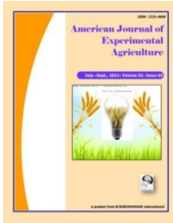

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Rice Cultivar Production and Seed Overwinter Potential in Upstate Missouri

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Research Article

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ABSTRACT

Climate change and opportunities for pharmaceutical rice (*Oryza sativa* L.) production in the U.S. may affect future production opportunities. Field research in 2005–2007 at Bethel (39º56'N, 92º3'W) and in 2005 at Novelty (40º01'N, 92º11'W) evaluated the production potential of rice cultivars (10 conventional or hybrid varieties), overwinter seed survival, and the effects of weeds on yield in upstate Missouri. Grain yields ranged from 3,880 kg ha^{-1} (Ilpumbyeo) to 10,540 kg ha^{-1} (Trenase). M103, M202 and XP723 yielded similarly to Trenase. Late-maturing cultivars had the greatest risk of yield loss due to frost damage. Weed interference [barnyard grass (*Echinochloa crus-galli* L.), fall panicum (*Panicum dichotomiflorum* Michx.), giant foxtail (*Setaria faberi* Herrm.), common cocklebur (*Xanthium strumarium* L.), and common waterhemp (*Amaranthus rudis* Sauer)] reduced grain yields of Cocodrie 35%, emergence by 4%, plant height by 21%, and head number by 21%. In fall 2005 and 2006, rice seed produced during the previous year was seeded on the soil surface, with vertebrate exclusion, and vertebrate plus invertebrate exclusion. Viable seed overwintered with 0.06 to more than 12% emergence the following spring. The yield potential of rice in upstate Missouri looks promising, but correct cultivar selection and weed control are essential for successful production.

Keywords: Cultivar selection; growth rates; seed predation; temperate production; weed interference; over winter survival.

ABBREVIATIONS

DAP, days after planting; USDA, United States Department of Agriculture.

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1. INTRODUCTION

Rice (*Oryza sativa* L.) is one of the world's most important cereal crops, (Gealy et al., 2003; Mohadesi et al., 2011; Rabbani et al., 2011) with about 154 million ha harvested in 2010 (FAOSTAT, 2010a). In 2002, nearly 50% of the world's population depended on rice for a substantial amount of its calories (>800 kcal person^{-1} day^{-1}) (Nguyen, 2008). Population increases and climatic change have made it difficult to meet demand for rice (Nguyen, 2008; Fan, 2011; Teixeira et al., 2011; Laborte et al., 2012). However, yields in some areas have increased due to advances in plant breeding and crop management. A number of cultivars now offer increased yield potential (Moldenhauer et al., 2001). Elite hybrid rice has increased yields 10-30% compared to elite inbred lines (Nguyen, 1998; Bueno and LaFarge, 2009). Raising the yield potential may be possible through higher yielding varieties and reducing the yield gap in farmer's fields (Laborte et al., 2012).

Exploring new regions for rice production could help meet world demand. Rice has been raised from latitudes 53ºN to 40ºS, though 75% of global rice production in 2004 was in tropical regions (Nguyen, 2008). Rice grown outside of the temperate region is grown in the Tropics of Cancer and Capricorn. However, temperate rice generally has greater yields (Nguyen, 1998). Most U.S. rice production is temperate rice (25ºN to 45ºN), or rice grown in latitudes north or south of 23º27' (Temperate Rice Research Consortium, 2011). In 2010, U.S. farmers harvested nearly 1.5 million ha (FAOSTAT, 2010b). The main rice production areas were the Mississippi Valley Region (Arkansas, Louisiana, Mississippi, Texas, and southeast Missouri) and north–central California. Arkansas produced more than 600,000 ha, or about half of the U.S. crop (Mencer, 2010; Gealy et al., 2003). Almost all U.S. rice is produced south of the Delta Region in Missouri (37ºN) in the Mississippi Valley Region. One exception is wild rice (7,000 ha) in Minnesota and North Dakota (northern most latitude 47ºN) (Zepp et al., 1996). The other exception is California, where some regions produced about 100,000 ha up to 40ºN (Hill et al., 2011) and a small amount of wild rice.

In 1911, Missouri began rice production and by 2001 production totaled 89,000 ha. For about the first two decades, all production was south of 37ºN, with average yields of 6,700 kg ha^{-1} (Guethle, 2004). From the 1930s to the 1970s, farmers produced rice in Marion (39º47'N) and St. Charles (38º47'N) counties, and a cultivar, 'Palmyra', was developed for this region. The scientific community generally agrees that Earth is experiencing climatic change, which will pose farming production challenges (Nguyen, 2008; Fan, 2011; Teixeira et al., 2011). Although it may at first be counterintuitive, northern Missouri's location in the Mississippi and Missouri River Valleys could benefit rice production in the midst of climate change. In contrast to tropical regions, whose high temperatures can constrain rice production (Nguyen, 2008), northern Missouri's growing season temperatures and rainfall may increase the growing period and suitable land (Olesen and Bindi, 2002). Although damage from low temperatures commonly occurs in temperate regions and can reduce yield up to 30% (Yoshida, 1981), climate change may make this region even more favorable to rice production. With the growing worldwide demand for food and fiber, we felt it was time to evaluate new cultivars and their production potential in the region. In addition, with the need for cost-effective pharmaceutical production, crops have been targeted as an option for producing large quantities of pharmaceuticals (Elbehri, 2005). In 2005, there were 84 biopharmaceuticals serving 60 million patients (Elbehri, 2005). Rice has potential for pharmaceutical production because it is self-pollinated, has limited allergenic properties that can be removed, and because this region is isolated from commodity rice production. Two rice protein fractions are allergenic: glutelin, and globulin (Shibasaki et al., 1979). These are easily extracted from rice grain endosperm using low concentrations of NaCl (Matsuda et al., 1988). In another study, rice grains pressurized at 100-400 MPa in distilled water released 0.2-2.5 mg per gram of proteins, which included globulins (Kato et al., 2000). Rice self-pollination occurs for a very short time period, generally in the morning. Pollen grains are viable for approximately 5 minutes after emerging from the anther of the flower, thus reducing cross-pollination to less than 1% (Yoshida, 1981) and limiting pollen drift. In addition, this region may be ideal for biopharming due to strict federal requirements that pharmaceutical plants not enter the food and commodity population (Elbehri, 2005). This region is isolated from commodity rice production and has no known red rice (*Oryza sativa* L.), thus avoiding possible gene transfer.

