Annals of Applied Biology ISSN 0003-4746

RESEARCH ARTICLE

Rice reproductive development stage thermal time and calendar day intervals for six US rice cultivars in the Grand Prairie, Arkansas, over 4 years

P. A. Counce[1], T. J. Siebenmorgen[2] & A. A. Ambardekar[3]

1 University of Arkansas Rice Research and Extension Center, Stuttgart, AR, USA
2 Department of Food Science, University of Arkansas, Fayetteville, AR, USA
3 Mars Food Global, Greenville, MS, USA

Keywords
Crop development; development; growth stage intervals; *Oryza sativa*; reproductive development; rice; rice growth stages; thermal time.

Correspondence
Paul A. Counce, Department of Crop, Soil and Environmental Sciences, University of Arkansas Rice Research and Extension Center, 2900 Highway 130 East, Stuttgart, AR 72160, USA.
Email: pcounce@uark.edu

Received: 4 March 2014; revised version accepted: 10 March 2015.

doi:10.1111/aab.12226

Abstract

The rice crop's reproductive developmental timing in days and thermal time is needed for effective modelling, research interpretation and management of the crop. To obtain these data, a field study was conducted at Stuttgart, Arkansas, USA in 2007, 2008, 2009 and 2010. The study utilised data collected from randomised complete block design field experiments with three replications and six rice lines in each of the years. Averaged across years and cultivars, the degree-day-10 (DD10) intervals (thermal time units with a base temperature of 10°C) for Reproductive Stages R3, R4, R5, R6, R7 and R8 were 21, 30, 19, 48, 70 and 189°C-day, respectively. The average intervals in calendar days for R3, R4, R5, R6, R7 and R8 were 2.3, 3.3, 2.3, 6.0, 4.5 and 26.7 days, respectively. For R4 and R5, cultivar rankings differed over the 4 years with cultivar differences being mostly small, non-significant or inconsistent. For R6, the cultivar Cypress had either the longest or among the longest intervals. For R7, the medium grains had the longest or among the longest intervals. For R3 and R8, cultivar differences were significant with no significant year by cultivar interactions. For the R3 intervals, the primary difference was between Bengal and the five other lines. For R8, the intervals in both days and DD10 were least for Cypress, followed by Wells, followed by LaGrue and XL723 followed by the medium grains Bengal and Jupiter which had the longest intervals for R8. Consequently, the R3 interval could be generalised to five of the six lines in the study while R4, R5, R6 and R7 intervals could be generally applied with some caution. The R8 intervals were different among lines and grain types. These differences should not be ignored. The extremely short R8 interval for Cypress is likely associated with its high head rice yields across a range of environments compared to other long-grain rice cultivars and hybrids in the USA The utilisation of the rice reproductive growth stage intervals can potentially improve analysis and interpretation of field plot research, model predictions and management of the rice crop.

Introduction

A uniform, adaptive and objective system has been developed and utilised for the communication of rice research results, management practices and education (Counce *et al.*, 2000). The system allows for consistent and uniform descriptions of plant developmental milestones adapted to the distinctive features and development of the rice plant and thus is inherently objective in that two people independently assessing the same plant will determine it to be the same growth stage using the criteria of the system. The system allows improved communication of developmental stages for observations, management timing and treatment applications for rice. The system was developed from widely utilised developmental milestones to which objective criteria were added.

The rice staging system comprises germination and seedling stages (S-stages), vegetative stages (V-stages), delineated by main stem leaf collar formation and reproductive stages (R-stages), classified by the development of the main stem panicle. A summary of rice developmental events and the coincident stages are delineated in the rice developmental timeline (Fig. 1). Stage R2 refers to flag leaf collar emergence. Stage R3 refers to panicle exertion of a collar on the flag leaf of the main stem. R3 is also known as 'heading'. The 50% heading date is the date at which 50% of the panicles in a field or plot are estimated to have reached R3 stage. The 'flowering' stage, or R4, indicates that one or more florets on the main stem panicle have reached anthesis (the period during which the anthers and filaments have emerged from the floret). The R5 stage occurs when at least one caryopsis on the main stem begins to elongate. The R6 stage occurs when at least one caryopsis on the main stem panicle has elongated to the end of the hull. The stages at which one yellow hull and one brown hull appear on the main stem panicle are termed R7 and R8, respectively. The stage R9 occurs when all grains on the panicle that had reached with R6 stage have completed R8 Stage. By noting the growth stages sequentially for individual plants, thermal time and calendar day intervals can be calculated for each rice growth stage. Consequently, calendar intervals between various developmental and physiological processes can be documented.

For rice, Keisling *et al.* (1984) presented a broad developmental interval data set in thermal time units for some critical rice development milestones which have been widely used in the southern US rice-producing areas. The programme is highly practical and provides a rough estimate of development for the rice crop. The formula used for thermal time by Keisling *et al.* (1984) is simple and the results are easily visualised: rice development does not proceed unless temperatures are above 10°C, it increases linearly between 10 and 34°C and rice development does not increase above the maximum rate 34°C. The method is used by large numbers of southern US rice producers on thousands of hectares of rice. The 90% emergence date (alternatively the date when ~100 plants m^{-2} have emerged) was the starting point for the progression of projected plant development in the Keisling method. The degree of detail allowed by the rice growth staging system (RGSS) described by Counce *et al.* (2000) is much greater than that provided in Keisling *et al.* (1984). Combining the level of detail in the RGSS (Counce *et al.*, 2000) and the simple calculation methods of Keisling *et al.* (1984) would permit multiple potential starting points for projected plant development using thermal time and thus it improved predictions of critical plant developmental events. This would in turn allow more accurate rice field characterisation and better rice crop management planning and decisions. A simple model utilising easily obtainable information such as air or soil temperatures has definite advantages in spite of potentially reduced accuracy.

Valuable phenological models have been published for (a) rice leaf appearance rates (Sié *et al.*, 1998*a,b,c*; Streck *et al.*, 2008) (b) comprehensive rice development data to R1, R4 and R9 (Streck *et al.*, 2012) and (c) predictions from seedling emergence to flowering (Yin *et al.*, 1997). Data on intervals between individual reproductive rice growth stages are lacking. Crop modelling studies have focused on simulating the effects of cultivar, planting density, weather, soil, water and nitrogen on crop growth, development, and yield responses. Less is known about the timing of individual reproductive rice growth staging developmental stage-length and thermal-unit accumulation. Thermal time and calendar intervals for the individual rice reproductive stages have not been reported in the literature.

The development of each stage can consequently be estimated by accumulating thermal units throughout the season. Accumulation of daily thermal units (DTU) or growing degree-days (abbreviated as DD) is currently used to predict rice phenological development. The canonical form of calculating DTU is:

$$\text{DTU} = \left[\left(T_{\text{max}} + T_{\text{min}}/2\right) - T_{\text{base}}\right] \tag{1}$$

where T_{max} and T_{min} are maximum and minimum daily temperatures, respectively, and T_{base} is the temperature below which development ceases.

The base temperature below which rice development is negligible is 10°C (50°F) (Bonhomme, 2000). Hence, accumulated DTUs are expressed as degree-day-10 (DD10) (DD50 for °F). The specific equation for daily DD10 calculation using a T_{base} of 10°C and expressing T_{max} and T_{min} as °C is given in Eqn 2:

$$\text{DD10} = \left[T_{\text{max}} - T_{\text{min}}/2\right] - 10 \tag{2}$$

In addition, rice developmental stages are primarily affected by diurnal trends of a 24-h photoperiod. Typically, rice developmental rate is known to increase linearly as a function of air temperature between minimum and maximum temperatures determined for development. Thermal time units can be accumulated over different time steps (minutes, hours, days). The Arkansas DD50 programme has used daily minimum and maximum temperatures. Daily temperature data are available on a daily basis for many years through weather stations administered by the US National Oceanographic and Atmospheric Agency (NOAA) throughout the nation.

