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Barnyardgrass; *Echinochloa crus-galli* (L.) P. Beauv.; bearded sprangletop; *Leptochloa fusca* (L.) Kunth ssp. *fascicularis* (Lam.) N. Snow; smallflower umbrella sedge; *Cyperus difformis* L.; rice; *Oryza sativa* L.

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Emergence timing of smallflower umbrella sedge (*Cyperus difformis*), barnyardgrass (*Echinochloa crus-galli*), and bearded sprangletop (*Leptochloa fusca* spp. *fascicularis*) in California water-seeded rice

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Abstract

Late-season weed emergence in California rice fields complicates decisions concerning the timing of control measures. The objective of this study was to predict the emergence of three problematic weed species in rice using thermal time models. Smallflower umbrella sedge, barnyardgrass, and bearded sprangletop seedlings were counted and removed daily at three locations across the Sacramento Valley rice-growing region in 2018. The accumulation of thermal time (growing degree days; GDD) commenced with the initial flooding of the fields at each location, utilizing the specific base temperatures corresponding to each species. The pattern of emergence as a function of GDD was modeled with a Weibull function. Root-mean-square values for comparing actual and model-predicted cumulative emergence values were 6% to 23%. Percent cumulative emergence initially increased rapidly for smallflower umbrella sedge and reached 90% emergence with accumulation of 13 GDD. Barnyardgrass emerged after smallflower umbrella sedge and reached 90% emergence with an accumulation of 124 GDD. Bearded sprangletop had a delay of 64 GDD compared to barnyardgrass to reach first emergence and reached 90% emergence at 215 GDD. The period of weed emergence at all field sites differed across the three species and led to a continuous spectrum of weed emergence over time. This study characterizes the emergence of three economically important rice weeds and provides useful information for the timing of weed management. Typical herbicide applications on the day of seeding may have less efficacy on the late-emerging weeds, causing reduced weed control. Delayed herbicide application, overlay of residual herbicides, or use of herbicides with longer residual activity are suggested to control late-emerging weeds.

Introduction

Rice is the most widely consumed staple food in the world (Maclean et al. 2002). U.S. rice production contributes approximately US$1.7 billion annually to the gross domestic product in export value, and California is the second-largest rice-producing state (USDA 2023). Rice fields are significant agroecologically managed systems benefiting agriculture production and wildlife habitat (Sterling and Buttner 2011). The approximately 200,000 ha of rice grown in California's Sacramento Valley have historically been water seeded (UCANR 2023). Water seeding rice is the practice of air seeding pregerminated rice seed onto a field with a 10- to 15-cm standing flood and then continuously flooding throughout the season up to 2 mo before harvest (UCANR 2023). Continuous rice cultivation is common, and nearly 90% of cultivated hectares are medium-grain rice (UCANR 2023).

Weeds are the main biological constraint in achieving economically adequate yields in California rice production (Brim-DeForest et al. 2017). Early-season rice weed species include smallflower umbrella sedge, barnyardgrass, and bearded sprangletop; furthermore, in-season rice yield losses associated with interference from these weed species have been reported up to 50% (Sanders 1994), 59% (Gibson et al. 2002), and 36% (Smith 1983), respectively, when left uncontrolled. The continuous monoculture cropping of rice in California has resulted in a proliferation of highly competitive weeds that are adapted to aquatic environments (Brim-DeForest et al. 2017). Apart from cultural practices like the use of certified weed-free seed, leveling fields, and maintaining flood levels, growers have relied heavily on herbicides for weed control (Becerra-Alvarez et al. 2023).

In any cropping system, the timing of weed control is crucial to achieving adequate efficacy (Swanton and Murphy 1996). The ability to predict seasonal weed seedling emergence has been associated with the development of more effective weed control management (Masin et al. 2010). Predicting key developmental stages of weeds to maximize the impact of management events has been a focus of weed control for some time (Holst et al. 2007). Cousens et al. (1987) highlighted understanding the timing of weed emergence as one of the major factors affecting crop yield losses due to weed competition. Weed emergence is a key phenological event that is explained primarily by temperature and moisture (Bradford 2002; Grundy and Mead 2000). Where water is not limiting (e.g., water-seeded rice), accumulation of thermal time or growing degree days (GDD) within a weed's physiologically relevant range can be used to predict germination and early growth with adequate accuracy (Grundy 2003).

