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Weedy rice (*Oryza sativa*) II. Response of Weedy Rice to Seed Burial and Flooding Depth

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Weedy rice is a serious problem of cultivated rice in most of the rice-growing areas in Asia, causing increased production costs and yield losses in rice. A study was conducted to determine the response of weedy rice accessions from India (IWR), Malaysia (MWR), Thailand (TWR), and Vietnam (VWR) to seed burial and flooding depths. The greatest emergence for each weedy rice accession (97% for IWR, 82% for MWR, 97% for TWR, and 94% for VWR) was observed in seeds placed on the soil surface. Seedling emergence decreased with increase in burial depth. For the IWR accession, 0.5% of the seedlings emerged from 8-cm depth, whereas for the other three weedy rice accessions, no seedlings emerged from this depth. When seeds were sown on the soil surface, flooding depth ranging from 0 to 8 cm had no or very little effect on seedling emergence of different weedy rice accessions. On the other hand, flooding decreased seedling emergence in all weedy rice accessions when seeds were sown at 1 cm deep into the soil. Compared with seedling emergence, flooding had a more pronounced effect on seedling biomass for all weedy rice accessions. A flooding depth of 2 cm reduced seedling biomass by an amount greater than 85% of each weedy rice accession. The results of this study suggest that emergence and growth of weedy rice could be suppressed by deep tillage that buries seeds below their maximum depth of emergence (i.e., $>$ 8 cm for the accessions studied) and by flooding fields as early as possible. The information gained from this study may help design cultural management strategies for weedy rice in Asia.

Nomenclature: Weedy rice, *Oryza sativa* L. ORYSA.
Key words: Asia, biomass, depth, emergence.

Weedy rice, weedy forms of *Oryza sativa* L., is a serious problem in many rice areas in Asia, causing increased production costs and yield losses in rice. In Malaysia, rice yield losses due to weedy rice infestation were reported to be 74% (Azmi et al. 1994). In Vietnam, weedy rice caused an average rice yield loss of 16% (Chin 2001). A later study estimated that infestations by about 35 weedy rice panicles m^{-2} caused a yield loss of about 1 Mg ha^{-1} (Azmi et al. 2005). Recently, Thomas (2009) suggested that the rice production in India may fall significantly if weedy rice is not controlled in the region. Most of the weedy rice accessions have colored pericarps (Chauhan and Johnson 2010a), which, as contaminants, reduce the value of the harvested crop in the rice market. In addition, milling costs of rice contaminated with weedy rice seeds are also higher. Seeds of weedy rice shatter early and easily and can remain dormant in the soil for several years. Some weedy rice accessions from Asia have been found to have greater N-use efficiency for shoot biomass production than cultivated rice (Chauhan and Johnson 2011a). In addition, weedy rice responds more strongly than cultivated rice to rising CO_2 level with greater competitive ability (Ziska et al. 2010), suggesting that weedy rice may become a more problematic weed in the future.

In the face of labor and/or water shortages, farmers in many Asian countries are shifting their rice establishment methods from transplanting to direct seeding (Chauhan 2012). However, the adoption of direct-seeded rice culture makes weedy rice infestation one of the most serious problems (Azmi and Karim 2008) because of the absence of flooding at the time of crop emergence and the simultaneous emergence of crop and weedy rice, which are hard to distinguish at the seedling stage. Therefore, in some countries (e.g., Malaysia and Thailand) where direct seeding is already a common practice, farmers are reverting to mechanized transplanting to manage weedy rice. The absence of selective herbicides to control weedy rice poses a big challenge for farmers.

In the absence of selective herbicides, cultural weed management approaches, including tillage and flooding, may help reduce the problem of weedy rice. Knowledge on weedy rice seedling emergence from different planting depths could contribute to the use of tillage systems that can reduce emerging seedlings. In a previous study, weedy rice ecotypes from the United States emerged from burial depths of 7.5 cm (Gealy et al. 2000). The information on seedling emergence from different soil depths is widely available on several other rice weeds (Chauhan and Johnson 2010b), but such information is very limited on weedy rice in Asia. Flooding is considered an important component of cultural weed management in rice; however, it is optimal timing and depth of flooding that affect the abundance and growth of weeds in rice fields (Chauhan and Johnson 2010b). In Vietnam, flooding depths of 5 cm and more were found to suppress the germination and emergence of weedy rice (Chin 2001). In a field experiment in Italy, winter flooding between rice crops resulted in greater than 95% reduction in the number of weedy rice seeds on the soil surface as compared to reductions in the range of 26 to 77% on fields left dry between rice crops (Fogliatto et al. 2010). In the field, weedy rice seeds may be present on the soil surface or deep in the soil, and flooding may influence these seeds differently. However, information on the combined effect of seed burial and flooding depth on seedling emergence and growth of weedy rice is not available in Asia. The availability of such information may help in the design of cultural management strategies for weedy rice in Asia.

