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Yield and yield components in autotetraploid and diploid rice genotypes (*indica* and *japonica*) sown in early and late seasons

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Abstract

Asian cultivated rice (*Oryza sativa* L.) can be divided into two sub-species *indica* and *japonica*. The present study was conducted to investigate the effect of inter-seasonal variations in meteorological parameters e.g., temperature, solar radiation and rainfall on morphological and yield traits of autotetraploid and diploid rice including *indica* and *japonica* genotypes. The contribution of dry matter production and harvest index in improving yield were also investigated. Mean daily solar radiation (MJ m^{-2} day^{-1}) was higher during late seasons (14.5) than early seasons (11.8). Daily maximum temperature (≥ 35°C) was observed for more than three consecutive days at flowering during early seasons. Photothermal quotient (MJ m^{-2} d^{-1} $°C^{-1}$) showed more close relationship with yield (0.905 and 0.807) and seed set (0.965 and 0.834) compared to temperature or solar radiation alone in autotetraploid and diploid rice. Inter-seasonal variations showed a strong influence on diploid cultivars compared to autotetraploid cultivars. Late seasons produced significantly higher yield, number of panicles per plant, filled grains, flag leaf area and dry matter production than early seasons. Autotetraploid cultivars produced significantly ($P<0.01$) greater grain length (0.15 cm), panicle length (1.5~3.5 cm), grain width (0.05 cm), 1000-grain weight (>10 g) and flag leaf area (2.6~9.6 cm^2) than diploid cultivars, but yielded very low due to low seed set (≤ 38.1%). The results suggest that greater amount of solar radiation, photothermal quotient (0.905 MJ m^{-2} d^{-1} $°C^{-1}$) and suitable temperature (25.6°C) during late seasons contributed to higher amount of sink and biomass accumulation, which increased the grain yield of diploid and autotetraploid cultivars during these seasons.

Keywords: Dry matter production; harvest index; *Oryza sativa*; photothermal quotient; seed set percentage; temperature.

Abbreviations: DM- dry matter production; ES- early season; FG- filled grains; FLA- flag leaf area; GL- grain length; GP- grains per panicle; GW- grain width; TGW- 1000-grain weight; HD- heading date; HI- harvest index; LS- late season; NP- number of panicles per plant; PL- panicle length; PTQ- photothermal quotient; SS- seed set.

Introduction

Rice (*Oryza sativa* L.) is the most important cereal food crop in the world. During the past decades, rice yield has been significantly improved due to the development of new cultivars, but still there is desperate need to enhance rice production because estimated number of new rice consumers will increase to 1.2 billion by 2020 (Babar et al., 2007). There must be an increase in rice production, approximately 12% over a decade to meet the rice requirement of world (Normile, 2008). Area under rice cultivation is decreasing continuously, so increasing yield per unit area is the only way to increase world rice production (Yang et al., 2007).

Rice plant growth can be divided into three developmental stages: vegetative, reproductive and ripening. The vegetative stage refers to a period from germination to the initiation of panicle primordial. The reproductive phase referred from panicle primordia initiation to heading; and ripening from heading (grain filling) to maturity (Yoshida, 1981). High temperature stress is defined as the rise in temperature beyond a critical threshold level for a sufficient time that cause irreversible damage to plant growth and development (Wahid et al., 2007). Reproductive and grain filling phases of rice are more sensitive to elevated temperature than vegetative phase. The optimum temperature for rice grain development and grain yield is 25°C (Baker et al., 1995). High temperature during night time can significantly reduce the spikelet fertility which, in turn, decreases the yield of rice (Peng et al., 2004). High temperature has a significant effect on the leaf appearance rates (Baker et al., 1995), organ temperature (Yan et al., 2010) and spikelet fertility but the extent of severity varies among different genotypes and time-of-day of anthesis (Prasad et al., 2006; Jagadish et al., 2007; Yan et al., 2010).