Echinochloa spp., *Oryza* spp. (weedy rice), and smallflower umbrella sedge have been the focus of more recent biology and phenology research to improve weed control efforts (Brim-DeForest et al. 2017; Galvin et al. 2023; Lundy et al. 2014; Pedroso et al. 2019). However, late-emerging weeds, such as bearded sprangletop, have now become more problematic in California rice fields (Driver et al. 2020a, 2020b). California rice growers have reported several cases of suspected herbicide resistance in bearded sprangletop, with the greatest number reporting resistance to clomazone. However, Becerra-Alvarez et al. (2023) reported that only 11% of suspected herbicide-resistant bearded sprangletop samples collected from grower fields were indeed resistant to clomazone. Driver et al. (2020b) reported that 95% of bearded sprangletop populations with suspected clomazone resistance were in fact susceptible when subjected to dose–response evaluations. This suggests that application issues, such as inappropriate clomazone timing, could be contributing to control failures of bearded sprangletop in the field.

Predicting the emergence of common problematic weed species would be important to optimizing scouting and weed control programs in California rice fields. Previous models have been developed to predict emergence for various *Echinochloa* species, weedy rice, and smallflower umbrella sedge (Brim-DeForest et al. 2017; Galvin et al. 2022; Gibson et al. 2002; Lundy et al. 2014; Pedroso et al. 2019). These models have assisted growers and consultants in determining optimal weed control measures for these economically important weeds. The model developed by Lundy et al. (2014) used thermal time to predict the emergence of *Echinochloa* species and smallflower umbrella sedge but did not include bearded sprangletop. No information is available on the emergence time of bearded sprangletop relative to other important rice weeds in California. Therefore the objectives of this study were to develop a thermal time emergence model for smallflower umbrella sedge, barnyardgrass, and bearded sprangletop under field conditions and to characterize the emergence of these weeds for weed control implications.

Materials and Methods

Emergence Study

Field experiments were established at three sites throughout the Sacramento Valley in California. Site 1, in Sutter County (38.93°N, 121.80°W), was seeded with 'M209' rice. The permanent flood in the field was established prior to seeding rice on April 26, 2018. Site 2, in Sutter County (38.89°N, 121.67°W), was seeded with 'M206' rice, and the permanent flood in the field was established on May 15, 2018. Site 3, in Butte County (39.45°N, 121.71°W), was seeded with 'M206' rice, and the permanent flood in the field was established on June 2, 2018. The rice seed was seeded 1 to 2 d after the permanent flood. The three sites were within 60 km of each other. All sites were established, seeded, and maintained according to the University of California Cooperative Extension recommendations (UCANR 2023).

The soil at Site 1 is classified as Byington loam, fine-silty, mixed calcareous, thermic Aeric Fluvaquents with 20% clay, 10% sand, 70% silt, 2% organic matter, and pH 8.5. The soil at Site 2 is classified as Clear Lake, fine, smectic, thermic Xeric Endoaquerts with 60% clay, 18% sand, 22% silt, 3.5% organic matter, and pH 7.0. The soil at Site 3 is classified as Esquon-Neerdobe, fine, smectic, thermic Xeric Epiaquerts and Duraquerts with 49% clay, 24% sand, 27% silt, 2.8% organic matter, and pH 5.1.

The emergence of three weed species, including smallflower umbrella sedge, barnyardgrass, and bearded sprangletop, was evaluated at each site. A plot was composed of a polyvinyl chloride (PVC) ring 76 cm in diameter and 38 cm in height placed 5 cm into the ground. Ten PVC rings were placed at each site in a completely randomized design with 1-m spacing between rings. The rings had two 2-cm-diameter openings drilled at the base near the soil surface to control water in the rings and were plugged with rubber plugs as needed. Inside each ring, 100 seeds of each species were planted in a row approximately 1 cm in depth, prior to the permanent flood. In a continuously flooded rice field, only the top 1 cm of soil depth is relevant for weed seed emergence (Galvin et al. 2022; Moon et al. 1999). Seeds were collected in the previous growing season from a field research site that is known to have herbicide-susceptible populations, and similar seed stock was used at all three sites. Seed was stored at 4 C in a dry location throughout the year after collection. Grass weed seeds were placed in plastic containers with water for wet chilling at 4 C 2 wk prior to seeding in the field. Emergence observations were made daily beginning from the flooding establishment until no further emergence had occurred for at least 3 d. Seedlings emerging within the panted row in each plot were counted as soon as they could be identified by species. Generally, this was the first day of emergence for smallflower umbrella sedge, where <0.5 cm in shoot height was visible. For barnyardgrass and bearded sprangletop, it was approximately 1 to 2 d after initial emergence, when shoot height was ~1 cm. Barnyardgrass and bearded sprangletop seedlings were removed after counting, but owing to their abundance, smallflower umbrella sedge seedlings were not removed but recounted.