The objectives of this study were (1) to determine the effect of seed burial depth on emergence of four weedy rice accessions from Asia and (2) to determine the effect of seed burial and flooding depth on emergence and growth of four weedy rice accessions from Asia.

Materials and Methods

Experiments were conducted at the International Rice Research Institute (IRRI), Los Baños, Philippines, with four

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accessions of weedy rice from India (IWR), Malaysia (MWR), Thailand (TWR), and Vietnam (VWR) (Chauhan and Johnson 2010a, 2011a). These accessions were grown in the same environment at IRRI, and seeds from these accessions were harvested and stored at room temperature for 1 yr before experiment initiation. The 1,000-seed weights of IWR, MWR, TWR, and VWR were 20.8 ± 0.6, 17.0 ± 0.2, 17.1 ± 0.1, and 18.4 ± 0.3 g, respectively (Chauhan and Johnson 2010a).

Effect of Seed Burial Depth on Seedling Emergence. The effect of seed burial depth on seedling emergence of weedy rice accessions was determined in a screen house in January 2011. Twenty-five seeds of each accession were placed on the soil surface in 15-cm-diam plastic pots and then covered with the same soil to achieve burial depths of 0, 1, 2, 4, and 8 cm. The soil used in this experiment was collected from rice fields, sieved through a 3-mm sieve, and sterilized. The soil had sand, silt, and clay contents of 31, 37, and 32%, respectively. Pots were subirrigated to maintain adequate soil moisture. Seedlings were considered emerged when the coleoptiles could be easily recognized, and the experiment was terminated 21 d after sowing.

Effect of Seed Burial and Flooding Depth on Seedling Emergence and Biomass. Twenty-five seeds of each weedy rice accession were sown on the soil surface in plastic pots and then covered with soil to achieve burial depths of 0 and 1 cm. After sowing, the pots were subjected to 0-, 2-, 4-, and 8-cm flooding depths. The soil used in this experiment was as described above for the seed burial experiment. After 21 d, emerged seedlings were counted, harvested, and oven dried at 70 C for 72 h for dry biomass measurements.

Statistical Analysis. The experiments were set up with the use of randomized complete block design with four replications. Both experiments were conducted twice in two independent trials. The effect of the trials was nonsignificant and there were no significant interactions between treatments and trials. Therefore, the data were combined over the experimental trials and subjected to ANOVA (GenStat 8.0 2005). Each weedy rice accession was analyzed separately. Treatment means were separated with the use of LSD at the 5% level of significance.

Results and Discussion

Effect of Seed Burial Depth on Seedling Emergence. Seed burial depth greatly affected the seedling emergence of all weedy rice accessions (Figure 1). The greatest levels of emergence for all weedy rice accessions (97% for IWR, 82% for MWR, 97% for TWR, and 94% for VWR) were observed in seeds placed on the soil surface. The emergence of all weedy rice accessions, except that of VWR, decreased significantly when seeds were buried at 1 cm. The seedling emergence of the VWR accession was similar at burial depths ranging from 0 to 2 cm. In all accessions, there was no difference in seedling emergence between depths of 1 and 2 cm. With further increase in burial depth to 4 cm (vs. 2 cm), the seedling emergence of the MWR, TWR, and VWR accessions decreased significantly. In the IWR accession, 60% of the seedlings emerged from the 4-cm burial depth and 0.5% of