Red rice, one of the most common weed species plaguing rice production, can cost producers up to \$300 ha^{-1} in production losses (Shivrain et al., 2009). This is especially important in transgenic and pharmaceutical rice. Several varieties of rice are herbicide-resistant. These include Clearfield® (imidazolinone resistant) whose first varieties appeared in the U.S. in 2002; RoundUp Ready® (glyphosate resistant) and LibertyLink® (glufosinate resistant) (Gealy et al., 2003). Glyphosate-resistant and glufosinate-resistant varieties are transgenic DNA insertions of existing species and so are considered genetically modified organisms (GMOs). Clearfield rice was derived from chemical mutation breeding and is not a GMO (Gealy et al., 2003). These herbicide-resistant varieties also present the risk of gene flow, which could result in the transfer of herbicide resistance to red rice through cross-pollination and render weed management programs ineffective (Shivrain et al., 2009). Although out-crossing rates between rice and red rice are less than 1%, once hybrids form they merge into the red rice population in a few generations (Gealy et al., 2003; Gressel and Valverde, 2009; Shivrain et al., 2009). According to Langevin et al. (1990), red rice needs two growing seasons to substantially introgress. The World Bank, Rockefeller Foundation, and USDA, describes "a low, but finite risk of out-crossing" in rice (Gealy et al., 2003). In temperate rice production, red rice is the most important threat of gene flow transfer of herbicide resistance because it is the only significant target of gene transfer (Gealy et al., 2003). Gene flow, which can occur when sexually compatible relatives of rice grow in close proximity, depends on flowering time, genetic compatibility, amounts of pollen and environmental conditions (Shivrain et al., 2009). Red rice and rice have similar genetic make-ups, with 12 pairs of chromosomes and thrive in the same ecological niches. This cohabitation and similarities make controlling red rice critical and make varieties such as Clearfield valuable for its management (Gealy et al., 2003). Both varieties are self-pollinated and have overlapping flowering periods, which allow natural out-crossing to occur (Gealy et al., 2003). The most effective method to prevent the establishment of red rice populations is to use seed certified to not carry it (Noldin, 1998). Since northern Missouri has no known red rice infestation, production of pharmaceutical rice in the region would have low risk of gene transfer to wild relatives.

Overwintering of transformed rice may provide an opportunity for its propagation. Three quantitative trait loci on chromosomes 1, 2, and 3 affect seed dormancy (Xie, 2010). In a study that placed rice seeds on the soil surface (Hosoi et al., 2010), seeds with deeper dormancy had a higher overwintering ability than those with shallow dormancy. In another study, buried seeds had delayed germination while seeds placed on the soil surface had an enhanced rate of germination (Fogliatto et al., 2011). The germination rate related directly to temperature (Yoshida, 1981; Zheng-wu et al., 2007). Germination can occurred slowly at very low temperatures, even 0º-5ºC, and more quickly (a few days) at higher temperatures (Yoshida, 1981). Seeds that remained fertile through the winter on the soil's surface germinated quicker. If transformed rice were produced in northern Missouri, it would be important to identify risks associated with its overwinter survival.

Genetic yield potential from inbred varieties has stagnated (Laborte et al., 2012) and significant yield increases have been realized using new cultivars (Moldenhauer et al., 2001). Choosing appropriate rice cultivars for northern latitudes is an option for adapting to global climate challenges (Nguyen, 2008; Laborte et al., 2012) and offers farmers crop production options. Many studies show that weed interference is a major yield-limiting factor in rice production (Agostinetto et al., 2010; Demotte et al., 2011; Mohadesi et al., 2011; Rabbani et al., 2011). Worldwide, an estimated 9.5% crop loss is due to weeds in rice (Rabbani et al., 2011). Weeds' harmful effects stem from factors including competition for space, light and nutrients (Mohadesi et al., 2011). Other factors include important physiological processes including root growth, shoot growth, number of panicles, number of tillers, and grain yield (Rabbani et al., 2011). To grow rice efficiently in upstate Missouri, it is critical to determine which weed species are prevalent and evaluate their effects on yield potential.