Seasons had strong influence on diploid rice production because dry season received higher solar radiation in comparison to wet season (Yang et al., 2008). Double cropping (two seasons) of rice is commonly practiced in southern China as: early rice season (1 March to 15 July) and late rice season (25 July to 30 Nov). Late season (LS) produced higher rice yield than early season in southern China (Jin et al., 2002). If the major effect of solar radiation on yield determining factors operates via a linear relationship with crop growth rate and that of temperature through a linear

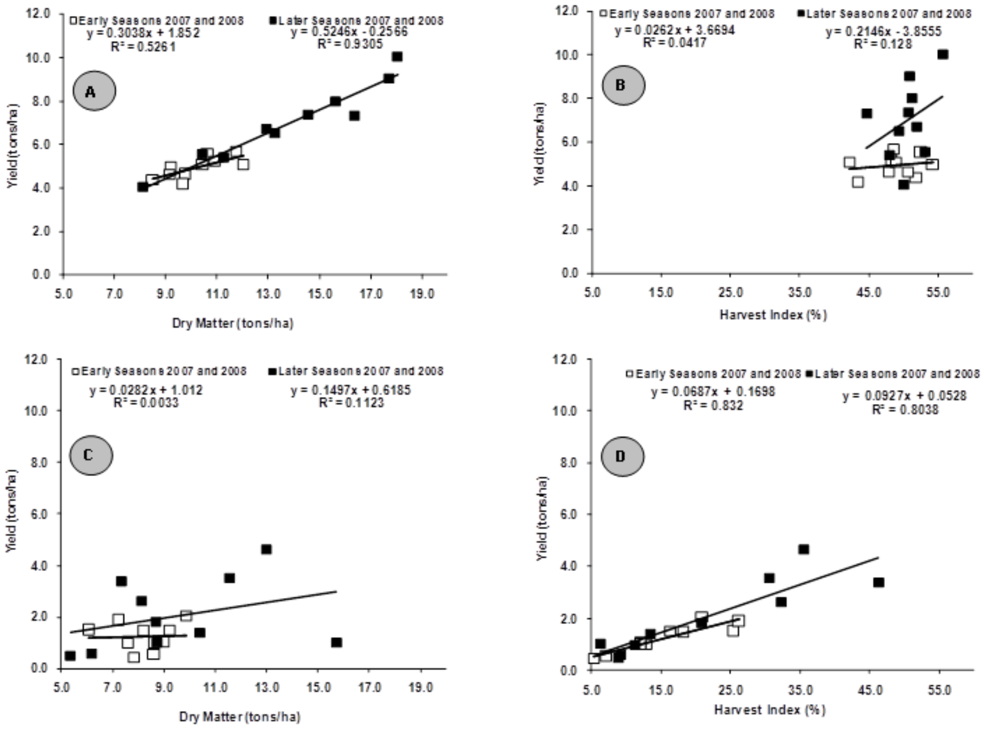

Fig 1. Relationship between grain yield and dry matter production during early and late seasons, in (A) diploid and (B) autotetraploid cultivars. Figs C and D represent the relation of grain yield with harvest index during early and late seasons in diploid and autotetraploid rice, respectively. Mean values of two seasons were used because two early and late seasons showed non-significant differences.

effect on crop development then it is possible that yield determining factors under natural conditions could be related to the photo-thermal quotient (ratio of solar radiation and average temperature) during the temperature sensitive pre-anthesis period (Nix, 1976; Fischer, 1985).

Grain yield of major cereals including rice, wheat, barley and sorghum is largely determined by the source-sink relationship. Source and sink are the limiting factors of biochemical reactions involved in life span of crops (Horton, 2000). In crops especially cereals, flag leaf significantly contributes to the yield and quality of grains because of its greater and sustained photosynthetic activity (Li et al., 1998). Flag leaf is the primary source of carbohydrates and over 80% of the carbohydrates accumulated in grains are produced by the top two leaves (Tomoshiro et al., 1983). Flag leaf plays an important role to increase rice yield by increasing grain weight (Rao, 1997). Grain yield is determined by harvest index (HI) and dry matter production (Yang et al., 2008). Scientists believe that crop yield can be increased by increasing the dry matter production instead of HI (Naylor et al., 1998; Ntanos and Koutroubas, 2002; Peng et al., 2000). It is also suggested that improving HI can improve yield (Austin et al., 1989; Kiniry et al., 2001). Harvest index of some crops including rice has attained nearly its maximum value, so further increase in yield depends on the improvement of dry matter production (Ying et al., 1998; Peng et al., 2000).