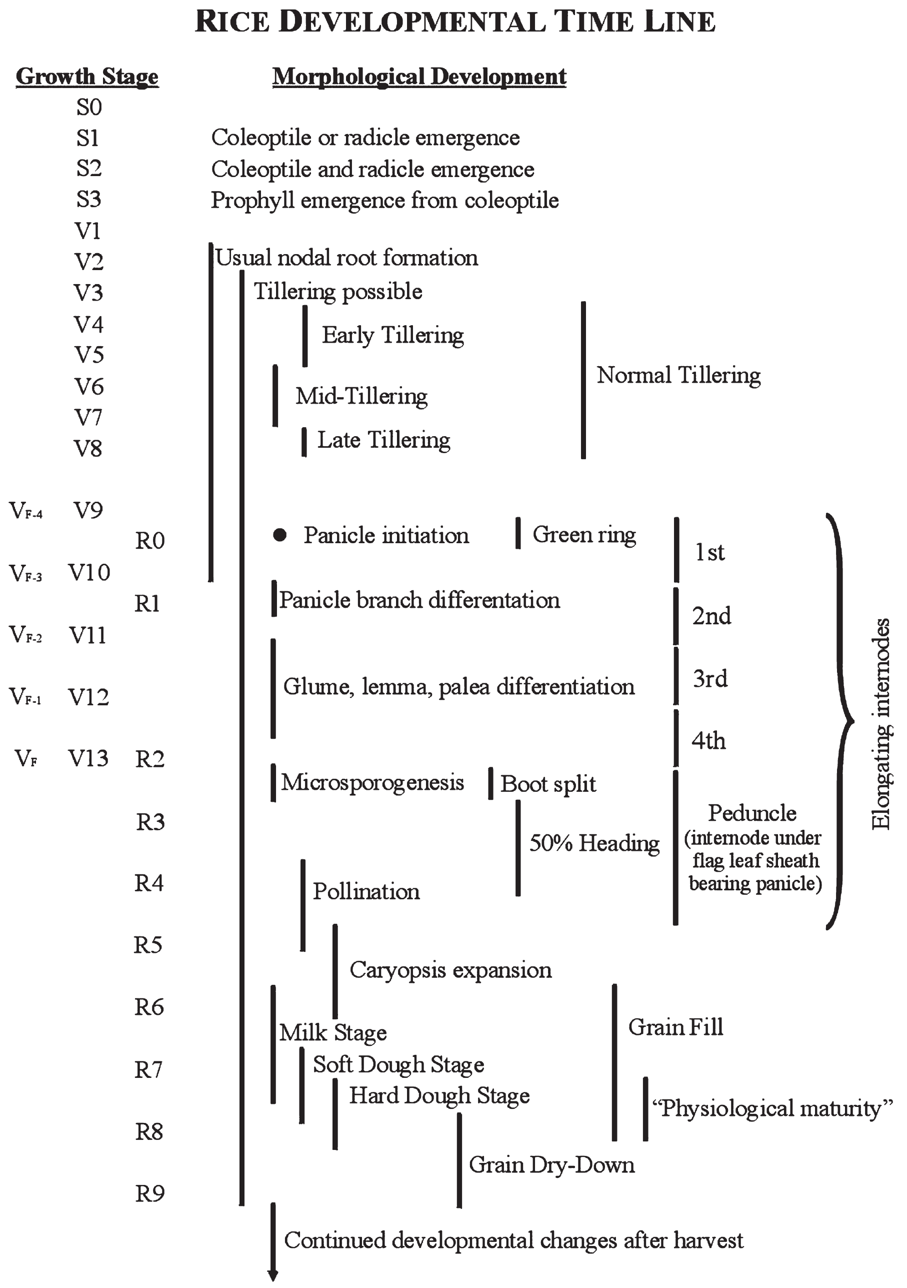

Figure 1 Rice developmental timeline. Reprinted with permission from *Crop Science* (Counce et al.,2000. A uniform, objective and adaptive system for expressing rice development. *Crop Science* 40:436–443).

The daily maximum and minimum temperature information is therefore used extensively in the USA for a variety of applications and the data are readily available through NOAA reports and in its website. Obviously, use of daily, rather than shorter intervals, ignores frequent variations in temperature patterns during a 24-h period and skewing of diurnal temperature distributions. Hence, computation of thermal units on an hourly basis is more accurate than on a daily (24 h) basis (Purcell, 2003). Shorter intervals for calculating thermal time units more accurately express the actual temperature regime for the crop. For this reason, we computed thermal time based on 30-min time intervals.

Each of the stages from seedling, vegetative and reproductive phases can be affected by the air temperatures. Low or high air temperatures reduce or extend the length of rice developmental stages, respectively, and influence the total growing season length, potentially interrupt physiological and metabolic processes and can result in low yields and end-use quality problems.

The lines in this study were selected for milling responses or widespread use within the southern US rice production area in the years of the study. Long-grain rice is the main type of rice grown in the southern US rice production region, and Cypress, LaGrue, Wells and XL723 were long-grain lines grown in this study. The state of Arkansas has the highest rice production area of any state in the USA and produces approximately half of the US rice crop. Cypress and LaGrue comprised of approximately 0.1%–0.2% of the Arkansas area grown to rice in the years of this study (Hardke & Wilson, 2013). Wells' and XL 723's acreages were 3.5% and 22.9%, respectively, of the Arkansas rice crops in those years. Bengal and Jupiter were widely grown medium-grain rice cultivars used in this study. Acreages for Bengal and Jupiter were 2.7% and 8.7% of the Arkansas acreage. Wells was the most widely grown long-grain inbred cultivar and XL 723 was the most widely grown non-Clearfield hybrid during the years of this study. The hybrid XL 723 is a proprietary product of the RiceTec Company of Alvin, Texas. Cypress and Bengal consistently produce higher and more stable head rice yield (a measurement of quality from determining unbroken kernels or kernels three-fourth or more of their original length after milling) than other available rice cultivars across a range of environments and years (Jodari & Linscombe, 1996; Counce *et al.*, 2005; Cooper *et al.*, 2008; Ambardekar *et al.*, 2011; Lanning *et al.*, 2011). LaGrue produces variable milling depending on the night temperatures during Stages R6, R7 and R8 (Counce *et al.*, 2005; Cooper *et al.*, 2008; Ambardekar *et al.*, 2011; Lanning *et al.*, 2011). The most typical and commercial hybrid rice, XL723, is characterised by a long panicle with more grains per panicle than adapted inbred cultivars.

This article provides (a) a new set of information and (b) a methodology for determining growth stages intervals in a useful and novel extension of the system presented in Counce *et al.* (2000). The overall contribution of this article is to define the timing intervals for the reproductive stages presented in Counce *et al.* (2000). The first two objectives of this paper is to present the (a) thermal time accumulations, (b) calendar day intervals for rice reproductive stages among the six lines and 4 years of the study. Other objectives include growth staging timing differences which might help explain (c) the degree to which growth stages are generally applicable for projections across cultivars and which require individual data collection for a given cultivar; and (d) differences among cultivars for milling quality, particularly between Cypress and other long-grain rice lines.

Methodology

Three long-grain (Cypress, LaGrue, and Wells) and two medium-grain (Bengal and Jupiter) pure-line cultivars and a long-grain hybrid (XL723) cultivar were grown at Stuttgart, AR as part of the Arkansas Rice Performance Trials (ARPT) each year from 2007 to 2010. Five of the six cultivars were tested in both the ARPT and this study. The exception was Cypress which was not grown in sufficient acreage to warrant its inclusion in the ARPT but required in this test because of its robust, high head rice yields. Eighteen experimental field plots were adjacent to and managed the same as the ARPT plots in each year. These 18 plots were arranged in randomised complete blocks with each of the six cultivars planted in three replications. Each of the five pure-line rice cultivars (Bengal, Jupiter, LaGrue, Cypress and Wells) was drill-seeded at the rate of 428 seeds m^{-2} in a nine-row wide (0.18-m spacing) plot, 4.57-m in length. The hybrid (XL723) was sown in plots with the same dimensions at the rate of 171 seeds m^{-2}. In order to produce near optimum grain yields, all plots received 120–135 kg N ha^{-1} as a single application of urea (depending on the conditions) at the V3 to V6 growth stage within one day of flooding. Management practices for the ARPT, including planting dates, flooding, fertilisation and pesticide applications, are carried out to achieve near maximum potential yields across the wide range of Arkansas conditions in which the trials are conducted. The flood was applied and maintained until at least 2 weeks after the rice reached the 50% heading stage. Weeds were controlled with applications of clomazone, propanil, quinclorac, halosulfuron and fenoxyprop, as required for particular weed control needs in each year of the study. No fungicides or insecticides were applied to the crops. Yields of the lines in this study collected from the ARPT are reported for reference purposes.

