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RESEARCH ARTICLE

Modelling Rice Competition with *Echinochloa crus-galli* and *Eleocharis kuroguwai* in Transplanted Rice Cultivation

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Abstract

Field experiments were conducted to investigate rice - *Echinochloa crus-galli* and rice - *Eleocharis kuroguwai* competition under transplanted rice cultivation in four major rice production areas; Suwon, Daejeon, Iksan, and Naju in Korea. Rice yield data were used to predict rice yield as a function of plant densities of *E. crus-galli* and *E. kuroguwai* using a rectangular hyperbola and to determine economic threshold (ET) levels of the weeds. Both weed species significantly reduced number of tillers at early rice growth stage, resulting in significant reduction in number of spikes, and the other yield components such as number of grains, maturity and 1,000-grain weight at later growth stage. The weed competitivity represented by parameter β ranged from 0.0145 to 0.0346 for *E. crus-galli* and from 0.0037 to 0.0187 for *E. kuroguwai*, indicating that the competition effect of *E. crus-galli* on rice yield was slightly greater than that of *E. kuroguwai*. The ET values of *E. crus-galli* were between 0.298 and 1.078 plants m^{-2}, while those of *E. kuroguwai* were between 0.848 and 5.298 plants m^{-2}, depending on weed competitivity and herbicide price. Therefore, our results can be used to support decision-making on herbicide application for *E. crus-galli* and *E. kuroguwai* management in transplanted rice cultivation.

Key words: competition, *Echinochloa crus-galli*, economic threshold, *Eleocharis kuroguwai*, rice

Introduction

In rice cropping, *Echinochloa crus-galli* L. (barnyardgrass) has long been considered as one of the most troublesome weeds (Smith 1983), causing significant yield loss due to its superiority to rice in competition (Ni et al. 1996). *Echinochloa* species has a wide geo-climatic adaptability ranging from north to south in the world (Holm et al. 1977). In comparison with rice, *E. crus-galli* emerges more quickly than rice, and has a lower temperature threshold, 11.0 ºC, than that for rice, 12.3 ºC (Kwon et al. 1996). Moreover, *E. crus-galli* emerges from deeper than 10 cm in the soil profile in a pot test (Kim et al. 2006b) and this ability was due to its mesocotyl growth (Kim 1993). These characteristics render *E. crus-galli* more competitive than rice, causing more than 50% of rice yield loss with dense infestations and without proper control (Hill et al. 1985).

Eleocharis kuroguwai Ohwi (water chestnut) is also one of the most important weed species in machine-transplanted rice fields (Chae and Guh 1999) and direct water-sown rice fields (Kim and Pyon 1998) in Korea. *Eleocharis kuroguwai* was reported to be the most important perennial weed species in temperate regions including Korea (Kim 1983) and Japan (Takabayashi 1988). *Eleocharis kuroguwai* spreads rapidly to cover rice fields and thus compete with rice. Ryang et al. (1976) reported that a single *E. kuroguwai* plant spreads to 2.3 x 2.4 m wide and produces about 1,600 tubers in monoculture. The tubers formed at different soil depths remain viable for at least 2 years (Kwon 2000), redistribute to various soil depths during cultivation, and emerge at different times. These ecophysiological characteristics of *E. kuroguwai* have contributed to its survival under current weed management systems, resulting in significant rice yield reduction in Korea and Japan.

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Since uncontrolled weeds can lead to rice yield losses as high as 80% (Smith 1983), weed control is an essential and important component of rice production. Accurate prediction of weed-crop interactions is required for the integrated weed management (Swanton and Murphy 1996). Mathematical models that summarize the quantitative knowledge (empirical model) of the impact of weed interference on crop yield can provide useful information to support weed management decisions (Vandevender et al. 1997). Many efforts have been made to develop weed-crop interference models (Cousens 1985; Kropff and Spitters 1991), which are commonly used to quantify competitive relationships and predict yield loss. Among those models, the rectangular hyperbola based on weed density (Cousens 1985) has been most widely used to predict crop yield losses as a function of weed density in various crops, such as wheat (Kim et al. 2002), soybean (Cowan et al. 1998), and maize (Lindquist et al. 1996). Many studies have been made to investigate relationships of rice-weed competition, particularly rice-*Echinochloa* species competition. Lindquist and Kropff (1996) introduced an ecophysiological model for irrigated rice-*Echinochloa* competition. Recently, Ni et al. (2004) analyzed competition between wet-seeded rice and *E. crus-galli* using a response-surface model based on the rectangular hyperbola. However, little study has been conducted to investigate the competition relationship between rice and *E. kuroguwai*. As *E. crus-galli* and *E. kuroguwai* are important in rice production, particularly in Korea and Japan, mathematical quantification and prediction of their competition impacts on rice are required for decision-making in weed management in transplanted rice cultivation.