Upstate Missouri provides several rice production opportunities. Because the region is isolated from commodity production and appears to have no red rice, it could be ideal for producing transgenic and pharmaceutical rice. No research has evaluated rice production in the Midwestern U.S. (39ºN latitude) in the midst of possible climate change. Neither is research available on overwinter survival for possible risk assessment of pharmaceutical rice production, nor on weed species and yield loss associated with weeds in upstate Missouri. The grain yield potential of rice cultivars must be identified if regulated rice is targeted for the region. This study sought to 1) determine rice growth, development and yield potential in upstate Missouri; 2) evaluate overwinter seed survival; and 3) determine prevalent weed species and associated yield loss in this region.

2. MATERIALS AND METHODS

2.1 Cultivar Evaluation

Field research was conducted at the University of Missouri Greenley Research Center at Novelty, Mo., (40º01'N, 92º11'W) in 2005 and University of Missouri Ross Jones Farm near Bethel, Mo., (39º56'N, 92º3'W) in 2005, 2006, and 2007. Rice cultivars were arranged in a randomized complete block design with three replications. The cultivars evaluated included the medium- (MG) and long-grain (LG) cultivars 'Taipei-309' (MG), 'M202' (MG), 'Cocodrie' (LG), 'M103' (MG), 'Ilpumbyeo' (MG), 'Wells' (LG), 'XP723' (LG), 'CLXL8' (LG), 'Trenase' (LG), and 'Ketiaki' (MG). These cultivars represented a variety of maturities and had been cultivated in southern Missouri.

The soil type was a Putnam silt loam (fine, montmorillonitic, mesic Vertic Albaqualfs). The sites were field cultivated and culti-mulched three times for seedbed preparation. Pre-flood nitrogen (56 kg N ha^{-1}) was applied on 31 March 2005 at Novelty, and at Bethel on 17 March 2005, 12 May 2006, and 12 May 2007. Plants were top-dressed once or twice with a total of 112 to 168 kg N ha^{-1}. Rice was drill seeded at 112 kg ha^{-1} using a 2-row push planter (Earthway® Precision Garden Seeder, Bristol, Indiana) in 19-cm rows, and produced using a delayed-flood system. Plot size, previous crop, planting dates, crop protection chemical management rates, and harvest dates are reported in Table 1.

Table 1. Management information at Novelty in 2005 and Bethel in 2005, 2006 and 2007.

Management information	**Novelty**	**Bethel**		
	2005	**2005**	**2006**	**2007**
Previous Crop	Corn	Corn	Soybean	Soybean
Plot size	3.1 by 4.6 m	3.1 by 4.6 m	3.1 by 6.1 m	3.1 by 6.1 m
Planting Date	6 May	6 May	12 May	25 May
Harvest Date	26 Aug. Ketiaki	26 Aug. Ketiaki	5 Oct. Ketiaki, M202, M103	6 Sep. Ketiaki
	5 Oct. M202, Cocodrie, M103, Wells, XP723, CLXL8,Trenase	1 Oct. M202, Cocodrie, M103, Wells, XP723, CLXL8, Trenase	24 Oct. Taipei-309, Cocodrie, Ilpumbyeo, Wells, XP723, CLXL8, Trenase	28 Sep. M202, Cocodrie, M103, Ilpumbyeo, Wells, XP723, CLXL8, Trenase
	11 Oct. Ketiaki, Ilpumbyeo, Taipei-309	12 Oct. Ilpumbyeo, Taipei-309		31 Oct. Taipei-309
Pest Management[a]				
Herbicide application[b]	10 May, Clomazone (0.9 kg a.i. ha^{-1}) + Quinclorac (0.3 kg a.i. ha^{-1})	10 May Clomazone (0.9 kg a.i. ha^{-1}) + Quinclorac (0.3 kg a.i. ha^{-1})		29 May Clomazone (0.9 kg a.i. ha^{-1})
	20 May Propanil (3.6 kg a.i. ha^{-1}) + NIS (0.125% vol./vol.) + Pendimethalin (1.1 kg a.i. ha^{-1})	20 May Propanil (3.6 kg a.i. ha^{-1}) + NIS (0.125% vol./vol.) + Pendimethalin (1.1 kg a.i. ha^{-1})	9 June Propanil (3.6 kg a.i. ha^{-1}) + NIS (0.125% vol./vol.) + Acifluorfen(0.3 kg a.i. ha^{-1})	25 June Propanil (1.8 kg a.i .ha^{-1}) + NIS (0.25% vol./vol.) + Acifluorfen (0.3 kg a.i. ha^{-1})
Insecticide application	11 July, and 11 Aug. Lambda-cyhalothrin (0.05 kg a.i. ha^{-1})	11 July, 26 July, and 11 Aug. Lambda-cyhalothrin (0.05 kg a.i. ha^{-1})		16 Aug. Zeta-cypermethrin (0.03 kg a.i. ha^{-1}) + NIS(0.25% vol./vol.) + DAS (2.24 kg a.i ha^{-1})
Fungicide application	11 July, 26 July, and 11 Aug. Azoxystrobin (0.18 kg a.i. ha^{-1})	11 July, 26 July, and 11 Aug. Azoxystrobin (0.18 kg a.i. ha^{-1})		16 Aug. Pyraclostrobin (0.1 kg a.i. ha^{-1})