Staging

Rice reproductive stages for all cultivars were visually identified according to the rice developmental staging system (Counce *et al.*, 2000). Previous studies, which related night-time air temperatures during the R3 to R8 stages of a rice lot's development to milling quality and kernel chalkiness, reported strongest correlations at the R6, R7 and R8 stages (Ambardekar *et al.*, 2011; Lanning *et al.*, 2011). The RGSS from R4 through R8 is based on the stage of the first kernels on the panicle to reach their respective stages (Counce *et al.*, 2000). At the beginning of crop growth stage R6, some grains on the panicle have elongated to the tip of the hull and begun to fill, but most of the grains on the panicle are at R3, R4 and R5. Likewise, at plant growth stages R7 and R8, many of the individual grains which will eventually mature and fill are at stages R5 and R6. Consequently, at growth stages R6, R7 and R8, there are large percentages of grains at R6. Thus, the grain-filling period for each panicle extends from plant stages R6 through R9 and therefore, environmental conditions at R6 through R9 determine grain filling for the panicle and by extension to the aggregate for the crop. In this study, the data collection for the staging process started with tagging panicles at Stage R2. Subsequently, the dates of each successive growth stage for individual panicles were recorded beginning at R3 and ending with R9. During this study, the reproductive stages from R3 to R9 were recorded daily for six to eight (usually seven) individual culms in each plot in each of the four study years. The day-of-year (DOY) for each identified R-stage for each culm was recorded, as were ambient temperatures throughout all reproductive stages; from these temperatures, thermal units were calculated (below) and thermal unit versus reproductive staging sequences were tallied for each cultivar.

Thermal unit accumulation

Ambient temperature was recorded on 30-min increments using two temperature sensors (HOBO Pro/Temp Data Logger, Onset Computer Co., Bourne, MA, USA) positioned 1.4 m above the soil surface at each growing location. Based on these 30-min temperatures, and using the following equation, DD10 thermal units (°C-day) over the course of each day were quantified

$$\mathrm{DD10} = \sum \left[\left\{ \left(T_{\max} \left(^\circ\mathrm{C} \right) + T_{\min} \left(^\circ\mathrm{C} \right) \right) /2 \right\} - 10 \left(^\circ\mathrm{C} \right) \right] \times 0.5\ \mathrm{h} \times \left[1\ \mathrm{day}/24\ \mathrm{h} \right] \quad (3)$$

- $T_{\max}$ and $T_{\min}$ represented the maximum and minimum temperatures, respectively, during a 30-min interval.
- The value for $T_{\max}$ in the formula was the actual maximum temperature or 34°C if the maximum temperature during 30-min interval was greater than 34°C.
- $T_{\min}$ in the formula was the actual minimum temperature.

Thermal unit accumulation at R3-stage initiation was assigned a value of zero. DD10 values were accumulated to delineate the progression through all R-stages. To determine the thermal units required for a rice cultivar to advance from one R-stage to another, the accumulated DD10 values were computed from the temperature readings. Duration of each R-stage in days was computed by subtracting the recorded DOY observed for the R-stage from the DOY observed for the next R-stage.

Statistics

The analysis was done for cultivar, replication (year), year and cultivar by year. Mean DD10 and duration of the cultivars expressed in days were averaged within plots across the individual plants within each plot. R-stage durations in days and DD10 units averaged across plants within each plot were the responses. The plots were the experimental units for which the analysis of variance was done with PROC GLM procedure with years and rep(year) analysed as random variables (SAS, 2012). The least significant differences were calculated to compare cultivars either averaged over years or the cultivar values within years, depending on whether the cultivar effects and the cultivar by year interactions were significant.

Results

The average temperatures of 2007–2010 growing seasons were 25.6, 23.9, 20.8, and 28.3°C, respectively. The average daily temperatures indicate 2007 and 2010 were relatively warmer years than 2008 and 2009. The average yields over the 4 years for Bengal, Jupiter, LaGrue, Wells and XL723 from the adjacent ARPT yield plots were 9.14, 9.90, 8.04, 8.98 and 9.43 Mg ha^{-1}, respectively. The last yields identified from Arkansas for optimum planting dates for Cypress were 8.72 Mg ha^{-1} in 2000 at the same Arkansas location as these tests (Norman *et al.*, 2003).

R3 intervals

The grand mean for the DD10 intervals for R3 was 19.2 with a minimum of 9.8 and a maximum of 32.0 (Table 1). The grand mean for interval in days for R3 was 2.3 with a low value of 1.1 and a high value of 3.8. Thermal-unit accumulation (DD10 units) for R3 stage and the duration of R3 stage in days had significant year and cultivar effects with no significant cultivar by year interaction. The medium-grain Bengal had longer R3 intervals in both DD10 and days than any other cultivar. The R3 interval in days was also greater for Cypress than for Jupiter and XL723.

R4 intervals

The grand mean for the DD10 intervals for R4 was 27.9 with a low value of 10.8 and a high value of 52.7 (Table 2). The grand mean for interval in days for R4 was 3.3 with a low value of 1.5 and a high value of 6.1. There were highly significant cultivar effects and cultivar by year interactions for both R4 DD10 and calendar day intervals. The year effect was significant for DD10 but not for days for R4. In 2007, the R4 intervals were greater for Wells than for Cypress. In 2008, no cultivars differed.

Table 1 Thermal-unit accumulation at R3 stage represented by DD10 values and R3-stage duration expressed in days ($n = 3^a$) across cultivars grown in Stuttgart, AR during 2007–2010

			Year									
			2007		2008		2009		2010		Cultivar mean	
Stage	Size	Cultivar	DD10	Days	DD10	Days	DD10	Days	DD10	Days	DD10	Days
R3	MG	Bengal	20.6	2.2	25.7	2.8	32.0	3.8	25.0	3.3	25.8	3.0
		Jupiter	14.8	1.6	12.4	1.3	24.2	2.9	13.4	1.8	16.2	1.9
	LG	Cypress	22.1	2.3	14.4	2.0	22.2	2.6	21.5	2.9	20.1	2.4
		LaGrue	17.0	1.8	15.4	2.0	22.3	2.5	21.8	2.9	19.1	2.3
		Wells	10.4	1.2	15.0	1.9	25.9	3.0	19.6	2.6	17.8	2.2
		XL723	11.6	1.5	9.8	1.1	25.0	3.0	18.8	2.4	16.3	2.0
	Year mean		17.4	1.9	16.4	2.0	28.2	3.3	20.0	2.6		

DD10		Days
Cultivar effect	***	***
Year effect	***	***
Cultivar by year interaction	ns[b]	ns[b]
$LSD_{0.05}$	4.3	0.5
Degrees of freedom[c]	40	40
Grand mean	19.2	2.3

Ns, not significant; MG, Medium-grain cultivar; LG, long-grain cultivar; $LSD_{0.05}$, Least Significant Difference, at the 0.05 level of probability, for treatment means averaged over years.

[a]Mean DD10 values and days are averages of three experimental plots and for each plot seven plants were monitored.

[b]$*P < 0.05$, $**P < 0.01$, $***P < 0.001$.

[c]Degrees of Freedom for the mean square for error used to calculate the $LSD_{0.05}$.

In 2009, XL723 R4 intervals were greater than all other cultivars. In 2010, Cypress R4 intervals were less than those of any other cultivar.

R5 intervals

The grand mean for the DD10 intervals for R5 was 19.2 with a low value of 8.8 and a high value of 28.9 (Table 3). The grand mean for interval in days for R5 was 2.3 with a low value of 1.2 and a high value of 3.7. The DD10 accumulations and intervals in days for the R5 stage had significant cultivar and cultivar by year interactions with no significant year effect. In most cases, differences among cultivars for both DD10 and daily accumulations were small. In 2007, Cypress had a longer DD10 interval than Bengal, LaGrue and Wells and was longer in days for Bengal and LaGrue. In 2008, the only difference was that Cypress had a greater interval in days than Wells. In 2009, Cypress and LaGrue had greater R5 intervals than XL723. Jupiter data for R5 in 2010 was deleted because of insufficient observations. For 2010, the R5 intervals were longer for LaGrue than for any other cultivar.