Therefore, this study was conducted to investigate competition relationships of *E. crus-galli* and *E. kuroguwai* with transplanted rice. The aims of the study were to predict crop yield as a function of weed density using the rectangular hyperbola as a prediction model and to determine the economic threshold levels for *E. crus-galli* and *E. kuroguwai* in a transplanted rice production system.

Materials and Methods

Field experiments

Field experiments were conducted to evaluate competition effects of *E. crus-galli* and *E. kuroguwai* on transplanted rice in Daejeon (N 36° 19´, sandy loam), Iksan (N 35° 55´, clay loam), Naju (N 35° 1´, clay loam) and Suwon (N 37° 1´, sandy loam), Korea in 2004. The experiments consisted of three replicates of a completely randomized block design. The plot size was 2 x 2 m.

Thirty-day-old-seedlings of rice (*Oryza sativa* cv. Ilmibyeo) were transplanted at a density of 23.8 hills m^{-2} (14 x 30 cm space) equivalent to about 72 rice seedlings m^{-2} on 25 May in 2004. The plant densities were artificially adjusted by sowing seeds of *E. crus-galli* and planting tubers of *E. kuroguwai* with thinning, transplanting, or hand-weeding to remove naturally occurring background weeds.

The densities of *E. crus-galli* were 0, 5, 10, 25, 50, and 75 plants m^{-2} in 2004 and 0, 1, 4, 8, 16, 24, 48, and 96 plants m^{-2} in 2004, while those of *E. kuroguwai* were 0, 1, 4, 16, 24, 48, 96, and 144 plants m^{-2}. Fertilizer was applied as a basal release with N-P_2O_5-K_2O of 55-67-225 kg ha^{-1} before harrowing, followed by top-dressing of 22 kg ha^{-1} of N at rice tillering stage, 10 days after transplanting (DAT), and 33-29 kg ha^{-1} of N-K_2O at rice panicle initiation stage. To investigate competition between rice and the weeds, the number of rice tillers were recorded by hand-counting total number of tillers in a pre-marked area of 0.5 m^2 every 20 days until 100 DAT. Dry weights of rice and the weeds were also measured after sampling their above-ground parts from a pre-marked area of 0.5 m^2 at 30, 60, and 90 DAT in Suwon in 2004 and drying at 90 °C for 24 h in a dry oven. At maturity, rice was harvested from an area of 1.0 m^2 for measuring grain yield.

Prediction model and statistical Analyses

Wilson et al. (1995) reported that weed biomass increased hyperbolically with weed density (X) at a fixed crop density. It is thus assumed that weed biomass (W) has a hyperbolic relationship with weed density as follows:

$$W = CX / (1+\alpha X) \qquad [1]$$

where parameter C is biomass of an individual weed plant without inter-specific competition and α is a measure of intraspecific competition of the weed. Dry weights of the weeds were fitted to eqn 1 to estimate parameters for predicting weed biomass at different timings.

Rice biomass and grain yields were fitted to the following eqn 2, rectangular hyperbola (Cousens 1985), to estimate parameters for predicting rice biomass and yields as a function of weed density.

$$Y = Y_o / (1+\beta X) \qquad [2]$$

where Y_o is weed-free rice yield (t ha^{-1}), β is a measure of weed competitivity (a weed density of $1/\beta$ reduces the rice yield by 50%) and X is weed density.

Economic thresholds (ET) of *E. crus-galli* and *E. kuroguwai* were estimated by equating the cost of controlling *E. crus-galli* and *E. kuroguwai* with the value of rice yield gained by herbicide application. Their calculation was based on the equation developed by Cousens (1987) as follows:

$$ET = (C_h+C_a) / (Y_o PLH) \qquad [3]$$

where C_h is herbicide cost (US\$ ha^{-1}), C_a is application cost (US\$ ha^{-1}), Y_o is weed free rice yield (t ha^{-1}), P is value per unit of crop (US\$ t^{-1}), L is proportional loss per unit weed density, and H is herbicide efficacy, a proportional reduction in weed density or weed biomass by the herbicide treatment.