[a] *Ammonium sulfate, 2-hydroxy-1,2,3-propanetricarboxylic acid; Azoxystrobin, methyl (E)-2-{2-[6-(2-cyanophenoxy)pyrimidin-4-yloxy]phenyl}-3-methoxyacrylate; Clomazone, 2-(2-chlorophenyl)methyl-4,4-dimethyl-3-isoxazolidinon; Lambda-cyhalothrin, [12(S*),3a(Z)]-cyano(3-phenoxyphenyl)methyl-3-(2-chloro-3,3,3-trifluoro-1-propenyl)-2,2-dimethylcyclopropanecarboxylate; Pendimethalin, N-(1-ethylpropyl)-3,4-dimethyl-2,6-dinitrobenzenamine; Propanil, N-(3,4-dichlorophenyl)propanamide; Quinclorac, 3,7-dichloro-8-quinolinecarboxylic acid; Zeta-cypermethrin, s-cyano (3-phenoxyphenyl)methyl(+) cis/tans 3-(2,2-dichloroethenyl)-2,2 dimethylcyclopropane carboxylate.*

[b] *abbreviations: DAS, diammonium sulfate ($(NH_4)_2\ SO_4$); NIS, non-ionic surfactant (a mixture of alkylpolyoxyethylene ethers and free fatty acids)*

Emergence was visually evaluated 9, 13, 16, 21, 25, and 30 d after planting (DAP) on a scale of 0 to 100% emergence. Plant heights were recorded throughout vegetative and reproductive development to determine crop growth rates for each cultivar. Rice seed heads were counted weekly from 60 to 159 DAP in a delineated 30-cm section of row to determine 50% heading dates. Rice was hand harvested from a 2.3 m^{-2} area and separated with a portable thresher (Almaco, Nevada, IA) and moisture determined (GAC 2100, DICKEY-john Corporation, Auburn, IL). Grain yields were adjusted to 120 g kg^{-1} prior to analysis. The cumulative growing degree days [(Tmax+Tmin)/2-10ºC] were determined to specify growth stages by a DD50 program developed by the University of Arkansas Cooperative Extension Service that takes into account emergence date and temperature to aid farmers in making crop management decisions (Slaton and Norman, 1994). Height dates were aligned for all three years, and data were plotted on a linear graph with a fourth-order polynomial (Table 2) (Microsoft Excel, Microsoft Office, 2007, Redmond, WA). Heading data were plotted individually for each cultivar averaged over site-years, and the 50% heading date (Table 2) was calculated. Data were subjected to ANOVA (SAS, 2010), means separated using Fisher's Protected LSD (P = 0.05), and combined over site-year in the absence of significant interactions. An *F-Max* test was used to evaluate homogeneity of variance, and data were combined when variances were homogenous (Kuehl, 1994).

2.2 Winter Survival and Seed Predation

Seed produced in the previous experiment (2005 and 2006) was placed in a field with no history of rice production in the fall to simulate seed that was lost due to shattering or combine loss. The field was fallow in 2005, and the previous crop was wheat (*Triticum aestivum* L.) in 2006. Exclusion techniques were employed to evaluate rice seed survival and predation (Menalled et al., 2000). The three exclusion methods used were no exclusion, vertebrate exclusion, vertebrate and invertebrate exclusion. Rice seed was placed beside a marking stake, inside a cage that prevented mammal (vertebrate) predation, and inside a cage and heat-sealed standard mesh, fiberglass insect screen (Phifer Wire Products, Inc., Tuscaloosa, Alabama) to prevent arthropod (invertebrate) and mammal predation (Fig. 1).

This study was conducted from the fall 2005 to spring 2006 and the fall 2006 to spring 2007 at the Greenley Memorial Research Center near Novelty, Mo. Seed germination rates prior to placing seeds in the field experiment ranged of 80 to 99% (data not presented). Seed were counted (300 in 2006 and 100 in 2007) for seven of the rice cultivars raised in the previous year. These included: 'Cocodrie', 'Wells', 'Trenase', 'CLXL8', 'XP723', 'M103', and 'M202'. The study was a split-plot design (main plot with 3 exclusion systems x 7 cultivar sub-plots) arranged as a randomized complete block with 10 replications each year. The soil was a Putnam silt loam. Seeds were placed on the soil surface on 28 Nov. 2005 and 18 Dec. 2006. Starting on 15 March, seedling emergence was counted every two weeks. Glyphosate (*N*-(phosphonomethyl)glycine) at 1.06 kg ha^{-1} a.e. was sprayed after counting to kill emerged seedlings and weeds. Data were subjected to ANOVA (SAS, 2010), means separated using Fisher's Protected LSD (P = 0.1), and presented separately by year due to a significant interaction (P = 0.1) between year and exclusion.

2.3 Weed Survey

Non-treated, replicated plots of 'Cocodrie' were planted at the University of Missouri Greenley Research Center at Novelty, Mo. (40º01'N, 92º11'W) in 2005 and the Ross Jones Farm near Bethel, Mo (39º56'N, 92º3'W) in 2005, 2006, and 2007. Plots were fertilized using methods described above in the cultivar evaluation study, but plots were not treated with crop protection chemicals listed in Table 1. Cocodrie was chosen as its yield comparisons showed great yield potential against other successful rice varieties (Slaton et al., 2000b). Weeds were harvested at physiological maturity from 2.3 m^2 area, dried, and weighed for all weed species in the non-treated and weed-free controls. The weed-free grain yield was compared to the weedy-check. This was not only to survey weed species that were competitive with rice but also to determine emergence, height 115 DAP, heading numbers 133 DAP, grain moisture, and grain yield loss potential in upstate Missouri in the absence of crop protection chemical management.

