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Red rice competition and control in cultivated rice

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RED RICE COMPETITION AND CONTROL IN CULTIVATED RICE

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ABSTRACT

Studies were conducted to evaluate rice competitiveness with red rice and how to utilize glufosinate- and imazethapyr-resistant rice in water-seeded rice to control red rice.

In the interference study, CL 121, Cocodrie, Drew, and Jasmine were seeded to obtain 95, 190, and 290 plants m^{-2}. Red rice density was 0 or 20 red rice plants m^{-2}. Jasmine, a tall, vigorous tillering, mid-season cultivar was more competitive with red rice. With the exception of Cocodrie grown red rice free, no benefit existed from increasing the seeding rate above 190 plants m^{-2}.

Another study examined the effect of permanent flood establishment in a glufosinate- and imazethapyr-resistant rice system. Glufosinate controlled hemp sesbania, red rice, barnyardgrass, and Amazon sprangletop at least 95%. Imazethapyr controlled hemp sesbania less than 35%. With one exception, barnyardgrass, red rice, and Amazon sprangletop control was at least 95%. Two postemergence imazethapyr applications controlled Amazon sprangletop 79%. All treatments reduced red rice panicle number to less than 1 m^{-2}, but did not delay red rice panicle emergence with respect to rice panicle emergence. Delaying the permanent flood improved rice yield in an imazethapyr system, but not for glufosinate.

Another study examined the effect of 500 g ha^{-1} glufosinate applied 14, 28, 42, 56, and 70 days after emergence fb 410 g ha^{-1} applied 7 d later on rice and red rice. All treatments controlled red rice 91 to 98%. Rice yield was optimized when applications occurred within 35 or 49 DAE for the red rice infested and red rice free treatments, respectively.

The fourth study examined imazethapyr use in a water-seeded system receiving no tillage or tilled in the water prior to seeding. Herbicide treatments were 70 g ha^{-1} imazethapyr applied 1, 3, or 5 d fb 70 g ha^{-1} applied 12 or 19 d after draining the seeding flood (DADSF), 140 g ha^{-1} applied 12 or

19 DADSF, and a nontreated. All treatments controlled red rice 88 to 95% and barnyardgrass 73 to 94%. Rice yields did not reflect barnyardgrass control and were higher when the two imazethapyr applications were farther apart.

CHAPTER 1

LITERATURE REVIEW

Rice (*Oryza sativa* L.) has been used as a food source in Thailand since 5000 B.C., but *O. glaberrima* was first domesticated by the Africans around 1500 B.C. (Holm et al. 1997). Rice provides 33 to 80% of the caloric intake in Asia, Latin America, and Africa for an estimated 1 to 2 billion people thereby distinguishing it as the world's most important crop (Chang 1984).

The primary U.S. rice producing states are Arkansas, California, Louisiana, Mississippi, Missouri, and Texas in order of total acreage planted (Agricultural Statistic Board 2004). Since record keeping began in 1895, U.S. rice acreage peaked in 1981 at 1.549 million hectares after rice prices peaked at \$12.80 cwt^{-1} in 1980 (USDA/NASS 2004). Production value in 1980 was the highest level recorded at \$1.873 billion. U.S. average rice yields were lowest at 971 kg ha^{-1} in 1896 and highest at 7280 kg ha^{-1} in 2001. The production value for rice has ranged from \$12.6 million in 1896 to the high reached in 1980 (Agricultural Statistics Board 2004; USDA/NASS 2004).
In Louisiana, rice production began in 1718 and expanded until 1994 when 251,000 ha were planted (Linscombe 1999). From 1999 to 2003, Louisiana has averaged 212,000 planted ha with an average yield of 6440 kg ha^{-1} and total farm value of \$2.179 million (Agricultural Statistics Board 2003; Louisiana Summary 1999, 2000, 2001, 2002, 2003).

The cultivated rice known today is believed to have occurred via mutations that resulted in awnless, non-shattering grains, and selection for favorable characteristics by the early agricultural inhabitants of Asia (Holm et al. 1997). The lineage of rice (*O. sativa*) is believed to originate from the wild perennial *O. rufipogon* which became *O. nivara*. Eventually *O. sativa* was derived (Chang 1976). During the domestication process, plants grew taller, produced longer leaves, thicker stems, decreased pigmentation, decreased rhizome formation, decreased dormancy mechanisms, and responded increasingly to temperature and photoperiod. The occurrence of cross-pollination was decreased making cultivated rice primarily self-pollinated (Chang 1984).

Red rice has several scientific and botanical names, but it is generally classified as (*Oryza sativa*), the same species as rice cultivated in the U.S. (Parker and Dean 1976). Red rice was first reported as a weed problem in the U.S. in 1846 in the Carolinas (Craigmiles 1978). By 1900, red rice had spread to Louisiana and became so problematic rice fields were abandoned due to heavy red rice infestations around the beginning of the 20th century (Dodson 1900; Nelson 1907). A survey conducted in 1929 revealed 54% of the rice samples tested contained red rice seed averaging 127 seed kg^{-1} of rice seed (Goss and Brown 1939). In 1981, Smith estimated red rice infestations caused revenue reductions totaling $50 million in the southern U. S. alone (Smith 1981). When adjusted for inflation, the revenue reductions would equal $103 million today (Sahr 2004). Red rice possesses many undesirable characteristics such as light green leaf color, profuse tillering, red pericarp, early and easily shattering seeds, seed dormancy, leaf and seed pubescence, awned lemmas, tall stature, weak stems, and susceptibility to lodging (Craigmiles 1978; Kwon et al. 1992; Noldin et al. 1999). Most of these undesirable characteristics distinguish red rice from rice. In addition, red rice germinating during cool, early season temperatures can serve as an alternate host for diseases and insects that infest cultivated rice (Aldrick et al. 1973; Babatola 1980; Eastin 1978).

Red rice in the southern U.S. is composed primarily of strawhull and blackhull types (Diarra et al. 1985a). Strawhull red rice is characterized by its tall stature, moderate tillering, drooping panicles, awnless and awned seed, and tan to brown lemma and palea (Diarra et al. 1985a; Sonnier 1978). Blackhull types are tall stature, densely tillering, compact plants that mature late, produce awned seed with black lemma and palea. On average, blackhull red rice has been shown to produce 27% more tillers, 18% more straw biomass, and mature later than strawhull red rice. Both types of red rice emerge earlier in the season, grow taller, and produce more panicles with seed that shatters more readily than cultivated rice (Diarra et al. 1985a).

Red rice is similar to cultivated rice in terms of nutritional value, but due to low grain weight and early seed shattering characteristics only a proportion of the total red rice seed in a field is harvested (Deosthale and Pant 1970; Kwon et al. 1992). Therefore, red rice competes with rice for space, light, and nutrients, and contributes little to yield. The height differential and vegetative biomass produced by red rice reduce harvest efficiency. The presence of red rice in packaged white rice is visually unattractive to consumers. To enhance the quality and visual appeal of rice before packaging, extra milling is required. This results in additional expense, increased broken grains, and a lower price paid to the producer due to reduced grade and milling yield (Craigmiles 1978; Diarra et al. 1985b; Dunand 1988; Smith et al. 1986).

To determine how quickly red rice can become a severe infestation, Huey and Baldwin (1978) theorized that one red rice plant could produce 1500 seed in a single season. That would result in 2.25 million seed after the following season assuming each plant produces 10 tillers, 150 seed panicle^{-1}, with 100 percent seed viability.

A number of studies have been conducted to understand how red rice infestations influence rice yield. As early as 1978, Baldwin (1978) reported 32 red rice panicles m^{-2} reduced rice yields 64%. In other studies, red rice produced 12% more root biomass and increased the number of infertile spikelets in cultivated rice (Leitao et al. 1972). Navarro (1985), using the cultivar 'Mars', found red rice at 4, 16, 25, and 300 plants m^{-2} reduced rice yield 20, 43, 57, and 91%, respectively. Diarra et al. (1985b) found that rice seeded at 100 kg ha^{-1} yielded 77 and 82% less when grown with red rice at

108 and 215 plants m^{-2}, respectively. Even red rice densities as low as five plants m^{-2} reduced rice yields 22%. Rice culm number was reduced 7 to 32% by harvest depending on red rice density. Straw dry weights were reduced 18, 66, and 68% at the red rice densities of 5, 108, and 215 plants m^{-2}, respectively. Rice yields were decreased as number of grains per panicle were reduced 8 to 18% at 5 red rice plants m^{-2}, and was reduced 56 to 70% for red rice densities of 108 and 215 plants m^{-2}, respectively.

Rice cultivars have been shown to differ with respect to their competitive ability with red rice. Mars, a cultivar maturing in 138 days, reduced red rice yield 24 to 33% more than 'Lebonnet', a cultivar maturing in 126 days (Diarra et al. 1985b). Differences in red rice competitive ability have also been observed between rice cultivars differing with respect to plant height (Kwon et al. 1991b). 'Lemont', a semi-dwarf cultivar (92 cm) was not as competitive with red rice due to its short stature compared with 'Newbonnet', a conventional cultivar (115 cm). Only 10 red rice plants m^{-2} were required to reduce plant height for Lemont, while 40 red rice plants m^{-2} were required to reduce Newbonnet height. Yields for both cultivars were reduced 178 kg ha^{-1} for Newbonnet and 272 kg ha^{-1} for Lemont for each additional red rice plant. Red rice grown with Lemont produced more panicles m^{-2} and greater straw dry weight than when grown with Newbonnet. Competition studies conducted by Fischer and Ramirez (1993) indicated even more substantial yield reductions from red rice competition than reported in previous research. Red rice at 5 and 20 plants m^{-2} reduced 'Oryzica 1' yields 40 and 60%, respectively. By harvest, the higher red rice population contributed 35 seeds m^{-2} to the seed bank due to shattering and contaminated harvested rice with 1100 kg ha^{-1} of red rice seed. Models evaluated by Pantone and Baker (1991) indicated that it would take three Mars plants to have the same effect on grain yield of Mars as one red rice plant. Red rice, conversely, was more competitive intraspecifically than interspecifically.

Another aspect affecting competition between crops and weeds is the length and period of weed competition. Smith (1988) reported season-long competition from 3 or 19 red rice plants m^{-2} reduced rice yields 10 and 50%, respectively. Red rice at 20 plants m^{-2} reduced yields of Lemont and Newbonnet when allowed to compete for at least 60 days. Lemont and Newbonnet yields were reduced 78 and 51%, respectively, when red rice competed for 120 days. Yield reductions could be attributed to reduction in panicle number m^{-2}, panicle length, spikelets and filled florets $panicle^{-1}$, and rice milling yields (Kwon et al. 1991b). Twenty-four red rice plants reduced yield 10% when allowed to compete within the first 40 days after emergence, but reduced rice yield 75% when allowed to compete during the entire growing season (Fischer and Ramirez 1993). Other studies indicate competition between rice and red rice is less severe during the first 50 days of emergence (Diarra et al. 1985b; Kwon et al. 1991a, 1991b; Smith 1988).

Due to the phenotypic and genotypic similarities between rice and red rice, control of red rice infestations is often marginal at best (Craigmiles 1978; Hoagland and Paul 1978). In the past, red rice management has involved a combination of mechanical, cultural, and chemical control measures. Rotation to pasture land is not always feasible for producers and even then would require disking four to six times for 2 years or mowing on a 28- to 42-day interval to prevent most of the red rice from producing seed (Klosterboer 1978; Sonnier 1978). Cultural practices include planting red rice-free seed, using rice seeding rates at the high end of the recommended range, roguing, and selecting tall-statured, long-season cultivars (Baker and Sonnier 1983; Diarra et al. 1985b; Kwon et al. 1991b; Smith 1974; Sonnier 1978). In Southwest Louisiana, water-seeding rice is used as a cultural management practice to ensure a weed-free seedbed at planting and to minimize weed germination and emergence before permanent flood establishment (Linscombe et al. 1999). Tillage operations may be performed either before or after the establishment of the seeding flood. In the past, tillage operations in the water have been used in conjunction with water seeding to destroy existing vegetation after the seeding flood was established. Public perception and increasing legislation concerning water quality have resulted in a shift of some of the water-seeded rice acreage to varying levels of conservation tillage. Since 1998, no-till and stale seedbed conservation tillage acreage has fluctuated between 7 and 15% of the water-seeded rice acreage (Anonymous 1998, 1999, 2000, 2001, 2002, 2003, 2004). Previous research has shown that benefits of conservation tillage include reducing soil erosion and conserving soil moisture, but rice seedling establishment and red rice control are sometimes diminished (Bollich 1992; Bollich and Feagley 1995).

Chemical control of red rice in rice is difficult due to the genetic similarities between the two. However, red rice has been found to be more sensitive to molinate (S-ethyl hexahydro-1*H*-azepine-1-carbothioate) and thiobencarb (S-[(4-chlorophenyl)methyl]diethylcarbamothioate) applied preplant in conjunction with pinpoint and continuous flood water management practices (Baker et al. 1986; Forner 1995; Smith 1981; Sonnier and Baker 1980). Water management involving continuous flooding alone resulted in 37 red rice seedlings m^{-2} compared with brief drainage or drainage lasting for 2 weeks which resulted in red rice seedling emergence of 140 and 895 plants m^{-2}, respectively (Sonnier and Baker 1980). Combining molinate application, drain-flood, or continuous flood water management provided 89 to 96% control of red rice (Diarra et al. 1985c; Smith 1981). The use of pregerminated seed, water management, and conservation tillage to control red rice is increasing in Louisiana in order to manage red rice, reduce production costs, and contend with water pollution issues.

Seeding rate studies with the medium-grain, early maturing cultivars ‘Nato’ and ‘Saturn’ found seeding rates of 101, 151, and 202 kg ha^{-1} provided a competitive advantage for rice growing with blackhull red rice (Sonnier

1966, 1968, 1969, 1970, 1971). Rice stand was increased almost 50% when seeding rates were increased from 101 to 202 kg ha^{-1}. By increasing the rice seeding rate, red rice tillering and seed production was decreased 26 to 83% and 27 to 60%, respectively. The effect of row spacing and drill-seeding rate on red rice has been briefly investigated. Sonnier (1969, 1970, 1971) reported increasing Mars seeding rate from 100 to 400 plants m^{-2} (at a constant red rice density of 10 plants m^{-2}) decreased red rice seed production 68%. Diarra et al. (1985b) compared seeding rates of 50, 100, and 134 kg ha^{-1} and found that 100 kg ha^{-1} optimized rice yield in 1 of 2 years. Overall, as rice seeding rate increased, culm and panicle number increased while grains per panicle decreased. Estorninos et al. (1998) reported red rice tillers and panicle number decreased 38% and 43% as the rice seeding rate increased from 50 to 150 kg ha^{-1}. Rice grain yield increased from the 50 to 100 kg ha^{-1} seeding rate, but did not increase from 100 to 150 kg ha^{-1} seeding rate. Jones and Snyder (1987) examined one tall and two semi-dwarf cultivars at three row spacings and three planting densities in monoculture. When high solar radiation was combined with moderate growing temperatures, grain yield increased as the row spacing became narrower. Increased seeding rates resulted in more panicles m^{-2}, but reduced filled grains $panicle^{-1}$. In these studies, the optimum seeding rate was 80 to 100 kg ha^{-1} for rice grown in monoculture in southern Florida.

Another method to manage red rice is to rotate rice to crops such as soybean and grain sorghum that allow alternative herbicides capable of controlling red rice (Baldwin 1978). Crop rotation combined with chemical and tillage treatments controlled red rice 98 to 100% in soybean and grain sorghum (Smith 1976). Before the introduction of herbicide-resistant crops, preplant herbicide treatments and water management in rice and postemergent treatments in rotational crops generally provided 83 to 95% red rice control

(Askew et al. 1998b; Barrentine et al. 1984; Khodayari et al. 1987; Noldin et al. 1998).