R6 intervals

The grand mean for the DD10 intervals for R6 was 48.4 with a low value of 14.7 and a high value of 76.1 (Table 4). The grand mean for interval in days for R6 was 6.0 with a low value of 1.8 and a high value of 10.4. The DD10 and interval in days for R6 had significant cultivar and year effects and a significant cultivar by year interaction. In 2007, R6 intervals were greater for Cypress than for LaGrue. In 2008, Cypress R6 intervals were greater than for all other cultivars. In 2009, Bengal had lower R6 intervals than any other cultivar and Wells had longer R6 intervals than Bengal and XL723. Jupiter data for R6 in 2010 was deleted because of insufficient observations. In 2010, R6 intervals were greater for Cypress and Wells than for Bengal, LaGrue and XL723.

R7 intervals

The grand mean for the DD10 intervals for R7 was 35.9 with a low value of 17.4 and a high value of 63.1 (Table 5). The grand mean for interval in days for R7 was 4.5 with a low value of 2.1 and a high value of 7.7. There were significant cultivar effects and significant cultivar by year interactions for the R7 intervals. In 2007, R7 intervals were greater for Jupiter than for Cypress, Wells and XL723. In 2008, the R7 intervals were greater for Jupiter than for Cypress, LaGrue and Wells. In 2009, the R7 interval in days was greater for Bengal than for any other cultivar. In 2010, the R7 intervals were greater for XL723 than for any other cultivar except Jupiter. Consequently, one of the medium-grain cultivars had either the longest

Table 2 Thermal-unit accumulation at R4 stage represented by DD10 values and R4-stage duration expressed in days ($n = 3^a$) across cultivars grown in Stuttgart, AR during 2007–2010

			Year									
			2007		2008		2009		2010		Cultivar mean	
Stage	Size	Cultivar	DD10	Days	DD10	Days	DD10	Days	DD10	Days	DD10	Days
R4	MG	Bengal	33.5	3.6	27.4	3.4	31.1	3.6	33.8	4.6	31.6	3.8
		Jupiter	32.0	3.4	28.6	3.4	32.2	3.7	23.1	3.1	28.0	3.4
	LG	Cypress	22.6	2.4	22.7	3.3	27.5	3.2	10.8	1.5	23.5	2.6
		LaGrue	33.0	3.5	22.7	3.2	25.9	3.0	23.7	3.2	27.0	3.2
		Wells	35.5	3.8	24.4	3.5	20.6	2.4	24.7	3.3	26.3	3.0
		XL723	23.9	2.7	29.9	3.4	52.7	6.1	27.4	3.6	37.5	4.0
	Year mean		30.1	3.2	25.9	3.4	31.7	3.7	23.9	3.2		

DD10		Days
Cultivar effect	**[b]	**
Year effect	*	ns[b]
Cultivar by year interaction	**	**
$LSD_{0.05}$	12.2	1.4
Degrees of freedom[c]	40	40
Grand mean	27.9	3.4

Ns, not significant; MG, Medium-grain cultivar; LG, long-grain cultivar; $LSD_{0.05}$, Least Significant Difference, at the 0.05 level of probability, for treatment means averaged over years.

[a]Mean DD10 values and days are averages of three experimental plots and for each plot seven plants were monitored.

[b]$*P < 0.05$, $**P < 0.01$, $***P < 0.001$.

[c]Degrees of freedom for the mean square for error used to calculate the $LSD_{0.05}$.

R7 interval or an R7 interval not significantly different than the longest in each of the 4 years.

R8 intervals

The grand mean for the DD10 intervals for R8 was 189.2 with a low value of 142.9 and a high value of 239.6. The grand mean for interval in days for R8 was 26.7 with a low value of 16.4 and a high value of 35.0 (Table 6). There were significant cultivar and year effects for R8 interval in both days and DD10 units. The cultivar by year interactions for both R8 intervals were non-significant. For R8, the intervals in both days and DD10 were least for Cypress, followed by Wells, followed by LaGrue and XL723 followed by the medium grains Bengal and Jupiter which had the longest intervals for R8. Jupiter had the longest R8 intervals compared to all other cultivars. Cypress had the shortest R8 intervals compared to all other cultivars. Bengal and Jupiter had longer R8 intervals than any of the long grains. The XL723 R8 intervals were longer than the other long-grains except LaGrue.

A comprehensive view of the data in Tables 1–6 are presented in Figs. 2 and 3. Calendar day intervals followed a similar pattern from R3 through R9 for all cultivars with the intervals for R8 being most different among cultivars (Fig. 2). DD10 intervals followed a similar pattern to that of calendar day intervals (Fig. 3). Overall, the cultivars followed a similar pattern with mostly subtle differences which are better understood by the data presentation in the Tables.

Discussion

The specific contributions of this article are (a) thermal time accumulation and (b) daily intervals are provided for reproductive developmental stages; (c) that the degree to which reproductive growth stage intervals are cultivar-specific; and (d) evidence that the milling quality stability differences among the rice lines is due partially to the differing R8 intervals among the rice lines.

Application of the data: overall value and limitations

This research has contributed to the accuracy with which reproductive stages are measured providing new approaches to measure intervals between stages. To apply the data from this study in a meaningful manner, both the potential value and the limitations of the data must be understood. Across the cultivars for this study, the average, maximum and minimum values among cultivar by year means for each growth stages provide critical information for scientists working with rice. The intervals presented in Tables 1–6 provide a useful reference to compare and predict the same intervals in different

Table 3 Thermal-unit accumulation at R5 stage represented by DD10 values and R5-stage duration expressed in days ($n = 3^a$) across cultivars grown in Stuttgart, AR during 2007–2010

			Year									
			2007		2008		2009		2010		Cultivar mean	
Stage	Size	Cultivar	DD10	Days	DD10	Days	DD10	Days	DD10	Days	DD10	Days
R5	MG	Bengal	19.5	2.0	20.1	3.1	14.6	1.7	8.8	1.2	15.8	2.0
		Jupiter	20.5	2.1	18.9	2.6	15.7	1.8	–	–	18.4	2.1
	LG	Cypress	27.7	3.0	20.2	2.9	20.2	2.5	9.9	1.3	24.3	2.4
		LaGrue	19.0	2.0	19.2	2.8	20.0	2.5	28.9	3.7	21.8	2.8
		Wells	19.9	2.1	13.9	2.0	18.3	2.2	19.8	2.6	18.0	2.2
		XL723	20.6	2.3	19.1	2.8	11.2	1.4	16.2	2.2	16.8	2.2
	Year mean		21.2	2.3	18.6	3.2	16.7	2.0	16.7	2.2		

DD10	Days	
Cultivar effect	*	*
Year effect	ns[b]	ns[b]
$LSD_{0.05}$	7.6	0.9
Degrees of freedom[c]	38	38
Cultivar by year interaction	***	***
Grand mean	19.2	2.3

Ns, not significant; MG, Medium-grain cultivar; LG, long-grain cultivar; $LSD_{0.05}$, Least Significant Difference, at the 0.05 level of probability, for treatment means averaged over years.

[a]Mean DD10 values and days are averages of three experimental plots and for each plot seven plants were monitored.

[b]$*P < 0.05$, $**P < 0.01$, $***P < 0.001$.

[c]Degrees of freedom for the mean square for error used to calculate the $LSD_{0.05}$.

situations. Combining the intervals can allow useful projections from a given point in time to a subsequent time and thermal time may be useful in this regards more than days.