All statistical analyses were conducted using Genstat (Genstat Committee 2002).

Results and Discussion

Competition of rice with *E. crus-galli* and *E. kuroguwai*

In order to characterize and compare the competition effects of *E. crus-galli* and *E. kuroguwai* on rice growth, biomass and seed or tuber production of weed, and number of tillers and biomass of rice were measured in Suwon at different timings, 30, 60, and 90 DAT.

In the field study conducted in Suwon, dry weights of both weed species increased linearly with increasing weed density with no significant intra-competition at early measurements (30 and 60 DAT), while they increased hyperbolically with significant intraspecific competition when measured at 90 DAT (Fig. 1). Individual dry weight (parameter C) and intraspecific competitivity (parameter α) were estimated by fitting dry weights to eqn 1. The individual dry weight of *E. crus-galli* was 0.47, 1.85, and 14.7 g at 30, 60, and 90 DAT, respectively, while that of *E. kuroguwai* was 0.68, 3.14, and 10.27 g, respectively. No intraspecific competition was observed at 30 and 60 DAT, but significant intraspecific competition was observed at 90 DAT having 0.0101 and 0.004 for *E. crus-galli* and *E. kuroguwai*, respectively. Overall, both species showed similar growth characteristics under competition with transplanted rice although the early growth of *E. kuroguwai* appears to be slightly greater than *E. crus-galli*.

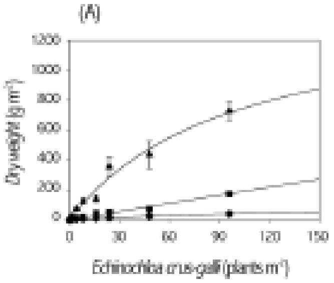
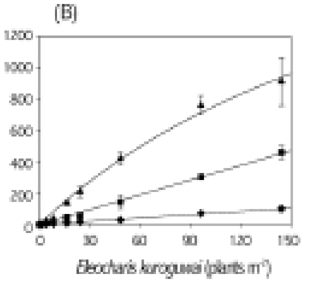

Fig. 1. Dry weights of *E. crus-galli* (A) and *E. kuroguwai* (B) observed at 30 (◇), 60 (■) and 90 (▲) days after rice transplanting (DAT). The vertical bars represent the standard deviations and the continuous lines are fitted dry weights calculated using eqn 1 and its parameters C and α. The parameter C for *E. crus-galli* was 0.4655, 1.846, and 14.7 g plant^{-1} for 30, 60, and 90 DAT, respectively, while that for *E. kuroguwai* was 0.6835, 3.143, and 10.27 g plant^{-1} for 30, 60, and 90 DAT, respectively. The parameter α was estimated to be 0 for 30 and 60 DAT for both species, while 0.01012 and 0.004 at 90 DAT for *E. crus-galli* and *E. kuroguwai*, respectively.

The number of rice tillers is a useful measure of early rice-weed competition as it is non-destructive and easy to measure. As expected, both weed species significantly reduced the number of rice tillers in proportion to weed density at all measurements and such effects became larger over time (Fig. 2). However, the patterns of their effects were different; *E. kuroguwai* reduced rice tillers from a much earlier stage than *E. crus-galli*, by showing significant reduction of rice tiller even at 30 DAT. This finding thus indicates that *E. kuroguwai* competes with rice and affects rice growth earlier than *E. crus-galli*.

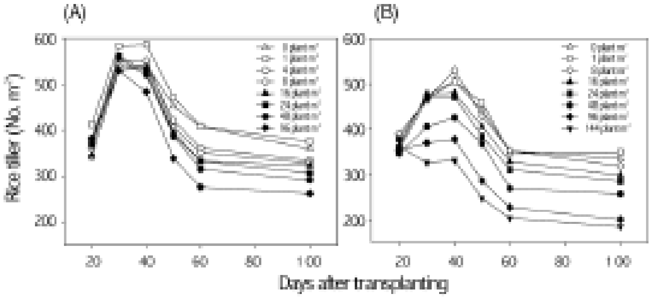

Fig. 2. Changes in the number of tillers of rice as affected by competitions with *E. crus-galli* (A) and *E. kuroguwai* (B) infested at a range of densities.