Autotetraploid rice is a special genetic material which has much potential to increase the rice yield, but it has major drawback of low seed set (Shahid et al., 2010). There are different reports pertaining to low seed set of autotetraploid rice such as embryo sac abortion, pollen abortion (Guo et al., 2006; Shahid et al., 2010), abnormal microtubule distribution pattern (He et al., 2011a), pollen sterility loci interaction and abnormal chromosome behaviour (He et al., 2011b). Autotetraploid rice grains are rich in nutrition contents (Song and Zhang, 1992) and depicted higher hybrid vigor than diploid rice (Shahid et al., 2011). Little is known about the comparative performance of diploid versus autotetraploid rice cultivars grown under different seasons. Therefore, it is important to investigate the seasonal effects on diploid and autotetraploid rice and to explore the reasons for difference in yield among the seasons. This study was planned to (1) investigate the effect of inter-seasonal variation in meteorological parameters e.g., temperature, solar radiation and rainfall, on morphological and yield traits of autotetraploid and diploid rice including *indica* and *japonica* genotypes and (2) study of contribution of dry matter production and harvest index in improving yield.

Results

Meteorological conditions during the rice growth seasons

Different temperature regimes during vegetative, reproductive and ripening stages, less rainfall and in consequence high solar radiation were found during late seasons. Daily average minimum and maximum temperatures during reproductive phase were 25.4°C and 32.2°C, respectively, in ES, whereas daily maximum temperature ≥ 35°C was recorded for more than three consecutive days in ES-2007 and ES-2008. Seasonal averages of daily minimum and maximum temperatures were 23.1°C and 30.6°C during late seasons, while daily maximum temperature ≥ 35°C prevailed for only one day during LS-2007. There were no detectable differences in mean daily solar radiation and minimum and maximum temperatures during ES (Table 2). Total precipitation received during the reproductive period

Table 1. Diploid and autotetraploid cultivars used during the study.

Code	Name	Ploidy	Source	Subspecies	Type
DE	E24	2×	Guangdong, China	*japonica*	Cold-resistant
D2	Guanglu'ai 4	2×	Guangdong, China	*indica*	Local and anti-diseases
D3	L202	2×	IRRI[a]	*japonica*	Long grain
D5	Jackson	2×	IRRI	*japonica*	Good quality
D23	Shengnong 265	2×	Shen Yang, China	*japonica*	Straight panicle
D24	Shengnong15	2×	Shen Yang, China	*japonica*	Cold-resistant and anti-diseases
D28	Linglun	2×	Hunan, China	*indica*	Wide compatibility variety
D47	IR36	2×	IRRI	*indica*	Resistant to insect, pest and diseases
D49	M18	2×	Guangdong, China	*japonica*	Female and male Wide compatibility variety, Cold-resistant
D51	Dali'nuo	2×	Guangdong, China	*indica*	Glutinous, large grains
TE	E24	4×	SCAU[b]	*japonica*	--
T2	Guanglu'ai 4	4×	SCAU	*indica*	--
T3	L202	4×	SCBG- CAS[c]	*japonica*	--
T5	Jackson	4×	SCBG- CAS	*japonica*	--
T23	Shengnong 265	4×	SCAU	*japonica*	--
T24	Shengnong15	4×	SCAU	*japonica*	--
T28	Linglun	4×	SCAU	*indica*	--
T47	IR36	4×	SCAU	*indica*	--
T49	M18	4×	SCAU	*japonica*	--
T51	Dali'nuo	4×	SCAU	*indica*	--

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Table 2. Averages of meteorological parameters during different developmental stages of rice plant.

