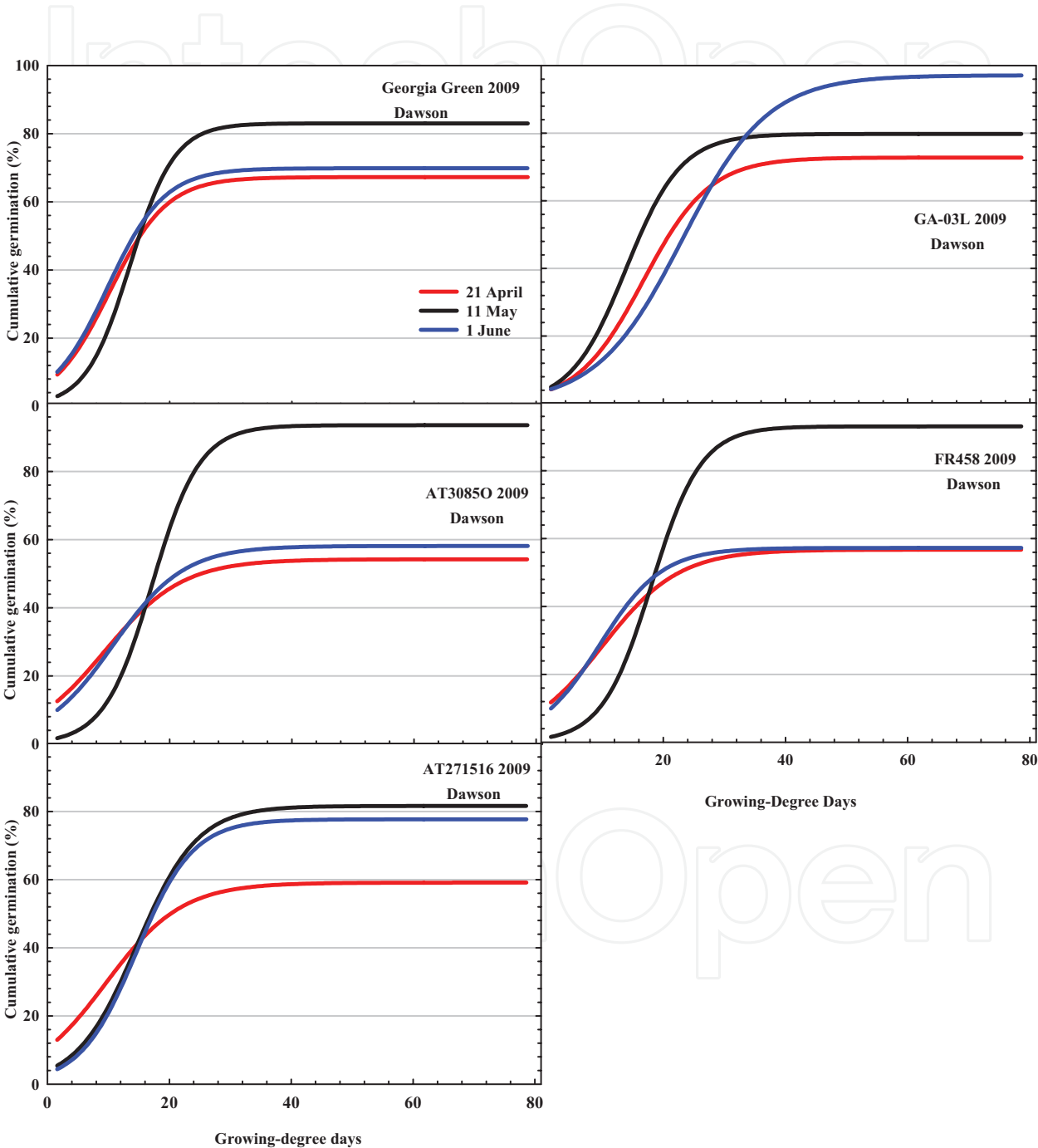

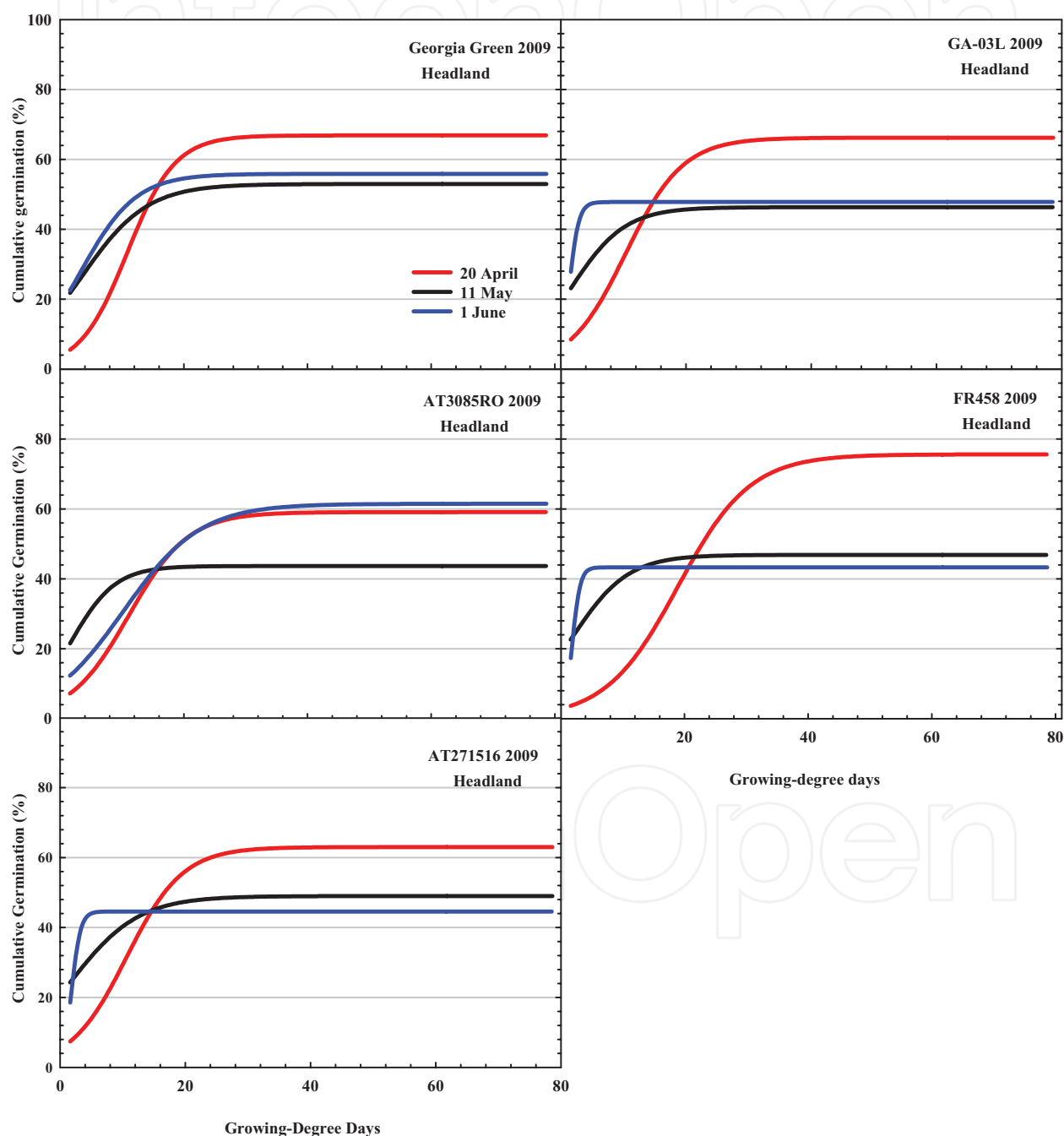**Figure 6.** Cumulative germination patterns for runner-type peanut seed produced in 2009 at Dawson Georgia, based on nonlinear regression using growing-degree day (GDD) accumulation with a base temperature 15°C. To calculate the regression equation for the respective seed lot, the parameter estimates shown in **Table 3** for the Eq. (2) were used. Germination was measured on a thermal gradient.

Cultivar	Planting date[a]	Germination[a]	Parameter a[c]			Parameter $b1$[c]			Parameter $b2$[c]			$Germ_{80}$
			Maximum rate	95% CL		Estimate	95% CL		Estimate	95% CL		
		%										GDD
GA Green	20 April	68	66.9	±2.6	a[d]	3.7	±2.2	a[d]	0.26	±0.06	b[d]	NA