The introduction of crops resistant or tolerant to glyphosate [*N*-(phosphonomethyl)glycine], glufosinate [2-amino-4-(hydroxymethylphosphinyl) butanoic acid] and imazethapyr {2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-5-ethyl-3-pyridinecarboxylic acid} have provided producers with more herbicides capable of controlling red rice (Klee et al. 1987; Thompson et al. 1987). Glyphosate applied to two-leaf to three-tiller red rice in soybean resulted in 88 to 91% control 2 weeks after treatment and 97% seedhead reduction when applied to two- to three-tiller red rice (Askew et al. 1998a). Red rice control in water-seeded rice culture with glyphosate was at least 94% at 14 DAT when glyphosate was applied early postemergence (EPOST), EPOST followed by (fb) late postemergence (LPOST) or postflood (POFL) and at least 85% at 30 DAT (Webster and Lanclos 2000).

Incorporation of the bialophos [4-(hydroxymethylphosphinyl)-L-2-aminobutanoyl-L-alanyl-L-alanine] resistance (BAR) gene in crops such as rice has conferred resistance to postemergence applications of glufosinate (Christou et al. 1991). Though not commercially available, BAR-transformed rice may one day provide another tool for the control of red rice. Current research indicates 90 to 100% red rice control can be achieved with two applications of glufosinate at 0.38 kg ai ha^{-1} applied 21 to 42 days after emergence (DAE) (Braverman and Linscombe 1994; Lanclos et al. 2003; Leon et al. 2002a; Wheeler et al. 1999).

A problem often encountered with herbicide resistant or tolerant cultivars is the injury caused by herbicide application at certain growth stages or under extreme environmental conditions. After the initial transformation event, breeding efforts can improve the level of resistance. Early glufosinate-resistant crops obtained from ‘Koshihikari’ and ‘Gulfmont’ transformed rice cultivars resulted in 0 to 53% injury ratings based on glufosinate rate and timing (Lanclos et al. 2003; Sankula et al. 1997a, 1997b; Wheeler et al. 1999). Subsequent rice transformation events and breeding efforts using 'Cypress' and 'Bengal' have generally resulted in crop injury ratings less than 10% (Lanclos et al. 2003; Leon et al. 2002a; Sankula et al. 1997a, 1997b; Wheeler et al. 1999).

In 1993, a chemically-induced mutation of Alexandria seed rice cultivar 'AS 3510' produced the first imidazolinone-resistant rice line '93 AS-3510' (Croughan 1994). Further breeding efforts have since improved the tolerance of the imidazolinone-tolerant rice lines such that injury ratings are now consistently less than 15% when imazethapyr is applied EPOST or earlier (Leon et al. 2002b; Masson and Webster 2001; Masson et al. 2001). Sequential applications of imazethapyr have consistently controlled red rice more than 90%, but seldom has 100% control been achieved (Dillon et al. 1999; Kurtz and Street 1999; Sanders et al. 1998; Steele et al. 2002). Greenhouse research indicates red rice control can be influenced by application timing and soil moisture (Zhang et al. 2001). Red rice activity with imazethapyr applied preplant incorporated (PPI) increased as soil moisture decreased from 50% to 13%. Imazethapyr activity was not affected with respect to the soil moisture contents observed when applied postemergence (POST) to red rice.

The importance of achieving 100% red rice control with any of the herbicide-resistant rice cultivars is to maintain the efficacy of the herbicides with respect to red rice control. Studies have shown that overall gene flow is from cultivated rice to red rice (Oka and Chang 1959). The florets of red rice tend to remain open one or more hours longer than cultivated rice, which most likely influences the direction of gene flow (Roy 1921). Improper management of herbicide-resistant cultivars could potentially result in loss of the technology due to movement (outcrossing) of the herbicide-resistance traits from rice to red rice. Field studies using imazethapyr and glufosinate-resistant rice have resulted in outcrossing of both herbicide-resistance traits to red rice (Dillon et al. 2002; Oard et al. 2000).

Very little research has been conducted in water-seeded rice production systems examining optimum seeding rates, competitiveness of rice cultivars currently being grown, or the length of time current cultivars can be allowed to compete with red rice before yield reductions occur. Research also needs to evaluate combinations of imazethapyr- and glufosinate-resistant rice cultivars with water management practices that may allow more consistent control of red rice in order to preserve these technologies. This research will attempt to expand previous red rice research conducted in drill-seeded rice, yet will use a combination of current conventional and transgenic rice cultivars to: 1) determine the effectiveness of increasing rice seeding rates to minimize red rice interference in water-seeded rice, 2) use glufosinate application timing to minimize red rice interference in-season and determine the effect of the application timings on the glufosinate-resistant rice line, 3) investigate glufosinate- and imazethapyr-resistant rice programs combined with pinpoint, intermittent, and delayed permanent flood establishment with respect to red rice control and crop yield, and 4) comparing the effect of imazethapyr application timing on weed control and rice yield in a water-seeded production system tilled or not tilled in the seeding flood.

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CHAPTER 2

RED RICE COMPETITION WITH FOUR RICE CULTIVARS

Introduction

Red rice (*Oryza sativa* L.) has several scientific and botanical names, but is generally classified as the same species as cultivated rice (*Oryza sativa* L.) in the U.S. (Parker and Dean 1976). Red rice was first reported as a weed problem in the U.S. in 1846 in the Carolinas (Craigmiles 1978). During the 1900’s, red rice spread to Louisiana and was so problematic that rice fields were abandoned due to heavy red rice infestations (Dodson 1900; Nelson 1907). A survey conducted in the United States in 1929 revealed 54% of the rice samples tested contained red rice seed averaging 127 seed kg^{-1} of rice seed (Goss and Brown 1939). In 1981, red rice infestations were estimated to cause revenue reductions totaling $50 million in the southern U.S. alone, which when adjusted for inflation would equal $103 million today (Sahr 2004; Smith 1981).

Red rice possesses many undesirable characteristics such as light green leaf color, profuse tillering, red pericarp, early and easily shattering seeds, seed dormancy, leaf and seed pubescence, awned lemmas, tall stature, weak stems, and susceptibility to lodging (Craigmiles 1978; Kwon et al. 1992; Noldin et al. 1999). Most of these undesirable characteristics distinguish red rice from rice. In addition, red rice germinating during cool, early season temperatures can serve as an alternate host for diseases and insects that infest cultivated rice (Aldrick et al. 1973; Babatola 1980; Eastin 1978).

Red rice in the southern U.S. is composed primarily of strawhull and blackhull types (Diarra et al. 1985a). Strawhull red rice is characterized by tall stature, moderate tillering, drooping panicles, awnless and awned seed, and tan to brown lemma and palea (Diarra et al. 1985a; Sonnier 1978). Blackhull types are tall stature, densely tillering, compact plants that mature late, produce awned seed with black lemma and palea. On average, blackhull red rice has been shown to produce 27% more tillers, 18% more straw biomass and mature later than strawhull red rice. Both types of red rice emerge earlier in the season, grow taller, and produce more panicles with seed that shatters more readily than cultivated rice (Diarra et al. 1985a).

In terms of nutritional value, red rice is similar to cultivated rice, but due to low grain weight and early seed shattering only a portion of the total red rice seed in a field is harvested (Deosthale and Pant 1970; Kwon et al. 1992). Therefore, red rice competes with rice for space, light, and nutrients, but contributes little to yield (Smith et al. 1986). The height differential and vegetative biomass produced by red rice reduce harvest efficiency (Dunand 1988; Smith et al. 1986). Even when red rice is harvested, it is considered visually unattractive to consumers in packaged white rice. To counteract the public's perception, white rice containing red rice is subject to extra milling (Dunand 1988; Smith et al. 1986). This results in additional expense, increased broken grains, and a lower price paid to the producer due to reductions in grade and milling yield (Craigmiles 1978; Diarra et al. 1985b; Dunand 1988; Smith et al. 1986).

A number of studies have been conducted to understand how red rice influences rice yield. Baldwin (1978) reported 32 red rice panicles m^{-2} reduced rice yields 64%. In other studies, red rice produced 12% more root biomass and increased the number of infertile spikelets in cultivated rice (Leitao et al. 1972). Navarro (1985), using the cultivar 'Mars', found red rice at 4, 16, 25, and 300 plants m^{-2} reduced rice yield 20, 43, 57, and 91%, respectively. Diarra et al. (1985b) found that rice seeded at 100 kg ha^{-1} yielded 77 and 82% less when grown with red rice at 108 and 215 plants m^{-2}, respectively. Even red rice densities as low as 5 plants m^{-2} reduced rice yields 22%. Rice culm number was reduced 7 to 32% by harvest depending on red rice density. Straw dry weights were reduced 18, 66, and 68% at red rice densities of 5, 108, and 215 plants m^{-2}, respectively. Rice yields were decreased as number of grains per panicle were reduced 8 to 18% at 5 red rice plants m^{-2}, and was reduced 56 to 70% for red rice densities of 108 and 215 plants m^{-2}, respectively.

Rice cultivars have shown differing levels of competitiveness with red rice. Mars, a cultivar maturing in 138 days, reduced red rice yield 24 to 33% more than 'Lebonnet', a cultivar maturing in 126 days (Diarra et al. 1985b). Kwon et al. (1991b) reported differences in red rice competitive ability between rice cultivars differing in plant height. 'Lemont', a semi-dwarf cultivar (92 cm) was not as competitive with red rice due to its short stature compared with 'Newbonnet', a conventional cultivar (115 cm). Only 10 red rice plants m^{-2} were required to reduce the height of Lemont, while 40 red rice plants m^{-2} were required to reduce Newbonnet height. Yields were reduced 178 kg ha^{-1} for Newbonnet and 272 kg ha^{-1} for Lemont for each additional red rice plant. Red rice grown with Lemont produced more panicles m^{-2} and greater straw dry weight than when grown with Newbonnet.

Competition studies conducted by Fischer and Ramirez (1993) indicated even more substantial yield reductions from red rice competition than reported in previous research. Red rice at 5 and 20 plants m^{-2} reduced 'Oryzica 1' yields 40 and 60%, respectively. By harvest, 20 red rice plants m^{-2} contributed 35 seeds m^{-2} to the seed bank due to shattering and contaminated harvested rice with 1100 kg ha^{-1} of red rice seed. Models evaluated by Pantone and Baker (1991) indicated that it would take 3 Mars plants to have the same effect on grain yield of Mars as 1 red rice plant. Red rice, conversely, was more competitive intraspecifically than interspecifically.

The effect of row spacing and drill-seeding rate of cultivated rice on red rice has been briefly investigated. Seeding rate studies with the medium-grain, early maturing cultivars 'Nato' and 'Saturn' found that seeding rates of 101, 151, and 202 kg ha^{-1} provided a competitive advantage for rice growing with blackhull red rice (Sonnier 1966, 1968, 1969, 1970, 1971). Rice stand was increased almost 50% when seeding rates were increased from 101 to 202 kg ha^{-1}. Red rice tillering and seed production was decreased 26 to 83% and 27 to 60%, respectively. Sonnier (1969, 1970, 1971) reported increasing Mars seeding rate from 100 to 400 plants m^{-2} (at a constant red rice density of 10 plants m^{-2}) decreased red rice seed production 68%. Diarra et al. (1985b) compared seeding rates of 50, 100, and 134 kg ha^{-1} with red rice densities of 0, 5, and 108 plants m^{-2}. The first year there was no difference in yield regardless of treatment, but in year two the 100 kg ha^{-1} rice seeding rate optimized rice yield when grown with red rice at 5 or 108 plants m^{-2}. Overall, as rice seeding rate increased, culm and panicle number increased, while grains per panicle decreased. Estorninos et al. (1998) reported red rice tiller and panicle number decreased 38% and 43%, respectively, as the rice seeding rate increased from 50 to 150 kg ha^{-1}. Rice grain yield increased from the 50 to 100 kg ha^{-1} seeding rate; however, this trend did not occur when increasing the seeding rate from 100 to 150 kg ha^{-1}. Jones and Snyder (1987) examined one tall and two semi-dwarf cultivars at three row spacings with three planting densities in a monoculture system. When high solar radiation was combined with moderate growing temperatures, grain yield increased with reduced row spacing. Increased seeding rates resulted in more panicles m^{-2}, but reduced filled grains $panicle^{-1}$. In these studies, the optimum seeding rate was 80 to 100 kg ha^{-1} for rice grown in monoculture in southern Florida.

Cultivar selection and seeding rate can play a role in combating red rice infestations when cultivars are chosen that are capable of out-competing the native red rice population. This research was undertaken to evaluate seeding density of four cultivars that vary in maturity, tillering ability, plant height at maturity, and lodging with respect to their competitive ability with red rice in a water-seeded production system.

Materials and Methods

A study was conducted at the Rice Research Station in Crowley, Louisiana, from 2002 to 2004. The soil type was a Crowley silt loam (fine montmorillonitic, thermic, Typic Albaqualf) with pH 6.4 and 0.79% organic matter. A split plot experimental design was used with rice cultivar as the main plot and cultivar seeding rate and presence or absence of red rice as the subplots. Main plot cultivars included 'CL 121', 'Cocodrie', 'Drew', and 'Jasmine'. Each cultivar was selected based on growth characteristics such as maturity date, height, and tillering ability (Table 2.1). The seeding rates

Table 2.1. Comparison of rice cultivars used in this competition study based on lodging, maturity date, days to 50% heading, and plant height.

Cultivar	Lodging	Maturity[a]	Days to 50% heading	Plant height
			d	cm
CL 121[b]	Highly resistant	Very early	72	86
Cocodrie[b]	Moderately resistant	Very early	79	91
Drew[c]	Susceptible	Early	80	114
Jasmine[d]	Susceptible	Mid-season	94	109

[a] Refers to days to 50% heading: <80 – very early; 80 to 89 – early; >90 – mid-season.
[b] Rice Varieties and Management Tips. 2005. LSU AgCenter. Pub. no. 2270.
[c] Rice Production Handbook. Univ. of Arkansas. Pub. no. MP192.
[d] 2001 Rice Production Guidelines. Texas Agric. Ext. Ser. Pub. no. D-1253.

were determined by calculating hundred seed weight, then soaking the seed for 24 hr in water, draining, and determining percent seed germination 36 hr later. Pregerminated rice seed was broadcast to establish 95, 190, and 290 rice plants m^{-2}. These rates correspond to the minimum, optimum, and maximum plant stands recommended for water-seeded rice production in Louisiana (Linscombe et al. 1999). Pregerminated red rice was broadcast to establish 20 plants m^{-2} in the respective treatments containing red rice. Based on earlier studies, the red rice was seeded at rates that caused approximately 50% yield reduction (Baldwin 1978; Navarro 1985; Fischer and Ramirez 1993).

Seedbed preparation consisted of fall and spring disking followed by (fb) a pass with a two-way bed conditioner equipped with S-tine harrows set at a 7.5-cm operating depth. The spring bed conditioning was fb application of 280 kg ha^{-1} 8-24-24 (N-P_20_5-K_20). A final pass of the bed conditioner was made before preplant flood establishment for fertilizer incorporation. A seeding flood was established 24 h after the final tillage. One day after flood establishment, rice was broadcast on May 3, 2002, May 25, 2004, and June 16, 2004. Approximately 24 hr later the flood was drained to allow seedling establishment. Plot size was 1.5 by 6 m^2.