Application of the data: context of crop growth stages to rice yield and quality

The application of the data to field situations requires that those data be understood in the actual context of the development of the crop in the field. It also requires that typical panicle developmental patterns and outcomes are clearly understood. Crop Growth Stages R3 through R5 encompass the period when much of the yield of the rice crop is determined. Rice yield is most closely related to the number of spikelets per unit area (Yoshida, 1972; Yoshida & Parao, 1976). The number of grains per unit area is the product of florets per unit area and the fraction of filled grain. The potential number of florets is determined from Growth Stages R0 through R2. The fraction of actual filled grains is determined primarily by conditions during R3, R4 and R5. Although the R3, R4 and R5 intervals are relatively short, much of the yield potential is set during period when pollination and fertilisation of the earliest florets (the superior florets) is accomplished. The superior grains and to a great extent the inferior grains (the later florets to open) are successfully fertilised during R4 for individual grains which encompasses R4 (for most of the superior grains) and R5 (for the remaining superior grains and most of the inferior grains). Regardless of the number of florets produced, the fraction of filled grains is limited primarily by the number and viability of the pollen grains. The female inflorescence is capable of being fertilised over several days but the pollen grains remain viable only minutes after being released. Moreover, fertilisation requires a minimum of 10 and an optimum of 40–80 pollen grains per female inflorescence (Satake & Yoshida, 1978; Matsui & Kagata, 2003). Consequently, the earliest florets to open are most likely to receive adequate numbers of viable pollen grains and be fertilised while the later florets are progressively less likely to receive adequate numbers of viable pollen grains. Potential yield is largely set during Crop Growth Stages R0 through R2 and percentage filled grain is determined during Crop Stages R3 through R5.

Milling qualities including head rice yield, chalk percentage, and rice functionality properties are determined in stages R6 through R8 (Cooper *et al.*, 2006; Ambardekar *et al.*, 2011; Lanning *et al.*, 2011). Most of the weight of the superior kernels is determined by the beginning of R7. Most of the superior kernels are filled during R6 and R7 crop growth stages while inferior kernels are filled primarily during R8. Individual grain weights within the panicle vary consistently with superior grains weighing more than inferior grains. The mean of individual grain

Table 4 Thermal-unit accumulation at R6 stage represented by DD10 values and R6-stage duration expressed in days ($n = 3^a$) across cultivars grown in Stuttgart, AR during 2007–2010

			Year									
			2007		2008		2009		2010		Cultivar mean	
Stage	Size	Cultivar	DD10	Days	DD10	Days	DD10	Days	DD10	Days	DD10	Days
R6	MG	Bengal	56.4	5.9	54.0	7.7	14.7	1.8	29.6	3.8	38.7	4.8
		Jupiter	65.1	6.8	60.5	8.7	44.7	5.4	-	-	44.5	5.5
	LG	Cypress	70.8	7.5	76.1	10.4	50.4	6.4	52.3	6.7	62.4	7.7
		LaGrue	52.4	5.5	52.0	7.3	49.8	6.1	29.0	3.8	45.6	5.7
		Wells	57.7	6.1	56.5	8.1	58.9	7.3	46.8	6.0	55.0	6.9
		XL723	64.2	6.9	49.9	7.2	39.3	4.8	23.0	3.0	44.1	5.5
	Year mean		61.1	5.3	58.2	8.2	43.0	5.3	31.4	4.1		

	DD10	Days
Cultivar effect	***[b]	***
Year effect	**	**
Cultivar by year interaction	***	***
$LSD_{0.05}$	14.5	1.7
Degrees of freedom[c]	39	39
Grand mean	48.4	6.0

Ns, not significant; MG, Medium-grain cultivar; LG, long-grain cultivar; $LSD_{0.05}$, Least Significant Difference, at the 0.05 level of probability, for treatment means averaged over years.

[a]Mean DD10 values and days are averages of three experimental plots and for each plot seven plants were monitored.

[b]$*P < 0.05$, $**P < 0.01$, $***P < 0.001$.

[c]Degrees of freedom for the mean square for error used to calculate the $LSD_{0.05}$.

weights for the crop, however, is a small percentage of yield variation in most cases while the variation in individual grains within the crop impacts quality. Consequently, rice quality is primarily determined from Crop Growth Stages R6 through R8. Crop Growth Stage R8 has been found to be most critical for high night temperatures because the inferior kernels are susceptible over the longer period of time they require to fill.

The different growth stage intervals, if applied judiciously, could be used more or less broadly depending on the particular growth stage. The R3 intervals differed for both DD10 and days for only between Bengal and the other cultivars. Caution should be used in applying R3 intervals because R3 duration can be greatly increased by low-incident solar irradiance and by lower than optimum temperatures during this stage interval. Consequently, R3 DD10 accumulations or intervals in days may not explain the duration of R3 in some cases. The R4 and R5 interval rankings varied over the 4 years of the study with most differences being either non-significant or inconsistent across years. The R6 intervals primarily differed in that Cypress had either the longest or among the longest R6 intervals. The R7 intervals were either longest or among the longest for one or both of the medium-grain cultivars. The R8 intervals had clear cultivar differences with no cultivar by year interactions. Consequently, growth stage intervals for R3, R4, R5, R6 and R7 could likely be applied across cultivars within the same grain type (long- or medium-grain) with a relatively small loss in accuracy of predictions. The R8 intervals had important cultivar differences which should not be ignored. The medium-grain cultivars had longer durations of R8 than the long grains. The R8 interval for Cypress is likely related to the much lower number of grains per panicle for Cypress compared to the other long-grains.

Application of the data: Cypress milling quality stability

Cypress has been identified for several years as a cultivar that is more resistant to head rice yield reduction than other southern US long-grain cultivars (Jodari & Linscombe, 1996; Counce *et al.*, 2005; Cooper *et al.*, 2006, 2008). The stability of Cypress head rice yield is likely the result of several factors but one reason appears to be the shortened duration of R8. Most of the duration of the grain-filling period for the panicle occurs in R8 as evidenced by data in Table 6. The individual kernels fill slower during R8 than those filling during crop growth stages R6 and R7. The earlier anthesis grains fill first and are the heaviest and largest (Mohapatra *et al.*, 1993). These kernels have completed grain filling and subsequently are subject to environmental conditions related to drying as the remaining grains (at R6 in this growth stage) continue to fill (Siebenmorgen *et al.*, 2007). The

Table 5 Thermal-unit accumulation at R7 stage represented by DD10 values and R7-stage duration expressed in days ($n = 3^a$) across cultivars grown in Stuttgart, AR during 2007−2010

			Year									
			2007		2008		2009		2010		Cultivar mean	
Stage	Size	Cultivar	DD10	Days	DD10	Days	DD10	Days	DD10	Days	DD10	Days
R7	MG	Bengal	46.9	5.1	35.3	4.7	63.1	7.7	31.2	4.1	44.1	5.2
		Jupiter	55.8	6.0	46.6	6.3	41.4	5.6	44.2	5.6	47.0	5.8
	LG	Cypress	30.8	3.2	17.7	2.1	20.8	2.9	30.9	4.1	25.1	3.1
		LaGrue	42.6	4.6	31.6	4.1	35.6	5.1	29.8	4.0	34.9	4.5
		Wells	34.1	3.6	29.6	3.8	17.4	2.6	28.2	3.8	27.3	3.5
		XL723	37.2	3.9	34.5	4.8	21.4	2.7	54.8	7.1	37.0	4.6
	Year mean		41.2	4.4	32.6	4.3	33.3	4.4	36.5	4.8		

DD10		Days
CV (%)	23.3	24.0
Cultivar effect	***	***
Year effect:	ns[b]	ns[b]
Cultivar by year interaction	***	***
$LSD_{0.05}$	13.9	1.8
Degrees of freedom[c]	40	40
Grand ean	35.9	4.5

Ns, not significant; MG, Medium-grain cultivar; LG, long-grain cultivar; $LSD_{0.05}$, Least Significant Difference, at the 0.05 level of probability, for treatment means averaged over years.

[a]Mean DD10 values and days are averages of three experimental plots and for each plot seven plants were monitored.

[b]*$P < 0.05$, **$P < 0.01$, ***$P < 0.001$.

[c]Degrees of freedom for the mean square for error used to calculate the $LSD_{0.05}$.

shorter the duration of R8, the shorter the exposure of R8 grains to drying in the field, potentially rewetting and fissuring. The data in this study confirm that Cypress, across years, had a shorter R8 duration than all other cultivars in the study. This is one likely reason for the greater resistance to high night temperatures noted for Cypress. Cypress has fewer grains per panicle and shorter panicles. Much of the yield potential for newer cultivars and hybrids comes, aside from greater tiller production, with greater grain number per panicle. If reducing grains per panicle increased rice quality, it might likely be at the cost of yield potential. Consequently, yield and quality are assessed simultaneously by rice breeders. Among medium-grain cultivars, Bengal has been found to be relatively more stable than Jupiter although both are relatively more stable for milling quality than most long-grain cultivars. In summary, the R8 intervals were found to be cultivar specific, the R8 intervals for Cypress were shorter than for the other cultivars and this difference accounts partially for the milling quality stability of Cypress.