To quantify competition effects of both weed species on the rice growth, dry weight of rice was measured at 30, 60, and 90 DAT in Suwon. Both weeds caused significant reduction in rice dry weight from 60 DAT, while no significant reduction was observed at 30 DAT (Fig. 3), suggesting that proper weed control must be made by 30 DAT. The weed competitivity (parameter β) estimated by fitting the rectangular hyperbola increased over time with greater increase from 30 DAT to 60 DAT than from 60 DAT to 90 DAT (Table 1), suggesting that the former period may be more critical than the latter as it determines fertile tillers, i.e., number of spikes, as shown in Fig. 2.

Table 1. Parameter estimates for the prediction of rice dry weights as a result of competition between rice and *E. crus-galli* and *E. kuroguwai* in Suwon. The numbers in parentheses are standard errors.

Timing (DAT)	*E. crus-galli*		*E. kuroguwai*	
	Y_o	β	Y_o	β
30	144.0 (3.2)	0.00195 (0.00071)	151.8 (5.4)	0.00331 (0.00100)
60	508.1 (14.5)	0.00725 (0.00147)	473.2 (14.6)	0.00638 (0.00123)
90	1315.4 (33.7)	0.01282 (0.00183)	1287.3 (32.3)	0.01805 (0.00207)

Y_o, weed free rice yield (t ha^{-1}); β, a measure of weed competitivity

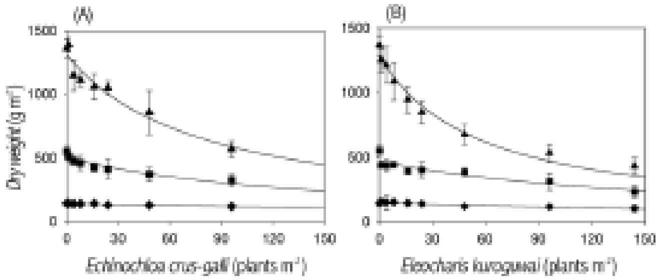

Fig. 3. Dry weights of rice as affected by E. crus-galli (A) and *E. kuroguwai* (B) infested at a range of plant densities. They were observed at 30 (◆), 60 (■) and 90 (▲) days after rice transplanting. The vertical bars represent the standard deviations and the continuous lines are fitted lines calculated using eqn 2 and estimated parameters (Table 1).

Correlation and linear regression analyses were also conducted to investigate the effects of weed interference on rice yield components measured in all the sites. All the components such as number of spikes, number of grains, maturity and 1,000-grain weight were all negatively affected by *E. crus-galli* and *E. kuroguwai* (Figs. 4 and 5). Among the components, number of spikes was most negatively affected by both weed species, followed by % maturity, 1,000-grain weight, and number of grains (Fig. 4). The reason why the number of spikes was most negatively affected may be because it had been affected from the early stage of rice-weed competition, while the other components were affected at a later stage of rice-weed competition after heading stages. Linear regression analyses to relate weed density and rice yield components showed that rice yield components were more negatively affected by *E. crus-galli* than *E. kuroguwai* (Fig. 5). When compared reduction rate of yield components with increasing weed density, 1000-grain weight was about 3.2 times more rapidly reduced by *E. crus-galli* interference than *E. kuroguwai*. Number of grains, number of spikes and maturity were also more rapidly reduced by *E. crus-galli* than *E.*

kuroguwai with differences of 1.8, 1.7, and 1.5 times, respectively, between them. Therefore, in spite of regional variation, it can be conclude that *E. crus-galli* is more competitive than *E. kuroguwai* under transplanted rice cultivation.

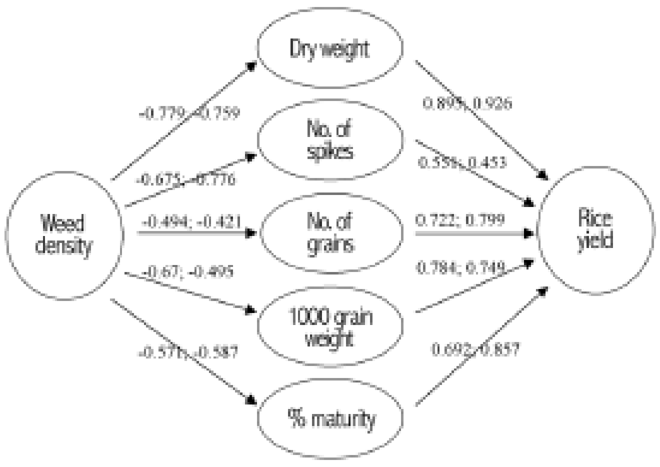

Fig. 4. Schematic representation of the correlations between plant densities of *E. crus-galli* (correlation coefficient in left) and *E. kuroguwai* (correlation coefficient in right), and rice yield components.