Fig. 1. Cage and seed arrangement for exclusion of vertebrates (top) and vertebrates plus invertebrates (bottom).

3. RESULTS AND DISCUSSION

3.1 Environmental Conditions

In 2005, the research sites had good growing conditions that were relatively warm and dry. Total rainfall for the growing season (159 days) was 466 mm, and the average air temperature was 21.9ºC (Fig. 2). There was no killing frost prior to maturity (visual observation), with the lowest temperature dropping to 1.5ºC on 8 Oct. Air temperature dropped below freezing late in the season on 26 Oct. In 2006, the total rainfall during the growing season was 438 mm with an average temperature of 20.2ºC (165 days). Overall maximum and minimum temperatures were lower in 2006 than 2005. Throughout late Sep. and Oct. 2006, temperatures were abnormally low with an average temperature of 11.2ºC from 25 Sep. through mid-Oct. The first killing frost (-1.8ºC) was on 11 Oct., which was the first of four days with temperatures below freezing. There was 406 mm of precipitation during the growing season (159 days) in 2007. The average temperature was 21.2ºC, and the only pre-harvest killing frost (-1.5ºC) was on 28 Oct. The cumulative solar radiation during the growing season was 3,240 MJ m^{-2} in 2005, 3,080 MJ m^{-2} in 2006, and 2,840 MJ m^{-2} in 2007 (data not presented).

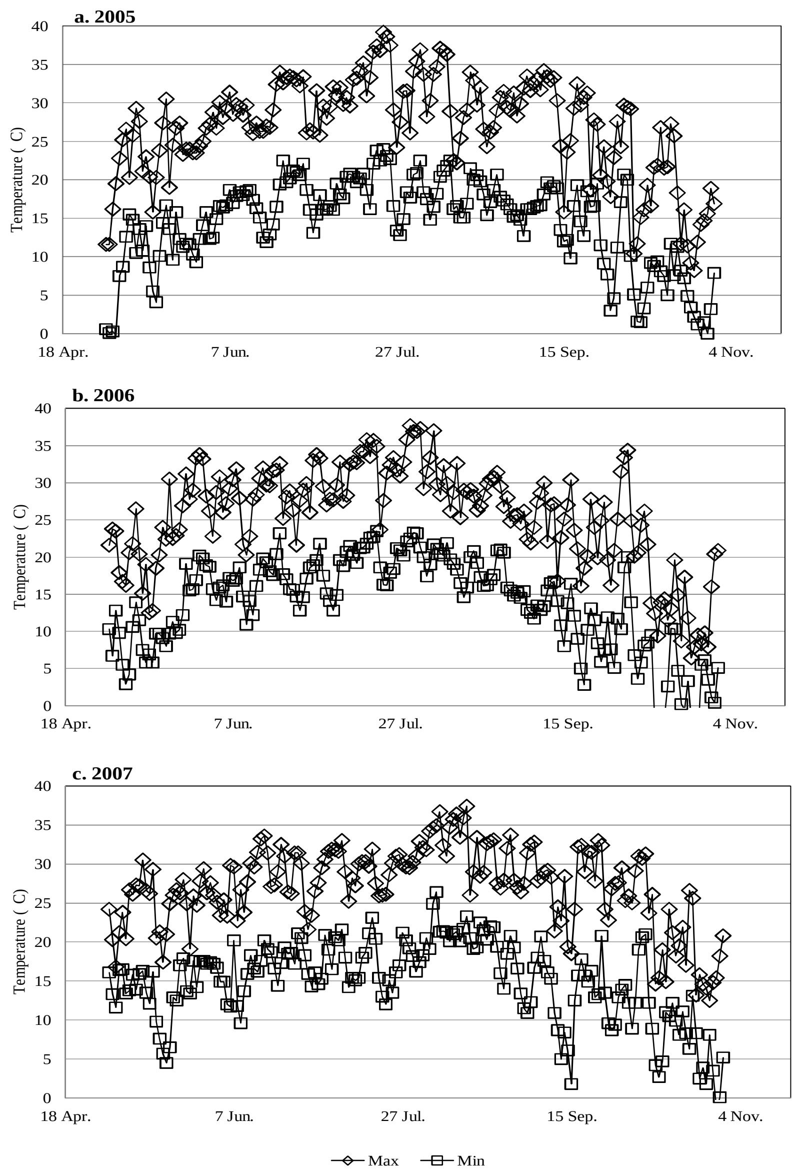

Fig. 2. Maximum and minimum temperatures in the growing season in 2005, 2006 and 2007.

3.2 Cultivar Evaluation

Seedling emergence was evaluated, but no differences among cultivars were detected (data not presented). Plant growth rates as measured by height differed by cultivar (Table 2).

Although there were a few year x cultivar interactions at a few measurement dates, the majority of interactions were within cultivars (data not presented). Rice heights were greatest during the growing degree days calculated by the DD50 program (Fig. 3). The greatest increase in height took place during June, July, and August (visual observation). We observed differences in 50% heading dates and maturity among cultivars (Table 2), which resulted in harvest at several different dates (Table 1) to prevent yield loss from shattering. The earliest maturing variety was Ketiaki, with early 50% heading dates (27 July, 6 Aug. and 6 July) (Table 2) as well as being harvested all three years (26 Aug., 5 Oct. and 6 Sep.) (Table 1) before a killing frost (Fig. 3).

