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Growth Competition between Rice (*Oryza sativa*) and Barnyardgrass (*Echinochloa oryzicola*) under Varying Mono-/Mixed Cropping Patterns and Air Temperatures

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Abstract: Increase in the concentration of atmospheric greenhouse gases significantly contributes to global warming, representing a substantial challenge for crop production. The study was conducted to determine the growth competition between rice (*Oryza sativa*) and barnyardgrass (*Echinochloa oryzicola*) under (i) different cropping patterns and (ii) elevated air temperatures in phytotrons under field condition, at two plant densities (4 and 16 plants per pot). Rice and barnyardgrass were planted with varying cropping patterns (rice: barnyardgrass mixture proportions); 100:0, 75:25, 50:50, 25:75 and 0:100. Air temperatures were maintained in phytotrons as follows: Ambient–A (Control), A +0.8 °C, A +1.9 °C and A +3.4 °C. Plant attributes such as plant height, number of effective tillers, shoot dry weight and grain yield of rice were recorded in this study in the rice/barnyardgrass mixture proportions in the order of 100:0 > 75:25 > 50:50 > 25:75. The highest rice grain yield (37.7 g/pot) was recorded in the monoculture (100:0 rice/barnyardgrass) under ambient temperature, whereas the lowest rice grain yield (0.3 g/pot) was recorded at the 25:75 rice/barnyardgrass mixture proportion under ambient +3.4 °C. The increase in temperature had a significant impact on growth, number of tillers and shoot dry weight of both rice and barnyardgrass plants and followed the order of ambient +3.4 °C > ambient +1.9 °C > ambient +0.8 °C > ambient. However, higher temperature negatively affected the yield of rice and resulted in a substantial decrease in the grain yield. Barnyardgrass showed the highest plant characteristics when grown alongside rice compared to the growth in monoculture. This indicates that barnyardgrass was highly competitive when grown under interspecific competition compared to an intraspecific competition. In contrast, rice grew better in monoculture than in mixture with barnyardgrass.

Keywords: rice; barnyardgrass; elevated temperature; mixture proportion; plant density; grain yield

1. Introduction

The rapid global industrialization has resulted in the production a large amount of greenhouse gases which already became a great concern all around the world [1]. The elevated atmospheric temperature in the last few decades is a response to the increased greenhouse gases level in the atmosphere, which also has a significant impact on plant growth and performance. The concentration of greenhouse gas is increasing compared to the industrial starting era, having reached 409.8 ppm (parts per million) during 2019, which is higher than in the past 800,000 years [1]. This suggests that even with significant efforts to reduce greenhouse gas emissions, substantial global warming is inevitable in the future. Climate change is a pressing global environmental issue, with agriculture being particularly vulnerable to adverse weather conditions that threaten food production [2]. Consequently, it is essential to mitigate the impacts of anthropogenic pressures on global warming, as crops are likely to undergo significant alterations, requiring adjustments in weed management practices to address competition effects with crops.

Rice is one of the most important staple foods in Asia and globally, given that more than half of the world's population consumes it. Asia alone produces around 90% of global rice [3]. It is an important source of protein, carbohydrate, fiber, vitamins, minerals, antioxidants with other biomolecules showing good impact on human health [4,5]. The increased demand for food is required to increase the rice production by 70% by 2050 [6,7]. In addition to water availability, rice yield may be affected by crop genotypes, nutrient and weed management, crop and weed population density, etc. Weed management is especially demanding in a rice cropping [8] due to competition for light, nutrients and moisture. For instance, in certain regions of Bhutan, rice yield can be reduced by 50% due to weed infestation with annual and perennial species [9]. Both annual and perennial weed species such as *Echinochloa oryzicola*, *Monochoria vaginalis*, *Ludwigia prostrata*, *Eleocharis kuroguwai*, *Scirpus planiculmis*, *Sagittaria sagittifolia*, *Rotala pusilla*, and *Lindernia procumbens* are predominant and frequently occurring weeds in Korean rice fields. Among these weeds, barnyardgrass is one of the weed species which causes a tremendous negative impact on rice production all around the world [10]. It is one of the highest infesting weed species in rice fields leading to a yield reduction from 21% to 79% [11]. It has also been found that rice grain quality is decreased when rice is associated with barnyardgrass [12]. Therefore, it is indispensable to determine the effective measures to control weed species in rice fields in order to provide more favorable conditions for crop growth. Selecting a competitive crop can be a better way to efficiently suppress weed enhancement without loss of crop yield. However, crop cultivars usually vary on the competitive capability with weed regimes. Apart from climatic factors, which play a crucial role in altering the competitive ability of plants, interplant competition is widespread. However, the competition between crops and weeds represents a prolific, natural, and undesired phenomenon within agroecosystems [13]. It has been reported that cultivar performance is specific to locations and growth conditions [14]. Negative impacts of temperature elevation can be alleviated by an appropriate selection of crop cultivars. In addition, several studies report on the response of rice cultivars and weed competition under elevated temperature conditions [15–17].

Many studies have investigated rice and barnyardgrass competition [6,18,19]. A previous study under climate change has described the plant modification in response to carbon dioxide concentrations [20], but not to increase in air temperature. The interaction between rice and barnyardgrass growth under elevated temperature conditions is yet to be explored in detail. Also, the information on the competitive ability of rice cultivars to adapt to the elevated temperatures regimes in Korea is still insufficient. Therefore, the current study was designed to investigate the competition between rice and barnyardgrass under elevated temperatures and also to provide some other information that could contribute to increasing rice production.