Each year the plots were surface irrigated twice before the permanent flood was established on May 28, 2002, June 16, 2004, and June 27, 2004, and maintained until 2 wk prior to harvest. A nitrogen application was applied into the permanent flood consisting of 280 kg ha^{-1} urea (46-0-0). General weed control was obtained using a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} at 190 kPa. Each study received 5 kg ai ha^{-1} of a 1:1 ratio of molinate [*S*-ethyl hexahydro-1*H*-azepine-1-carbothioate] plus propanil [*N*-(3,4-dichlorophenyl) propanamide][1] applied 13 d after planting fb 0.42 kg ai ha^{-1} cyhalofop-butyl [2-[4-(4-cyano-2-fluorophenoxy)phenoxy] propanoic acid, butyl ester, (R)] plus 0.05 kg ai ha^{-1} halosulfuron [3-chloro-5-[[[[(4,6-dimethoxy-2-pyrimidinyl)amino]carbonyl] amino]sulfonyl]-1-methyl-1*H*-pyrazole-4-carboxylic acid] plus 2.5% v/v crop oil concentrate[2] 27 d after permanent flood. The second study in 2004 received 0.03 kg ai ha^{-1} penoxsulam [2-(2,2-

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[1] Arrosolo herbicide label, RICECO Corporation, 5100 Poplar Avenue, Suite 2428, Memphis, TN 38137.

[2] Agridex, a mixture of 83% paraffinic mineral oil and 17% polyoxyethylene sorbitan fatty acid ester. Helena Chemical Company, 225 Schilling Boulevard, Collierville, TN 38017.

difluoroethoxy)-*N*-(5,8-dimethoxy[1,2,4] triazolo[1,5-*c*]pyrimidin-2-yl)-6-(trifluoromethyl) benzenesulfonamide] for ducksalad [*Heteranthera limosa* (SW.) Willd.] control.

Rice and red rice height were recorded for two plants plot^{-1} at 47, 60, 75, 85, and 110 d after planting. Percent heading based on panicle emergence was collected. Subsamples of rice and red rice were harvested at rice maturity from 0.65 m^{-2} of the plot area to determine plant and stem density m^{-2}. The samples were bagged and dried at 35 C for 3 wk at which time rice and red rice dry weight, panicle number, and panicle weight were recorded.

Prior to harvest, red rice panicles were removed from the plot area in order to avoid contamination of the yield samples with red rice seed. Yield was collected from the center 0.75 by 6 m area of the plot using a small plot combine. Grain yield was adjusted to 12% moisture.

In order to make comparisons between the four cultivars that differed genetically and phenotypically, the data were converted to percent of respective red rice free control. This permitted standardization of the data.

Data was analyzed using the Mixed Procedure of SAS (SAS Institute 2003) with year used as a random factor. Experiment, replication (nested within experiment), cultivar by replication (nested within experiment) and all interactions containing either of these effects were considered random effects; treatment was considered a fixed effect. Considering year or combination of year as random effects permits inferences about treatments over a range of environments (Carmer et al 1989; Hager et al. 2003). Type III statistics were used to test all possible effects of fixed factors (cultivar, seeding rate, and presence of red rice) and least square means were used for mean separation at 5% probability level ($p \leq 0.05$).

Results and Discussion

The main effect of cultivar was significant (Table 2.2). At harvest, the rice cultivars produced 66 to 87% of the plant density of the respective

Table 2.2. Response of rice plant density, stem density, dry weight, and panicle weight to red rice presence taken as a percent of the red rice-free control.[a,b,c]

Cultivar	Plant density[b,c]	Stem density	Dry weight	Panicle weight
	%			
CL 121	75 ab (320)	71 ab (590)	57 b (1820)	49 b (900)
Cocodrie	66 b (270)	61 b (510)	51 b (1820)	41 b (890)
Drew	85 a (250)	69 b (480)	59 b (1900)	51 b (850)
Jasmine	87 a (280)	80 a (630)	71 a (2100)	66 a (910)

[a] Data were averaged over low, optimum, and high seeding rates and experiments.
[b] The actual value(number m^{-2} for plant and stem density and g m^{-2} for dry and panicle weight) for the respective red rice-free control for each cultivar is given in parentheses.
[c] Means within each column followed by the same letter were not significantly different according to the t-test on difference of least square means at P = 0.05.

red rice-free control. The total rice stem density was 61 to 80% of the respective red rice-free control. With the exception of Drew, the reduction in stem density for each cultivar was 4 to 7% lower than the reduction in plant density. With Drew, the stem density was 69% of the respective red rice-free control, which was a 16% reduction in plant density. Jasmine was the only cultivar that produced more than twice the stem density in its red rice-free control, which is a direct indication of its tillering ability. Jasmine dry weight and panicle weight were reduced the least of the four cultivars as it produced 71 and 66% of the respective red rice-free control, respectively. The dry weight and panicle weight for the other three cultivars was 41 to 59% of the respective red rice-free control. Jasmine and CL 121 stem densities were similar; however, in the presence of red rice, Jasmine was able to maintain a higher percentage of its biomass (dry weight) and panicle weight compared with the other cultivars in this study. The improved competitiveness of tall, long-season cultivars such as Jasmine has been reported by others (Ahmed and Hogue 1981; Diarra et al. 1985b; Kwon et al. 1991b; Smith 1974).

The main effect of seeding rate was also significant (Table 2.3). The high seeding rate produced 85% of the plants of the nontreated, and 9 to 10% more yield than the low and optimum seeding rates. There was no difference observed for rice height, d to 50% panicle emergence, harvest grain moisture, or rice panicle number m^{-2} (data not shown).

Our observation that the height of red rice tends to be related to the height of the cultivar with which it is grown with has been observed by others (Kwon et al. 1991b). Red rice height was tallest in the presence of Drew, the tallest cultivar in this study (Table 2.4). Others have stated that competition for light is the main factor in mixed populations; therefore, red rice may elongate in order to out compete its neighbors (Jennings and Aquino 1968). Red rice panicle weights were lowest for Jasmine compared with

Table 2.3. Effect of red rice on rice plant density and rough rice yield at the low, optimum, and high seeding rates taken as a percent of the red rice-free control[a].

Rice seeding rate[b]	Plant density[c,d]	Rough rice yield
	%	
Low	79 ab (210)	71 b (4300)
Optimum	72 b (270)	70 b (5000)
High	85 a (350)	80 a (5200)

[a] Data were averaged over cultivars and experiments.
[b] Rice seed was broadcast to establish 95, 190, and 290 plants m^{-2} for the low, optimum, and high seeding rates, respectively.
[c] The actual value for plant density (number m^{-2}) and rough rice yield (kg ha^{-1}) for the red rice-free control is given in parentheses.
[d] Means within a column followed by the same letter were not significantly different according to the t-test on difference of least square means at P = 0.05.

Table 2.4. Effect of four rice cultivars on red rice height and panicle weight at harvest.[a,b]

Cultivar	Height	Panicle weight
	cm	g m^{-2}
CL 121	114 bc	190 ab
Cocodrie	113 c	268 a
Drew	121 a	206 a
Jasmine	117 b	120 b

[a] Data were averaged over low, optimum, and high seeding rates and experiments.
[b] Rice heights were 86, 89, 100, and 94 cm for CL 121, Cocodrie, Drew, and Jasmine, respectively.
[c] Means within a column followed by the same letter were not significantly different according to the t-test on difference of least square means at P = 0.05.

Cocodrie and Drew, but there was no difference between Jasmine and CL 121. Compared with Cocodrie and Drew, Jasmine had the least reduction in stem density when in competition with red rice and there was no difference between Jasmine and CL 121 (Table 2.2).

Red rice plant density was not affected by rice seeding rate (data not shown); however, increasing the seeding rate from low to high reduced red rice stem density and panicle weight 34 and 41%, respectively (Table 2.5). In order to achieve a similar reduction in red rice dry weight and panicle density, the seeding rate only needed to be increased from low to optimum. This resulted in a 33 to 35% decrease in red rice dry weight and panicle density. With respect to the four red rice characteristics, no significant reduction was observed between the optimum and high seeding rates. There was no difference in d to 50% heading for red rice, regardless of treatment (data not shown).

There was a cultivar by seeding rate by red rice interaction for rice grain yield (Table 2.6). No combination of cultivar or seeding rate was able to overcome the yield reducing effects of 20 red rice plants m^{-2} on rice yield. Across all cultivars and seeding rates, rice yields were reduced 9 to 46% in the presence of red rice. Of the four cultivars, CL 121 was consistently and equally affected at each seeding rate by red rice. CL 121 grain yield declined in a similar manner, regardless of seeding rate. Cocodrie exhibited the least decline in yield at the lowest seeding rate and the greatest decline at the highest seeding rate. With Drew, the greatest decline occurred at the middle seeding rate. Compared with the other cultivars, Jasmine produced the highest yields regardless of red rice presence. Increasing the seeding rate from optimum to high did not increase Jasmine yield for either the red rice free or infested treatment. However, a trend was observed in Jasmine percent yield reduction as yield decreased numerically from 29 to 27 to 21% at the high, optimum, and low seeding rates,

Table 2.5. Effect of rice seeding rate on red rice stem density, dry weight, panicle density, and panicle weight at harvest.[a]

	Red rice			
Rice seeding[b] rate	Stem[c] density	Dry weight	Panicle density	Panicle weight
	— # m^{-2} —	— g m^{-2} —	— # m^{-2} —	— g m^{-2} —
Low	333 a	1043 a	353 a	250 a
Optimum	292 ab	704 b	231 b	190 ab
High	220 b	582 b	209 b	148 b

[a] Data were average over cultivars and experiments.
[b] Rice seed was broadcast to establish 95, 190, and 290 plants m^{-2} for the low, optimum, and high seeding rates, respectively.
[c] Means within a column followed by the same letter were not significantly different according to the t-test on difference of least square means at P = 0.05.

Table 2.6. Effects of red rice interference on rough rice yield for the four cultivars and three seeding rates averaged across experiments.[a]

	Low seeding rate[b]		Optimum seeding rate		High seeding rate	
Cultivar	0[c]	20	0	20	0	20
CL 121	2630 kl[d]	1430 pq	2920 h-k	1590 nop	3470 e-j	2050 m-p
Cocodrie	2100 l-o	1520 pq	3550 g-j	2250 k-n	4170 c-f	2260 k-n
Drew	2850 jkl	2450 klm	3980 c-g	2430 klm	3770 d-g	3450 f-i
Jasmine	5100 b	3640 e-h	5950 a	4330 cd	5700 a	4530 c

[a] Data were averaged across experiments.

[b] Rice seed was broadcast to establish 95, 190, and 290 plants m^{-2} for the low, optimum, and high seeding rates, respectively.

[c] Red rice treatments consisted of 0 or 20 red rice plants m^{-2}.

[d] Means followed by the same letter were not significantly different according to the t-test on difference of least square means at P = 0.05. Letters are used to make comparisons across seeding rates, red rice presence, and cultivars.

respectively. Diarra et al. (1985) found that Mars drill-seeded at 100 kg ha^{-1} yielded higher than the 134 kg ha^{-1} seeding rate. As the seeding rate increased, they found the grains $panicle^{-1}$ decreased. With the exception of Drew at the low and high seeding rates, the presence of red rice reduced rice yield compared with the respective red rice-free control for all cultivars. With the exception of Cocodrie grown red rice-free and Drew grown with red rice, grain yield was not increased for any cultivar by increasing the seeding rate from optimum to high.

In this water-seeded study yield reductions among the cultivars was less than the yield reductions observed in drill-seeded rice by Navarro (1985) and Fischer and Ramirez (1993). Based on the stem density of Jasmine and its ability to produce more biomass and higher panicle weights in the presence of red rice compared with the other cultivars (Table 2.2), taller, vigorous tillering, mid-season cultivars may offer a competitive advantage in fields where red rice infestations exist. With Jasmine, percent yield reduction was 21 to 29% across all seeding rates. In the case of Drew, it is difficult to interpret the results since yield was reduced 39% at the optimum seeding rate, but only reduced 14 and 9% at the low and high seeding rates, respectively. However, in the presence of red rice Drew yields were higher at the high seeding rate and this may be because Drew does not produce as many tillers. The tall, early season Drew did yield more than the very early season, semi-dwarf cultivars CL 121 and Cocodrie at the high seeding rate when grown with red rice and more than CL 121 at the optimum seeding rate grown with red rice. Results from previous studies indicate that taller, later-maturing cultivars are more competitive with red rice (Ahmed and Hogue 1981; Diarra et al. 1985b; Jennings and Aquino 1968; Jennings and Herrera 1968; Jennings and Jesus 1968; Smith 1974). It is believed that competition for light is the main factor when other resources such as water and nutrients are not limiting; therefore, tall cultivars have an advantage (Jennings and

Aquino 1968). The results of this research indicate that cultivar selection and, in some instances, seeding rate can be used to minimize the competitive ability of red rice in rice.

Cultivar such as Drew and Jasmine that are tall, tiller vigorously, and is mature later were more favorable with respect to minimizing red rice interference. With the exception of Cocodrie grown red rice-free and Drew grown with red rice, this research verifies the optimum plant stands needed for water-seeding rice in Louisiana (Linscombe et al. 1999). In addition to verifying the optimum planting rate for these cultivars, this research was conducted with red rice infested rice. In three of four cultivars, there was no need to increase seeding rate beyond what is necessary to establish the optimum plant stand. However, when growing a cultivar that does not tiller vigorously such as Drew, selecting a later maturing cultivar and increasing the seeding rate would be beneficial when planting into a field with a history of red rice infestations. Furthermore, combining a competitive rice cultivar with imazethapyr-, glufosinate-, and glyphosate-resistant technologies that are available or may become available in the future may provide another tool to aid the ability of rice to out compete red rice that escaped control by the herbicides.

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CHAPTER 3

RED RICE MANAGEMENT IN CLEARFIELD AND LIBERTY-LINK WATER-SEEDED RICE

Introduction

In terms of nutritional value, red rice (*Oryza sativa* L.) is similar to cultivated rice (*Oryza sativa* L.), but due to low grain weight and early shattering characteristics, only a portion of the total red rice seed in a field is harvested (Deosthale and Pant 1970; Kwon et al. 1992). Therefore, red rice competes with rice for space, light, and nutrients, but contributes little to yield. The height differential and vegetative biomass produced by red rice slows harvest and reduces efficiency. The presence of red rice in packaged white rice is visually unattractive to consumers. To enhance the quality and visual appeal of rice before packaging, extra milling is required. This results in added expense, increased broken grains, and a lower price paid to the producer due to reductions in milling yield and grade (Craigmiles 1978; Diarra et al. 1985a; Dunand 1988; Smith et al. 1986).

Due to the phenotypic and genetic similarities between rice and red rice, control of red rice infestations is often marginal at best. In the past, red rice management has involved a combination of mechanical, cultural, and chemical control measures. Rotation to pasture is not always feasible for producers and even so, would require disking four to six times for 2 years or mowing on a 28- to 42-day interval to prevent most of the red rice from producing seed (Klosterboer 1978; Sonnier 1978). Cultural practices include purchasing red rice free seed, increasing rice seeding rates, roguing, and selection of competitive cultivars such as tall-statured, long-season cultivars that are more competitive (Baker and Sonnier 1983; Diarra et al. 1985a; Kwon et al. 1991; Smith 1974; Sonnier 1978). Chemical control of red rice in rice is difficult due to the genetic and physiological similarities between the two. However, red rice has been found to be more sensitive to molinate (S-ethyl hexahydro-1*H*-azepine-1-carbothioate) and thiobencarb (S-

[(4-chlorophenyl)methyl]diethylcarbamothioate) applied preplant in conjunction with pinpoint and continuous flood water management practices (Baker et al. 1986; Forner 1995; Smith 1981; Sonnier and Baker 1980). Water management involving continuous flooding alone resulted in 37 red rice seedlings m^{-2} compared with brief drainage or drainage lasting for 2 weeks, which resulted in red rice seedling emergence of 140 and 895 plants m^{-2}, respectively (Sonnier and Baker 1980). Combining molinate application and drain-flood or continuous flood water management, 89 to 96% control of red rice was achieved (Diarra et al. 1985b; Smith 1981). The use of pregerminated seed, water management, and conservation tillage is increasing in Louisiana in order to manage red rice, reduce production costs, and improve water quality.