Growth stage	Daily mean temperature (°C)		Daily maximum temperature ≥35°C (Days)		Solar radiation (MJ m^{-2} day^{-1})		Total rainfall (mm)	
	ES	LS	ES	LS	ES	LS	ES	LS
Vegetative	22.4	29.0	0	16	10.0	15.6	401.0	447.4
Reproductive	27.9	26.3	5	1	12.1	14.7	514.6	94.3
Ripening	28.5	21.6	4	0	13.4	13.1	235.0	41.1

ES: Early Season; LS: Late Season, The data are mean of two growing seasons.

was 287.5, 741.6, 20.9, and 167.6 mm, while the highest temperatures (°C) were 36.8, 36.6, 35.0, and 34.4°C during ES-2007, ES-2008, LS-2007 and LS-2008, respectively. The significant ($P<0.01$) lower averages of temperature were recorded during the vegetative phase in ES than LS (Table 2). Daily maximum temperature ≥ 35°C prevailed for 16 days during ES, whereas daily maximum temperature remained lower than 35°C during whole vegetative phase in LS. Late seasons received significantly ($P<0.01$) higher mean daily solar radiation than ES during whole growth duration (Table 2).

Phenology

Autotetraploid cultivars have significantly longer growth duration (135 d) as compared to diploid cultivars (126 d), while there was non-significant relationship of growth duration between *indica* (132 d) and *japonica* (130 d). There was significant effect of seasons on growth duration. The late seasons had shorter growth duration (127 d) than early seasons (136 d). Reproductive phase is the most important stage of plant life cycle. The minimum and maximum temperature and rainfall trend before and after heading (panicle initiation to milk grain stage) were significantly varied among seasons during this period. All the diploid and autotetraploid cultivars showed early heading (flowering) in LS compared to ES, and highly significant ($P<0.01$) differences were found among diploid (86 d) and autotetraploid (93 d) cultivars for heading (Table 3). D23, D24, and T3 were earliest in heading, while statistically more days were taken by DE, TE, and T-51 than other cultivars during ES-2007 and ES-2008. Early heading was observed in D-24 and T-23, while DE, D-51, TE, and T-51 were late in this regard during LS-2007 and LS-2008. Early heading was found in *japonica* than *indica* cultivars during all four seasons, but the difference was non-significant. There was a significant effect of high temperature on flag leaf area (FLA) of diploid cultivars, but non-significant effect on autotetraploid cultivars. Flag leaf appeared earlier due to high temperature at vegetative stage during LS than ES in both diploid and autotetraploid cultivars. There was a great variation among genotypes for FLA during the four seasons under study.

Yield and its numerical components

Number of panicles (NP), grains per panicle (GP) and filled grains (FG) are the yield determining traits and great variation was found in these parameters among the all genotypes. There was significant effect of seasons on PL (panicle length), NP and FG, but GP showed non-significant effect of seasons. Late seasons had higher values for all these traits than ES. D28 (27.6 cm) and T28 (30.2 cm) had significantly long PL, while D23 (17.9 cm), T23 (19.7 cm), D24 (16.8 cm) and T24 (23.3 cm) had short PL during all growing seasons under study. Autotetraploid and *indica* cultivars were found with longer panicles in relation to diploid and *japonica* cultivars, respectively. D47 (13.4) and T47 (8.8) produced significantly highest number of panicles per plant, while D28 (179.5) and T28 (153.8) displayed the highest number of grains per panicle than other cultivars during all seasons. Substantial variation was found among genotypes for high and low levels of FG, NP and GP.

There was non-significant effect of seasons on 1000-grain weight (TGW), grain length (GL) and grain width (GW), whereas highly significant ($P<0.01$) differences were found between diploid and autotetraploid cultivars for these three traits (Table 3). More than 10 g increase in TGW, and more than 0.15 and 0.05 cm/grain increase in GL and GW, respectively, was observed in autotetraploid cultivars than diploid counterparts. Higher values were found for GL and GW in *indica* than *japonica* cultivars, which led to higher TGW in *indica* than *japonica* cultivars (Table 4). The highest GL and TGW were produced by D51 (10.9 cm and 40.1 g) and T51 (12.8 cm and 49.4 g), while highest GW was found in D28 (3.5 cm) and T28 (4.1 cm) than other cultivars. Some diploid cultivars showed lodging during ES-2008 but all autotetraploid cultivars were found resistant against strong winds and typhoon.