2. Materials and Methods

2.1. Installation of Temperature Manipulation Device in Field Phytotrons

The study was conducted at the experimental farm of Chungnam National University, Daejeon, Korea (127°21′ E, 36°22′ N, alt. 34 m). A heater was set in the phytotrons under field conditions with a digital temperature sensor to maintain four different air temperature treatments: Ambient–A (Control), A +0.8 °C, A +1.9 °C, and A +3.4 °C. A temperature control device was engineered using sensors to automatically open and close the ventilation of plastic windows to pre-calculated variable apertures to allow for exchange of air which maintained desired elevation of temperatures (ambient, 0.8 °C, 1.9 °C, and 3.4 °C above ambient level). A heater with a digital temperature sensor was installed in each phytotron, and the temperature was maintained at 0.8 °C, 1.9 °C, and 3.4 °C above the ambient temperature during the experiment. One phytotron was maintained at ambient temperature as a control. The various temperature variables in the phytotrons were designed to simulate the effect of global climate change on rice and barnyardgrass competition. The sensors in the phytotron recorded temperature every 10 s and temperature values were stored in a record storage system.

2.2. Plant Materials

The seeds of the rice cultivar (Dongjin 1) and barnyardgrass were obtained from the National Institute of Crop Science Korea. The cleaned seeds were stored at room temperature until use in the experiment. All seeds were treated with a 25% benomyl (Merck, Munich, Germany) solution to sterilize them from fungal infections before sowing. The seeds were sown as one seed per cell (40 cells/tray) in a plastic tray filled with upland rice field soil. Rice and barnyardgrass seedlings were grown inside the phytotrons under different air temperature conditions. Three weeks after sowing, 3–5 cm tall seedlings were transplanted into plastic pots (according to proportions of the replacement series design) until the development of 2–3 leaves. The experiments were performed with four replications in a completely randomized design within each temperature regime.

2.3. Experimental Design and Competition Study

The seeds of rice and barnyardgrass were grown in plastic pots (surface area 0.02 m^2) filled up with a mixture of soil and sand. Replacement series design was used for the plant competition study in which plants were grown at different ratios over various densities. Under this method, seedlings were planted at two densities (4 and 16 plants per pot), which was equivalent to 200 and 800 plants per m^2. Rice and barnyardgrass were set up in proportions of 100:0, 75:25, 50:50, 25:75, and 0:100 within separate pots. The aim was to investigate whether elevated temperature influences the growth of rice and barnyardgrass plants under different plant density ratios and considering the density situation in large areas where rice is grown in close proximity of weed plants. Furthermore, we considered the specific characteristics of the selected plant species, including their growth habits, root structures, and competitive interactions. This allowed for us to tailor the densities to ensure adequate space for individual plant development while facilitating intercropping dynamics and resource sharing within the system.

The proportions of each plant species in the mixture were carefully determined based on their complementary growth traits, nutrient requirements, and ecological interactions. Our goal was to design a diverse plant community that maximizes overall productivity, resilience to environmental stressors, and ecosystem services.

In each phytotron, a total of 40 pots were used for both plant species with four replicates with 40 cm space between pots. After that, different temperature regimes were maintained as per experimental design and the water volume in pots was maintained up to 3 ± 1 cm by irrigation of 2 to 3 times per day. During the panicle initiation stage, standard fertilizers were used in all treatments as described by Yoshida [21].

2.4. Effect of Elevated Temperature on Heading and Maturity Time of Rice

Heading is considered as the beginning of the heading stage when the panicle of rice and barnyardgrass starts to emerge from the boot. Plants were maintained to grow into the plastic pots in the phytotron under various temperatures including ambient, ambient +0.8 °C, ambient +1.9 °C, and ambient +3.4 °C. The heading period was spread over two to ten weeks due to the variations in ages within tillers of rice and barnyardgrass plants in the phytotron. The heading period of plants was considered to start when at least fifty percent of the panicles emerged from the boot. Usually, the heading period was shorter under elevated temperature and longer under ambient temperature, respectively [22].

2.5. Plant Sampling

Test plants were harvested at full maturity of the grains. Grain moisture content (GMC) was measured by taking an average of 3 values from the apex, middle and lowest part of the panicles using a grain moisture tester. Each experimental pot was harvested separately where 11 plants were bulked and 19 g of filled grains was used for milling. After harvesting, the grain moisture content was gradually reduced to 14% in a climate-controlled room (humidity 15% and temperature 21 °C) for more than 45 days.

At the fully matured stage, tiller number per pot was counted and plant height was measured from the ground level of the plant to the apex of the panicle. Plants of each species were harvested at the soil surface, and afterward the aboveground shoots of rice and barnyardgrass were bundled and labeled separately. Threshed rice heads were grain-cleaned, grain yield was recorded individually from each pot, and the weight was adjusted to a 14% moisture content. To measure the dry weight of the aboveground plant parts such as seeds and stems of rice and barnyardgrass, samples from each pot were harvested separately and put in paper bags. The collected aboveground parts of the plants were dried at 72 °C for three days and weighed. During harvesting, agronomic characteristics were assessed on per-plant basis of rice and barnyardgrass, which included plant height, shoot dry weight, tiller number, and grain yield.