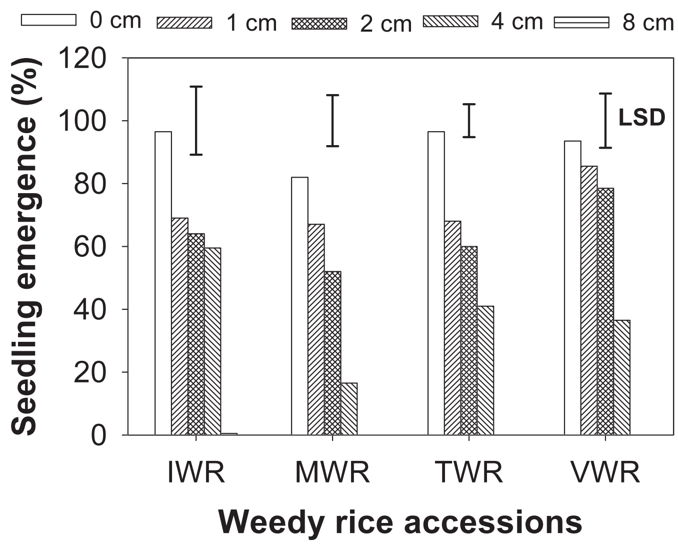

Figure 1. Effects of seed burial depth on seedling emergence of weedy rice accessions from India (IWR), Malaysia (MWR), Thailand (TWR), and Vietnam (VWR).

the seedlings were able to emerge from the 8-cm depth. In the other three weedy rice accessions (MWR, TWR, and VWR), no seedlings emerged from a depth of 8 cm.

Decreased seedling emergence with an increase in burial depth is a common phenomenon in weed and crop species. Several factors, depending on seed size and conditions for seeds to germinate, could be responsible for this response. Decreased seedling emergence of weedy rice with increased burial depth could be due to hypoxia and low rates of gaseous diffusion. CO_2 concentrations derived from soil biological activity are often greater at depth (Benvenuti and Macchia 1995; Chauhan and Johnson 2010b) and decreased O_2 concentrations in deeper soil may lead to hypoxia (Botha et al. 1992), which can decrease seed germination and, ultimately, seedling emergence. The decreased emergence of weedy rice seedlings with increased burial depth could also be a function of specific physical characteristics of the soil, which are crucial for maintaining gas exchange with the external atmosphere (Benvenuti and Macchia 1995). Another possible explanation for low seedling emergence at deep depths may involve decreasing temperature fluctuation with increasing burial depth, as temperature fluctuation is a known germination stimulant for many weed species (Roberts and Totterdell 1981).

In a previous study in the United States, greater than 50% of the seedlings of the Arkansas, Louisiana, and Mississippi weedy rice accessions emerged from a depth of 7.5 cm (Gealy et al. 2000). This is in contrast to this study, where three weedy rice accessions could not emerge from 8 cm and where, for the fourth accession, only 0.5% seedlings emerged from this depth. The differing results between the two studies could be due to different soil compaction, soil texture, and weedy rice accession.

As seedling emergence of all weedy rice accessions was optimal at shallow depths, any farming practices that aim to achieve shallow cultivations would potentially enhance seedling emergence of these weedy rice accessions. Rice area is being promoted under no- and reduced-till systems in some Asian countries, and the results of this study suggest that the weedy rice problem may increase in these systems if not controlled. However, the buildup of weedy rice seed banks in

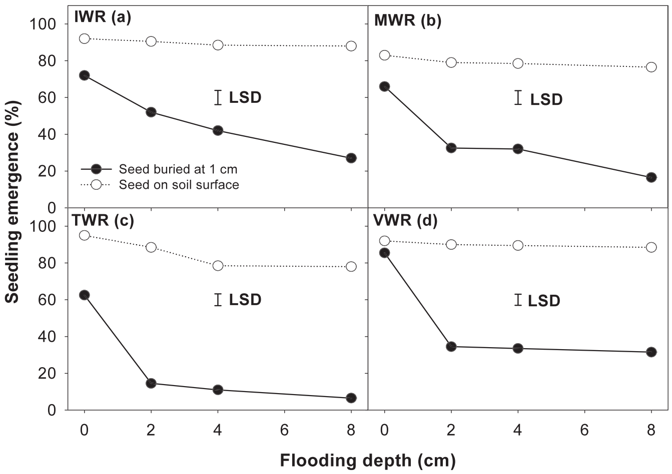

Figure 2. Effects of seed burial depth and flooding depth on seedling emergence of weedy rice accessions from India (IWR; a), Malaysia (MWR; b), Thailand (TWR; c), and Vietnam (VWR; d).