Late seasons produced significantly higher grain yield than early seasons, while diploid cultivars showed significantly higher grain yield than autotetraploid cultivars. Significantly highest yield was produced by D2 (ES-2007, LS-2007 and LS-2008) and D47 (ES-2008) among the diploid cultivars, while T5 (ES-2007) and T47 (LS-2007, ES-2008 and LS-2008) produced the highest yield among all autotetraploid cultivars (Table 4). There was non-significant effect of *indica* and *japonica* types on the yield of diploid cultivars.

Seasons showed a significant influence on seed set (SS) in diploid cultivars, while non-significant effect of seasons was found in autotetraploid cultivars. Most of the cultivars showed high SS during late seasons except D5 and T5 which produced low SS in late seasons. D24 produced higher SS than other diploid cultivars in ES-2007, D24 and D49 in LS-2007 and LS-2008, and D2 in ES-2008 (Table 4). SS was found more than 50% in one autotetraploid cultivar (T5) during ES-2007 and in three other cultivars (T2, T3 and T47) during LS-2007 and LS-2008. In four seasons, SS of *japonica* and diploid cultivars was higher than *indica* and autotetraploid cultivars, respectively.

The variation in yield and SS was closely related to weather changes in preceding or during flowering. The relationship between yield and mean temperature was negative, while yield was positively correlated with solar radiation in diploid and autotetraploid rice and same trend was followed in case of SS (Table 5). Yield and SS showed highly positive correlation with the photothermal quotient before and during anthesis in diploid and autotetraploid rice, and it was closer than that either with solar radiation or temperature alone. These correlations values were slightly lower in autotetraploid than diploid rice. The relationship between temperature and solar radiation was negative.

Dry matter and its partitioning

Dry matter production (DM) and harvest index (HI) are two important constituents of grain yield. Seasons showed a significant effect on DM in diploid cultivars, while non-significant effect on autotetraploid cultivars. Significantly higher DM was produced by *indica* than *japonica* cultivars in both diploid and autotetraploid rice. All the diploid cultivars produced high HI (41.4-56.3%) during all seasons, while autotetraploid cultivars showed very low HI and only one cultivar (T3) produced more than 40% HI during late seasons.

The relationship of yield with DM and HI is presented in Fig 1. Yield showed a significant correlation with DM in diploid cultivars (Fig. 1A), while yield of autotetraploid cultivars demonstrated non-significant relationship with DM (Fig. 1B). Harvest index and yield represented weak relationship (Fig. 1C) in diploid rice, while strong correlation (Fig. 1D) was found in autotetraploid rice.

Traits correlations

Correlation matrix indicated that autotetraploid and diploid cultivars had differences among correlation of traits (Table 6). A significant positive correlation was found between PL and FLA in diploid cultivars. Autotetraploid cultivars showed significant positive correlations between PL and GP, and NP and FG. There was significant and positive correlation between HD and TGW in autotetraploid, while non-significant in diploid rice. Diploid cultivars showed significant positive correlation between FLA and TGW, while non-significant relationships among these traits were found in autotetraploid rice. There was negative relationship between GP-NP and FG-TGW in both diploid and autotetraploid rice, but it was significant in diploid rice. In diploid cultivars, yield showed significant positive correlation with HD, NP and FG, while in autotetraploid cultivars yield had significant positive correlation with NP, FG and SS. Seed set showed significant negative correlation with FLA and TGW, while significant positive correlation with PL in diploid cultivars. Seed set depicted significant positive correlation with NP and FG, while negative correlation with FLA in autotetraploid cultivars.

Discussion

This study was focused to evaluate the performance of autotetraploid and diploid cultivars under different meteorological conditions of ES and LS in the field. Our results indicated that autotetraploid cultivars had varied features, but had some limitations for commercial use.