2.6. Statistical Analyses

One way analyses of variance (ANOVA) was conducted to examine the effects of elevated air temperature and plant density on plant growth performance and yield parameters and their competition using the SPSS 16.0 software. Based on non-linear regression analysis, plant height, shoot dry weight, tiller number, and grain yield for each pot were evaluated. Means were separated by Duncan's Multiple Range Test.

3. Results

3.1. Competitive Ability of Plant Traits

The competitive ability of rice and barnyardgrass was studied based on a number of plant characteristics such as plant height, dry weight, number of tillers, and grain yield (Section 3). There was a significant impact of mixture proportions and different temperatures on plant height, dry weight, number of tillers, and grain yield parameters. In monoculture, rice performance was superior to that of barnyardgrass considering all plant traits. Plant growth parameters of rice in mixture declined with the increase in the proportion of barnyardgrass. On the contrary, barnyardgrass grew well in mixture proportions alongside rice when rice proportion was low. This outcome implies that barnyardgrass was highly competitive when grown under interspecific compared to intraspecific competition. On the other hand, rice performed well when grown under monoculture compared to in mixture.

3.2. Plant Height

Plant height is one of the major growth characteristics of rice that was visibly different from that of barnyardgrass in this experiment. The plant height of rice and barnyardgrass significantly increased when rice and barnyardgrass were grown alone or in a mixture proportion under different temperature conditions (Table 1). The highest plant height of rice was recorded in the monoculture (100:0 mixture proportions of rice/barnyardgrass) in both four and sixteen plant densities under ambient +3.4 °C. The order of plant height of rice was 100:0 > 75:25 > 50:50 > 25:75 of rice/barnyardgrass proportions in both four and sixteen per-pot plant densities. Temperature had a positive effect on rice growth, and the increase in plant height was in the following order: ambient +3.4 °C > ambient +1.9 °C > ambient +0.8 °C > ambient for both rice and barnyardgrass plants.

Table 1. Plant height (cm) of rice (R) and barnyardgrass (B) in monoculture and mixture under elevated temperature in a replacement series experiment.

Density	Temperature	Plant Species	Plant Mixture Proportion (%)				
			R 100 **B 0**	**75** **25**	**50** **50**	**25** **75**	**0** **100**
4 plants per pot	Ambient	R	97.4 ± 1.51 d	93.6 ± 2.37 h	81.5 ± 2.08 f	85.0 ± 2.52 f	0
		B	0	121.3 ± 3.59 c	120.1 ± 3.64 c	118.0 ± 2.21 c	123.2 ± 3.61 b
	Ambient +0.8 °C	R	100.9 ± 1.69 c	97.1 ± 2.33 e	89.1 ± 1.71 e	86.0 ± 4.81 e	0
		B	0	122.5 ± 2.66 c	124.3 ± 7.79 b	124.9 ± 2.60 b	123.9 ± 2.76 b
	Ambient +1.9 °C	R	109.4 ± 0.90 b	98.5 ± 2.50 e	90.1 ± 2.33 de	90.8 ± 1.65 de	0
		B	0	126.0 ± 3.03 b	127.5 ± 3.17 b	131.9 ± 2.69 ab	128.4 ± 2.52 ab
	Ambient +3.4 °C	R	110.4 ± 0.78 a	107.2 ± 2.19 d	92.1 ± 2.61 d	92.3 ± 2.90 d	0
		B	0	136.3 ± 3.50 a	134.1 ± 4.26 a	134.7 ± 3.53 a	130.2 ± 3.08 a
16 plants per pot	Ambient	R	88.9 ± 1.14 d	77.6 ± 0.64 h	79.8 ± 1.06 e	79.8 ± 1.47 g	0
		B	0	107.4 ± 2.83 d	112.9 ± 3.08 b	106.8 ± 2.59 d	103.3 ± 1.61 d
	Ambient +0.8 °C	R	95.9 ± 0.81 c	83.6 ± 0.82 g	80.1 ± 1.27 e	81.8 ± 1.96 f	0
		B	0	116.1 ± 3.22 c	113.5 ± 2.08 b	110.2 ± 2.24 c	107.2 ± 2.31 c
	Ambient +1.9 °C	R	99.7 ± 1.04 b	88.6 ± 0.93 f	85.7 ± 1.41 d	83.4 ± 1.58 e	0
		B	0	121.5 ± 3.63 b	113.5 ± 2.25 b	113.7 ± 2.23 b	112.6 ± 1.87 b
	Ambient +3.4 °C	R	105.5 ± 0.93 a	94.6 ± 1.62 e	93.3 ± 1.55 c	84.8 ± 2.69 e	0
		B	0	129.0 ± 2.85 a	118.6 ± 2.53 a	121.0 ± 1.68 a	115.1 ± 1.88 a

Values with different letters within the same row differ significantly ($p < 0.05$).

The highest plant height of barnyardgrass was recorded at the 75:25 ratio of rice/barnyardgrass in both four and sixteen plant per-pot densities, at ambient +3.4 °C. The order of the plant height of barnyardgrass was 75:25 > 50:50 > 25:75 > 0:100 at the rice/barnyardgrass proportions in both four and sixteen per-pot plant density conditions. The height of both species gradually declined as the ambient temperature reduced. Barnyardgrass plants were taller in mixtures than rice in monoculture.