Data Analysis

Air temperature was recorded at 15-min intervals via a shielded Onset Hobo U23 Prov2 external temperature data logger (Onset, Bourne, MA, USA) placed in the center of each experimental area, 1.5 m above the soil surface. Data were transformed to thermal time using GDD (Equation 1):

$$\theta_T = \sum_{i=1}^{n} \left(\overline{T}_i - T_b \right) \quad [1]$$

where θ_T is GDD accumulated from the *i*th day for the duration of the study, that is, *n* days; $\bar{T}_i$ is the mean daily air temperature (C)

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Table 1. Weed seedling emergence model of three weed species across three sites in the Sacramento Valley rice-growing region of California in 2018.[a,b]

Species	Weibull model parameter			Base temperature, T_b	RMSE
	z	c	k		
				C	% cumulative emergence
Smallflower umbrella sedge	9.2	3	6	17	28.1
Barnyardgrass	12.9	2.6	1.5×10^{-5}	14.4	9.1
Bearded sprangletop	63.9	2.5	5.1×10^{-5}	13.9	6.6

[a]The three-parameter Weibull model was fit to percent cumulative emergence plotted as a function of thermal time (θ_T). Weibull models were in the form $Y = M\{1 - \exp[-k(\theta_T - z)^c]\}$, where Y is the percent cumulative emergence, M is the asymptote and is fixed at 100, k is the rate of increase, θ_T is thermal time accumulated, z is θ_T to first emergence, and c is a curve shape parameter. RMSE provides an indication of the average difference between predicted and actual values.
[b]Abbreviation: RMSE, root-mean-square error.

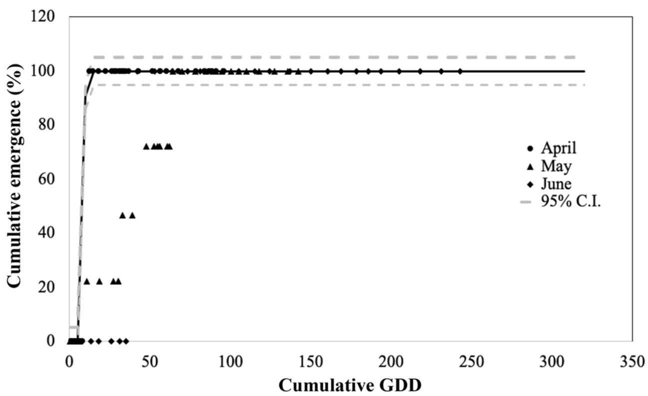

Figure 1. Smallflower umbrella sedge seedling emergence in three fields across the Sacramento Valley rice-growing region of California in 2018 fitted to a Weibull distribution (solid line) with a 95% confidence interval (dashed line). Symbols represent observed emergence at each location labeled by its respective planting month and are the means of 10 replicates. Emergence was modeled using a Weibull model; for associated model parameters, see Equation 2. Root-mean-square error = 28.1. Abbreviation: GDD, growing degree days.

calculated from 15-min temperature intervals; and T_b is the base temperature (C) for a given weed species. The GDD accumulation began the day the flood was established. Emergence was modeled using a Weibull model with lag phase (Equation 2):

$$Y = M\{1 - \exp[-k(\theta_T - z)^c]\} \quad [2]$$

where Y is the percent cumulative emergence; M is the asymptote, which was fixed at 100%; k is the rate of increase; θ_T is thermal time accumulated; z is θ_T of first emergence (or lag); and c is a curve shape parameter (Brown and Mayer 1988). The Weibull function was fit to the emergence values using the nonlinear built-in NLS package in R (R Core Team 2023). Agreement between predicted and actual emergence values was determined with the root-mean-square error (RMSE). The RMSE is expressed in the same units as the original data, and a lower RMSE value indicates a better fit of the model to the data (Mayer and Butler 1993).

Results and Discussion

Across rice planting dates, smallflower umbrella sedge emerged first, followed by barnyardgrass and, later, bearded sprangletop (Table 1). The emergence patterns of each weed species were predicted by a single Weibull model with reasonable accuracy (Table 1). The RMSE values for this experiment compared favorably to those of other seedling emergence models. RMSE values of 5.8% to 10.1% cumulative emergence were reported by Ekeleme et al. (2005) for billygoat weed (*Ageratum conyzoides* L.), Roman et al. (2000) reported RMSE values of 6.5% to 37.1% cumulative emergence for common lambsquarters (*Chenopodium album* L.), and Schutte et al. (2008) reported RMSE values of 8.0% to 9.5% cumulative emergence for giant ragweed (*Ambrosia trifida* L.).