There was a year x cultivar interaction for grain yields (P = 0.0001), but data were combined over site-years because variances were homogeneous (Table 2). Grain yields ranged from 10,540 kg ha^{-1} (Trenase) to 3,880 kg ha^{-1} (Ilpumbyeo). Trenase, XP723, M202, M103 had similar yields, while Wells, Cocodrie, Ketaiki, and Taipei-309 yields were 3,765 to 2,470 kg ha^{-1} less than Trenase. Wells, a high-yielding, long-grain cultivar developed at the University of Arkansas Agricultural Experiment Station in 1999 (Slaton et al., 2000), was utilized as a standard to measure the productivity of cultivar yields in the region. Wells performed well with a yield of 8,120 kg ha^{-1}, which was greater than average yields (6,460 kg ha^{-1}) in 1998 and 1999 at the Missouri Rice Research Station near Glenonville, Missouri (Slaton et al., 2000).

Yield differences were probably due to maturity because several cultivars matured slowly. Both Taipei-309 and Ilpumbyeo had late 50% heading dates (Table 2) that delayed harvest dates (Table 1). Crop development duration has been reported as one trait underlying different performance (Bueno and LaFarge, 2009). Heading may have occurred during the hottest part of the season and suffered damage (Figure 3) and yield losses from frost damage before maturity (visual observation).

In 2005, all cultivars showed a 3,440 to 4,390 kg ha^{-1} greater average yield compared to 2006 and 2007 (data not presented). Several factors combined to create this difference. First, in 2006, there was an early killing frost (11 Oct.), and the temperature remained very cold until harvest (5 Oct. and 24 Oct.) (Fig. 2). The optimal temperature range for rice at ripening is 20º-29ºC (Yoshida, 1981), but in 2006 the average temperature of 11ºC during ripening was below the low-critical range of 12º-18ºC (Yoshida, 1981). The cold caused substantial damage to grain yields in 2006. Second, 2005 had a dry, warm and sunny growing season with cumulative solar radiation reaching 3,240 MJ m^{-2}. The cumulative solar radiation was greater than the average of 2,005 MJ m^{-2} found in most rice-growing areas (Yoshida, 1981).

It was also greater than the total of 1,678 MJ m^{-2} and 1,822 MJ m^{-2} during the wet and dry seasons of tropical regions (Bueno and LaFarge, 2009). Although upstate Missouri's cumulative solar radiation was greater than the tropical regions, it was only 2,840 MJ m^{-2} in 2007 and 2006 was 160 MJ m^{-2} less than 2005. Solar radiation was important for rice growth; estimation for potential maximum rice yield is a product of maximum photosynthetic net production per unit of solar radiation and the number of effective days (Yoshida, 1981). The difference between temperature and solar radiation among years as well as an early frost in 2006 led to higher yields in 2005 compared to 2006 and 2007.

Table 2. Plant height, 50% heading date, grain moisture and yield of rice cultivars at Novelty in 2005 and Bethel in 2005, 2006 and 2007. Data were combined over years and location unless noted otherwise.

Cultivar	Plant growth rate[a]	R^2	50% Heading[b] 2005	2006	2007	Grain moisture	Grain yield
			---------------------- Date	---------------------		$g\ kg^{-1}$	$kg\ ha^{-1}$
Trenase	$y = -6E-05x^3 + 0.0122x^2 - 0.202x$	0.99	12 Aug.	31 Aug.	23 July	138	10,540
XP723	$y = -7E-05x^3 + 0.0136x^2 - 0.2677x$	0.99	18 Aug.	8 Sep.	23 July	67	10,510
M202	$y = -7E-05x^3 + 0.0129x^2 - 0.2468x$	0.99	7 Aug.	27 Aug.	23 July	136	9,540
M103	$y = -7E-05x^3 + 0.0129x^2 - 0.2496x$	0.99	6 Aug.	26 Aug.	20 July	225	9,590
Wells	$y = -6E-05x^3 + 0.0114x^2 - 0.1562x$	0.99	21 Aug.	11 Sep.	25 July	49	8,120
Cocodrie	$y = -6E-05x^3 + 0.0119x^2 - 0.1901x$	0.99	25 Aug.	6 Sep.	27 July	49	7,860
Ketiaki	$y = -6E-05x^3 + 0.0114x^2 - 0.196x$	0.99	27 July	6 Aug.	6 July	35	7,705
Taipei-309	$y = -5E-05x^3 + 0.0113x^2 - 0.2338x$	0.99	28 Aug.	18 Sep.	11 Aug.	75	6,775
CLXL8	$y = -7E-05x^3 + 0.0134x^2 - 0.2812x$	0.99	24 Aug.	15 Sep.	25 July	46	6,560
Ilpumbyeo	$y = -7E-05x^3 + 0.0136x^2 - 0.307x$	0.99	9 Sep.	18 Sep.	1 Aug.	51	3,880
LSD (*P* = 0.05)						113	1,300

[a]*y is the height in cm, and x is the days after planting. R^2 value is for the plant growth rate. The y-intercept was set at zero for each cultivar.*
[b]*Based on weekly counts which were fit to a best-fit curve and 50% heading date was calculated.*