3.3. Number of Effective Tillers

Tiller numbers of rice and barnyardgrass significantly differed in this study. Tiller number was significantly reduced from 23.8 to 15.7 and from 6.2 to 4.4 in rice and from 70.8 to 41.1 and from 24.1 to 12.2 in barnyardgrass in monoculture and mixture (100:0 and 75:25) proportions over four and sixteen plant density per pot, respectively, at ambient +3.4 °C (Table 2). This indicates that the maximum numbers of tillers in rice and barnyardgrass were recorded in rice monoculture at ambient +3.4 °C. The tiller number of rice was recorded in the following order: 100:0 > 75:25 > 50:50 > 25:75 at the rice/barnyardgrass proportions at both four and sixteen per-pot plant densities. Similarly, the order of the tiller number of barnyardgrass was 75:25 > 50:50 > 25:75 > 0:100 at the rice/barnyardgrass mixture proportions at both four and sixteen plant densities per pot. Tiller numbers were substantially higher in the lower plant density (four plants per pot) compared to the higher plant density (sixteen plants per pot).

The increase in temperature had a significant impact on the number of tillers in both rice and barnyardgrass plants and followed the order of ambient +3.4 °C > ambient +1.9 °C > ambient +0.8 °C > ambient. The minimum number of tillers in barnyardgrass was found at ambient temperature under the lowest proportion of rice in mixture. The total number of tillers in barnyardgrass was considerably higher than that of rice.

Table 2. Tiller number of rice (R) and barnyardgrass (B) in monoculture and mixture under elevated temperature in a replacement series experiment.

Density	Temperature	Plant Species	Plant Mixture Proportion (%)				
			R 100 / **B** 0	75 / 25	50 / 50	25 / 75	0 / 100
4 plants per pot	Ambient	R	19.9 ± 0.93 b	14.8 ± 0.94 d	11.4 ± 0.84 g	8.0 ± 1.08	0
		B	0	49.5 ± 5.45 c	43.3 ± 3.57 d	40.8 ± 2.19	33.6 ± 1.24 c
	Ambient +0.8 °C	R	20.3 ± 1.15 b	15.0 ± 1.11 d	12.0 ± 0.80 f	11.3 ± 2.10	0
		B	0	56.5 ± 7.51 b	48.8 ± 3.10 c	45.5 ± 2.88	38.4 ± 1.72 b
	Ambient +1.9 °C	R	20.4 ± 0.79 b	15.3 ± 0.75 d	13.1 ± 0.88 e	11.8 ± 1.70	0
		B	0	56.5 ± 4.99 b	51.6 ± 4.11 b	45.6 ± 2.97	40.3 ± 2.32 a
	Ambient +3.4 °C	R	23.8 ± 0.69 a	15.7 ± 0.81 d	13.6 ± 1.50 e	13.5 ± 0.96	0
		B	0	70.8 ± 6.18 a	59.6 ± 5.28 a	47.6 ± 3.36	41.1 ± 3.11 a
16 plants per pot	Ambient	R	5.5 ± 0.22 d	4.0 ± 0.18 e	2.8 ± 0.18 f	2.5 ± 0.18 h	0
		B	0	17.8 ± 0.91 c	15.3 ± 1.06 c	12.4 ± 0.53 d	9.3 ± 0.28 c
	Ambient +0.8 °C	R	5.7 ± 0.23 c	4.0 ± 0.22 e	3.2 ± 0.17 e	2.7 ± 0.27 g	0
		B	0	19.4 ± 1.75 b	18.1 ± 0.88 b	14.3 ± 0.50 c	11.5 ± 0.44 b
	Ambient +1.9 °C	R	5.8 ± 0.20 b	4.2 ± 0.20 de	3.4 ± 0.25 de	2.7 ± 0.36 f	0
		B	0	23.8 ± 1.65 a	18.1 ± 0.92 b	14.5 ± 0.83 b	12.2 ± 0.38 a
	Ambient +3.4 °C	R	6.2 ± 0.22 a	4.4 ± 0.26 d	3.6 ± 0.26 d	3.8 ± 0.46 e	0
		B	0	24.1 ± 1.82 a	19.9 ± 1.04 a	14.8 ± 0.62 a	12.2 ± 0.47 a

Values with different letters within the same row differ significantly ($p < 0.05$).

3.4. Shoot Dry Weights

An increase in dry weight of rice and barnyardgrass was observed with the increase in temperature in the phytotrons and proportion of rice in the mixture (Table 3). Based on the non-linear regression analysis of dry weights of rice and barnyardgrass, the estimated maximum dry weight of rice and barnyardgrass was found at 100:0 and 75:25 of rice/barnyardgrass proportions, respectively, regarding plant densities at ambient +3.4 °C (Table 3, Figures 1 and 2). Shoot dry weight was significantly reduced from 42.7 to 20.0 and from 118 to 85.5 g per pot in rice, and from 12.3 to 4.4 and from 39.4 to 21.2 g per pot in barnyardgrass when rice/barnyardgrass monoculture and mixture proportions reduced from 100:0 to 25:75 at the densities of four and sixteen plants per pot, respectively, under ambient +3.4 °C. The order of shoot dry weight of the barnyardgrass was 75:25 > 50:50 > 25:75 > 0:100 at the rice/barnyardgrass proportions in both four and sixteen per-pot plant density conditions. Similarly, shoot dry weight of rice followed the order of 100:0 > 75:25 > 50:50 > 25:75 at the rice/barnyardgrass proportions in both four and sixteen per-pot plant densities.