Effect of meteorological parameters on morphological and yield traits

Inter-seasonal variations showed a strong effect on the growth and development of both autotetraploid and diploid rice and FLA significantly increased during LS. These results are consistent with previous study that seasons had significant effect on flag leaf development of diploid rice (Kobayashi et al., 2003). Autotetraploid cultivars produced significantly higher FLA than diploid rice during all seasons. Optimum temperature for leaf development was found to be substantially higher than for flowering (Yin and Kropff, 1996). High temperature at vegetative stage triggers early development of leaves and reduced the growth duration of autotetraploid and diploid rice during LS. These results agree with those of Baker et al. (1995) and Prasad et al. (2006), who reported that diploid rice leaves appeared earlier due to high temperature at vegetative stage.

The present study revealed that autotetraploid rice had great potential for increasing productivity but low SS is a major constraint in its utilization. All the autotetraploid

Table 3. Effect of seasons on morphological and yield traits of diploid and autotetraploid cultivars.

Traits Seasons	HD (Days)	PL (cm)	FLA (cm^2)	DM (t ha^{-1})	NP	GP	FG	TGW (g)	GL (cm)	GW (cm)	Yield (t ha^{-1})	SS (%)	HI (%)
Diploid													
Early 2007	98.3 A**[a]	22.6 B**	32.2 B**	10.4 B**	7.1 B**	132.3**	714.6 B**	24.34**	8.10**	3.00**	5.0 B**	78.9 AB**	48.7**
Early 2008	95.6 B**	22.0 C*	31.7 B**	10.0 B**	7.2 B**	132.9**	712.9 B**	24.07**	8.05**	3.01**	4.9 B**	77.6 B**	49.4**
Late 2007	76.4 C**	23.0 AB**	36.8 A*	13.9 A**	8.9 A**	140.1**	984.1 A**	24.61**	8.19**	3.02 **	7.1 A**	82.0 A**	50.7**
Late 2008	75.2 C**	23.4 A**	38.6 A	13.8 A**	8.9 A**	136.4**	966.8 A**	24.59**	8.16**	3.01**	6.9 A**	81.4 A**	50.3**
LSD (0.05)[b]	2.103	0.6003	4.84	1.519	0.6655		109.4				0.8390	3.279	
Autotetraploid													
Early 2007	106.6 A	26.1 A	38.8	8.2	4.9 B	84.9	121.3 B	34.67	9.81	3.56	1.2 B	29.3	15.5
Early 2008	102.7 B	23.5 B	41.3	8.3	5.5 A	85.5	129.5 B	34.19	9.78	3.57	1.3 B	28.7	15.8
Late 2007	81.1 C	25.8 A	41.1	9.4	5.7 A	91.9	196.5 A	34.23	9.82	3.54	2.0 A	36.4	21.1
Late 2008	81.3 C	25.8 A	41.2	9.6	5.9 A	89.6	208.4 A	34.16	9.84	3.54	2.1 A	38.1	21.9
LSD (0.05)	2.491	1.417			0.5271		52.36				0.5604		

Column means followed by the same letter are not significantly different at the 0.05 probability level. [a]*, ** significant at the 0.05 and 0.01 probability levels, respectively, indicates that diploid cultivars are significantly different from autotetraploid cultivars. [b]LSD values are for the comparison of seasons. HD = Heading Date, PL= Panicle Length, FLA= Flag Leaf Area, DM= Dry Matter production, NP= Number of Panicles per plant, GP= Number of Grains per Panicle, FG= Filled Grains per plant, TGW= 1000-Grain Weight, GL= 10-Grains Length, GW= 10-Grains Width, SS= Seed set and HI= Harvest Index.

cultivars had longer and wider grains, leading to more increase in grain size after cooking in autotetraploid than their diploid counterparts. Rice grain length and grain width are two important components of rice grain shape (Zhang, 2007). Non-significant effect of seasons was found on GL, GW and TGW, but highly significant differences were found among genotypes and ploidy levels, indicating that these traits were mainly controlled by genotype. We found that number of panicles per plant and grains per panicle decreased in autotetraploid cultivars than diploid cultivars. Traditionally, rice breeders preferred these features to increase the grain yield (Fischer, 1985; Ying et al., 1998).