Only one emergence flush of smallflower umbrella sedge was observed during this study (Figure 1), and a base temperature of 17 C provided the best fit for the model (Equation 2). In addition, smallflower umbrella sedge needed the fewest GDD to reach first emergence (Table 1). These observed values are consistent with other studies of smallflower umbrella sedge emergence conducted in California (Boddy et al. 2012; Lundy et al. 2014; Pedroso et al. 2019). The general emergence pattern for smallflower umbrella sedge was characterized by a rapid emergence to 90% (Figure 1; Table 2). Pedroso et al. (2019) suggested that no primary dormancy was present in smallflower umbrella sedge, and the synchronous germination pattern observed is desirable for greater weed control achieved with minimal control measures. The results from this study corroborate the synchronous germination nature of smallflower umbrella sedge in the field. However, variability in site-specific populations and real-time weather data each season are important to consider (Lundy et al. 2014).

Barnyardgrass emerged after smallflower umbrella sedge with a base temperature of 14.4 C for the model (Equation 2; Table 1). These observed temperature values are consistent with other barnyardgrass emergence studies (Masin et al. 2010; Steinmaus et al. 2000; Swanton et al. 2000). The general emergence pattern for barnyardgrass was characterized by a 13 GDD lag to first emergence, then by the additional accumulation of 30, 66, and 111 GDD to achieve 10%, 50%, and 90% emergence, respectively (Table 2). This pattern resulted in the relatively constant emergence of barnyardgrass (Figure 2). A similar emergence pattern for barnyardgrass in Arkansas was observed by Bagavathiannan et al. (2011); however, Bagavathiannan et al. observed naturally occurring seedbanks from each location and demonstrated an even more prolonged emergence throughout the season than we observed in this study. Therefore it is important to consider subpopulations within one location that can give rise to prolonged emergence in the field.

Bearded sprangletop emergence had a base temperature similar to barnyardgrass at 13.9 C but required more GDD to reach first emergence (Table 1). Emergence patterns of bearded sprangletop can be characterized by a lag of 64 GDD, followed by an additional accumulation of 151 GDD to reach 90% emergence (Table 2; Figure 3). The lag to first emergence observed in bearded sprangletop could be due to the uncharacterized emergence that has been observed in California populations (Driver et al. 2020a). Altop et al. (2015) demonstrated that bearded sprangletop possesses a high level of primary dormancy and needs a prechilling

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Table 2. Observed and predicted number of growing degree days required to reach 10%, 50%, and 90% emergence for smallflower umbrella sedge, barnyardgrass, and bearded sprangletop across three sites in the Sacramento Valley rice-growing region of California in 2018.[a,b]

	Smallflower umbrella sedge		Barnyardgrass		Bearded sprangletop	
Emergence	Observed	Predicted	Observed	Predicted	Observed	Predicted
%	GDD					
10	8	10	43	44	100	99
50	13	10	79	77	147	149
90	13	10	124	115	215	211

[a]Observed data were collected for method validation. Predicted values were produced using the models presented in Equations 1 and 2.
[b]Abbreviation: GDD, growing degree days.

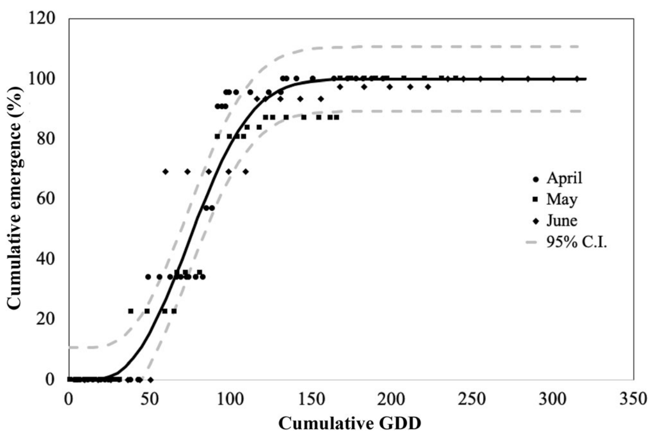

Figure 2. Barnyardgrass seedling emergence in three fields across the Sacramento Valley rice-growing region of California in 2018 fitted to a Weibull distribution (solid line) with a 95% confidence interval (dashed line). Symbols represent observed emergence at each location labeled by its respective planting month and are the means of 10 replicates. Emergence was modeled using a Weibull model; for associated model parameters, see Equation 2. Root-mean-square error = 9.1. Abbreviation: GDD, growing degree days.