Table 3. Shoot dry weight (g) of rice (R) and barnyardgrass (B) in monoculture and mixture under elevated temperature in a replacement series experiment.

Density	Temperature	Plant Species	Plant Mixture Proportion (%)				
			R 100 / **B** 0	75 / 25	50 / 50	25 / 75	0 / 100
4 plants per pot	Ambient	R	32.9 ± 1.96 d	24.9 ± 1.48 g	16.4 ± 0.86 e	15.1 ± 2.29 f	0
		B	0	103.8 ± 3.83 c	84.3 ± 10.71 c	69.9 ± 6.32 c	62.1 ± 4.66 c
	Ambient +0.8 °C	R	34.6 ± 1.95 c	25.7 ± 1.24 f	18.4 ± 1.28 de	17.1 ± 3.40 e	0
		B	0	109.1 ± 14.12 b	89.6 ± 11.20 b	71.4 ± 4.45 c	64.3 ± 4.92 b
	Ambient +1.9 °C	R	36.4 ± 1.14 b	26.2 ± 1.33 f	19.8 ± 1.37 d	18.1 ± 1.27 e	0
		B	0	113.6 ± 11.62 ab	93.3 ± 5.95 ab	78.4 ± 4.69 b	65.0 ± 3.21 b
	Ambient +3.4 °C	R	42.7 ± 2.09 a	28.8 ± 2.54 d	20.1 ± 1.56 d	20.0 ± 0.73 d	0
		B	0	118.8 ± 9.84 a	97.9 ± 6.74 a	85.7 ± 6.10 a	69.7 ± 3.47 a

Table 3. *Cont.*

Density	Temperature	Plant Species	Plant Mixture Proportion (%)				
			R 100 B 0	75 25	50 50	25 75	0 100
16 plants per pot	Ambient	R B	9.7 ± 0.32 d 0	5.7 ± 0.32 g 31.7 ± 2.99 c	4.5 ± 0.33 f 24.2 ± 1.87 c	3.6 ± 0.59 e 18.4 ± 0.81 c	0 14.7 ± 0.41 b
	Ambient +0.8 °C	R B	10.2 ± 0.39 c 0	6.0 ± 0.32 f 34.0 ± 3.16 b	4.7 ± 0.35 e 26.3 ± 1.36 b	4.2 ± 0.49 de 19.6 ± 0.89 b	0 16.2 ± 0.59 a
	Ambient +1.9 °C	R B	11.5 ± 0.41 b 0	6.3 ± 0.33 e 37.4 ± 2.70 ab	4.8 ± 0.28 e 27.0 ± 1.52 b	4.3 ± 0.40 d 20.7 ± 1.00 a	0 16.4 ± 0.65 a
	Ambient +3.4 °C	R B	12.3 ± 0.38 a 0	7.1 ± 0.44 d 39.4 ± 3.94 a	5.3 ± 0.30 d 29.1 ± 1.66 a	4.4 ± 0.64 d 21.2 ± 1.37 a	0 16.6 ± 0.68 a

Values with different letters within the same row differ significantly ($p < 0.05$).