	11 May	68	53.0	±2.8	b	18.0	±8.0	b	0.19	±0.09	a	NA
	1 June	67	55.9	±2.7	b	18.0	±8.8	b	0.22	±0.10	b	NA
AT3085R0	20 April	65	59.1	±2.7	a	5.4	±2.7	a	0.21	±0.05	a	NA
	11 May	57	43.7	±2.4	b	16.8	±11.6	b	0.28	±0.20	a	NA
	1 June	65	61.5	±3.0	a	10.0	±3.7	a	0.16	±0.04	a	NA
AT271516	20 April	65	63.0	±2.7	a	5.4	±2.9	a	0.22	±0.05	a	NA
	11 May	64	49.0	±2.8	b	20.7	±9.2	b	0.18	±0.11	a	NA
	1 June	60	44.6	±2.0	b	3.2	±12.5	b	1.4	±1.8	b	NA
GA-03 L	20 April	70	66.2	±2.7	a	6.2	±2.9	a	0.22	±0.05	a	NA
	11 May	62	46.3	±2.6	b	18.9	±10.6	b	0.23	±0.15	a	NA
	1 June	64	47.8	±2.0	b	7.0	±28.7	b	1.3	±2.2	b	NA
FR458	20 April	65	75.6	±2.8	a	2.8	±1.1	a	0.17	±0.02	a	NA
	11 May	60	46.7	±2.6	b	18.5	±10.1	b	0.22	±0.14	a	NA
	1 June	58	43.3	±1.9	b	2.2	±10.0	b	1.6	±2.1	b	NA