Applications of the data: utilisation in rice research analysis and interpretation

Applications of this research can improve rice crop research data interpretation, management decisions and modelling efforts. Collection and subsequent use of growth staging data can improve data interpretation, management decisions and modelling efforts greatly. By utilising the timing provided in data sets such as the one in this article, growth stage predictions can be made from various points along the rice development progression from R3 to R9. The relevant environmental conditions during the predicted stages can be used as covariants in the statistical and graphical analysis of various treatment responses.

Rice crop growth models could potentially enhance the value of rice research. These models are underutilised in the interpretation of research data. Yield responses to a number of treatments are affected simultaneously by both environmental conditions and rice developmental stages. The responses to a number of crop management experimental treatments are greatly affected by environmental conditions including irradiance, precipitation, relative humidity and temperature. The need for effective models in the interpretation of research results is very clear: much research data are poorly utilised, or underutilised because of lack of meaningful analysis of relevant environmental conditions made possible by predictive models which include meaningful predictions of rice growth stages.

High night temperature effects on rice quality

One example of the use of reproductive growth stage timing is the effort to determine the effect of night

Table 6 Thermal-unit accumulation at R8 stage represented by DD10 values and R8-stage duration expressed in days ($n = 3$[a]) across cultivars grown in Stuttgart, AR during 2007–2010

			Year									
			2007		2008		2009		2010		Cultivar mean	
Stage	Size	Cultivar	DD10	Days	DD10	Days	DD10	Days	DD10	Days	DD10	Days
R8	MG	Bengal	192.8	24.5	216.7	32.3	206.3	30.4	202.3	28.7	204.5	28.9
		Jupiter	190.0	24.7	219.8	35.0	230.4	34.4	239.6	34.3	220.0	32.1
	LG	Cypress	144.4	16.4	161.8	24.6	142.9	21.1	163.2	22.2	153.1	21.1
		LaGrue	177.6	22.1	211.5	32.5	190.7	28.1	167.8	22.9	186.9	26.4
		Wells	149.6	17.2	204.4	30.7	178.4	26.3	172.8	23.5	176.3	24.4
		XL723	177.5	19.7	223.5	32.8	201.6	30.0	174.5	24.7	194.3	26.8
	Year mean		172.0	20.8	207.9	31.1	191.7	28.4	186.7	26.1		

DD10		Days
CV (%)	9.33	10.3
Cultivar effect	***	***
Year effect	**	*
Cultivar by year interaction	ns[b]	ns[b]
$LSD_{0.05}$	14.6	2.3
Degrees of freedom[c]	40	40
Grand mean	189.2	26.7

Ns, not significant; MG, Medium-grain cultivar; LG, Long-grain cultivar; $LSD_{0.05}$, Least significant difference, at the 0.05 level of probability, for treatment means averaged over years.

[a]Mean DD10 values and days are averages of three experimental plots and for each plot seven plants were monitored.

[b]$*P < 0.05$, $**P < 0.01$, $***P < 0.001$.

[c]Degrees of freedom for the mean square for error used to calculate the $LSD_{0.05}$.

temperatures on rice grain quality. Standard field experiments were conducted with cultivar treatments and multiple years and locations. Reproductive Growth Stage R3 was noted for each plot of each cultivar, location and year of the study. At one location in each year, all reproductive growth stages from R3 through R9 were noted. Diurnal air temperatures were measured at each location and year during the study. At the end of the study multiple measurements of rice quality were made. Data sets were generated containing temperature profiles at each projected growth stage and rice grain quality responses for each cultivar, location and year combination. From these data we found that many rice quality parameters were negatively impacted for all cultivars in response to increasing night-time air temperatures during R6, R7 and R8 (Cooper *et al.*, 2006; Ambardekar *et al.*, 2011; Lanning *et al.*, 2011, 2012). Moreover, the cultivars varied in the degree of this response with Bengal among the medium-grain rice cultivars and Cypress among the long-grain rice cultivars being less severely affected. Consequently a simple cultivar experiment conducted over multiple locations and years was analysed in a very useful manner by employing the growth staging system, projections of growth stages, pertinent environmental data and relevant responses. This work confirmed, in the field, anecdotal surmises by breeders over the years (Jodari & Linscombe, 1996) and controlled climate experimental data (Cooper *et al.*, 2008; Counce *et al.*, 2005) concerning the negative effects of night-time air temperature on critical components of rice grain quality.

Historical data

Historical data can be effectively exploited to explore experimental trends more accurately. Streck *et al.* (2012) compared a group of rice cultivars in Rio Grande do Sul in Brazil, over a 100-year period. Their model and data allowed predictions of RGSS intervals for seedling emergence (presumably S3 to V1) to V3, emergence to R1, emergence to R4 and emergence to R9. They found all intervals decreased over the period modelled (Streck *et al.*, 2012). Cooper *et al.* (2006) used a set of data to determine the effect of night- and day-time air temperatures across 18 years of a standard field test at Stuttgart, Arkansas, USA with yield and milling quality response measurements to night-time air temperatures. They found over rice milling quality decreased in response to increased night-time air temperatures during the predicted R8 stage of development while daytime air temperatures had a negative effect on milling quality only at the R6 stage of development and a positive effect during R7 and R8 (Cooper *et al.*, 2006).