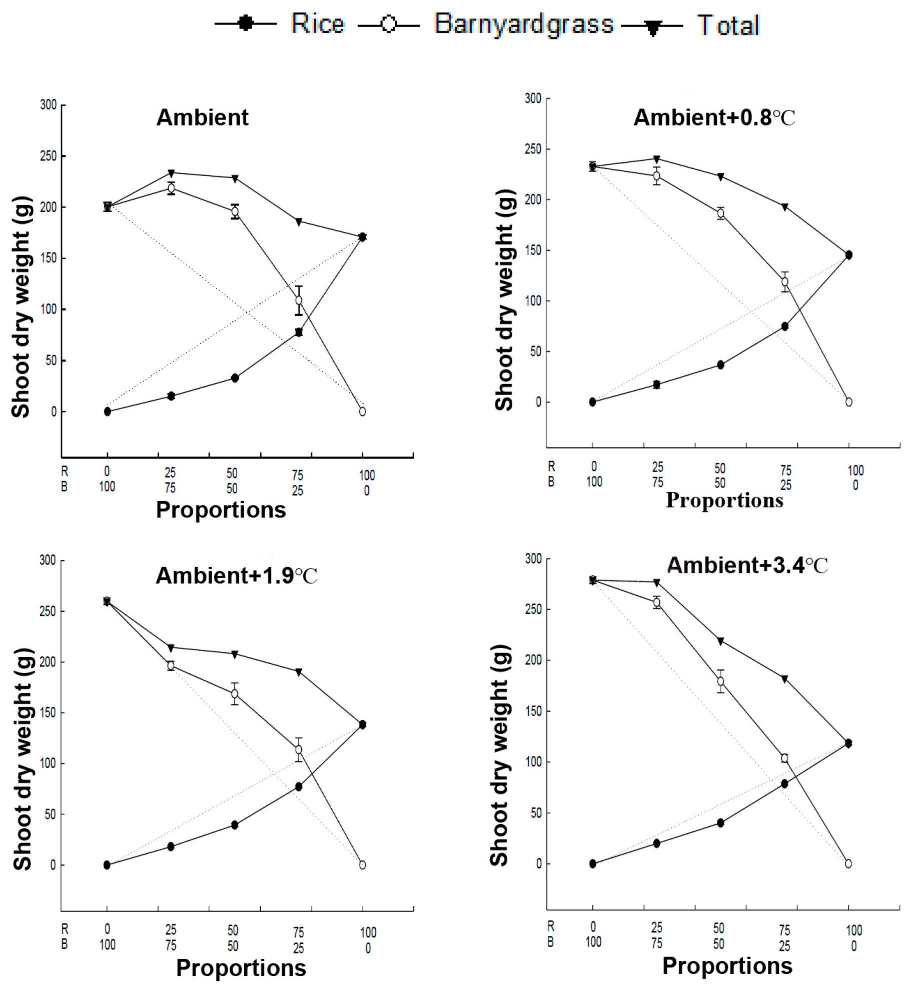

Figure 1. Shoot dry weight per pot comparison between rice and barnyardgrass grown at five proportions with a constant density (4 plants pot^{-1})(4 plants/pot^{-1}) under elevated temperature conditions. Dotted lines indicate theoretical shoot dry weight when the plants are equally competitive. Vertical bars present 95% confidence of the mean.

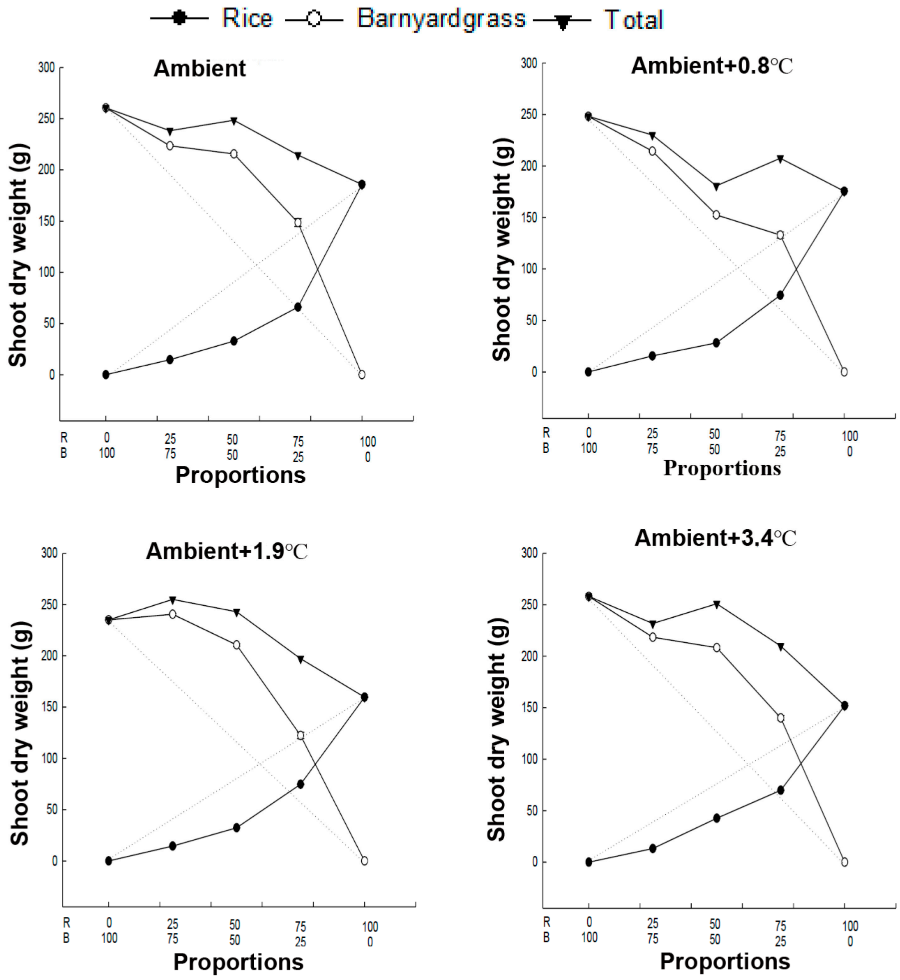

Figure 2. Shoot dry weight per pot comparison between rice and barnyardgrass grown at five proportions with a constant density (16 plants pot^{-1}) under elevated temperature conditions. Dotted lines indicate theoretical shoot dry weight when the plants are equally competitive. Vertical bars present 95% confidence of the mean.

In the case of temperature effect, the increase in shoot dry weight followed the order of ambient +3.4 °C > ambient +1.9 °C > ambient +0.8 °C > ambient for both rice and barnyardgrass plants (Table 3). This result indicated that the shoot dry weight of barnyardgrass was more pronounced at the 75:25 mixture proportion of rice and barnyardgrass under both plant densities. But the rice dry weight increased substantially when rice was grown alone comparted to the mixture competition. This result showed that rice had more intraspecific competition than interspecific competition against barnyardgrass.

3.5. Grain Yield

Grain yield of rice was significantly affected by varied densities of barnyardgrass and temperature conditions (Table 4). Rice grain yield decreased progressively with the decrease in the proportion of rice in the rice/barnyardgrass mixtures and drastically increased together with rice increasing in proportion. The highest rice grain yield (37.7 g/pot) was recorded in the monoculture (100:0 rice/barnyardgrass) under ambient temperature, whereas the lowest rice grain yield (0.3 g/pot) was recorded at the 25:75 rice/barnyardgrass mixture proportion under ambient +3.4 °C. The impact of different temperatures on rice yield followed the order of ambient > ambient +0.8 °C > ambient +1.9 °C > ambient +3.4 °C. This indicates that the highest temperature (ambient +3.4) tested in this experiment negatively affected the rice grain yield and resulted in the substantial decrease in the grain yield.