Another method to manage red rice is to rotate rice to crops such as soybean [*Glycine max* (L.) Merr.] and grain sorghum [*Sorghum bicolor* (L.) Moench] that allow application of alternative herbicides capable of controlling red rice (Baldwin 1978). Crop rotation combined with chemical and tillage treatments controlled red rice 98 to 100% in soybean and grain sorghum (Smith 1976). Before the introduction of genetically modified crops, control of red rice using herbicide treatments alone provided 83 to 95% red rice control (Askew et al. 1998b; Barrentine et al. 1984; Khodayari et al. 1987; Noldin et al. 1998).

The introduction of crops resistant or tolerant to glyphosate [*N*-(phosphonomethyl)glycine], glufosinate [2-amino-4-(hydroxymethylphosphinyl) butanoic acid] and imazethapyr {2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-5-ethyl-3-pyridinecarboxylic acid} has provided producers with additional herbicides capable of controlling red rice (Klee et al. 1987; Thompson et al. 1987). Glyphosate applied to two-leaf (lf) to three-tiller red rice in soybean resulted in 88 to 91% control 2 weeks after treatment and 97% seedhead reduction when applied to two- to three-tiller red rice (Askew et al. 1998a). Red rice control in water-seeded rice culture with glyphosate was at least 94% at 14 d after treatment (DAT) when glyphosate was applied early postemergence (EPOST), EPOST followed by (fb) late postemergence (LPOST), or postflood (POFL) and at least 85% at 30 DAT (Webster and Lanclos 2000).

Glufosinate is a nonselective, postemergence (POST) herbicide that controls many weeds commonly found in rice (Vencill 2002). Incorporation of the bialophos [4-(hydroxymethylphosphinyl)-L-2-aminobutanoyl-L-alanyl-L-alanine] resistance (BAR) gene in crops such as rice has conferred resistance to POST applications of glufosinate (Christou et al. 1991). Though not commercially available, BAR-transformed rice may one day provide another tool for control of red rice. Current research indicates 90 to 100% red rice control can be achieved with two applications of 0.38 kg ai ha^{-1} glufosinate applied 21 to 42 d after emergence (DAE) (Braverman and Linscombe 1994; Lanclos et al. 2003; Leon et al. 2002; Wheeler et al. 1999). A problem often encountered with herbicide resistant or tolerant cultivars is the injury caused by herbicide application at certain growth stages or under extreme environmental conditions. After the initial transformation event, breeding efforts can improve the level of resistance. Early glufosinate-transformed rice obtained from 'Koshihikari' and 'Gulfmont' resulted in 0 to 53% injury based on glufosinate rate and timing. Glufosinate-transformed rice derived from 'Cypress' and 'Bengal' have resulted in crop injury ratings less than 10% when treated with glufosinate (Lanclos et al. 2003; Leon et al. 2002; Sankula et al. 1997a, 1997b; Wheeler et al. 1999).

In 1993, a chemically-induced mutation of Alexandria Seed rice cultivar 'AS 3510' produced the first imidazolinone-resistant rice line '93 AS-3510' (Croughan 1994). Imidazolinone-resistant rice allows the application of imazethapyr, an acetolactate synthase (ALS) inhibiting herbicide, to control red rice and other weeds both preemergence (PRE) and POST (Stidham and Singh

1991; Vencill 2002). Early rice injury problems have been largely overcome by further breeding efforts that have improved the tolerance of imidazolinone-resistant rice lines with crop injury consistently less than 15% (Masson and Webster 2001; Masson et al. 2001; Pellerin and Webster 2004; Steele et al. 2002). Two applications of imazethapyr control red rice more than 90%, but seldom has 100% control been achieved (Dillon et al. 1999; Kurtz and Street 1999; Sanders et al. 1998; Steele et al. 2002). Because 100% control is seldom achieved and gene flow is typically from cultivated rice to red rice, numerous research studies have been conducted to find the optimum timing for imazethapyr application to maximize red rice control and minimize the occurrence of outcrossing of the herbicide resistant trait (Dillon et al. 2002; Oard et al. 2000; Oka and Chang 1959; Roy 1921). Greenhouse research indicates red rice control with imazethapyr can be influenced by application timing and soil moisture (Zhang et al. 2001). Activity on red rice with imazethapyr applied preplant incorporated (PPI) increased as soil moisture decreased from 50% to 13%. Imazethapyr activity was not affected with respect to the soil moisture contents observed when applied POST. Numerous studies have reported that two imazethapyr applications control red rice and barnyardgrass 92 to 98% with no difference being observed between imazethapyr applied PPI or PRE fb a POST application (Ottis et al. 2003; Pellerin and Webster 2004; Steele et al. 2002; White and Hackworth 1999).

In the past, early permanent flood establishment has provided partial suppression of red rice. This research was conducted to evaluate weed and crop response to glufosinate- and imazethapyr-resistant rice utilizing three permanent flood establishment timings. The objective was to determine whether the timing of permanent flood establishment would increase weed control or if the herbicide applications alone would be adequate.

Materials and Methods

A study was conducted at the Rice Research Station in Crowley, Louisiana, from 2002 to 2004. The soil type was a Crowley silt loam (fine montmorillonitic, thermic, Typic Albaqualf) with pH 6.4 and 0.79% organic matter. A split plot experimental design was used with a three factor factorial arrangement of treatments. The water management systems consisted of establishing the permanent flood 3, 14, and 27 d after seeding (DAS). Establishing the flood 3 DA planting is referred to as a pinpoint flood. In a pinpoint flooding system, the seeding flood is drained for a minimal time for seedling establishment, but the soil remains saturated to limit weed germination and emergence. After approximately 3 d, the rice root has penetrated the soil and the permanent flood is established. The flood depth is increased as the rice plant height increases. The 14 and 27 d after seeding permanent floods were established one d after EPOST and LPOST application, respectively. Herbicide resistant cultivar, its associated treatment, and presence or absence of red rice were the subplots.

'LL 001' (2002) and 'LL 401' (2003 and 2004), both medium grain, Bengal-derived glufosinate-transformed lines were chosen for the glufosinate treatments. A long grain cultivar, 'CL 161', possessing improved tolerance to imazethapyr compared with previous lines was selected for the imidazolinone treatments. Glufosinate treatments consisted of 500 g ai ha^{-1} applied to two- to three-leaf (lf) rice and red rice (EPOST) fb a four-lf to one-tiller (LPOST) application. Imazethapyr treatments included 70 g ha^{-1} surface applied (PRE) fb a three- to four-lf mid-POST (MPOST) application or EPOST fb LPOST. POST applications of imazethapyr contained 1% v/v crop oil concentrate[3]. The controls for this study were treatments receiving no herbicide with no red

[3] Agridex, a mixture of 83% paraffinic mineral oil and 17% polyoxyethylene sorbitan fatty acid ester. Helena Chemical Company, 225 Schilling Boulevard, Collierville, TN 38017.

rice and no herbicide with red rice seeded to obtain 20 plants m^{-2}. Based on earlier studies, the red rice was seeded at rates that caused approximately 50% yield reduction (Baldwin 1978; Navarro 1985; Fischer and Ramirez 1993). Plot size was 1.8 m wide by 5.2 m long. In 2002 and 2004, hemp sesbania [*Sesbania exaltata* (Raf.) Rydb. ex A. W. Hill] naturally infested the study area at a density of two to 10 plants m^{-2}. Hemp sesbania was at the one- to two-lf, three- to five-lf, and four- to six-lf growth stage at the EPOST, MPOST, and LPOST application timings, respectively. Barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.] and Amazon sprangletop [*Leptochloa panicoides* (Presl) Hitchc.] infested the area with an estimated density of 70 to 115 plants m^{-2}. At the EPOST, MPOST, and LPOST application timings, barnyardgrass and Amazon sprangletop were at the one- to three-lf, two- to four-lf, and three-lf to two-tiller growth stage, respectively.

Seedbed preparation consisted of fall and spring disking, fb a pass with a two-way bed conditioner equipped with S-tine harrows set at a 7.5-cm operating depth. The spring bed conditioning was fb application of 280 kg ha^{-1} 8-24-24 (N-P_2O_5-K_2O). A final pass of the bed conditioner was made before preplant flood establishment for incorporation of fertilizer. One day after flood establishment, rice was broadcast on May 3, 2002, May 14, 2003, and May 25, 2004. Pregerminated rice was broadcast at 146 kg ha^{-1}, and red rice was broadcast to the plots containing red rice. Approximately 24 hr later the flood was drained to allow seedling establishment. A 10-cm permanent flood was established 3, 10, and 27 DAS. Treatments that were permanently flooded 10 and 27 DAS received surface irrigations 7 DAS and at 7 d intervals until the permanent flood was established. This was done to maintain adequate soil moisture for imazethapyr activation and optimum rice growing conditions. A second nitrogen application was applied into the flood at the three- to four-lf growth stage consisting of 280 kg ha^{-1} urea (46% nitrogen). Herbicide applications were made using a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} solution at 190 kPa. In 2002, a broadcast application of 52 g ai ha^{-1} halosulfuron [3-chloro-5-[[[[(4,6-dimethoxy-2-pyrimidinyl)amino] carbonyl]amino]sulfonyl]-1-methyl-1*H*-pyrazole-4-carboxylic acid] plus 28 g ai ha^{-1} carfentrazone [α,2-dichloro-5-[4-(difluoromethyl)-4,5-dihydro-3-methyl-5-oxo-1*H*-1,2,4-triazol-1-yl]-4-fluorobenzenepropanoic acid, ethyl ester] plus 0.25% v/v nonionic surfactant[4] was applied 25 DA permanent flood for control of hemp sesbania and Indian jointvetch (*Aeschynomene indica* L.). In 2004, hemp sesbania and Indian jointvetch were removed by hand.

Weed control and rice injury ratings were made 8 DA EPOST, and 8, 21, 35 and 49 DA LPOST. Weed control and injury ratings were visually estimated using a scale of 0 to 100%, where 0 = no injury and 100 = plant death. When present, injury consisted of a slight chlorosis at the apical meristem for the imazethapyr-resistant rice and chlorosis at the leaf margins of the glufosinate-resistant rice.

Rice and red rice height were recorded 47, 60, 75, 90, and 108 DA planting. Height measurements were taken from two plants per plot from the ground to the tip of the tallest leaf or from the ground to the tip of the panicle at harvest. Rice and red rice percent heading (panicle emergence) was collected until plots reached 50% panicle emergence.

Plots were harvested on August 27, 2002, September 3, 2003, and September 20, 2004. Yield was collected from the center 0.75 by 6 m area of the plot using a small plot combine. Grain yield was adjusted to 12% moisture.

Total milling data were obtained using a modified number two McGill miller. A 125-g sample from each plot was milled for 30 s and weight was recorded. Head rice data were obtained using a shaker-type sizing device to

[4] Nonionic surfactant Latron AG-98® is a mixture of alkylaryl polyoxyethylene glycols. Dow AgroSciences LLC, 9330 Zionsville Road, Indianapolis, IN 46268.

separate rice grains that were at least 3/4 the length of a full grain from smaller broken grains. Long grain samples were separated using a #10 plate on top with a #12 plate on bottom; medium grain samples were separated using a #7 plate on top and #10 plate on bottom. The sample remaining was weighed and recorded as head rice. Total milling and head rice percent were found by multiplying the weight of each sample by 0.8. Rice samples were then graded to United States standards for milled rice (United States Standards for Rice 1995).

Data were analyzed using the Mixed Procedure of SAS (SAS Institute 2003) with year used as a random factor. Years, replication (nested within years), and all interactions containing either of these effects were considered random effects; treatment was considered a fixed effect. Considering year or combination of year as random effects permits inferences about treatments over a range of environments (Carmer et al 1989; Hager et al. 2003). Type III statistics were used to test all possible effects of fixed factors (flood management, herbicide treatment, and presence of red rice) and least square means were used for mean separation at a 5% probability level ($p \leq 0.05$).

Results and Discussion

Weed Control. Hemp sesbania control was evaluated 21 DALPOST application (before removal from the study) in 2002 and 2004. Hemp sesbania control was at least 98% regardless of permanent flood establishment timing with two glufosinate applications (Table 3.1). In contrast, hemp sesbania control was less than 35% when treated with imazethapyr at any timing and no benefit was observed from early permanent flood establishment. As others have reported, hemp sesbania control cannot be expected with imazethapyr alone (Dillon et al 1999; Pellerin et al. 2003; Scherder et al. 2001; Webster and Baldwin 1998).

Table 3.1. Effect of flood management on hemp sesbania control with glufosinate and imazethapyr 21 days after late postemergence application in 2002 and 2004 at Crowley, Louisiana.[a,b]

			Permanent flood establishment[c]		
Herbicide	Rate	Timing	3 DAS	14 DAS	27 DAS
	g ai ha^{-1}			%	
Glufosinate	0		0 e	0 e	0 e
	500	EPOST fb LPOST	98 a	98 a	98 a
Imazethapyr	0		0 e	0 e	0 e
	70 fb 70	PRE fb MPOST	19 c	34 b	14 cd
	70 fb 70	EPOST fb LPOST	23 bc	2 de	17 c

[a] Data were averaged over red rice presence.

[b] Abbreviations: DAS, days after seeding; EPOST, early postemergence, applied at the two- to three-leaf rice stage; fb, followed by; MPOST, mid postemergence, applied at the three- to four-leaf rice stage; PRE, preemergence; LPOST, late postemergence, applied at the four-leaf to one-tiller rice growth stage.

[c] Means followed by the same letter were not significantly different according to the t-test on difference of least square means at P = 0.05. Letters are used to make comparison within and across columns.

Table 3.2. Red rice, barnyardgrass, and Amazon sprangletop control at 49 days after late postemergence application of glufosinate and imazethapyr, 2002 through 2004 at Crowley, Louisiana.[a,b]

Herbicide	Rate	Timing	Control[c] ORYSA	ECHCG	LEFPA
	g ai ha^{-1}		%	%	%
Glufosinate	0		0 b	0 c	0 c
	500	EPOST fb LPOST	96 a	98 a	98 a
Imazethapyr	0		0 b	0 c	0 c
	70 fb 70	PRE fb MPOST	95 a	98 a	96 a
	70 fb 70	EPOST fb LPOST	97 a	97 b	79 b

[a] Data were averaged over flood management system and red rice presence.
[b] Abbreviations: ECHCG, barnyardgrass; EPOST, early postemergence, applied at the two- to three-leaf rice stage; fb, followed by; MPOST, mid postemergence, applied at the three- to four-leaf rice stage; LEFPA, Amazon sprangletop; LPOST, late postemergence, applied at the four-leaf to one-tiller rice growth stage; PRE, preemergence; ORYSA, red rice.
[c] Means within a column followed by the same letter were not significantly different according to the t-test on difference of least square means at P = 0.05.

Glufosinate controlled red rice, barnyardgrass, and Amazon sprangletop 96 to 98% (Table 3.2). With the exception of one imazethapyr treatment, red rice, barnyardgrass, and Amazon sprangletop control were at least 95%. Imazethapyr applied PRE fb POST controlled Amazon sprangletop 96%, while two POST applications resulted in 79% control. In an evaluation of acetolactate synthase inhibiting (ALS) herbicides, Webster and Masson (2000) found nicosulfuron controlled Amazon sprangletop 80% at a 2X rate, but all other herbicides, including imazethapyr resulted in less than 60% control of Amazon sprangletop when applied POST at a 2X rate.