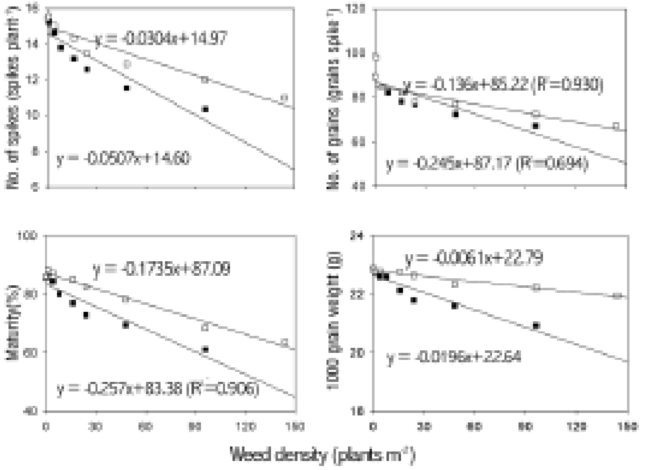

Fig. 5. Relationships between plant densities of *E. crus-galli* (■) and *E. kuroguwai* (□), and rice yield components, number of spikes (A), number of grains (B), maturity (C), and 1,000-grain weight (D).

Prediction of rice yields

By fitting the rectangular hyperbola (eqn 2) to rice yield, weed-free rice yield (Y_o), and weed competitivity (β) of both weeds were estimated. In rice and E. crus-galli competition, estimated weed-free rice yield was 5.65 - 5.83 t ha^{-1}, while that was 5.55 - 6.33 t ha^{-1} in rice and *E. kuroguwai* competition (Table 2). The competitivity of *E. crus-galli* was 0.0197, 0.0184, 0.0346, and 0.0145 in Daejeon, Suwon, Iksan, and Naju, while that of *E. kuroguwai* was 0.0037, 0.0187, 0.0092, and 0.0042, respectively, showing much larger regional variation in *E. kuroguwai* than *E. crus-galli*. This larger regional variation in *E. kurguwai* appears to be related to difference in early seedling establishment depending on how to plant *E. kuroguwai* tubers.

Based on parameter estimates and eqn 2, rice yields as a function of *E. crus-galli* and *E. kuroguwai* interferences were simulated (Figs. 6 and 7, respectively), showing that the rectangular hyperbolic model well described the competition between rice and the two weed species in various sites.

Table 2. Parameter estimates for the prediction of rice grain yields as a result of interferences of *E. crus-galli* and *E. kuroguwai*. The numbers in parentheses are standard errors.

Site	Parameter estimates		R^2
	Y_o	β	
E. crus-galli			
Daejeon	5.68 (0.084)	0.0197 (0.0014)	0.964
Suwon	5.65 (0.087)	0.0184 (0.0014)	0.960
Iksan	5.65 (0.065)	0.0346 (0.0017)	0.988
Naju	5.83 (0.133)	0.0145 (0.0018)	0.887
E. kuroguwai			
Daejeon	5.81 (0.071)	0.0037 (0.0003)	0.906
Suwon	5.55 (0.015)	0.0187 (0.0023)	0.920
Iksan	5.65 (0.059)	0.0092 (0.0005)	0.977
Naju	6.33 (0.077)	0.0042 (0.0004)	0.918

Y_o, weed free rice yield (t ha^{-1}); β, a measure of weed competitivity

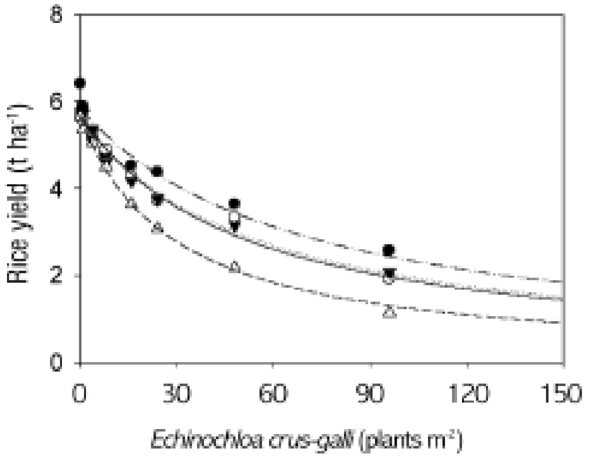

Fig. 6. Observed and predicted rice grain yields as a function of *E. crus-galli* density in Daejeon (●), Suwon (○), Iksan (▼), and Naju (△). The predicted rice grain yield (continuous line) was calculated using eqn 2 and parameter estimates in Table 2.