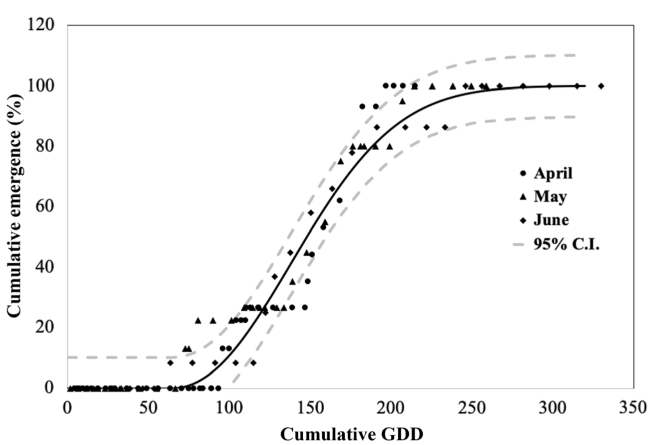

Figure 3. Bearded sprangletop seedling emergence in three fields across the Sacramento Valley rice-growing region of California in 2018 fitted to a Weibull distribution (solid line) with a 95% confidence interval (dashed line). Symbols represent observed emergence at each location labeled by its respective planting month and are the means of 10 replicates. Emergence was modeled using a Weibull model; for associated model parameters, see Equation 2. Root-mean-square error = 6.6. Abbreviation: GDD, growing degree days.

period prior to germination, which could be influential in the late emergence observed in the field.

Suspected clomazone-resistant bearded sprangletop is a concern of growers. However, results from this study may suggest that bearded sprangletop emerges late enough in the season that residual activity of clomazone applied on the day of seeding no longer provides effective control. Tomco et al. (2010) demonstrated faster degradation of clomazone in anaerobic field conditions than in aerobic conditions with a half-life of 8 d. Although clomazone-resistant bearded sprangletop is not widespread, it has been documented (Driver et al. 2020b). The low levels of herbicide residuals in the soil by the time of sprangletop emergence could have been influential in developing tolerance to clomazone and, eventually, resistance (Driver et al. 2020a, 2020b).

Practical Implications

Weed emergence in California rice fields is characterized by protracted and somewhat overlapping emergence periods of various weed species, complicating the timing of weed control measures. Rice yields are substantially decreased if herbicide applications are delayed to 30 d after seeding, highlighting the critical weed-free period (Gibson et al. 2002). It is not in the best interest of weed control to target only one weed species or to have only one herbicide application timing. A few herbicides for California rice are currently available to provide an initial weed-free period applied on the day of seeding up to the 2-leaf rice stage, including clomazone, halosulfuron, benzobicyclon, and thiobencarb. On the basis of the models, herbicide applications on the day of seeding can successfully control smallflower umbrella sedge and the majority of barnyardgrass. However, bearded sprangletop may emerge late enough in the season to avoid effective control by the herbicide residual activity applied on the day of seeding. The available herbicides have variable control over the weed species tested in this study, and their strengths and weaknesses should be understood to develop effective weed management programs (Becerra-Alvarez et al. 2023).

Furthermore, to obtain greater control of late-emerging weeds, a delay in herbicide application, an overlay of residual-activity herbicide applications, or herbicides with longer residual activity will be needed to capture the late-emerging cohorts. A delay in herbicide applications should be coupled with suitable flood management strategies to suppress further weed emergence, reduce herbicide-induced damage to rice, and effectively manage water-holding periods to prevent potential off-target herbicide contamination (Becerra-Alvarez et al. 2022). Overlay of soil residual herbicides has been a successful method to improve weed management in dry-seeded rice systems (Osterholt et al. 2019); however, it has not been extensively studied in the California water-seeded system. Differences in soil/water residual activity are observed across the currently available herbicides for California rice (UCANR 2023). Variable combinations of the available herbicides can assist in balancing the dominant weed year to year.

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Therefore growers or consultants must understand the historical weed populations in their fields and adapt their cultural and herbicide management to successfully manage weed interference each year.

The emergence models presented here characterize emergence patterns for three economically important California rice weeds. Prior to this study, the emergence of bearded sprangletop in California rice was not well understood. The emergence forecast derived from these models provides rice growers and consultants with weed seed emergence knowledge during the critical weed-free period to assist in developing appropriate weed management programs.

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