Rice and Red Rice Response. Rice injury was 5% or less in the glufosinate- and imazethapyr-resistant rice for all treatments (data not presented). In the glufosinate system, herbicide application, flood establishment, and weed interference did not delay rice heading (Table 3.3). In the imazethapyr system, rice reached 50% heading 2 to 5 d later when weed interference was removed from the plots and the permanent flood was established 3 or 27 DAS, while no difference was observed when the permanent flood was established 14 DAS. It may be that as interference between rice and weeds increases, resources become limiting and rice is forced to produce panicles sooner compared with rice in monoculture. Conversely, red rice d to 50% heading was different when the permanent flood was established early or late. Imazethapyr applied PRE fb MPOST and flooded 3 DAS delayed red rice heading 7 d compared with the nontreated. The remaining three treatments in the 3 and 14 DAS flood establishment systems resulted in red rice heading 7 to 9 d before the respective nontreated. Red rice, compared with its respective glufosinate and imazethapyr treatments, reached 50% heading 3 d before to 12 d after in the 3 DAS flood establishment, 6 d before or after when the permanent flood was established 14 DAS, and 2 d before or after when the flood was established 27 DAS. Regardless of flood management or herbicide

Table 3.3. Days to 50% rice and red rice heading when treated with glufosinate and imazethapyr under different flood management systems.[a,b]

			Rice			Red rice		
			Permanent flood establishment			Permanent flood establishment		
Herbicide	Rate	Timing	3 DAS[c]	14 DAS	27 DAS	3 DAS	14 DAS	27 DAS
	g ai ha^{-1}			d[e]			d	
Glufosinate	0		76 c-f[d]	75 e-g	76 c-f	77 bc	76 c	77 bc
	500	EPOST fb LPOST	77 c-e	74 g	75 e-g	70 d	80 ab	77 bc
Imazethapyr	0		75 e-g	75 e-g	75 e-g	76 c	77 bc	77 bc
	70 fb 70	PRE fb MPOST	80 a	75 e-g	77 cd	83 a	69 d	77 bc
	70 fb 70	EPOST fb LPOST	79 ab	76 c-f	77 bc	67 d	70 d	76 c

[a] Data were averaged over years and red rice presence.
[b] Abbreviations: d, days; EPOST, early postemergence, applied at the two- to three-leaf rice stage; fb, followed by; MPOST, mid postemergence, applied at the three- to four-leaf rice stage; PRE, preemergence; LPOST, late postemergence, applied at the four-leaf to one-tiller rice growth stage.
[c] To determine d after MPOST application subtract 30 d and to determine d after LPOST application subtract 23 d.
[d] Means followed by the same lowercase letter were not significantly different according to the t-test on difference of least square means at P = 0.05. Letters are only used for comparisons within rice or within red rice.

system, the extended and overlapping heading of rice and red rice creates the possibility of outcrossing or movement of the herbicide resistant traits from rice to red rice.

At harvest, rice plant height for both the glufosinate and imazethapyr systems was reduced 8 to 12% in the nontreated, respectively (Table 3.4). There was no difference within each system in total or whole milling yield. After milling, graded samples were U.S. number 1 or 2 for plots receiving glufosinate or imazethapyr. The average grade for nontreated plots was U.S. number 4. There are no loan discounts for U.S. number 1 or 2, but rice that grades U.S. number 4 results in a $0.60 discount hundredweight^{-1} (Farm Service Agency Online 2004). The U.S. number 4 grade was the result of red rice contamination exceeding 4% of the milled rice sample. Red rice infested rice (nontreated) was difficult to harvest due to the taller-growing red rice plants that tend to lodge, and the increased biomass that red rice produces that must be processed by the combine. The reduction in efficiency and increase in harvest time due to red rice contamination is difficult to quantify, but also increases costs and reduces profit for the producer.

When the flood was established 3 DAS in the nontreated, red rice panicle production was reduced 39 to 45% compared with the other two permanent flood establishment systems (Table 3.5). Early flood establishment reduced red rice emergence to the brief drainage period for rice establishment; whereas in the other two systems multiple wetting and drying cycles allowed extended red rice emergence. When treated with either imazethapyr or glufosinate, red rice produced less than 1 panicle plot^{-1}. The potential disadvantage to the continuous flood system is that standing water at the time of herbicide application may prevent adequate coverage and/or imazethapyr binding to the soil to provide optimum red rice control.

When no herbicide application was made, rice yields were reduced 63 to 82% (Table 3.5). Yield of the glufosinate- and imazethapyr-resistant rice

Table 3.4. Effect of glufosinate and imazethapyr application on rice height and grain quality from 2002 through 2004 at Crowley, Louisiana.[a,b]

Herbicide	Rate	Timing	Plant height[c]	Whole milling yield	Total milling yield	USDA grade
	g ai ha^{-1}		— cm —	— % —	— % —	— # —
Glufosinate	0		77 c	60 c	61 b	4 a
	500	EPOST fb LPOST	84 b	62 bc	62 b	1 b
Imazethapyr	0		85 b	62 a-c	62 ab	4 a
	70 fb 70	PRE fb MPOST	96 a	64 a	63 a	2 b
	70 fb 70	EPOST fb LPOST	97 a	64 ab	63 a	1 b

[a] Data were averaged over flood management system and red rice presence.
[b] Abbreviations: EPOST, early postemergence, applied at the two- to three-leaf rice stage; fb, followed by; MPOST, mid postemergence, applied at the three- to four-leaf rice stage; PRE, preemergence; LPOST, late postemergence, applied at the four-leaf to one-tiller rice growth stage.
[c] Means within a column followed by the same letter were not significantly different according to the t-test on difference of least square means at P = 0.05.

Table 3.5. Effect of glufosinate and imazethapyr application and flood management system on red rice panicle density and rough rice yield from 2002 to 2004 at Crowley, Louisiana.[a,b]

			Red rice panicle density[c]			Rough rice yield		
			Permanent flood establishment			Permanent flood establishment		
Herbicide	Rate	Timing	3 DAS	14 DAS	27 DAS	3 DAS	14 DAS	27 DAS
	g ai ha^{-1}		# m^{-2}			kg ha^{-1}		
Glufosinate	0		8 b	14 a	15 a	1800 e	980 e	1290 e
	500	EPOST fb LPOST	1 c	<1 c	<1 c	4930 cd	5490 a-c	5520 a-c
Imazethapyr	0		8 b	14 a	14 a	1670 e	1640 e	1070 e
	70 fb 70	PRE fb MPOST	<1 c	<1 c	1 c	4960 cd	5270 a-d	6080 a
	70 fb 70	EPOST fb LPOST	1 c	<1 c	<1 c	4600 d	5080 b-d	5800 ab

[a] Rough rice yield was averaged over presence or absence of red rice.
[b] Abbreviations: DAS, days after seeding; EPOST, early postemergence, applied at the two- to three-leaf rice stage; fb, followed by; MPOST, mid postemergence, applied at the three- to four-leaf rice stage; PRE, preemergence; LPOST, late postemergence, applied at the four-leaf to one-tiller rice growth stage.
[c] Means followed by the same letter were not significantly different according to the t-test on difference of least square means at P = 0.05. Letters are only used for comparisons within red rice panicle density or within rough rice yield.

generally increased the sooner the flood was established; however, no statistical difference was observed. Earlier flood establishment reduced the length of time for weed germination and emergence. In contrast, when herbicides were used, rice yield increased the longer the establishment of permanent flood was delayed. When the weed interference was removed using herbicides, it is likely the rice root system had longer to become established and resulted in increased yields. Regardless of the herbicide system used, there was no difference in yield within each flood management system for either herbicide. Imazethapyr applied PRE fb MPOST or EPOST fb LPOST yielded 1120 and 1200 kg ha^{-1} more when delayed flood management was used compared with the continuous flood management system, respectively.

Glufosinate- and imazethapyr-resistant rice are important technologies for rice producers that cultivate rice in fields infested with red rice. In this study, rice yields were 2.7 to 5.7 times higher when treated with either herbicide. From 1999 to 2003, average rice yield in Louisiana was 6440 kg ha^{-1} and price $hundredweight^{-1}$ in the U.S. was $5.51 (Agricultural Statistics Board 2003; USDA/NASS 2004). Assuming red rice did not lower rice yield, a $0.60 $hundredweight^{-1}$ loan discount on 6440 kg ha^{-1} based on USDA number four grade would cost a rice producer $85.09 ha^{-1}. When yield reductions, time, and equipment wear are added to the costs, it becomes apparent how valuable this technology is to the producer.

While imazethapyr-resistant rice has been commercially released, it is important that glufosinate-resistant rice technology be made available to rice producers. Before this study, no research documented the effect of glufosinate and imazethapyr application on red rice heading. The unpredictability of red rice heading when treated with each herbicide and the overlapping heading period of rice and red rice exhibit the distinct possibility that movement of the herbicide-resistance genes will eventually be incorporated into red rice. Without the commercial release of additional technologies such as glufosinate-resistant rice that control red rice with alternative modes of action, this technology may be short-lived and producers will be right back where they started.

Although early flooding can reduce weed populations, it may not be in the best interest of these technologies if proper herbicide coverage cannot be obtained and weeds, especially red rice, are not controlled. Another factor that deserves research is delaying the permanent flood establishment after the final POST herbicide application. This study was established using small plot sizes that allow permanent flood establishment within several hours. This is not realistic in production fields where emergence of weeds may occur in the 5 d or more required to establish the permanent flood.

Glufosinate provides no residual red rice control. In a glufosinate system, proper management may require multiple applications to fields with a shallow permanent flood to adequately control red rice. In an imazethapyr system, PPI or PRE application has resulted in optimum red rice and Amazon sprangletop control in this study and others (Ottis et al. 2003; Pellerin and Webster 2004; Steele et al. 2002; White and Hackworth 1999). The effectiveness and longevity of this technology will be determined by the effective use of the herbicides to achieve effective red rice control. It will be important for rice producers to apply herbicides timely according to weed size, manage water to maximize red rice control, and follow stewardship practices aimed at preventing herbicide resistance in red rice. The availability of additional modes of action to control red rice will be critical for the longevity of imazethapyr-resistant rice.

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CHAPTER 4

RICE AND RED RICE RESPONSE TO GLUFOSINATE APPLICATION TIMING

Introduction

Red rice (*Oryza sativa* L.) was first reported as a weed problem in the U.S. in 1846 in the Carolinas and spread to Louisiana by 1900 (Craigmiles 1978; Dodson 1900). Red rice possesses many undesirable characteristics such as light green leaf color, profuse tillering, red pericarp, early and easily shattering seeds, seed dormancy, leaf and seed pubescence, awned lemmas, tall stature, weak stems, and susceptibility to lodging (Craigmiles 1978; Kwon et al. 1992; Noldin et al. 1999). Most of these undesirable characteristics distinguish red rice from rice. In addition, red rice germinating during cool, early season temperatures can serve as an alternate host for diseases and insects that infest cultivated rice (Aldrick et al. 1973; Babatola 1980; Eastin 1978).

Red rice in the southern U.S. is composed primarily of strawhull and blackhull types (Diarra et al. 1985a). Strawhull red rice is characterized by tall stature, moderate tillering, drooping panicles, awnless and awned seed, and tan to brown lemma and palea (Diarra et al. 1985a; Sonnier 1978). Blackhull types are tall stature, densely tillering, compact plants that mature late, produce awned seed with black lemma and palea. Both types of red rice emerge earlier in the season, grow taller, and produce more panicles with seed that shatters more readily than cultivated rice (Diarra et al. 1985a).

Another aspect influencing interference between crops and weeds is the length and period of weed presence. Research has shown competition between rice and red rice is not severe during the first 50 days of emergence (Diarra et al. 1985b; Kwon et al. 1991a, 1991b; Smith 1988). Smith (1988) reported season-long competition from 3 or 19 red rice plants m^{-2} reduced rice yields 10 and 50%, respectively. Red rice at 20 plants m^{-2} reduced yields of 'Lemont' and ‘Newbonnet’ when allowed to compete for at least 60 days. Lemont and Newbonnet yields were reduced 78 and 51%, respectively, when red rice competed for 120 days. Yield reductions could be attributed to reduction in panicle number m^{-2}, panicle length, spikelets $panicle^{-1}$, filled florets $panicle^{-1}$, and total milled and head rice yields (Kwon et al. 1991b). Twenty-four red rice plants m^{-2} reduced yield 10% when allowed to compete within the first 40 days after emergence, but reduced rice yield 75% when allowed to compete during the entire growing season (Fischer and Ramirez 1993).

In the past, red rice management has involved a combination of mechanical, cultural, and chemical control measures. The introduction of crops resistant or tolerant to glyphosate [*N*-(phosphonomethyl)glycine], glufosinate [2-amino-4-(hydroxymethylphosphinyl)butanoic acid] and imazethapyr {2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-5-ethyl-3-pyridinecarboxylic acid} have provided producers herbicides capable of controlling red rice (Klee et al. 1987; Thompson et al. 1987). Glyphosate applied to two-leaf to three-tiller red rice in soybean [*Glycine* max (L.) Merr.] resulted in 88 to 91% control of red rice 2 wks after treatment and 97% seedhead reduction when applied to two- to three-tiller red rice (Askew et al. 1998). Red rice control in water-seeded rice culture with glyphosate was at least 94% at 14 d after treatment (DAT) with glyphosate applied early postemergence (EPOST), EPOST followed by (fb) late postemergence (LPOST) or postflood (POFL) and at least 85% at 30 DAT (Webster and Lanclos 2000).

Incorporation of the bialophos [4-(hydroxymethylphosphinyl)-L-2-aminobutanoyl-L-alanyl-L-alanine] resistance (BAR) gene in crops such as rice has conferred resistance to postemergence applications of glufosinate (Christou et al. 1991). Though not commercially available, BAR-transformed rice may one day provide another tool for the control of red rice. Current research indicates 90 to 100% red rice control can be achieved with two applications of 0.38 kg ai ha^{-1} glufosinate applied 21 to 42 days after emergence (DAE) (Braverman and Linscombe 1994; Lanclos et al. 2003; Leon et al. 2002; Wheeler et al. 1999).

A problem often encountered with herbicide resistant or tolerant cultivars is the injury caused by herbicide application at certain growth stages or under extreme environmental conditions. After the initial transformation event, breeding efforts can improve the level of resistance. Early glufosinate-resistant crops obtained from 'Koshihikari' and 'Gulfmont' transformed rice cultivars resulted in 0 to 53% injury when treated with glufosinate. Subsequent rice transformation events and breeding efforts using 'Cypress' and 'Bengal' have generally resulted in crop injury ratings less than 10% (Lanclos et al. 2003; Leon et al. 2002; Sankula et al. 1997a, 1997b; Wheeler et al. 1999).

The importance of achieving 100% red rice control with any of the herbicide-resistant rice cultivars is to maintain the efficacy of the herbicides with respect to red rice control. Improper management of herbicide-resistant cultivars could potentially result in loss of the technology due to outcrossing of the herbicide-resistance to red rice. Studies have shown that overall gene flow is from cultivated rice to red rice (Oka and Chang 1959). The florets of red rice tend to remain open one or more hours longer than cultivated rice which most likely influences gene flow (Roy 1921). Field studies using herbicide-resistant rice have resulted in outcrossing of herbicide resistant/tolerant traits (Dillon et al. 2002; Oard et al. 2000).

In order to preserve the use of this technology and prevent outcrossing, this research was conducted to examine the effect of glufosinate application timings on red rice control and seed head production. The effects of glufosinate applied to rice at various intervals during the production season were measured to determine the effects of glufosinate on BAR-transformed rice parameters and yield.