Reproductive stage is the most important period to achieve high yield of rice (Baker et al., 1995). We found that HI decreased in autotetraploid and diploid cultivars during ES, which in turn, decreased the grain yield. It might be due to significantly higher temperature during whole growth duration, especially at reproductive and grain filling phases. These results are in consistent with Prasad et al. (2006) who reported that lower HI at high temperature was related to reduction in yield. High temperature reduced the grain yield by reducing assimilates supply to the developing grains (Kobata and Uemuki, 2004). This study revealed that seasons with substantially high amount of solar radiation and less rains produced high grain yield of autotetraploid and diploid rice. High solar radiation without excessive rains during grain filling stage gave the best rice seed yield with high quality (Krishnan and Rao, 2005). Solar radiation demonstrated a significant effect on the grain yield of diploid rice (Evans and De Datta, 1979; Peng et al., 2004).

Even though seasons had significant effect on panicle length, genotype effect was more prominent for panicle length. Selection of the genotypes with longer panicles would be more useful for a breeder to increase rice production (Yang et al., 2008). All the autotetraploid cultivars produced longer panicles than their diploid counterparts, showing superiority over diploid rice. Ying et al. (1998) reported that grains per panicle and number of panicles per plant were negatively correlated with each other in diploid rice. They further explained that the cultivars with longer panicles showed lower SS than short panicle cultivars, but still their yield was higher. The present study showed a positive relationship between SS and panicle length in both diploid and autotetraploid genotypes.

Higher sink size during dry season was related to higher conversion efficiency of sink at flowering stage (Yang et al., 2007). High amounts of sink were found during LS under the favorable conditions (optimum temperature and solar radiation) which resulted in high yield of diploid and autotetraploid rice during LS. These results are in consistent with Yoshida and Parao (1976), who revealed that 81% of seasonal variation occurred due to differences in sink size. The difference in the diploid rice yield between two sites (IRRI and Yunnan, China) was only due to difference in the sink size (Ying et al., 1998).

There was genotypic variation for SS at high temperature in diploid and autotetraploid rice during different seasons. Other studies also reported different ratios of SS among genotypes at high temperature (Satake and Yoshida, 1978; Matsui et al., 2001; Yan et al., 2010). The present study was unable to classify the *indica* or *japonica* types on the base of tolerance to high temperature, while Snyder (2000) revealed that *indica* and *japonica* had same upper limit of high temperature tolerance. Our results indicated that high temperature showed non-significant effect on SS of D5 and T5 (*japonica*), but still yield was low at high temperature. Prasad et al. (2006) suggested that *indica* and *japonica* types were not the basis of classification for high temperature tolerance.

Seed set percentage is an important component of grain yield and low seed setting is the major drawback of autotetraploid cultivars over diploid cultivars. We found more decrease in SS during ES than LS in both diploid and autotetraploid cultivars. In the present study, significantly high temperature (≥ 35°C), high precipitation and low amount of solar radiation were recorded at the heading and grain-filling stages in ES, which might be the major reason for difference in seed set and yield of diploid and autotetraploid rice among seasons. Exposure to high temperature (≥35°C) during flowering significantly increased the sterile spikelets which, in turn, reduced the yield of diploid rice (Satake and Yoshida, 1978; Kim et al., 1996; Matsui et al., 2001; Yan et al., 2010). When the insufficient solar radiation reduced the source, then in turn, it decreased the SS (Yoshida, 1981). High temperature and precipitation during the grain filling stage led to the abnormal development of grains, which caused low SS in diploid rice (Zhao et al., 2007).

Table 4. Yield, 1000-grain weight and seed set of autotetraploid and diploid cultivars during four seasons.

