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Site-specific, real-time temperatures improve the accuracy of weed emergence predictions in direct-seeded rice systems

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ABSTRACT

The efficacy of crop management is highly sensitive to the timing of operations. This study tested the hypothesis that using site-specific, real-time temperatures to predict weed emergence at the regional scale can improve the timing of weed management in stale-seedbed and drill-seeded rice (*Oryza sativa*) relative to the use of regional emergence averages that incorporate the spatiotemporal variability. First, thermal models of emergence for smallflower umbrella sedge (*Cyperus difformis*) and watergrass (*Echinochloa* ssp.), two of the most problematic weeds in California's direct-seeded rice system, were developed from field-scale observations made across 3 sites and 2 years. The models predicted smallflower umbrella sedge and watergrass emergence in an independently collected dataset with accuracy [root mean square error (RMSE) = 21% emergence and 1.3 d; model efficiency index (EF) = 0.80; and RMSE = 14% emergence and 2.2 d; EF = 0.88, respectively]. Subsequently, in order to quantify the degree to which spatially and temporally precise temperatures affect predicted emergence at the regional scale, the models were applied to a daily regional temperature dataset precise to 2 km × 2 km. For each species, the number of days to emergence was simulated for 48 dates (April 15–June 1), 9 years (2003–2011), and 193 locations in the Sacramento Valley rice growing region (83,376 total emergence predictions per species). The variability of the resulting emergence predictions due to the intra-annual, inter-annual and spatial heterogeneity of temperatures was measured with a linear model. Each of the spatiotemporal effects affected the emergence predictions ($P < 0.001$), with the temporal effects (intra- and inter-annual variability) having the greatest impact on predicted emergence. In management terms, using site-specific, real-time temperatures to predict weed emergence would have improved the timing of weed management by as much as 14 days for smallflower umbrella sedge and 12 days for watergrass when compared to using regionally-specific averages that ignored spatiotemporal variability for the simulated period. These results argue for further efforts to merge phenological models with spatiotemporally-specific environmental data in order to improve their accuracy when applied to real-time management decisions.

1. Introduction

In any cropping system, the timing of weed control is crucial to its efficacy (Swanton and Murphy, 1996). Much effort has been made to predict the timing of key developmental stages of weeds as a means of maximizing the impact of management events aimed at their control (Holst et al., 2007). Weed emergence is a key phenological event that is primarily explained by temperature and moisture (Bradford, 2002; Grundy and Mead, 2000). Where water is not limiting (e.g. irrigated cropping systems), accumulation of temperatures within a weed's physiologically relevant range (thermal time) can alone predict germination and early growth with accuracy (Grundy, 2003). With the growing availability of environmental data at ever-finer spatial and temporal resolutions (Hart et al., 2009; Hijmans et al., 2005), the potential exists to improve the accuracy of phenological models applied at regional scales by improving the precision of their input data (Kriticos and Leriche, 2010; Miller et al., 2004, 2007; Shaw, 2005). Therefore, as the driving variable in weed emergence models, the precision of the temperature input may affect the accuracy of an applied model as much or more as the model parameterization itself.

Rice (*Oryza sativa*) is the most widely consumed staple food in the world (Maclean et al., 2002), and weeds are the major biological constraint to its productivity (Ni et al., 2000). Weed control represents a significant portion of input costs and management effort in rice cropping systems (Pandey et al., 1999). As a semi-aquatic plant, rice has been transplanted and grown under

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flooded conditions for millennia, primarily as a means of weed suppression (Rao et al., 2007). However, the diminishing availability of water and labor, combined with improvements in herbicide and mechanization technology are leading to an increase in direct-seeded rice systems across the world (Farooq et al., 2011). Because weed and rice plants emerge in closer temporal proximity in direct-seeded than in transplanted systems, weed competition is generally greater in direct-seeded rice (Hill et al., 1994). As a result, weed control in direct-seeded rice systems is a research priority of growing importance (Rao et al., 2007).

The approximately 200,000 ha of rice grown in California's Sacramento Valley has long been direct-seeded. California rice has among the highest number of herbicide resistant weed species in the United States (Heap, 2012) due, in part, to a reliance on herbicides for weed control and soils that offer limited options in terms of crop rotation (Hill et al., 1994; Pittelkow et al., 2012). As a response to the growing problem of herbicide resistant weeds (Fischer et al., 2000; Osuna et al., 2002), the use of stale seedbed and drill-seeded systems with intermittent early-season flooding has been investigated in recent years (Pittelkow et al., 2012). These establishment systems attempt to diversify the weed recruitment environment and herbicides used while also improving the timing and efficacy of herbicide applications, thereby reducing selection pressure for herbicide resistance as well as reducing the overall usage of herbicides (Fischer et al., 2009).