Materials and Methods

Studies were conducted at the Rice Research Station in Crowley, Louisiana, from 2002 to 2004. The soil type was a Crowley silt loam (fine montmorillonitic, thermic, Typic Albaqualf) with pH 6.4 and 0.79% organic matter. A randomized complete block experimental design was used with 4 replications. 'LL 401' (2002) and 'LL 001' (2003 and 2004), both medium grain, Bengal-derived glufosinate transformed lines were chosen for the glufosinate treatments. Glufosinate treatments consisted of 0.50 kg ha^{-1} glufosinate applied 14, 28, 42, 56, and 70 d after rice emergence. Each application was followed 7 d later by 0.41 kg ha^{-1} glufosinate. Each treatment was infested with and without red rice, and a nontreated with and without red rice was included for comparison.

Seedbed preparation consisted of fall and spring disking fb a pass with a two-way bed conditioner equipped with S-tine harrows set at a 7.5-cm operating depth. The spring bed conditioning was fb 280 kg ha^{-1} 8-24-24 fertilizer ($N-P_2O_5-K_2O$). A final pass of the bed conditioner was made for fertilizer incorporation. Rice was drilled at 113 kg ha^{-1} April 30, 2002, May 12, 2003, and at 78 kg ha^{-1} May 13, 2004 with eight 19-cm rows, 5.2-m long.

After planting, red rice was broadcast by hand at a predetermined rate based on percent seed germination to establish 20 plants m^{-2} over the designated red rice-infested treatments. Based on earlier studies, the red rice was seeded at rates that caused approximately 50% yield reduction (Baldwin 1978; Navarro 1985; Fischer and Ramirez 1993; Smith 1988).The experimental area was surface irrigated 5, 3, and 2 times to maintain adequate soil moisture and rice growth in 2002, 2003, and 2004, respectively. A second nitrogen application was applied one d prior to permanent flood establishment consisting of 280 kg ha^{-1} urea (46% nitrogen). A permanent 6-cm flood was established after the 21 DAE application on June 6, 2002, June 11, 2003, and June 16, 2004, and maintained until 2 wk prior to harvest.

Herbicide applications were made using a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} solution at 190 kPa. In order to remove weeds other than red rice, 18 g ai ha^{-1} carfentrazone [α,2-dichloro-5-[4-(difluoromethyl)-4,5-dihydro-3-methyl-5-oxo-1*H*-1,2,4-triazol-1-yl]-4-fluorobenzenepropanoic acid, ethyl ester] plus 86 g ai ha^{-1} fenoxaprop-p-ethyl [(±)-2-[4-[(6-chloro-2-benzoxazolyl)oxy]phenoxy]propanoic acid] was broadcast applied in 2002; 42 g ai ha^{-1} cyhalofop-butyl [2-[4-(4-cyano-2-fluorophenoxy)phenoxy]propanoic acid, butyl ester, (R)] plus 1% crop oil concentrate (COC)[5] in 2003; and 42 g ha^{-1} cyhalofop-butyl plus 1% COC fb 86 g ha^{-1} fenoxaprop-p-ethyl 11 d later in 2004.

Rice and red rice height were recorded 40, 60, and 104 d after emergence (DAE). Plant heights were recorded from the ground to the tip of the tallest leaf or to the extended panicle at harvest. Red rice heights were taken from two strawhull and two blackhull plants $treatment^{-1}$ and averaged. Percent heading (panicle emergence) was collected until all treatments reached 50% panicle emergence. Red rice panicle density $plot^{-1}$ (8 m^2) was recorded prior to harvest at 104 DAE. Yield was collected from the center 0.75 by 6 m area with a small plot combine in 2002 and 2003. Grain yield was adjusted to 12% moisture.

Data were analyzed using the Mixed Procedure of SAS (SAS Institute 2003) with year used as a random factor. Years, replication (nested within years), and all interactions containing either of these effects were considered random effects; treatment was considered a fixed effect. Considering year or combination of year as random effects permits inferences

[5] Agridex, a mixture of 83% paraffinic mineral oil and 17% polyoxyethylene sorbitan fatty acid ester. Helena Chemical Company, 5100 Poplar Avenue, Memphis, TN 38137.

about treatments over a range of environments (Carmer et al 1989; Hager et al. 2003). Type III statistics were used to test all possible effects of fixed factors (presence of red rice and glufosinate timing) and least square means were used for mean separation at 5% probability level ($p \leq 0.05$).

Results and Discussion

Rice. Rice injury did not exceed 10% regardless of application timing (data not shown) and consisted of a slight chlorosis around the margins of the leaf blade similar to that reported by others (Lanclos et al. 2003; Ohmes et al. 2001; Wheeler et al. 1999). Averaged across red rice presence, d to 50% rice heading occurred 89 to 90 DAE (Table 4.1).

By 69 DAE, there were no differences in rice plant height regardless of treatment (data not shown). At maturity, the presence of red rice did not significantly affect rice plant height; therefore, treatments were averaged over red rice presence. Rice plant height was 77 to 82 cm (Table 4.1). When treated with glufosinate, rice plant heights were within 4-cm of the nontreated. Delaying glufosinate treatment beyond 21 DAE reduced plant heights 2 to 5 cm compared with a 14 fb 21 DAE application timing. In previous research, nontreated Bengal and nontreated, glufosinate-transformed 'BNGL 11/62' were 8 to 11 cm taller than glufosinate treated rice (Lanclos et al. 2003). This indicates that LL 001 and LL 401, newer glufosinate-transformed rice lines derived from Bengal, may exhibit increased resistance to glufosinate compared with BNGL 11/62.

Red Rice. Red rice control was at least 98% when glufosinate was applied after permanent flood establishment or 28 DAE (Table 4.2). Glufosinate applied at 14 fb 21 DAE controlled red rice 91%. Red rice remaining was either not completely controlled or red rice emerged immediately after application and before permanent flood establishment. Red rice control observed in this study is similar to that reported by others based on red rice growth stage and sequential applications (Hessler et al. 1998; Ohmes et

Table 4.1. Days to 50% heading and plant height at rice maturity for glufosinate-resistant rice treated with 0.50 fb 0.41 kg ai ha^{-1} glufosinate at various timings (days after rice emergence) from 2002 to 2004.[a,b]

	Rice	
Timing	Days to 50% heading	Plant height
d after rice emergence	–– d ––	–– cm ––
14 fb 21	89 b	82 a
28 fb 35	90 a	79 bc
42 fb 49	90 a	77 c
56 fb 63	90 a	79 bc
70 fb 77	90 a	80 ab
No glufosinate	90 a	81 ab

[a] Data were averaged over red rice presence.
[b] Means within a column followed by the same letter were not significantly different according to the t-test on difference of least square means at P = 0.05.

Table 4.2. Red rice control 28 days after final glufosinate application, plant height, and panicle density at maturity when treated with 0.50 fb 0.41 kg ai ha^{-1} glufosinate at different application timings from 2002 to 2004.

	Red Rice		
Timing[a]	Control[b]	Plant height[b]	Panicle density
	— % —	— cm —	— # 8 m^{-2} —
No glufosinate	0 c	139 a	151 a
14 fb 21	91 b	122 b	16 b
28 fb 35	98 a	128 b	<1 b
42 fb 49	98 a	112 c	5 b
56 fb 63	98 a	94 c	2 b
70 fb 77	99 a	——[c]	0 b

[a] Glufosinate application timing (d after emergence).
[b] Means within a column followed by the same letter were not significantly different according to the t-test on difference of least square means at P = 0.05.
[c] Indicates the absence of live red rice plants in glufosinate-treated plots.

al. 2001; Sankula et al. 1997a, 1997b; Wheeler et al. 1999). There was no difference in red rice d to 50% heading regardless of treatment for plots producing viable red rice seed (data not shown). It should be noted that red rice d to 50% heading occurred 88 to 96 DAE and rice d to 50% heading occurred 89 to 90 DAE for all application timings. Therefore, it cannot be assumed glufosinate application will provide differences in heading between rice and red rice; therefore, outcrossing is possible.

All treatments reduced red rice height compared with the nontreated (Table 4.2). Initial glufosinate applications 14 or 28 DAE reduced red rice plant heights 11 to 17 cm, while initial glufosinate applications 42 and 56 DAE reduced heights 27 to 45 cm.

Nontreated red rice averaged 151 panicles 8 m^{-2} (Table 4.2). Although red rice control was 91% when glufosinate was applied 14 fb 21 DAE, the red rice remaining produced 16 panicles 8 m^{-2}. Glufosinate applied from 28 to 77 DAE (after permanent flood establishment) resulted in 0 to 5 red rice panicles 8 m^{-2}. Glufosinate applied at 70 DAE coincided with red rice heading, but was before anthesis. Red rice treated at this timing produced sterile seed heads; therefore, panicle height was not recorded and panicle number was recorded as zero. Although the late application is promising for reducing red rice seed production and reducing the potential for outcrossing, only applications occurring at or before 35 DAE would meet the pre harvest application interval currently found on the glufosinate label[6] for canola (*Brassica napus* L.), corn (*Zea mays* L.), and soybean.

Rice Grain Yield. At harvest, no difference in rice grain moisture was observed regardless of treatment (data not shown). Season long red rice interference reduced rice yield to 1730 kg ha^{-1} which was 47% less than the

[6] Liberty herbicide label. Bayer CropScience LP, PO Box 12014, 2 T. W. Alexander Drive, Research Triangle Park, NC 27709.

nontreated, red rice free treatment (Table 4.3). Regardless of red rice presence, rice yields were optimized when glufosinate was applied within 49 DAE. In the red rice-infested treatments, rice yields decreased for each additional 28 DAE interval that red rice was not treated with glufosinate. Rice yield was decreased when glufosinate was applied 56 to 77 DAE compared with the 14 to 49 DAE treatment. The rice growth stage 56 to 77 DAE coincided with panicle elongation to 40% heading. This application timing corresponds to the pre-boot to boot stage of growth when Lanclos et al. (2003) reported a reduction in rice yield from glufosinate application.

In this study, yields of treatments containing red rice treated at 14 fb 21 DAE yielded 1370 kg ha^{-1} more than noninfested rice treatments. Fischer and Ramirez (1993) found 24 red rice plants m^{-2} reduced yield 10% when allowed to compete within the first 40 days after emergence. Others have shown that weed competition prior to 50 DAE is not severe with respect to rice yield (Diarra et al. 1985b; Kwon et al. 1991a, 1991b; Smith 1988). Previous research indicates glufosinate applications after the three- to five-lf growth stage, but prior to green ring resulted in higher yields (Lanclos et al. 2003; Sankula et al. 1997b). The development of LL 401 and LL 001 appear to be more tolerant to glufosinate than BNGL 11/62 since glufosinate applications before the three- to five-lf stage and at panicle initiation did not reduce yield nor result in an increase in grain moisture at harvest which would indicate a delay in maturity.

Based on the results of this study, two applications of at least 0.50 kg ha^{-1} glufosinate may be needed to achieve red rice control approaching 100% at the 14 fb 21 DAE timing. Glufosinate applied within 35 DAE to red rice infested rice resulted in maximum grain yield, reduced the duration of interference from red rice, and follows the current glufosinate label for

Table 4.3. Effect of weed interference and 0.50 fb 0.41 kg ai ha^{-1} glufosinate applied at different timings on glufosinate-resistant rice yield in 2002 and 2003 and P-values to compare the differences between treatment means.[a]

Treatment[b]	14/21[c]	28/35	42/49	56/63	70/77	NT[d]	14/21	28/35	42/49	56/63	70/77	Grain yield[e]
				P > |t|								kg/ha
No Red Rice												
NT	0.0015[f]	<0.0001	<0.0001	0.0029	0.0042	0.0110	<0.0001	<0.0001	<0.0001	0.0396	NS[c]	3290 g
14/21[e]		NS	NS	NS	NS	<0.0001	0.0244	NS	NS	NS	0.0045	5620 b-e
28/35			NS	NS	NS	<0.0001	0.0169	NS	NS	0.0130	<0.0001	5870 b-d
42/49				0.0404	0.0278	<0.0001	NS	NS	NS	0.0014	<0.0001	6260 ab
56/63					NS	<0.0001	0.002	NS	NS	NS	0.0061	5210 c-e
70/77						<0.0001	0.0001	0.0456	NS	NS	0.0094	5130 de
Red Rice												
NT							<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	1730 h
14/21[f]								NS	0.0228	<0.0001	<0.0001	6990 a
28/35									NS	0.0027	<0.0001	6150 a-c
42/49										0.0097	<0.0001	5920 b-d
56/63											NS	4590 ef
70/77												3790 fg

(Table 4.3 continued)

[a] Abbreviation: NS, not significantly different according to the t-test on differences of least square means at P = 0.05; NT - nontreated.

[b] Glufosinate was applied 0.50 fb 0.41 kg ha^{-1} at 14 fb 21 DAE – treatments 2 and 8; 28 fb 35 DAE – treatments 3 and 9; 42 fb 49 DAE – treatments 4 and 10; 56 fb 63 DAE – treatments 5 and 11; 70 fb 77 DAE – treatments 6 and 12; or no glufosinate – treatments with NT.

[c] Red rice density was 0 red rice plants m^{-2} for first six treatments.

[d] Red rice density was 20 red rice plants m^{-2} for remaining treatments.

[e] Means followed the same letter were not significantly different according to the t-test on difference of least square means at P = 0.05.

[f] Compare treatment means of rice grain yield using the P-values in the table.

grain crops. This study was the first to document that red rice, even when treated with glufosinate, may still head at the same time as rice. It is generally expected that injury to red rice from herbicide application would delay heading. In this study that was not the case. Although the number of red rice panicles was reduced, the panicles that were produced emerged at the same time rice was heading. Glufosinate-resistant rice is no different from imazethapyr-resistant rice in that the movement of herbicide resistance traits from rice to red rice is possible. Shortening the pre-harvest application interval for glufosinate may be necessary to allow for a late-season application after red rice panicle emergence to prevent flowering and transfer of the glufosinate-resistance traits to red rice.

The eventual use of this technology will require stewardship by the producer similar to the recommendations currently used in imazethapyr-resistant rice production (Anonymous 2004). Glufosinate-resistant rice would provide another management tool for red rice control and minimize the impact of red rice on rice harvest, yield, and grain quality. In addition, glufosinate would provide another herbicide mode of action to combat red rice especially in the event red rice becomes resistant to imazethapyr. Should imazethapyr-resistant red rice become widespread before the commercial release of glufosinate-resistant rice, the ability to grow consecutive rice crops on a field and alternate herbicide modes of action would not be possible.

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CHAPTER 5

WATER MANAGEMENT AND CHEMICAL CONTROL OF RED RICE IN WATER-SEEDED CLEARFIELD RICE PRODUCTION

Introduction

Genotypic and phenotypic similarities between rice and red rice make the control of red rice problematic. In the past, red rice management has involved a combination of mechanical, cultural, and chemical control measures (Flint 1993). Chemical control of red rice in rice is difficult due to the genetic similarities between the two. However, red rice has been found to be more sensitive to molinate (S-ethyl hexahydro-1*H*-azepine-1-carbothioate) and thiobencarb (S-[(4-chlorophenyl)methyl]diethylcarbamothioate) applied preplant in conjunction with pinpoint and continuous flood water management practices (Baker et al. 1986; Forner 1995; Sonnier and Baker 1980; Smith 1981). Water management involving continuous flooding alone resulted in 37 red rice seedlings m^{-2} compared with brief drainage or drainage lasting for two wks which resulted in red rice seedling emergence of 140 and 895 plants m^{-2}, respectively (Sonnier and Baker 1980). Combining molinate application and drain-flood or continuous flood water management, 89 to 96% control of red rice was achieved (Diarra et al. 1985; Smith 1981).