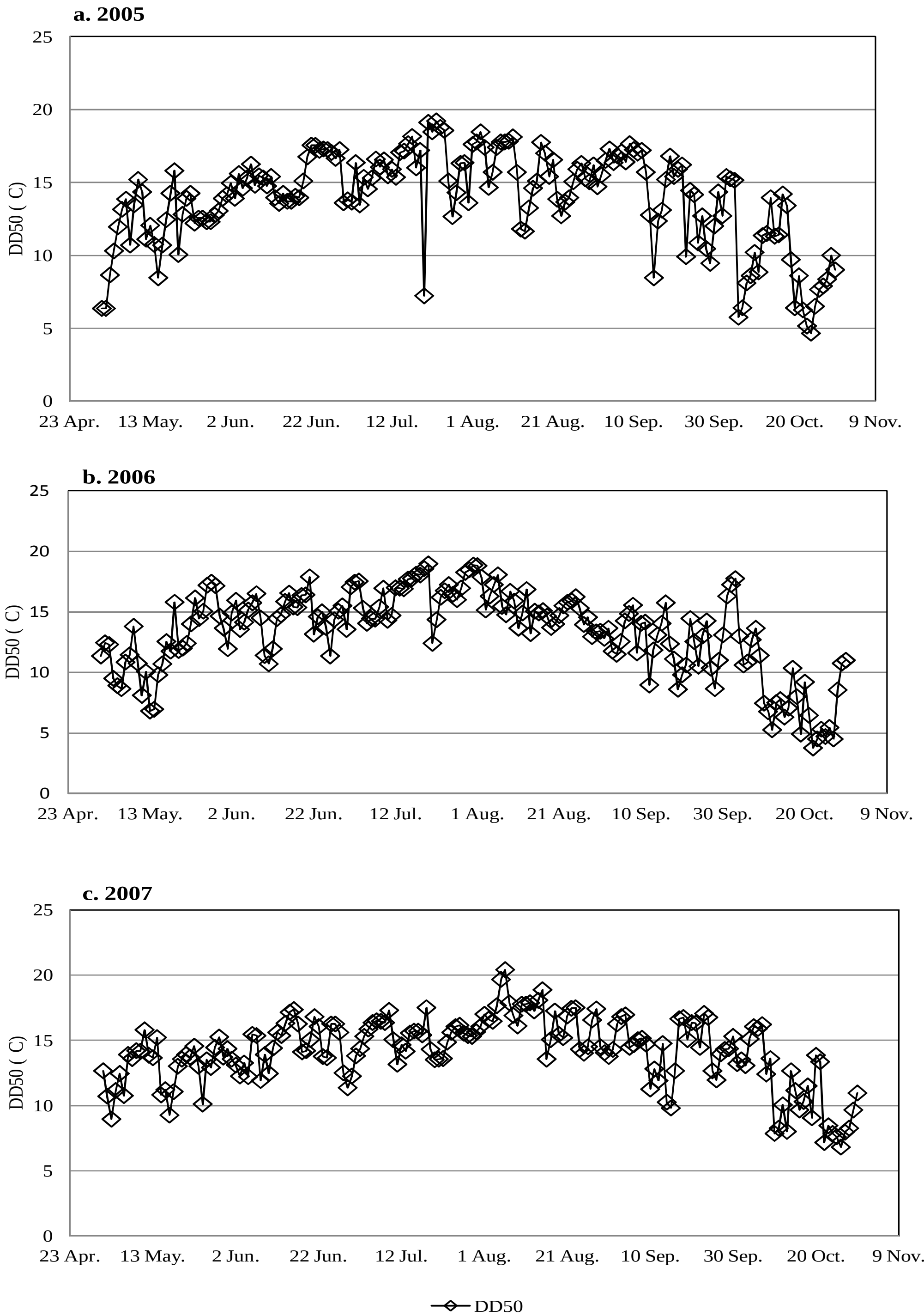

Fig. 3. DD50 for 2005 (a), 2006 (b), and 2007 (c).

3.3 Winter Survival and Seed Predation

Seed produced in 2005 and 2006 was evaluated for over winter survival the following spring. There was no significant two- (exclusion x cultivar) or three-way (year x exclusion x cultivar) interaction; therefore, main effects were presented (Tables 3 and 4). Seed emergence differences among rice cultivars were significant (P=0.05) on 16 May (Table 3). The two highest-yielding cultivars (Trenase and XP723) also had the greatest emergence on that date. We observed a year x exclusion interaction on 30 Mar. (P=0.0001), 16 May (P=0.005), 30 May (P=0.0001), 27 June (P=0.0001), and total emergence (P = 0.0001); therefore, data were presented separately (Table 4). In 2006, our total emergence was 12% for no exclusion, 1.1% for vertebrate exclusion, and 0.6% for vertebrate and invertebrate exclusion. In 2007, the total emergence was 0.06% for no exclusion, 3.6% for vertebrate exclusion, and 0.7% vertebrate and invertebrate exclusion. In 2006, exclusion appeared to have a negative effect on emergence. Seeds left on the soil germinated at a much higher rate (12%) than seeds that were protected from vertebrates (1%) and invertebrates (0.6%). However, in 2007, vertebrate exclusion was very important. The seeds left unprotected germinated at the low rate of 0.06%, and seeds with vertebrate-only exclusion germinated at 3.6%. In both years, seeds with vertebrate-only exclusion germinated better than seeds with both vertebrate and invertebrate exclusion. The heat-sealed screen enclosing seeds to exclude invertebrates may have reduced emergence due to less seed-to-soil contact. Similarly, Hosoi et al. (2010) found that rice seeds with greater soil contact and protection by the soil survived longer than seeds exposed to the elements. However, seeds exposed to the soil surface germinated better (Fogliatto et al., 2011). Also, it's possible that more vertebrates followed wheat stubble in 2006, which may be more representative of rice rather than a fallow field in 2005, causing exclusion to affect emergence more.