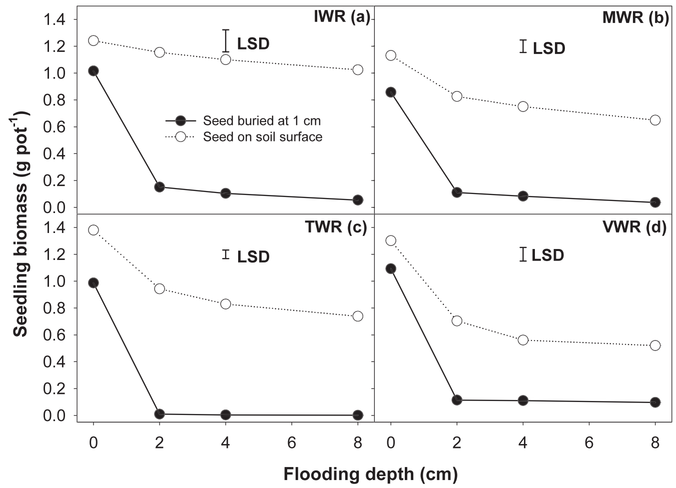

Figure 3. Effects of seed burial depth and flooding depth on seedling biomass of weedy rice accessions from India (IWR; a), Malaysia (MWR; b), Thailand (TWR; c), and Vietnam (VWR; d).

no- and reduced-till systems could be discouraged by an alternate or intermittent deep tillage operation that would bury the weedy rice seeds below their maximum depth of emergence (i.e., below 8 cm). A deep seed burial can play an important role in depleting the weedy rice seed bank (Delouche et al. 2007). However, deep tillage can be effective only if it does not bring back large quantities of seeds, buried in the previous deep tillage operation, to the soil surface (Chauhan and Johnson 2010b). If weedy rice seeds buried in the previous deep-tillage operations are still viable, they may reinfest the field after being brought back to the soil surface (Chauhan 2012). Therefore, it is necessary to understand the persistence of weedy rice seeds buried in the previous deep-tillage events.

Effect of Seed Burial and Flooding Depth on Seedling Emergence and Biomass. The interaction effects of seed burial and flooding depth were significant on seedling emergence and biomass of all weedy rice accessions (Figures 2 and 3). The seedling emergence (88 to 92%) of the IWR accession was not influenced by flooding depth for seeds sown on the soil surface (Figure 2a). On the other hand, the seedling emergence of this accession was influenced significantly when seeds buried in the soil at 1 cm were subjected to different flooding depths. The emergence decreased significantly with increase in each flooding depth. The seedling emergence of seeds buried at 1 cm, for example, decreased by 28% at a flooding depth of 2 cm compared with 0-cm flooding depth, and decreased further to 63% at a flooding depth of 8 cm. Compared with seedling emergence, flooding had a more pronounced effect on seedling biomass. For example, compared with no flooding, 2-cm-deep flooding reduced seedling biomass by 85% (vs. 28% reduction in emergence) for the seeds buried at 1 cm deep in the soil (Figure 3a).

As in the IWR accession, seedling emergence (77 to 83%) of the MWR accession was not influenced by flooding depth when seeds were sown on the soil surface (Figure 2b). When seeds sown at 1-cm depth were subjected to 2-cm flooding depth (compared with 0-cm flooding), seedling emergence of the MWR accession was reduced by 50%. A flooding depth of 8 cm reduced seedling emergence of this accession by 74%. For seeds sown on the soil surface, a flooding depth of 2 cm reduced the biomass of the MWR seedlings by 27%. This was further reduced to 42% when flooding was increased to 8 cm (Figure 3b). For seeds sown at 1-cm depth, however, seedling biomass was reduced by 87% with a flooding depth of only 2 cm compared with no flooding.

The seedling emergence of the TWR accession was slightly reduced ($P < 0.05$) when seeds sown on the soil surface were subjected to 4- and 8-cm flooding depths (Figure 2c). Without flooding (0 cm), 63% of the seedlings of the TWR accession emerged when seeds had been sown 1 cm deep into the soil. Seedling emergence was reduced sharply when seeds of this accession sown at 1 cm depth were flooded. Emergence, for example, decreased by 76%, even with a flooding depth of 2 cm compared with 0 cm. The flooding influenced seedling biomass more severely than did seedling emergence. Compared with no flooding, a flooding depth of only 2 cm reduced the biomass of the TWR accession by 99% when seeds had been sown 1 cm deep into the soil (Figure 3c).