The introduction of crops resistant or tolerant to imazethapyr {2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-5-ethyl-3-pyridinecarboxylic acid} provided producers with a herbicide capable of controlling red rice during the production season (Klee et al. 1987; Thompson et al. 1987). In 1993, a chemically-induced mutation of Alexandria seed rice cultivar 'AS 3510' produced the first imidazolinone-resistant rice line named '93 AS-3510' (Croughan 1994). Further breeding efforts have since improved the tolerance of the imidazolinone-tolerant rice lines such that injury ratings are now consistently less than 15% (Masson and Webster 2001; Masson et al. 2001; Pellerin and Webster 2004; Steele et al. 2002). Imidazolinone-tolerant rice lines allow the application of acetolactate synthase (ALS) inhibiting herbicides such as imazethapyr to control red rice and other weeds both preemergence (PRE) and postemergence (POST) (Stidham and Singh 1991; Vencill 2002). Sequential applications of imazethapyr have consistently controlled red rice more than 90%, but seldom has 100% control been achieved (Dillon et al. 1999; Kurtz and Street 1999; Sanders et al. 1998; Steele et al. 2002). Because 100% control is seldom achieved and gene flow is typically from cultivated rice to red rice, numerous research studies have been conducted to find the optimum timing for imazethapyr application to maximize red rice control and minimize outcrossing potential (Dillon et al. 2002; Oard et al. 2000; Oka and Chang 1959; Roy 1921). Greenhouse research indicates red rice control can be influenced by application timing and soil moisture. Activity on red rice with imazethapyr applied preplant incorporated (PPI) increased as soil moisture decreased from 50% to 13%. Imazethapyr activity was not affected with respect to the soil moisture contents observed when applied POST to red rice (Zhang et al. 2001). Numerous studies have reported that sequential imazethapyr applications control red rice and barnyardgrass 92 to 98% with no difference being observed between imazethapyr applied PPI or PRE when it was followed by (fb) a POST application (Ottis et al. 2003; Pellerin and Webster 2004; Steele et al. 2002; White and Hackworth 1999).

The use of pregerminated seed, water management, and conservation tillage is utilized in Louisiana to manage red rice, reduce production costs, and contend with water pollution issues (Linscombe et al. 1999). Typically, water-seeded rice fields are mechanically tilled after the seeding flood has been established to destroy existing vegetation and create a uniform seedbed. This cultural practice is generally referred to as “mudding in” (Bollich and Feagley 1995).

Since 1998, no-till and stale seedbed conservation tillage acreage has fluctuated between seven and 15% of the water-seeded rice acreage (Anonymous

1998, 1999, 2000, 2001, 2002, 2003, 2004). Previous research has shown conservation tillage benefits include reducing soil erosion and conserving soil moisture, but rice seedling establishment and red rice control are sometimes diminished (Bollich 1992; Bollich and Feagley 1995). This research was conducted to evaluate weed and crop response in a simulated stale seedbed system compared with a system receiving tillage in the flood prior to water-seeding imidazolinone-tolerant rice. Evaluations were made to determine optimum timing of imazethapyr application after drainage for seedling establishment and prior to permanent flood establishment.

Materials and Methods

A study was conducted in Acadia Parish at the Rice Research Station, near Crowley, Louisiana; at R & D Research Farm in St. Landry Parish, near Washington, Louisiana; and at a producer location in Jefferson Davis Parish, near Jennings, Louisiana, in 2004. The soil type was a silt loam, sandy loam, and silt loam, for the Crowley, Washington, and Jennings locations, respectively.

Seedbed preparation at Crowley consisted of fall and spring disking fb a pass with a two-way bed conditioner equipped with S-tine harrows set at a 7.5-cm operating depth. The spring bed conditioning was fb application of 280 kg ha^{-1} 8-24-24 ($N-P_2O_5-K_2O$). A final pass of the bed conditioner was made before preplant flood establishment for incorporation of fertilizer. General agronomic practices consisting of a single disking and harrowing to establish a weed-free seedbed were used at the Jennings and Washington, Louisiana locations.

A split plot experimental design was used with water and tillage system (muddy- or clear-water seeding flood) as the main plot and herbicide treatment as the subplot. The seeding flood was established on the muddy-water system and a 10 by 10 by 240 cm landscaping timber was pulled over the soil surface to simulate “mudding in”. In the clear-water system, seeding occurred immediately prior to the establishment of the seeding flood in order to keep the water free of sediment and simulate clear-water seeding.

A long grain, imazethapyr-resistant cultivar, 'CL 161', was selected for the study. Imidazolinone treatments included 70 g ai ha^{-1} imazethapyr plus 1% v/v crop oil concentrate (COC)[7] applied 1, 3, or 5 d after draining for rice seedling establishment. The second 70 g ha^{-1} imazethapyr plus 1% v/v COC application was made either 7 d or 14 d after the 5 d after draining application. The permanent flood was established within 48 hr after the final imazethapyr application. A nontreated was included as a control. Plot size at Crowley and Jennings was 1.8 m wide by 5.2 m long and 3 m wide by 12 m long at Washington, Louisiana.

Rice was broadcast on March 31, May 3, and May 25, 2004, at Jennings, Washington, and Crowley, Louisiana, respectively. Pregerminated rice was broadcast at 78 kg ha^{-1} at Jennings and Crowley, Louisiana, and 160 kg ha^{-1} at Washington, Louisiana. Within 24 hr, the flood was drained to allow seedling establishment. Surface irrigations were applied twice to ensure adequate moisture for herbicide activation and ideal rice growing conditions. Each test received a nitrogen application applied into the flood consisting of 280 kg ha^{-1} urea (46% nitrogen) at Crowley and Jennings and 170 kg ha^{-1} urea at Washington.

Herbicide applications were made using a CO_2-pressurized backpack sprayer delivering 140 L ha^{-1} solution at 190 kPa. At Jennings, Louisiana, a broadcast application of 52 g ai ha^{-1} halosulfuron [3-chloro-5-[[[[(4,6-dimethoxy-2-pyrimidinyl)amino]carbonyl]amino]sulfonyl]-1-methyl-1*H*-pyrazole-4-carboxylic acid] plus 28 g ai ha^{-1} carfentrazone [α,2-dichloro-5-[4-(difluoromethyl)-4,5-dihydro-3-methyl-5-oxo-1*H*-1,2,4-triazol-1-yl]-4-

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[7] Agridex, a mixture of 83% paraffinic mineral oil and 17% polyoxyethylene sorbitan fatty acid ester. Helena Chemical Company, 225 Schilling Boulevard, Collierville, TN 38017.

fluorobenzenepropanoic acid, ethyl ester] plus 0.25% v/v nonionic surfactant was applied for control of hemp sesbania [*Sesbania exaltata* (Raf.) Rydb. ex A. W. Hill] and Indian jointvetch (*Aeschynomene indica* L.). At Crowley, Louisiana, hemp sesbania and Indian jointvetch were removed by hand.

Weed control and rice injury ratings were made 21, 35, and 60 d after final POST application. Weed control and injury ratings were visually estimated on a scale of 0 to 100%, where 0 = no injury and 100 = plant death.

Rice height was recorded at harvest in Crowley and Jennings, Louisiana. Height measurements were taken from two plants per plot from the ground to the tip of the extended panicle. Rice percent heading (panicle emergence) was recorded at Crowley and Jennings, Louisiana.

Plots were harvested on August 1, 2004 at Jennings, Louisiana, and September 20, 2004 at Crowley, Louisiana. Yield was collected from the center 0.75 by 6 m area of the plot using a small plot combine. Grain yield was adjusted to 12% moisture.

Data were analyzed using the Mixed Procedure of SAS (SAS Institute 2003) with year used as a random factor. Years, replication (nested within years), and all interactions containing either of these effects were considered random effects; treatment was considered a fixed effect. Considering year or combination of year as random effects permits inferences about treatments over a range of environments (Carmer et al 1989; Hager et al. 2003). Type III statistics were used to test all possible effects of fixed factors (water tillage system and imazethapyr timing) and least square means were used for mean separation at 5% probability level ($p \le 0.05$).

Results and Discussion

Weed Control. At 60 d after final POST application, red rice control was no more than 89% when 140 g ha^{-1} imazethapyr was applied immediately prior to permanent flood in the clear-water seeding system (Table 5.1). All other clear- and muddy-water herbicide applications controlled red rice 90 to 95%.

Application timing was more critical for adequate barnyardgrass control. Imazethapyr applied 1, 3, or 5 d after draining fb by another application 12 d after initial drainage controlled barnyardgrass 88 to 94% in the clear-water seeding system (Table 5.1). Applying imazethapyr 1 fb 19 d after initial drainage controlled barnyardgrass 92%, but delaying the initial application any longer resulted in control equal to or less than 80% in the clear-water system. A single 140 g ha^{-1} imazethapyr application at 12 or 19 d after initial draining controlled barnyardgrass 86 and 76%, respectively. In the muddy-water seeding system, red rice and barnyardgrass control were 93 and 88%, respectively, regardless of imazethapyr timing.

Establishing a smooth seedbed using tillage in the water immediately prior to rice seeding destroyed any weeds that had germinated prior to establishing the seeding flood. This provided more time for herbicide application, although it did not necessarily improve weed control over the clear-water seeding system. Weed control in this study was similar to other studies in which sequential imazethapyr applications control red rice and barnyardgrass 92 to 98% (Levy 2004; Ottis et al. 2003; Pellerin and Webster 2004; Steele et al. 2002; White and Hackworth 1999).

Rice Response. Regardless of water tillage or application timing, rice injury was less than 5% and d to 50% heading was reached at 70 d after rice emergence (data not shown). At harvest, no difference in plant height was observed (data not shown).

Rice yields were 4080 to 5790 and 3630 to 5300 kg ha^{-1} for the clear- and muddy-water seeding systems, respectively (Table 5.2). Weed control was not a good indication of rice yield since treatments controlling barnyardgrass the least (73 and 76%) were two of the four highest yielding treatments (Table 5.1). However, this does indicate that imazethapyr was effective in providing rice a competitive advantage over the weeds and that

Table 5.1. Effect of imazethapyr application timing, preplant tillage, and water management on red rice and barnyardgrass control 60 days after final postemergence application.[a]

			Weed Control			
			Red Rice[b]		Barnyardgrass[c]	
Herbicide	Rate	Timing[d]	Clear[e]	Muddy[f]	Clear	Muddy
	g ai ha^{-1}	— d —	— % —		— % —	
Imazethapyr	70 fb 70	1 fb 12	95 a[g]	93 ab	94 a	88 ab
Imazethapyr	70 fb 70	3 fb 12	94 a	93 ab	92 a	88 ab
Imazethapyr	70 fb 70	5 fb 12	92 a-c	93 ab	88 ab	88 ab
Imazethapyr	140	12	88 d	92 a-d	86 ab	88 ab
Imazethapyr	0		0 e	0 e	0 d	0 d
Imazethapyr	70 fb 70	1 fb 19	94 a	93 ab	92 a	88 ab
Imazethapyr	70 fb 70	3 fb 19	93 ab	93 ab	80 bc	88 ab
Imazethapyr	70 fb 70	5 fb 19	90 b-d	93 ab	73 c	88 ab
Imazethapyr	140	19	89 cd	93 ab	76 c	88 ab
Imazethapyr	0		0 e	0 e	0 d	0 d

[a] Abbreviations: POST, postemergence.
[b] Percent control at Jennings and Washington, Louisiana.
[c] Percent control at Crowley and Washington, Louisiana.
[d] Days after draining for seedling establishment.
[e] The field received no tillage prior to planting.
[f] The field was tilled in the seeding flood prior to planting.
[g] Means followed by the same letter were not significantly different according to the t-test on difference of least square means at P = 0.05. Letters are used for comparisons within red rice or within barnyardgrass control.

Table 5.2. Effect of imazethapyr application timing and tillage system on rice yield at Crowley and Jennings, Louisiana.

			Water tillage	
Herbicide	Rate	Timing[a]	Clear[b]	Muddy[c]
	g ai ha^{-1}	—— d ——	———— kg ha^{-1} ————	
Imazethapyr	70 fb 70	1 fb 12	4080 ef[d]	4740 b-e
Imazethapyr	70 fb 70	3 fb 12	4370 c-f	5190 a-c
Imazethapyr	70 fb 70	5 fb 12	5170 a-d	4700 b-e
Imazethapyr	140	12	4290 d-f	4750 b-e
Imazethapyr	0		1990 g	1680 g
Imazethapyr	70 fb 70	1 fb 19	5190 a-c	3630 f
Imazethapyr	70 fb 70	3 fb 19	5790 a	4330 c-f
Imazethapyr	70 fb 70	5 fb 19	5750 a	5300 ab
Imazethapyr	140	19	5230 a-c	4370 c-f
Imazethapyr	0		2460 g	2480 g

[a] Days after draining for seedling establishment.
[b] The field received no tillage prior to planting.
[c] The field was tilled in the seeding flood prior to planting.
[d] Means followed by the same letter were not significantly different according to the t-test on difference of least square means at P = 0.05. Letters are used for yield comparisons within and across water tillage.

muddy- or clear-water seeding did not offer a distinct advantage over the other.

The benefits of reducing soil erosion and surface water contamination from muddy-water discharge at seedling establishment can be obtained in a clear-water system without experiencing a decrease in weed control or rice yield. As water quality regulations become more stringent, these data indicate imazethapyr provides producers the option to use conservation tillage in a water-seeded rice production system. When planting into a weed-free seedbed, imazethapyr applications should be timed according to weed size in order to ensure adequate weed control and optimum yields.

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CHAPTER 6

SUMMARY

This research was undertaken to determine the competitive ability of current rice (*Oryza sativa* L.) cultivars with red rice (*Oryza sativa* L.) and evaluate weed control and crop response in glufosinate- [2-amino-4-(hydroxymethylphosphinyl) butanoic acid] and imazethapyr- {2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-5-ethyl-3-pyridinecarboxylic acid} resistant water-seeded rice production systems.

Field experiments were conducted in 2002 and repeated twice in 2004 at Crowley, La. Cultivars included 'CL 121', 'Cocodrie', 'Drew', and 'Jasmine'. Each cultivar was selected based on growth characteristics such as maturity date, height, and tillering ability. At harvest, the rice cultivars produced 61 to 87% of the plants and stems m^{-2} of the nontreated. Jasmine dry weight and panicle number was reduced the least of the four cultivars as it produced 71 and 66% of the nontreated, respectively. The dry weight and panicle weight for the other three cultivars was 41 to 59% of the nontreated. For each of the four measurements, Cocodrie was the least competitive in the presence of red rice. Overall, Jasmine produced more stems, dry weight, and panicle weight than the other cultivars, except for stem density where CL 121 excelled.

The main effect of seeding rate was also significant. The high seeding rate produced 85% of the plants of the nontreated, and 9 to 10% more yield than the low and medium seeding rates. There was no difference observed for rice stature, maturity, or panicle density.

Red rice heights increased in the presence of Drew, the tallest cultivar in this study. Red rice panicle weights were lowest for Jasmine compared with Cocodrie and Drew, but there was no difference between Jasmine and CL 121. Compared with Cocodrie and Drew, Jasmine produced the highest stem density.

Red rice plant density was not affected by rice seeding rate; however, increasing the seeding rate from low to high reduced red rice stem density and panicle weight. In order to achieve a reduction in red rice dry weight and panicle density, the seeding rate only needed to be increased from low to medium. This resulted in a 33 to 35% decrease in red rice dry weight and panicle density.