Prediction of economic thresholds

Single year economic thresholds of *E. crus-galli* and *E. kuroguwai* were calculated by using eqn 3 and parameter estimates including herbicide prices ranging 46 - 92.9 US$ ha^{-1} for *E. crus-galli* control and 79.6 - 123 US$ ha^{-1} for *E. kuroguwai* control in Table 3. The estimated economic threshold (ET) of *E. crus-galli* was least in Iksan with 0.298, 0.435, and 0.489 plants m^{-2}, while greatest in Suwon with 0.551, 0.805, and 0.905 plants m^{-2} for early, early one-shot, and mid one-shot herbicide, respectively (Table 3). By comparison, the ET of *E. kuroguwai* was estimated to be least in Suwon with 0.848, 1.165, and 1.193 plants m^{-2}, while greatest in Daejeon with 3.768, 5.173, and 5.298 plants m^{-2} for early one-shot and mid one-shot, 2-way

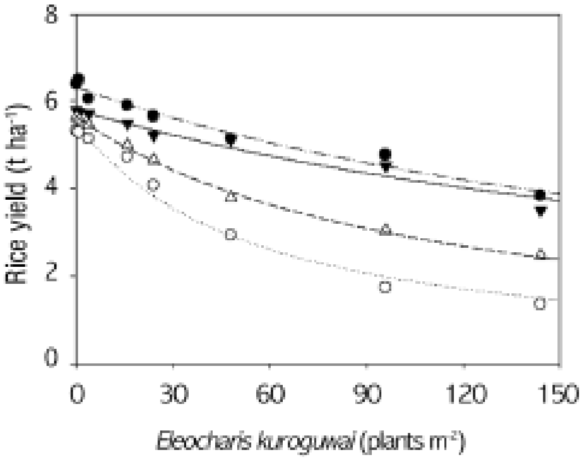

Fig. 7. Observed and predicted rice grain yields as a function of *E. kuroguwai* density in Daejeon (●), Suwon (○), Iksan (▼), and Naju (△). The predicted rice grain yield (continuous line) was calculated using eqn 2 and parameter estimates in Table 2.

mixture and mid one-shot, 3-way mixture herbicide, respectively (Table 3). The overall ET of *E. crus-galli* was smaller than *E. kuroguwai* due to its greater competitivity and cheaper herbicide costs than *E. kuroguwai*. As flucetosulfuron can control both *E. crus-galli* and *E. kuroguwai* (Kim et al. 2006a), its application in Suwon can be recommended at plant densities of *E. crus-galli* and *E. kuroguwai* greater than 0.8 and 0.85 plants m^{-2}, respectively.

Table 3. Parameter estimates and economic threshold (ET) of *E. crus-galli* in machine transplanted rice cultivation.

Site	Parameter estimates and economic thresholds (ET)										
	C_h $(\$\ \mathrm{ha}^{-1})$			C_a	Y_o	P	L	H	ET (No. m^{-2})		
	A	B	C	$(\$\ \mathrm{ha}^{-1})$	(t ha^{-1})	$(\$\ \mathrm{t}^{-1})$			A	B	C
E. crus-galli											
Daejeon	46.0	79.6	92.9	27.1	5.68	1442.5	0.0193	0.9	0.513	0.749	0.842
Suwon	46.0	79.6	92.9	27.1	5.65	1442.5	0.0181	0.9	0.551	0.805	0.905
Iksan	46.0	79.6	92.9	27.1	5.65	1442.5	0.0335	0.9	0.298	0.435	0.489
Naju	46.0	79.6	92.9	27.1	5.83	1442.5	0.0147	0.9	0.656	0.959	1.078
E. kuroguwai											
Daejeon	79.6	119.5	123.0	27.1	5.81	1442.5	0.0037	0.9	3.768	5.173	5.298
Suwon	79.6	119.5	123.0	27.1	5.55	1442.5	0.0187	0.9	0.848	1.165	1.193
Iksan	79.6	119.5	123.0	27.1	5.65	1442.5	0.0092	0.9	1.597	2.193	2.246
Naju	79.6	119.5	123.0	27.1	6.33	1442.5	0.0042	0.9	3.111	4.272	4.375