In both establishment systems, a moist, primarily aerobic seedbed rapidly recruits problematic weeds such as watergrass (*Echinochloa phyllopogon* and *Echinochloa oryzoides*) and smallflower umbrella sedge (*Cyperus difformis*) (Pittelkow et al., 2012), which are resistant to a broad range of herbicides and cause the most economic damage in the California rice system (Fischer et al., 2000; Osuna et al., 2002). In the stale seedbed system, once maximum weed emergence has been attained, a broad-spectrum herbicide for which resistance has not yet evolved (such as glyphosate) is applied to the weed foliage. The field is subsequently flooded, and rice is seeded aerially without further seedbed disturbance. A post-emergence herbicide (such as propanil) can be used later to control weeds that might escape the stale seedbed treatment. The drill seeded system typically employs propanil and pendimethalin to control watergrass with multiple resistance. These herbicides are usually mixed and applied to the non-flooded seedbed after a critical growth threshold is reached and prior to the permanent flood (CRPW, 2011). Further management details for these systems can be found in Pittelkow et al. (2012), Linquist et al. (2008) and in Section 2 of this paper. Both systems have shown promise as alternatives to the conventional establishment systems in terms of weed control and rice yield (Pittelkow et al., 2012).

Despite the promise of these systems, their efficacy is sensitive to the timing of herbicide applications. Also, in the case of the stale seedbed, planting of rice must be delayed to allow for weed emergence and sufficient foliage exposure to the herbicide application. This affects rice variety choice and introduces late season risk of low temperature induced spikelet sterility (blanking) if rice is planted too late in the season (Board and Peterson, 1980). As a result, information on the timing of weed emergence and early growth in alternative stand establishment systems is necessary for farmers to be able to implement effective weed management.

Hart et al. (2009) combined surface measured climate variables with remote sensed climate variables to interpolate maximum and minimum air temperatures (among other variables) on a 2 km × 2 km grid throughout California. Data are available on a daily interval between 2003 and the present day (COMET, 2012). Preliminary analysis of these interpolations indicated that temperature is relatively uniform across the Sacramento Valley rice growing region for the majority of the growing season. However, early in the growing season [during the weed recruitment period for alternative establishment systems (April 15–June 1)], the accumulation of thermal time may vary across space and time due to orographically induced climate variation caused by the presence of the Sutter Buttes (Wright et al., 2006) and the inter-annual variability of climate phenomena such as El Niño—Southern Oscillation (Dettinger et al., 2004). Further, the base temperature (lowest temperature required for physiological activity) for smallflower umbrella sedge germination is greater than average nighttime lows during the period of interest, which is in contrast to base temperature estimates for watergrass germination (Boddy et al., 2012; Pedroso, 2012). As such, the spatial and temporal distribution of physiologically relevant temperatures may not be uniform among weed species.

This study employed a historical simulation to test the hypothesis that the use of site-specific, real-time temperatures to predict rice weed emergence can improve the timing of weed management in stale-seedbed and drill-seeded systems relative to management decisions informed by average regional emergence over the same period. The objectives of the study were threefold. The first was to develop and validate thermal-unit driven emergence models for smallflower umbrella sedge and watergrass based on field-scale observations. The second objective was to apply these models with a regional temperature data set accurate to 2 km × 2 km (COMET, 2012) in order to predict emergence across 9 years of historical data. The final objective was to quantify the degree to which the intra-annual, inter-annual and spatial variability affected the simulated emergence in order to illustrate the value of using site-specific, real-time data to inform decision support tools.

2. Methodology

2.1. Model development: data collection

In 2010 and 2011 emergence of smallflower umbrella sedge and watergrass was observed in three rice fields where their presence had been confirmed the previous growing season. One of the fields (location 1: 39°33′51″N, −122°4′14″W) was managed as a stale seedbed, while the other two fields (location 2: 38°53′43″N, −121°43′43″W; and location 3: 39°00′35″N, −121°42′29″W) were drill seeded fields (see Fig. 1). Fields were 8.1–11.2 ha in size. The soils in two of the three fields were Mollisols (locations 1 and 3) and the other was a Vertisol (location 2).

Although overall crop management differs between stale seedbed and drill seeded fields in California rice, both management systems employ irrigation flushes during the first 2–4 weeks of the growing season to encourage the rapid emergence of weeds, which are then eliminated via post-emergence herbicide application. As a result, water management during the period of observation was similar between the three fields and resulted in a moist to near-saturated soil surface during the periods of observation.

Following pre-season tillage [which included passes with a chisel plow, disc, tri-planer, and soil roller (stale seedbed) or drill-seeder], 4–8 main plots per field were established in areas of substantial weed infestation as reported by the growers. Main plots were 5 × 10 m in size and were bisected lengthwise by an elevated 6 m wooden plank that served as an observation platform to prevent soil surface disturbance within the plot. Air temperature (1.5 m above the soil surface) was recorded at the center of the main plot at 15 min intervals via a shielded Onset Hobo U23 Pro v2 External Temperature Data Logger. Soil temperature at 2 cm depth was also recorded at the same interval with the same equipment in the center of the plot. Each main plot contained four 0.3 m × 0.3 m subplots, situated at least 1 m apart and established