Seedling emergence (89 to 92%) of the VWR accession was not influenced by flooding depth when seeds had been sown on the soil surface (Figure 2d). Compared with no flooding, a flooding of 2-cm depth reduced the seedling emergence of the VWR accession by 59% for seeds sown 1 cm deep into soil. There was no further significant decrease in seedling emergence with increase in flooding depths. A flooding depth of 2 cm reduced the biomass of the VWR accession by 46% when seeds were sown on the soil surface; the biomass was further reduced to 60% when flooding depth was increased to 8 cm (Figure 3d). However, when seeds that had been sown 1 cm deep into soil were subjected to flooding, a depth of 2 cm flooding reduced seedling biomass by 90% compared with 0 cm flooding.

The response of weedy rice to flooding is likely to be related to the effects of the physical, chemical, or biological properties of flooded soils. Reduced O_2, accumulation of CO_2 and toxic gaseous products of anaerobic decomposition, and the presence of reduced forms of chemical radicals may be responsible for the effects of flooding on weedy rice emergence and growth (Smith and Fox 1973). The water-depth sensing mechanisms of the seeds of some weed species may also be related to the amplitude of temperature fluctuation (Pons 1982). This is likely the case where weedy rice seeds buried at 1 cm were subjected to flooding. The seeds buried in soil and under water would experience smaller

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temperature fluctuations than the seeds present on the soil surface with no flooding.

In Vietnam, a flooding depth of 5 to 7 cm was suggested to suppress weedy rice infestation in rice (Chin 2001). Recently, in Malaysia, Azmi and Karim (2008) indicated that 5- to 10-cm flooding depth can inhibit weedy rice emergence. In a previous study, the seedling emergence of weedy rice from the top 1 cm of soil was reduced by 60% when soil was kept flooded with 2 cm of water compared with moist soil (Ferrero 2001). The results of the current study show that growth of weedy rice, irrespective of accession, can be reduced considerably ($> 85\%$) by flooding the fields with only 2 cm of water. However, to achieve such a precise flooding depth, the fields should be well leveled.

Currently, in direct-seeded rice systems, flooding is carried out after the crop has emerged and, by that time, weed seedlings may have already emerged and may be difficult to manage by flooding. The availability and use of rice cultivars capable of anaerobic germination will prove useful in suppressing weedy rice emergence and growth during crop establishment (Chauhan 2012). In the future, many farmers will have limited availability of water to flood their fields as a weed control mechanism (Chauhan and Johnson 2010b). In such situations, early (vs. later) flooding would make the best use of water to control weeds. In direct wet-seeded systems, early flooding could be possible by seeding pregerminated seeds and using cultivars with high vigor, which can emerge in a short time (Chauhan and Johnson 2011b). Weedy rice growth may also be suppressed by using high seeding rates. In Malaysia, the grain yield of rice increased with increased in seeding rate from 20 to 80 kg ha^{-1} in a direct-seeded field infested with weedy rice (Azmi et al. 2000). Similarly, different studies in the Philippines suggested that increasing the seeding rates of rice suppresses weed growth and reduced grain yield losses from weed competition (Chauhan et al. 2011; Zhao et al. 2007).

In summary, optimal emergence from shallow depth suggests that the emergence of the weedy rice accessions included in this study would be favored by farming practices that achieve shallow cultivation. To reduce the buildup of weedy rice seed banks on or near the soil surface, a deep tillage operation that buries seeds below 8-cm depth could be used as a tool in integrated weed management programs. The growth of weedy rice and similar weed species could be suppressed by tilling and flooding the fields as early as possible after seeding, provided that flooding does not affect rice establishment. The results of this study also suggest that flooding after crop emergence could also suppress growth of late-emerging weedy rice seedlings. However, deep burial of seeds and flooding without additional measures will not give complete control of weedy rice. Integrated crop management practices with varietal aspects such as increased seeding rate, narrow row spacing, and weed-competitive cultivars with early vigor need to be evaluated for weedy rice management in Asia.

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