There was a cultivar by seeding rate by red rice interaction for rice grain yield. No combination of cultivar or seeding rate was able to overcome the yield reducing effects of 20 red rice plants m^{-2} on rice yield. Across all cultivars and seeding rates, rice yields were reduced 9 to 46% in the presence of red rice. Of the four cultivars, CL 121 was consistently and equally affected at each seeding rate by red rice. CL 121 grain yield declined in a similar manner, regardless of seeding rate. Cocodrie exhibited the least decline in yield at the lowest seeding rate and the greatest decline at the highest seeding rate. With Drew, the greatest decline occurred at the middle seeding rate. Compared with the other cultivars, Jasmine produced the highest yields regardless of red rice presence. Increasing the seeding rate from optimum to high did not increase Jasmine yield for either the red rice free or infested treatment. However, a trend was observed in Jasmine percent yield reduction as yield decreased numerically from 29 to 27 to 21% at the high, optimum, and low seeding rates respectively. With the exception of Drew at the low and high seeding rates, the presence of red rice reduced rice yield compared with the respective red rice-free control for all cultivars. With the exception of Cocodrie grown red rice-free and Drew grown with red rice, grain yield was not increased for any cultivar by increasing the seeding rate from optimum to high.

Based on the stem density of Jasmine and its ability to produce more biomass and higher panicle weights in the presence of red rice compared with the other cultivars, taller, vigorous tillering, mid-season cultivars may offer a competitive advantage in fields where red rice infestations exist. With Jasmine, percent yield reduction was 21 to 29% across all seeding rates. In the case of Drew, it is difficult to interpret the results since yield was reduced 39% at the optimum seeding rate, but only reduced 14 and 9% at the low and high seeding rates, respectively. However, in the presence of red rice Drew yields were higher at the high seeding rate and this may be because Drew does not produce as many tillers. The tall, early season Drew did yield more than the very early season, semi-dwarf cultivars CL 121 and Cocodrie at the high seeding rate when grown with red rice and more than CL 121 at the optimum seeding rate grown with red rice. The results of this research indicate that cultivar selection and, in some instances, seeding rate can be used to minimize the competitive ability of red rice in rice.

Cultivar such as Drew and Jasmine that are tall, tiller vigorously, and is mature later were more favorable with respect to minimizing red rice interference. In addition to verifying the optimum planting rate for these cultivars, this research was conducted with red rice infested rice. In three of four cultivars, there was no need to increase seeding rate beyond what is necessary to establish the optimum plant stand. However, when growing a cultivar that does not tiller vigorously such as Drew, selecting a later maturing cultivar and increasing the seeding rate would be beneficial when planting into a field with a history of red rice infestations. Furthermore, combining a competitive rice cultivar with imazethapyr-, glufosinate-, and glyphosate-resistant technologies that are available or may become available in the future may provide another tool to aid the ability of rice to out compete red rice that escaped control by the herbicides.

Herbicide resistant rice cultivars were evaluated in conjunction with delaying the permanent flood establishment in a water-seeded rice production system for weed control, crop injury, and rice yield. Glufosinate treatments consisted of 500 g ai ha^{-1} glufosinate applied to two- to three-leaf (lf) rice and red rice EPOST followed by (fb) a four-lf to one-tiller late postemergence (LPOST) application. Imidazolinone treatments included 70 g ha^{-1} imazethapyr surface applied preemergence (PRE) followed by (fb) a three- to four-lf mid postemergence (MPOST) application or early postemergece (EPOST) fb LPOST. Postemergence (POST) applications of imazethapyr contained 1% v/v crop oil concentrate (COC). The controls for this study were treatments receiving no herbicide without red rice or containing red rice seeded to obtain 20 plants m^{-2}.

Glufosinate controlled hemp sesbania at least 98% regardless of permanent flood establishment timing, while imazethapyr did not control hemp sesbania more than 35%. No benefit was observed from permanent flood establishment.

With the exception of one imazethapyr treatment, red rice, barnyardgrass, and Amazon sprangletop control were at least 95%. Imazethapyr applied PRE fb POST compared with two POST applications resulted in an increase in Amazon sprangletop control from 79 to 96%.

Rice injury was 5% or less regardless of the herbicide system. This is supported because there was no difference in rice heading between the treated and nontreated glufosinate-resistant rice. In the imazethapyr system, rice heading was delayed 2 to 5 d when red rice was removed from the plots and the permanent flood was established 3 or 27 days after seeding (DAS), while no difference was observed when the permanent flood was established 14 DAS. Red rice heading was different in the 3 and 27 DAS permanent flood establishment system, but no recognizable pattern exists since the length of time was both reduced and increased in each system. Red rice, compared with the herbicide resistant rice evaluated, reached 50% heading 3 d before to 12 d after (DA) when the permanent flood was established 3 DAS , 6 d before or after in the when the flood was established 14 DAS, with 2d when the flood was established 27 DAS. Regardless of permanent flood establishment and herbicide applied, the possibility of outcrossing was always present and the technologies should be managed with that in mind to ensure outcrossing does not occur.

At harvest, rice plant heights for both the glufosinate and imazethapyr systems were reduced 8 to 12% in the nontreated, respectively. There was no difference within each system in milling yield. After milling, graded samples were U.S. number 1 or 2 for plots receiving glufosinate or imazethapyr. The average grade for nontreated plots was U.S. number 4. There are no loan discounts for U.S. number 1 or 2, but rice that grades U.S. number 4 results in a $0.60 discount per hundredweight. The U.S. number 4 grade was the result of red rice contamination exceeding 4% of the milled rice sample. Red rice infested rice (nontreated) was difficult to harvest due to the taller-growing red rice plants that tend to lodge, and the increased biomass that red rice produces that must be processed by the combine. The reduction in harvest efficiency due to red rice contamination is hard to quantify.

When the permanent flood was established 3 DAS, red rice panicle production in the nontreated was reduced 39 to 45% compared with the other two permanent flood management systems. Early flooding limited the time for red rice germination and establishment. In the other two systems, multiple wetting and drying cycles allowed an extended period of red rice emergence. When treated with either imazethapyr or glufosinate, red rice produced less than 1 panicle $plot^{-1}$. The potential disadvantage to early permanent flood establishment is that standing water at the time of herbicide application may prevent adequate coverage and/or imazethapyr binding to the soil to provide optimum red rice control.

When no herbicide application was made, rice yields were reduced 63 to 82%. The rice yields of the nontreated generally improved the sooner the flood was established. Earlier flood establishment reduced the length of time for weed germination and establishment. In contrast, when herbicides were used, rice yield increased the longer the permanent flood was held off the field. When the weed interference was removed by using herbicides, it is likely the rice root system had longer to become established and resulted in increased yields. Regardless of the herbicide system used, there was no difference in yield within each flood management system for either herbicide. Imazethapyr applied PRE fb MPOST or EPOST fb LPOST yielded 1120 and 1200 kg ha^{-1} more, respectively, when the permanent flood was not established until 27 DAS compared with establishing the flood 3 DAS.

Glufosinate- and imazethapyr-resistant rice production systems improve the ability to manage weeds especially red rice that is genetically similar to rice. This research shows that although early flooding can reduce weed populations, it may not be in the best interest of these technologies if proper herbicide coverage cannot be obtained and outcrossing of these traits occurs. On the other hand, small plot research such as this allowed floods to be established within several hours after herbicide application, which is not realistic on producer fields where flood establishment and emergence of weeds may occur in the 5 d or more window required to establish a permanent flood. In a glufosinate-resistant system, proper management may require multiple applications to fields with a shallow permanent flood to adequately control red rice since glufosinate has no residual soil activity. In an imazethapyr system, PPI or PRE applications have resulted in optimum red rice control in this study. The effectiveness and longevity of this technology will be determined by the rice producers and their ability to manage red rice on a field-by-field basis.

Glufosinate application timing was evaluated in drill-seeded rice to determine the effect of the herbicide on rice and red rice during the growing season. Glufosinate was applied at 500 g ha^{-1} 14, 28, 42, 56, and 70 DA rice emergence. Each application was followed 7 d later by 0.41 kg ha^{-1} glufosinate. Rice injury did not exceed 10% regardless of application timing

At maturity rice plant height was 77 to 82 cm. When treated with glufosinate, rice plant heights were within 4-cm of the nontreated plants. Delaying glufosinate treatment beyond 21 DAE reduced plant heights 2 to 5 cm compared with the 14 fb 21 DAE application timing.

Red rice control was at least 98% when glufosinate was applied after permanent flood establishment or 28 DAE. Glufosinate applied at 14 fb 21 DAE controlled red rice 91%. Red rice remaining was either not completely controlled or red rice emerged immediately after application and before permanent flood establishment. There was no difference in red rice heading regardless of treatment for plots producing viable red rice seed. It should be noted that red rice heading occurred 88 to 96 DAE and rice heading occurred 89 to 90 DAE for all application timings. Therefore, it cannot be assumed glufosinate application will provide differences in heading between rice and red rice and that outcrossing remains a possibility.

Initial glufosinate applications 14 or 28 DAE reduced red rice plant heights 11 to 17 cm, while initial glufosinate applications 42 and 56 DAE reduced heights 27 to 45 cm. Nontreated red rice averaged 151 panicles 8 m^{-2}. Applying glufosinate at 14 fb 21 DAE reduced production to 16 panicles 8 m^{-2} and all other treatments resulted in fewer than 5 panicles 8 m^{-2}. Glufosinate applied at 70 DAE coincided with red rice heading, but was before anthesis. Red rice treated at this timing produced sterile seed heads; therefore, panicle height and panicle density were not recorded. Although the late application shows promise for reducing red rice seed production and reducing the potential for outcrossing, only applications occurring at or before 35 DAE would meet the pre harvest application interval currently found on the glufosinate label for canola (*Brassica napus* L.), corn (*Zea mays* L.), and soybean [*Glycine* max (L.) Merr.].

At harvest, no difference in rice grain moisture was observed regardless of treatment. Season long red rice interference reduced rice yield to 1730 kg ha^{-1} which was 47% less than the nontreated, red rice free treatment. Rice yields decreased the longer red rice was allowed to compete and interfere with rice growth. This was evident by delaying the first application to 42 DAE. A similar trend occurred in the red rice free treatments, but the decrease in rice yield was observed when glufosinate treatment was applied at 56 fb 63 and 70 fb 77 DAE compared with the 42 fb 49 DAE treatment. The rice growth stage during these later timings was from panicle elongation to 40% heading. Rice yield was maximized when glufosinate was applied in the 14 to 49 DAE time frame. In this study, yields of treatments containing red rice treated at 14 fb 21 DAE yielded 1370 kg ha^{-1} more than noninfested rice treatments. The development of LL 401 and LL 001 appear to be more tolerant to glufosinate than BNGL 11/62 since glufosinate applications before the three- to five-leaf stage and at panicle initiation did not reduce yield nor result in an increase in grain moisture at harvest which would indicate a delay in maturity.

Based on the results of this study, two applications of at least 0.50 kg ha^{-1} glufosinate may be needed in order to achieve red rice control approaching 100% at the 14 fb 21 DAE timing. Glufosinate applied at or before 35 DAE to red rice infested rice resulted in maximum grain yield, reduced the duration of interference from red rice, and follows the current glufosinate label for grain crops.

The eventual use of this technology will require stewardship by the producer similar to recommendations currently used in imazethapyr-resistant rice production. Glufosinate-resistant rice would provide another management tool for red rice control and minimize the impact of red rice on rice harvest, yield, and grain quality. In addition, glufosinate would provide another herbicide mode of action to combat red rice especially if red rice becomes resistant to imazethapyr.

Another experiment evaluated imazethapyr-resistant rice used in a water-seeded system receiving tillage (muddy water) or not receiving tillage (clear-water) immediately prior to rice seeding. Imidazolinone treatments included 70 g ha^{-1} imazethapyr plus 1% v/v COC applied 1, 3, or 5 DA draining for rice seedling establishment. The second 70 g ha^{-1} imazethapyr plus 1% v/v COC application was made either 7 or 14 DA the 5 DA draining application.

At 60 DA final POST application, red rice control was 88 to 89% when 140 g ha^{-1} imazethapyr was applied in a single application immediately prior to permanent flood in the clear-water seeding system. All other clear- and muddy-water imazethapyr applications controlled red rice 90 to 95%.

Application timing was more critical for barnyardgrass control. Imazethapyr applied 1, 3, or 5 d fb by another application 12 DA initial drainage controlled barnyardgrass 88 to 94% in the clear-water seeding system. Applying imazethapyr 1 fb 19 DA initial drainage controlled barnyardgrass 92%, but delaying the initial application any longer resulted in control equal to or less than 80%. A single 140 g ha^{-1} imazethapyr application at 12 or 19 DA initial draining controlled barnyardgrass 86 and 76%, respectively. In the muddy-water seeding system, red rice and barnyardgrass control were 93 and 88%, respectively.

Regardless of water-seeding method or application timing, rice injury was less than 5% and heading occurred 70 DA rice emergence. At harvest, no difference in plant height was observed. Rice yields were 3630 to 5300 and 4080 to 5790 kg ha^{-1} for the muddy- and clear-water seeding systems, respectively. Weed control was not a good indication of rice yield since treatments controlling barnyardgrass the least (73 and 76%) were two of the four highest yielding treatments. However, this does indicate that imazethapyr was effective in providing rice a competitive advantage over the weeds and that muddy- or clear-water seeding did not offer a distinct advantage over the other. Generally yields were also higher when the initial application of imazethapyr was applied 3 or 5 DA initial draining.

The benefits of reducing soil erosion and surface water contamination from muddy-water discharge at seedling establishment can be obtained in a stale seedbed system without experiencing a decrease in weed control or rice yield. As water quality regulations become more stringent, this data shows that imazethapyr provides producers the option to use conservation tillage in a water-seeded rice production system. When planting into a weed-free seedbed, imazethapyr applications should be timed according to weed size in order to ensure adequate weed control and optimum yields.

In three of four cultivars that differed with respect to several characteristics, no benefit was observed by using a higher seeding rate than the optimum or recommended seeding rate. This was the first interference research conducted in water-seeded rice and the first study that examined the recommended seeding rates in a red rice-infested situation. This research also documents the value of imazethapyr-resistant rice technology for red rice control and indicates the need for glufosinate-resistant rice in order to control red rice in the event that outcrossing results in red rice with resistance to imazethapyr. Through these studies it was shown that the use of these herbicides will not delay red rice heading in order to prevent outcrossing. It is important that producers follow stewardship practices to preserve this technology for the future.

VITA

Christopher Todd Leon was born on November 1, 1975, in Canton, Mississippi. He attended elementary and high school at Canton Academy and graduated with honors May 1994. Chris attended Mississippi State University under the Cooperative Education program in Agricultural Pest Management. While in the Cooperative Education Program, Chris interned three semesters for a private cotton consultant and one semester as a technical intern for American Cyanamid. He graduated *Magna Cum Laude* in December 1998. In January 1999, Chris accepted a graduate assistantship under Dr. David Shaw in the Department of Plant and Soil Science. He graduated with his Master of Science in May 2001 and his thesis was entitled “Crop Monitoring Utilizing Remote Sensing, Soil Parameters, and GPS Technologies”. Prior to completing the requirements for the master’s degree, Chris accepted the Research Associate position under Dr. Eric P. Webster in the Department of Agronomy and Environmental Management at Louisiana State University and began fulfilling the requirements for the Doctor of Philosophy degree. His research focused on the competition and control of red rice in rice.

During his graduate career, Chris was a member of numerous professional organizations and presented papers at each of the annual conferences of these organizations. He was an active participant in the Southern Weed Science Society Weed Contest where he was a member of the second place team at Mississippi State University in 2000 and a member of the third place team at Louisiana State University in 2001 and 2002. In individual overall awards, he placed ninth, fifth, and second in 2000, 2001, and 2002, respectively. Chris has authored or co-authored 5 refereed journal articles, 58 abstracts, and 12 annual research reports.