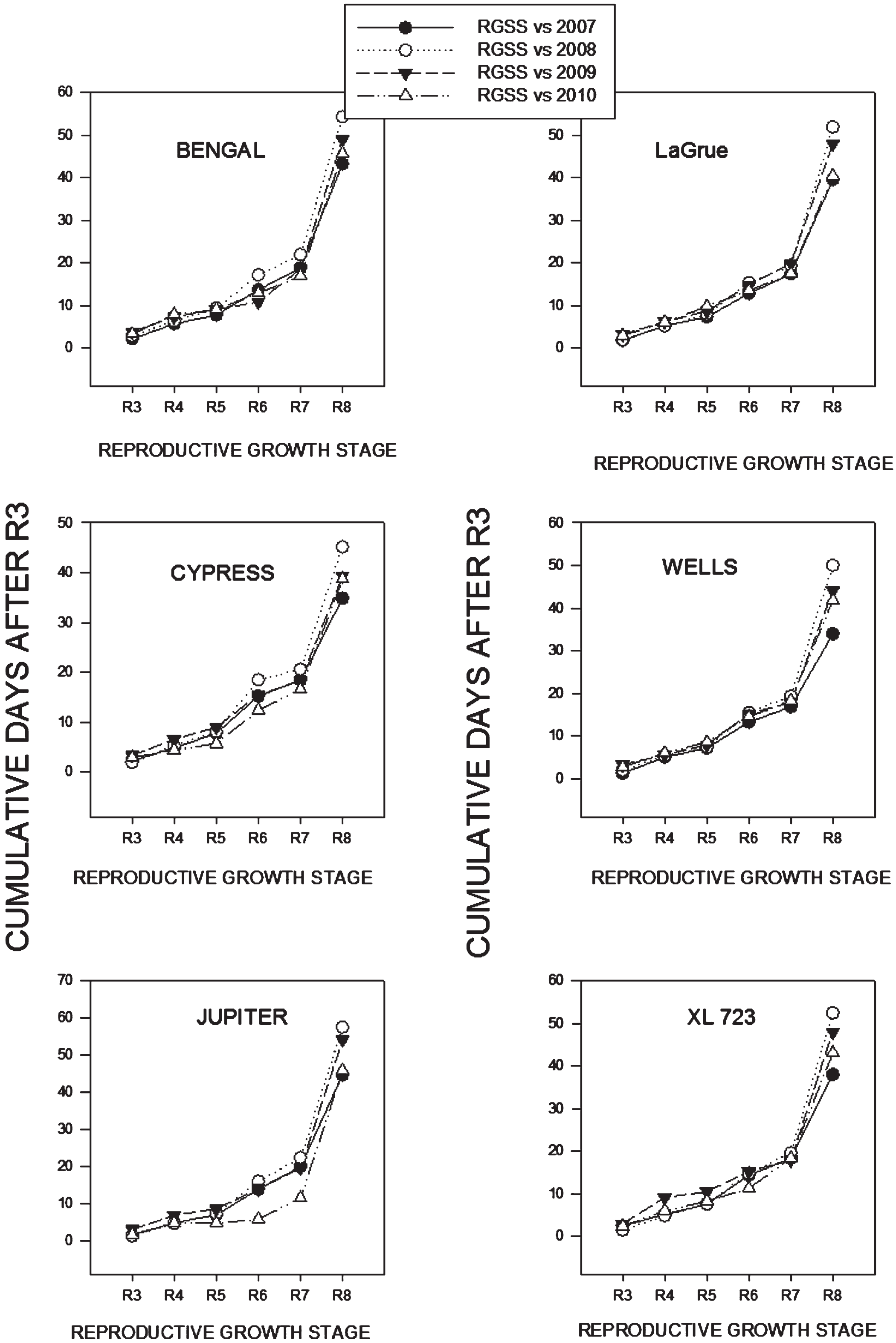

Figure 2 Cumulative days for growth stages beginning at R3 through the end of R8 for six rice cultivars in each of four years from field tests at Stuttgart, AR, USA.

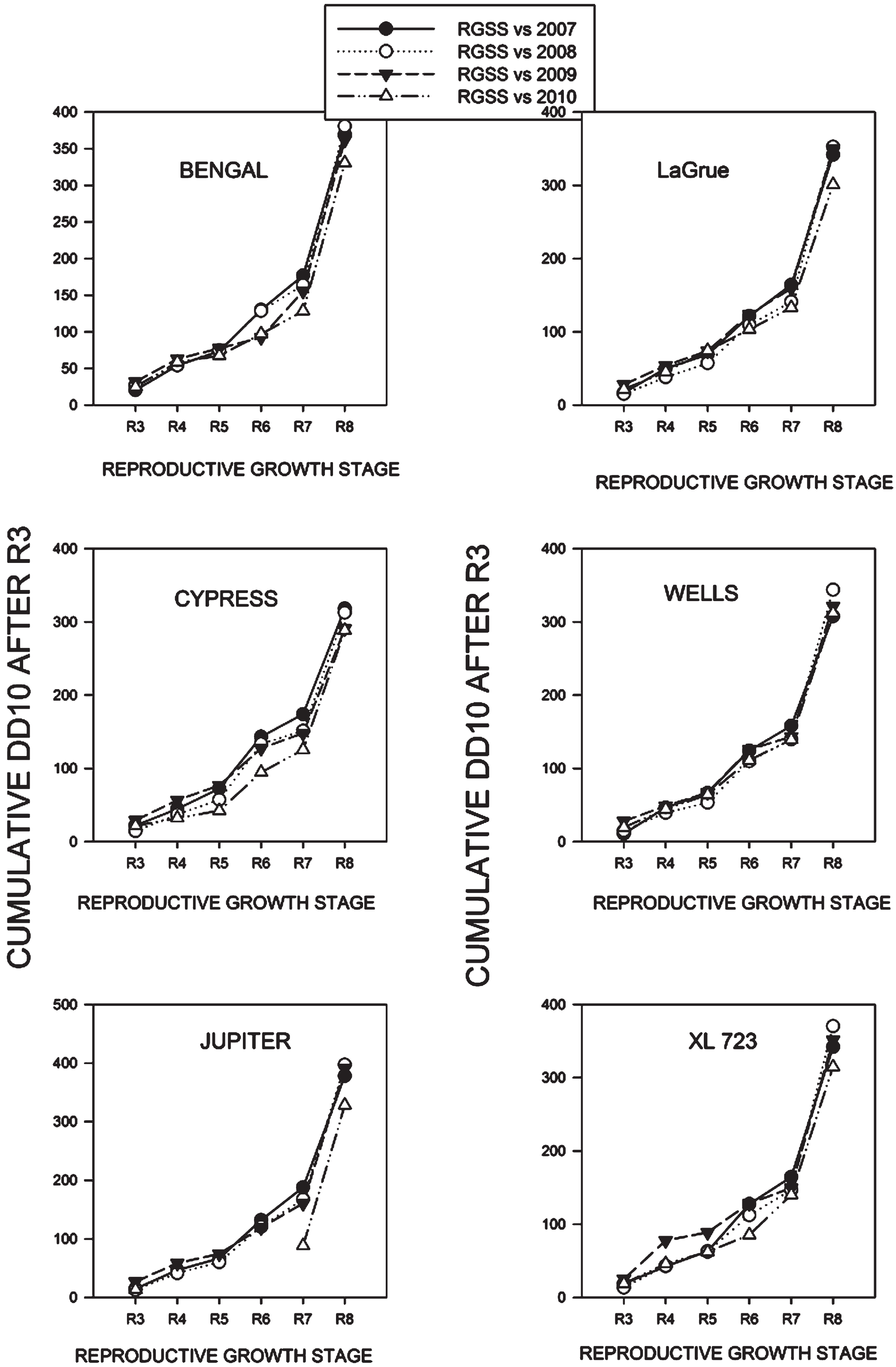

Figure 3 Cumulative DD10 (thermal time units) for growth stages beginning at R3 through the end of R8 for six rice cultivars in each of four years from field tests at Stuttgart, AR, USA.

Use of reproductive staging data: rice crop management

Many agronomic and other management practices are based on growth stages of the crop. One example is rice field drainage. Counce *et al.* (2009) used a model of growth stages to predict the growth stage at which a rice field growing could be safely drained without reducing head rice yield or grain yield. The model used a growth stage prediction beginning at R3 and proceeding to R9 with water use per day assumed maximum during each respective reproductive stage of development. The model allowed successful prediction of a safe, minimum growth stage for draining in the years of the study as well in subsequent tests of the model. The model resulted were verified in that rice growing in the Arkansas Grand Prairie could be safely drained for harvest at Stage R7 (Counce *et al.*, 2009). Similar data to that described in this article would permit the extension of that model to other cultivars and hybrids.

Potential uses of the growth staging system and the data reported herein include several applications to integrated pest management in rice. Numerous studies have utilised the RGSS (Counce *et al.*, 2000) identifying rice growth stages that are vulnerable to pest occurrence and damage and also for initiating management practices for control. Scientists studying blast (Bogo *et al.*, 2010), sheath blight (Eizenga *et al.*, 2002) and other diseases have utilised the growth staging system to various degrees in describing, implementing and applying their research efforts. Likewise studies of insect damage and characterisation of rice water weevil (Stout *et al.*, 2002), rice stink bug (Rashid *et al.*, 2006) and sugarcane borer (Sidhu *et al.*, 2013) have been performed using the staging system. Finally, numerous weed and weed control studies have employed the growth staging system (Sales *et al.*, 2008, 2011; Shivrain *et al.*, 2009; Bagavathiannan *et al.*, 2011; Camargo *et al.*, 2011; Marchesan *et al.*, 2011; Streck *et al.*, 2011). In all these applications, accurate prediction of rice growth stages is critical, which in turn is contingent upon having accurate schedules of cultivars' growth stage intervals in heat units; these patterns are herein characterised for several cultivars grown over multiple seasons. A thermal unit timeline of reproductive development for a particular situation or cultivar should allow optimal pest control applications and thus allow the data produced from various pest control studies to be employed more effectively in crop management. Moreover, many other crop management decisions could be improved by the judicious application of the growth stage timing data.

Conclusion

Employing rice crop growth stage projections can improve the execution, analysis, presentation and utilisation of rice research efforts. By collecting data on even one reproductive growth stage, meaningful projections of subsequent stages of development could be made. These projections can substantially enhance effectiveness of scientists working with rice and those employing their research.

References

Ambardekar A.A., Siebenmorgen T.J., Counce P.A., Lanning S.B., Mauromoustakos A. (2011) Impact of field-scale nighttime air temperatures during kernel development and rice milling quality. *Field Crops Research*, **122**, 179–185.