[a]Year seed were grown, tested the following year after processing; n = 1920 seed.

[b]CL, confidence limit; $Germ_{80}$, cumulative growing degree day value at 80% germination; NA, not applicable as the seed lot of that cultivar did not achieve 80% germination over the duration of the assay; GDD, growing degree day.

[c]Parameter estimates calculated by nonlinear regression equation (2) for seed germination with respect to time based on GDD accumulation: a is the height of the horizontal asymptote at a very large X, $b1$ is expected value of Y (cumulative germination) at time X = 0, and $b2$ is a measure of growth rate.

[d]Values for each parameter within a column for each cultivar followed by the same letter are not significantly different at the 5% probability level. General linear models procedures were used with mean separation using 95% asymptotic confidence intervals. To obtain the equation for the respective regression line in **Figure 1**, the parameters from this table are used.

Table 4. Standard germination[a], logistic growth parameter estimates, 95% confidence limits (CL[b]), and vigor indices ($Germ_{80}$[b]) for germination of seed lots of runner-type peanut planted over 40-day period in 2009[a] at headland Alabama using a thermogradient germination assay.

plantings, however, seed from the 21 April plantings had poor vigor and never achieved Germ$_{80}$, while only GA-03 L had a Germ$_{80}$ of 35 GDD for seed from the 1 June planting date.

Runner-type seed produced by any planting date for Headland 2009 had very poor germination and vigor. Germination was less than 70% (**Table 4**). The maximum rate of germination (parameter *a*) for vigor was less than 75.6% for all cultivars and planting dates. Germ$_{80}$ was not achieved indicating low vigor (**Figure 7**). Previous research has indicated that there can

Figure 7. Cumulative germination patterns for runner-type peanut seed produced in 2009 at Headland Alablama, based on nonlinear regression using growing-degree day (GDD) accumulation with a base temperature 15°C. To calculate the regression equation for the respective seed lot, the parameter estimates shown in **Table 4** for the Eq. (2) were used. Germination was measured on a thermal gradient.

be variability of vigor for runner-type peanut seed of unknown origin, especially when the environmental condition under which that seed is produced is unknown [22].

6. Conclusion/recommendations

All cultivars exhibited phenotypic vigor variation by planting and harvest date across years. Comparing data generated from the thermal gradient using these growth curve models provided maximum germination rates with optimal temperatures (**Tables 2–4**). Cold germination testing can be used as a measure to stress peanut to evaluate vigor [52], using the thermal gradient apparatus used to evaluate peanut cultivars in this study established variation in seed vigor across a wide range of temperatures simultaneously. This method of seed evaluation provided an indication of vigor which assist peanut seed producers in determining the success of the cultivar over a range of temperatures, unlike the standard peanut germination test [30]. Seed produced from mid-May plantings each year were consistent with respect to germination, $Germ_{80}$, and GDD to reach maximum germination (a) among the five cultivars evaluated in Dawson for 2008 and 2009. Phenotypic differences were noted when these same cultivars were grown in Headland in 2009. These data assisted in determining phenotypic variation between planting dates when grown under known environmental conditions. This information will assist growers with making planting decisions based on these vigor testing methods.

Author details

Timothy L. Grey[1]*, Charles Y. Chen[2], Russell Nuti[3], Walter Scott Monfort[1] and George Cutts III[2]

*Address all correspondence to: tgrey@uga.edu

1 Crop and Soil Sciences Department, University of Georgia, Tifton, Georgia, United States

2 Crop, Soil & Environmental Sciences, Auburn University, Auburn, Alabama, United States

3 PhytoGen Cottonseed, Dow Chemical Inc. Shellman, Georgia, United States

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