Table 4. Grain yield (g) of rice (R) and barnyardgrass (B) in monoculture and mixture under elevated temperature in a replacement series experiment.

Density	Temperature	Plant Species	Plant Mixture Proportion (%)				
			R 100 B 0	75 25	50 50	25 75	0 100
4 plants per pot	Ambient	R	37.1 ± 2.25 a	25.8 ± 1.30 a	12.6 ± 2.32 a	11.7 ± 3.65 a	0
		B	0	15.2 ± 5.34 c	9.1 ± 2.07 c	8.5 ± 2.29 b	8.5 ± 1.73 a
	Ambient +0.8 °C	R	36.4 ± 2.45 a	22.9 ± 2.19 b	11.7 ± 2.62 ab	8.5 ± 0.66 b	0
		B	0	12.4 ± 4.28 d	8.7 ± 3.08 cd	6.3 ± 1.41 c	5.5 ± 1.27 b
	Ambient +1.9 °C	R	12.5 ± 1.53 b	6.5 ± 0.96 e	2.6 ± 0.30 f	2.8 ± 1.62 e	0
		B	0	9.7 ± 6.88 de	6.9 ± 2.18 d	5.1 ± 1.70 d	5.0 ± 1.06 bc
	Ambient +3.4 °C	R	10.3 ± 0.72 c	4.7 ± 0.34 f	1.3 ± 0.23 g	2.8 ± 1.05 e	0
		B	0	6.3 ± 1.72 e	3.8 ± 0.98 e	4.5 ± 1.14 de	4.8 ± 0.95 c
16 plants per pot	Ambient	R	11.3 ± 1.46 a	3.8 ± 0.33 a	3.3 ± 0.38 a	1.0 ± 0.21 c	0
		B	0	3.7 ± 0.76 a	3.2 ± 0.38 a	1.6 ± 0.18 a	1.8 ± 0.17 a
	Ambient +0.8 °C	R	7.4 ± 0.36 b	3.2 ± 0.37 ab	1.7 ± 0.19 c	0.7 ± 0.28 d	0
		B	0	2.7 ± 0.54 b	2.1 ± 0.51 b	1.3 ± 0.20 b	1.6 ± 0.18 b
	Ambient +1.9 °C	R	3.0 ± 0.18 c	0.8 ± 0.10 d	0.5 ± 0.08 f	0.5 ± 0.08 e	0
		B	0	1.8 ± 0.43 c	1.4 ± 0.18 d	1.2 ± 0.15 b	1.2 ± 0.11 c
	Ambient +3.4 °C	R	2.6 ± 0.15 d	0.5 ± 0.07 e	0.4 ± 0.05 f	0.3 ± 0.04 f	0
		B	0	1.7 ± 0.43 c	1.1 ± 0.26 e	0.3 ± 0.05 f	0.3 ± 0.04 d

Values with different letters within the same row differ significantly ($p < 0.05$).

According to the results described above, the order of the rice grain yield in the rice/barnyardgrass mixture proportions was 100:0 > 75:25 > 50:50 > 25:75. On the contrary, barnyardgrass produced less grain per pot at the higher proportions of its population and followed the order of 75:25 > 50:50 > 25:75 > 0:100 in the rice/barnyardgrass proportions. The increase in temperature negatively affected the yield of both plants and followed the order of ambient > ambient +0.8 °C > ambient +1.9 °C > ambient +3.4 °C. For both species, the grain yield was higher at a density of 4 plants per pot than at 16 plants per pot. These results imply that the grain yield of both plants was also reduced by intraspecific competition.

4. Discussion

The results of this experiment revealed that barnyardgrass grew more vigorously than rice under elevated temperature conditions. However, both species exhibited an increase in plant height with increase in temperature and followed the order of ambient +3.4 °C > ambient +1.9 °C > ambient +0.8 °C > ambient. These results are in accordance with the findings of Oh-e et al. [23] who reported that greater plant height enhancement usually occurs under elevated temperature than under the ambient temperature condition.

This experiment demonstrated that plant height, tiller number and rapid early growth are important determinants of potential yields, and those characteristics can be useful criteria of rice production under elevated temperature. Thus, farmers may be able to reduce weed pressure and improve weed management by planting cultivars with enhanced competitiveness against weeds and also to provide some other information that could contribute to increased rice production.

Barnyardgrass grew better in mixture with rice compared to the monoculture. Nevertheless, rice growth increased considerably when grown alone than in mixtures. This indicates that barnyardgrass is highly competitive when grown in a mixture than in monoculture. Aminpanah et al. [24] found that the plant height of rice was remarkably reduced with a decrease in the rice portion in rice/barnyardgrass mixtures. Estorninos et al. [25] reported that the plant height of the Kaybonent rice variety was lower when grown with red rice than in monoculture, whereas the height of the PI 312777 rice variety was not affected by red rice competition. It was revealed that PI 312777 was more competitive than the Kaybonnet rice genotype, and the authors concluded that the competitive ability of rice depends on the genotype.