3.4 Weed Survey

We used Cocodrie to study how weeds affected rice growth and yield. Data were combined over site-years because there was no interaction between year and treatment for the parameters reported. Weed-free Cocodrie yielded 2,750 kg ha^{-1} greater than the weedy check. Compared to the non-treated control, weed-free rice emergence was 4% greater, plants were 21% taller 115 DAP, and head number was 21% greater 133 DAP. Weed interference is a detriment to rice yield (Agostinetto et al., 2010; Demotte et al., 2011; Mohadesi et al., 2001; Rabbani et al., 2011), which our results supported. Some of the most prominent and destructive weeds in tropical and temperate regions were not present in the three years of research in upstate Missouri. Total weed biomass averaged over the four site-years was 560 kg ha^{-1}. Of the weeds associated with rice production in upstate Missouri, the percentage of the total weed biomass was 20% barnyard grass (*Echinochloa crus-galli* L.), 30% fall panicum (*Panicum dichotomiflorum* Michx.), 3% giant foxtail (*Setaria faberi* Herrm.), 44% common cocklebur (*Xanthium strumarium* L.) and 4% common waterhemp (*Amaranthus rudis* Sauer). Farmers could consider organic rice production in this area because it is isolated from other rice production areas. Strictly organic production can be unattractive to farmers due to its high risks and yield variability (Delmotte et al., 2011). No red rice was observed in the four site-years of this research.

Table 3. The effect of cultivars on percentage of over-wintered, germinated rice seeds in 2006 and 2007. Data were combined over 2006 and 2007.

Cultivar[a]	17 Mar.	30 Mar.	6 Apr.	21 Apr.	16 May	30 May	13 June	27 June	Total emergence
	%								
Trenase	0	0.17	0	0	0.34	2.74	0.08	0.47	3.76
XP723	0	0.10	0	0	0.28	1.92	0.11	0.35	2.76
M202	0	0.37	0.02	0	0.09	2.40	0.01	0.45	3.33
M103	0	0.17	0	0	0.12	2.09	0.01	0.25	2.64
Wells	0	0.18	0	0	0.15	2.03	0.01	0.32	2.72
Cocodrie	0	0.23	0	0	0.03	2.48	0.01	0.27	3.02
CLXL8	0	0.32	0	0	0.16	1.94	0.11	0.45	2.88
LSD (*P*=0.1)	0	NS	NS	NS	0.18	NS	NS	NS	NS
P-value	0	0.33	0.43	0	0.07	0.96	0.23	0.69	0.90

[a]*100 seeds were evaluated.*

Table 4. The effect of exclusion on the percentage of germinated rice seeds from mid-March to late-June in 2006 and 2007. Data were combined over 2006 and 2007 in the absence of a significant interaction.

Exclusion	17 Mar.	30 Mar.				16 May		30 May			27 June		Total emergence	
		2006	2007	6 Apr.	21 Apr.	2006	2007	2006	2007	13 June	2006	2007	2006	2007
None	0	0	0	0	0	0.043	0.029	11.91	0	0.05	0	0.027	12.06	0.06
Vertebrate	0	0	1.28	0.007	0	0.071	0.514	0.98	0.014	0.03	0	1.829	1.10	3.66
Vertebrate + Invertebrate	0	0	0	0	0	0.029	0.329	0.5	0	0.03	0	0.329	0.58	0.66
LSD (*P*=0.1)	NS	----- 0.2 -----		NS	NS	----- 0.17 -----		----- 1.34-----		NS	----- 0.24-----		-----1.44-----	
P-value	0	0.0001		.3693	0	0.005		0.0001		.6710	0.0001		0.0001	

Table 5. The effect of weeds on rice emergence, height 115 days after planting (DAP), head number 133 DAP, grain moisture, and yield at Novelty in 2005 and Bethel in 2005, 2006 and 2007.

Treatments	Emergence	Height	Seed heads	Moisture	Yield
	no. m^{-2}	cm	no. m^{-2}	g kg^{-1}	kg ha^{-1}
Weed-free	1170	105	853	49	7870
Weedy check	1120	102	673	47	5120
P-value	0.025	0.400	0.048	0.243	0.004

4. CONCLUSION

Upstate Missouri is a promising area for rice cultivation because of the yield potential of the region, and particularly for pharmaceutical-transgenic rice because it is isolated from commodity production areas. Cultivar selection was critical for producing high yields of rice in upstate Missouri. Rice yields ranged from 3,880 kg ha^{-1} (Ilpumbyeo) to 10,540 kg ha^{-1} (Trenase) in this study's four site-years. XP723, M202, and M103 yielded similarly to Trenase. These cultivars should be targeted for productive rice production in the future. Weed interference reduced grain yields 35%, emergence by 4%, plant height by 21%, and head number by 21%. Rice seed over-wintered at our upstate Missouri sites and germinated in spring at rates from 0.06% to more than 12%. If pharmaceutical rice were produced in the region, the rice seed may overwinter, which warrants control in a rotational crop.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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