Bagavathiannan M.V., Norsworthy J.K., Scott R.C. (2011) Comparison of weed management programs for furrow-irrigated and flooded hybrid rice production in Arkansas. *Weed Technology*, **25**, 556–562.

Bogo A., Casa R.T., Sangoi L., Bianchet P., Saldanha A. (2010) Soil drainage periods during tillering brast progress and grain yield of paddy rice cultivars grown with pre-germinated seeds. *Summa Phytopathologica*, **36**, 233–236.

Bonhomme R. (2000) Bases and limits to using degree day units. *European Journal of Agronomy*, **13**, 1–10.

Camargo E., Senseman S., McCauley G., Guice J. (2011) Rice tolerance to saflufenacil in clomazone weed control program. *International Journal of Agronomy*, **2011**, 402461. DOI:10.1155/2011/402461.

Cooper N., Siebenmorgen T., Counce P., Meullenet J.F. (2006) Explaining rice milling quality variation using historical weather data analysis. *Cereal Chemistry*, **83**, 447–450.

Cooper N., Siebenmorgen T., Counce P. (2008) Effects of nighttime temperature during kernel development on rice physicochemical properties. *Cereal Chemistry*, **85**, 276–282.

Counce P.A., Keisling T.C., Mitchell A.J. (2000) A uniform, objective, and adaptive system for expressing rice development. *Crop Science*, **40**, 436–443.

Counce P., Bryant R., Bergman C., Bautista R., Wang Y., Siebenmorgen T., Moldenhauer K., Meullenet J. (2005) Rice milling quality, grain dimensions, and starch branching as affected by high night temperatures. *Cereal Chemistry*, **82**, 645–648.

Counce P.A., Watkins K.B., Brye K.R., Siebenmorgen T.J. (2009) A model to predict safe stages of development for rice field draining and field tests of the model predictions in the Arkansas Grand Prairie. *Agronomy Journal*, **101**, 113–119.

Eizenga G., Lee F., Rutger J. (2002) Screening *Oryza* species plants for rice sheath blight resistance. *Plant Disease*, **86**, 808–812.

Hardke J.T., Wilson C.E. Jr. (2013) Introduction. In *Arkansas Rice Production Handbook*, pp. 1–8. Ed. J.T. Hardke. Little Rock, AR, USA: University of Arkansas.

Jodari F., Linscombe S.D. (1996) Grain fissuring and milling yields of rice cultivars as influenced by environmental conditions. *Crop Science*, **36**, 1496–1502.

Keisling T.C., Wells B.R., Davis G.L. (1984) Rice management decision aid based on thermal time base 50°F. Arkansas Cooperative Extension Service Technical Bulletin No.1. Little Rock, AR, USA: University of Arkansas Division of Agriculture Cooperative Extension Service.

Lanning S.B., Siebenmorgen T.J., Counce P.A., Ambardekar A.A., Mauromoustakos A. (2011) Extreme nighttime air temperatures in 2010 impact rice chalkiness and milling quality. *Field Crops Research*, **124**, 132–136.

Lanning S.B., Siebenmorgen T.J., Ambardekar A.A., Counce P.A., Bryant R.J. (2012) Effects of nighttime air temperature during kernel development of field-grown rice on physicochemical and functional properties. *Cereal Chemistry*, **89**, 168–175.

Marchesan E., Massoni P., Grohs M., Villa S., Avila L., Roso R. (2011) Imidazolinone-tolerant rice: red rice seed bank and gene flow. *Planta Daninha*, **29**, 1099–1105.

Matsui T., Kagata H. (2003) Characteristics of floral organs related to reliable self-pollination in rice (*Oryza sativa* L.). *Annals of Botany*, **91**, 473–477.

Mohapatra P., Patel R., Sahu S. (1993) Time of flowering affects grain quality and spikelet partitioning within the rice panicle. *Functional Plant Biology*, **20**, 231–241.

Norman R., Wilson C. Jr., Boothe D., Slaton N., Moldenhauer K., Gibbons J. (2003) Influence of seeding date on the degree day 50 thermal unit accumulations and grain yields of new rice cultivars. In *Rice Research Studies 2002*. University of Arkansas Agricultural Experiment Station Series 504, pp. 280–287. Eds R.J. Norman and J.F. Muellenet. Arkansas Agricultural Experiment Station: Fayetteville, AR, USA.

Purcell L.C. (2003) Comparison of thermal units derived from daily and hourly temperatures. *Crop Science*, **43**, 1874–1879.

Rashid T., Johnson D., Bernhardt J. (2006) Sampling rice stink bug (Hemiptera: Pentatomidae) in and around rice fields. *Environmental Entomology*, **35**, 102–111.

Sales M.A., Shivrain V.K., Burgos N.R., Kuk Y.I. (2008) Amino acid substitutions in the acetolactate synthase gene of red rice (*Oryza sativa*) confer resistance to imazethapyr. *Weed Science*, **56**, 485–489.

Sales M.A., Burgos N.R., Shivrain V.K., Murphy B., Gbur E.E. (2011) Morphological and physiological responses of weedy red rice (*Oryza sativa* L.) and cultivated rice (*O. sativa*) to N supply. *American Journal of Plant Sciences*, **2**, 569–577.

SAS (2012) The SAS system for Windows, *Version 9.2*. Cary, NC, USA: SAS Institute.

Satake T., Yoshida S. (1978) High temperature-induced sterility in Indica rices at flowering. *Japanese Journal of Crop Science*, **47**, 6–17.

Shivrain V.K., Burgos N.R., Gealy D.R., Sales M.A., Smith K.L. (2009) Gene flow from weedy red rice (*Oryza sativa* L.) to cultivated rice and fitness of hybrids. *Pest Management Science*, **65**, 1124–1129.

Sidhu J., Stout M., Blouin D., Datnoff L. (2013) Effect of silicon soil amendment on performance of sugarcane borer, *Diatraea saccharalis* (Lepidoptera: Crambidae) on rice. *Bulletin of Entomological Research*, **103**, 656–664.

Sié M., Dingkuhn M., Wopereis M.C.S., Miezan K.M. (1998a) Rice crop duration and leaf appearance rate in a variable thermal environment. I. Development of an empirically based model. *Field Crops Research*, **57**, 1–13.

Sié M., Dingkuhn M., Wopereis M.C.S., Miezan K.M. (1998b) Rice crop duration and leaf appearance rate in a variable thermal environment. II. Comparison of genotypes. *Field Crops Research*, **58**, 129–140.

Sié M., Dingkuhn M., Wopereis M.C.S., Miezan K.M. (1998c) Rice crop duration and leaf appearance rate in a variable thermal environment. III. Heritability of photothermal traits. *Field Crops Research*, **58**, 141–152.

Siebenmorgen T., Bautista R., Counce P. (2007) Optimal harvest moisture contents for maximizing milling quality of long-and medium-grain rice cultivars. *Applied Engineering in Agriculture*, **23**, 517–527.

Stout M., Rice W., Ring D. (2002) The influence of plant age on tolerance of rice to injury by the rice water weevil, *Lissorhoptrus oryzophilus* (Coleoptera: Curculionidae). *Bulletin of Entomological Research*, **92**, 177–184.

Streck N.A., Lago I., Bosco L.C. (2008) Simulating leaf appearance in rice. *Agronomy Journal*, **100**, 490–501.

Streck N., Lago I., Oliveira F., Heldwein A., de Avila L., Bosco L. (2011) Modeling the development of cultivated rice and weedy red rice. *Transactions of the ASABE*, **54**, 371–384.

Streck N.A., Uhlmann L.O., Gabriel L.F. (2012) Long-term changes in rice development in Southern Brazil during the last ten decades. *Pesquisa Agropecuária Brasileira*, **47**, 727–737.

Yin X., Kropff M.J., Aggarwal P.K., Peng S., Hone T. (1997) Optimal preflowering phenology of irrigated rice for high yield potential in three Asian environments: a simulation study. *Field Crops Research*, **51**, 19–27.

Yoshida S. (1972) Physiological aspects of grain yield. *Annual Review of Plant Physiology*, **23**, 437–464.

Yoshida S., Parao F. (1976) Climatic influence on yield and yield components of lowland rice in the tropics. In *Proceedings of the Symposium on Climate and Rice*, pp. 471–494. The International Rice Research Institute: Los Baños, Philippines.