Tiller numbers of rice were reduced with the increasing proportions of barnyardgrass in the mixtures, indicating the cultivar's competitive ability. The most competitive interaction of cultivars was associated with the production of a large number of tillers [26]. Chavez et al. [27] also noticed in the experiments that the ability of higher tiller production is one of the advantages related to the suppression of barnyardgrass by rice.

Yield-contributing characteristics of rice differed extensively with density; nevertheless, there was a significant difference in yield attributes due to density and its interactions with other variables. In monocultures, performance did not vary among rice and barnyardgrass due to density. But when plants were grown in mixtures, the performance of barnyardgrass plants was significantly higher than that of rice with greater plant height, shoot dry weight, and number of tillers than in monoculture. On the contrary, the rice did not exhibit any competitive ability against barnyardgrass under elevated temperature as well as in the combination of planting ratio and density. For instance, the order of plant height, shoot dry weight, and number of tillers of barnyardgrass was 75:25 > 50:50 > 25:75 > 0:100 in rice/barnyardgrass proportions at both plant densities. In rice, this value followed the order of 100:0 > 75:25 > 50:50 > 25:75 in rice/barnyardgrass proportions in both plant densities. Rice dry weight was substantially larger when rice was grown alone than in mixture. This result demonstrated that rice was a weak competitor against barnyardgrass. On the contrary, barnyardgrass was a stronger competitor when grown alone than in a mixture.

Perhaps aboveground competition from barnyardgrass was the main cause for the reduction in the dry matter of rice mixtures during the reproductive development period [28]. Therefore, invasive weeds may become more incursive under warmer conditions [29]. Rice and barnyardgrass positions (lines) were equally bisected in a 75:25 mixture proportion. The regression curve for the rice cultivar was concave and the curve for barnyardgrass was convex. This indicates that barnyardgrass was gaining more biomass and hence was more competitive than rice. The rice grain yield in the rice/barnyardgrass mixtures followed the order of 100:0 > 75:25 > 50:50 > 25:75. This result is in agreement with the earlier findings of Wolfe et al. [30] who reported that weeds gain more advantages than crops in mixed cultivation. McDonald and Gill [31] observed competitive ability development in crops which generally have a negative correlation with crop yield; thus, it is difficult for breeders to enhance competitive ability without crop yield loss. Onishi et al. [32] worked on the competitive ability of cultivated and wild annual rice genotypes, and they concluded that these wild rice plants might have accumulated genes during evolution to survive among weed species.

The impact of different temperatures on the yield of both species followed the order of ambient > ambient +0.8 °C > ambient +1.9 °C > ambient +3.4 °C. This indicates that the highest temperature (ambient + 3.4) tested in this experiment negatively affected the yield of both species and resulted in the 360.2% and 177.1% reduction in the grain yield in rice and barnyardgrass, respectively, in monoculture. This result indicates that rice suffered more than barnyardgrass under elevated temperature conditions. These results are similar to the findings of Rosenzwei and Hiller [33] who reported that increasing temperature and CO_2 levels make crop plants less competitive than weeds. On the contrary, in the experiments conducted by Namuco et al. [34], it was detected that some rice cultivars are capable to produce higher biomass and grain yields in competition with weeds. Therefore, this finding suggested that some rice varieties are more competitive and capture resources better than barnyardgrass. At particular ratios and densities, the yield of rice was higher and that of barnyardgrass grain was lower than predicted. Oh-e et al. [23] reported that twenty days after the start of the heading stage in rice, grain yield significantly decreased when the ambient temperature increased to over 28 °C. The changes in plant performance under ompetition were closely examined in this study. However, when grown in mixtures, the performance of barnyardgrass was significantly greater than that of rice plants with regard to plant heights, dry weight, number of tillers, and grain yield. On the contrary, barnyardgrass grew well in mixture proportions alongside rice when the rice proportion was low. This finding implies that barnyardgrass was highly competitive when grown under interspecific compared to intraspecific competition. On the other hand, rice performed better when grown under monoculture than it did in mixture.

This experiment demonstrated that plant height, tiller number and rapid early growth are important determinants of potential yields, and those characteristics can be useful criteria of rice production under elevated temperature. Thus, farmers may be able to reduce weed pressure and improve weed management by planting cultivars with enhanced competitiveness against weeds and also provide some other information that could contribute to increased rice production. These findings suggested that various competitive environments may alter the species contribution to competition between rice and barnyardgrass plants.

5. Conclusions

In this study, elevated temperature positively influenced rice and barnyardgrass growth, but it showed a negative impact on the grain yield of rice as well as barnyardgrass. Rice was less competitive than barnyardgrass in the mixture proportions, especially under higher temperatures. The low yield of rice might have been caused by poor pollination and fertilization due to the increase in temperatures. Therefore, it is important to efficiently control barnyardgrass in paddy fields.

Phytotrons offer precise control over environmental variables; they often cannot fully replicate the complexity of natural ecosystems. They have some limitations such as differences in light quality, temperature fluctuations, soil microbiota, and atmospheric composition compared to natural conditions. Therefore, plants may respond differently in the absence of interactions present in natural environments; as the differences may be in areas such as growth rates, biomass allocation, nutrient uptake, stress tolerance, and interactions with other organisms (e.g., pollinators, herbivores, pathogens).

Keeping these limitations in mind, we need to develop a holistic approach that integrates controlled experiments with field-based research to advance our understanding of plant–environment interactions and inform sustainable management practices.

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