C_h, herbicide cost; A, pretilachlor GR; B, flucetosulfuron GR; C, flucetosulfuron + pretilachlor for *E. crus-galli*, A, flucetosulfuron GR; B, flucetosulfuron + imazosulfuron GR; C, flucetosulfuron + imazosulfuron + carfentrazone-ethyl for *E. kuroguwai*, C_a, application cost; Y_o, weed free crop yield; P, value per unit of crop; L, proportion of yield loss per unit weed density; H, herbicide efficacy calculated as efficacy (%)/100.

Implications

Echinochloa crus-galli and *E. kuroguwai* are serious threats to rice cultivation, but not many studies have been made, particularly their effects on transplanted rice cultivation. Although some studies investigated the competition between rice and *E. crus-galli* (Lindquist and Kropff 1996; Ni et al. 2004), little research has been conducted to investigate the competition relationship between rice and *E. kuroguwai*. Our study showed that early competition of both weed species with rice significantly affects number of tillers, resulting in significant reduction of rice spikes, while later competition affects number of grains, maturity, and 1,000-grain weight.

Regional variations in our study involve site-specific climatic and other environmental factors including soil conditions. Ni et al. (2004) reported that rice yield loss was higher in the wet season than in the dry season due to faster *E. crus-galli* growth in the wet season and limited solar radiation. Lindquist and Kropff (1996) found that if competition was for light only, weather variation had little impact on rice - *E. crus-galli* interference relationships. A greater proportion of such variations may be accounted for by including site-specific climate or environmental data as an additional independent variable in the rectangular hyperbola. Eco-physiological models accounting for environmental variation may be useful. Further studies may be required to investigate environmental factors affecting competition between rice and the weeds, in order to interpret this regional variation.

The economic threshold level depends upon weed competition effects, rice yield and price, and herbicide cost. Lindquist and Kropff (1996) estimated that the ET value of *E. crus-galli* was 2.93 plants m^{-2} in South Asia, where the herbicide cost was 24.14 US$\$$ ha^{-1}, the rice yield 4.0 t ha^{-1}, the rice price 198 US$\$$ ha^{-1}, the herbicide efficacy 0.9, and yield loss 0.016% plant^{-1}. However, our study suggests much lower ET values ranging from 0.298 to 1.078 plants m^{-2} depending on herbicide cost and site. In Korea and Japan, the herbicide cost is higher than South Asia and ranges from 40 to 150 US$\$$ ha^{-1} in Korea and from 80 to 250 US$\$$ ha^{-1} in Japan. The high rice price in Korea reduced significantly the ET value. However, due to increasing import of low-priced rice from other countries, the rice price will be inevitably decreased year by year, implying that the ET value will be increased accordingly. This market situation will require more accurate prediction of weed competition on rice yield and sophisticated decision-making for herbicide application. In the USA, weed control costs for rice production varied between $\$62$ ha^{-1} and $\$180$ ha^{-1} and elimination of a single unnecessary herbicide application could have increased the net economic return from $\$7$ to $\$57$ ha^{-1} (Vandevender et al. 1997), clearly showing that decisions on herbicide application affect the profitability of rice farming.

Our study clearly demonstrates that the rectangular hyperbolic model effectively describes the competition relationships between the weeds and rice and successfully predicts rice yields as a function of weed density and estimates ET values. Therefore, our results can be used to support decision-making on herbicide application in machine transplanted rice cultivation. However, it still has limitations in regard to how much herbicide is required in practical fields infested with multiple weed species. Recently, Kim et al. (2002) developed an integrated model for winter cereals by combining the rectangular hyperbolic model and the standard dose-response curve to predict the interaction between crop-weed competition and herbicide dose, and thus to provide an answer to how much herbicide is required. Kim et al. (2006c) also investigated effects of multiple weed species on the interaction and incorporated the effects on the model. Therefore, further studies are required to include the effects of herbicide dose-response on crop-weed competition in various rice paddy conditions, including multiple weed infestation and different rice cropping systems, and to develop such an integrated model for rice. The integrated model should provide more precise and practical information for decision-making on herbicide application and for economic assessment of weed management strategies in rice.

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