Traits		Yield (t ha^{-1})				1000-grain weight (g)				Seed set (%)			
Cultivars	Sub-species	ES 2007	ES 2008	LS 2007	LS 2008	ES 2007	ES 2008	LS 2007	LS 2008	ES 2007	ES 2008	LS 2007	LS 2008
Diploid													
DE	*japonica*	5.26 ABC**[a]	4.89 BCD**	9.26 B**	8.77 B**	23.74 C**	22.75 CD**	27.18 B**	26.90 B**	86.3 AB**	86.4AB**	88.4 B**	85.5 B**
D3	*japonica*	4.99 BCD**	4.98 BCD**	5.56 F*	5.53 F*	21.44 G**	21.98EF**	24.62 C**	24.62 C**	78.6 D**	73.2 C**	80.1 D*	77.7 C*
D5	*japonica*	5.29 ABC**	5.15 ABC**	6.64 E**	6.43 E**	21.36 G**	21.27 G**	21.50 F**	21.30 F**	84.4 BC**	82.8 AB**	75.3 E**	76.3 C**
D23	*japonica*	4.46 DE**	4.85 BCD**	4.03 G**	4.10 G**	23.30 D**	21.65 FG**	22.49 E**	22.70 E**	80.5 CD**	82.6 B**	83.2 C**	84.1 B**
D24	*japonica*	4.31 DE**	4.47 CD**	5.43 F**	5.40 F**	23.40 CD**	23.03 C**	22.35 EF**	22.60 E**	90.3 A**	85.2AB**	93.1 A**	92.7 A**
D49	*japonica*	4.70 CDE**	4.56 CD**	7.49 CD**	7.27 D**	18.87 H**	18.64 H**	18.19 G**	18.27 G**	85.7 AB**	85.0AB**	91.9 A**	91.4 A*
D2	*indica*	5.79 A**	5.34 AB**	10.19 A**	9.90 A**	22.77 E**	22.21DEF**	25.11 C**	25.00 C**	88.3 AB**	89.6 A**	90.4 AB**	87.6 AB*
D28	*indica*	5.16 ABC**	4.99 BC**	6.76 DE**	6.63 E**	25.53 B**	25.62 B**	23.53 D**	23.43 D**	65.3 EF**	59.0 D**	75.1 E**	77.0 C**
D47	*indica*	5.70 AB**	5.70 A**	8.07 C*	7.93 C**	21.91 F**	22.49DE**	22.00 EF**	21.86 F**	68.2 E*	72.5 C**	76.8 E*	77.0 C*
D51	*indica*	4.15 E**	4.25 D**	7.18 DE**	7.43 D**	41.11 A**	41.09 A*	39.17 A**	39.20 A**	61.9 F**	60.2 D**	65.7 F**	64.9 D**
LSD [b] (0.05)		2.153	2.187	2.497	0.33	0.3388	0.6441	0.8611	0.6577	4.384	6.136	2.955	4.864
Autotetraploid													
TE	*japonica*	0.75 DE	1.25 CD	1.34 E	1.46 DE	34.69 BC	33.77 BC	34.73 B	34.07 C	21.8 D	31.1 BCD	28.6 E	30.0 CD
T3	*japonica*	1.52 ABC	1.51 BC	3.29 B	3.50 B	32.27 D	33.22 BC	34.63 B	35.10 B	42.1 B	37.4 AB	57.6 B	60.0 AB
T5	*japonica*	1.98 A	1.81 AB	1.83 D	1.80 D	29.04 E	29.13 DE	30.46 E	30.00 G	52.7 A	45.0 A	37.1 D	37.8 C
T23	*japonica*	0.29 E	0.65 F	0.45 G	0.50 F	34.20 C	32.00 CD	32.11 CD	32.17 E	16.0 D	23.2 DE	16.8 F	17.6 EF
T24	*japonica*	0.42 E	0.68 EF	0.53 FG	0.63 F	32.53 D	33.29 C	34.06 B	34.00 C	14.9 D	23.8 CDE	15.8 F	19.7 EF
T49	*japonica*	1.55 AB	1.40 BCD	2.45 C	2.80 C	31.50 D	31.17 CDE	30.94 DE	31.03 F	38.5 B	35.0 ABC	47.2 C	51.4 B
T2	*indica*	1.50 ABC	1.49 BC	3.39 B	3.67 B	28.73 E	28.80 E	32.37 C	33.13 D	40.4 B	34.5 ABC	59.8 B	62.9 A
T28	*indica*	1.03 CD	1.08 CDE	1.04 EF	0.93 EF	35.82 B	32.56 C	31.28 CDE	30.97 F	16.1 D	17.1 E	17.2 F	14.8 F
T47	*indica*	1.91 A	2.16 A	4.75 A	4.50 A	34.79 BC	36.31 B	35.12 B	34.93 B	29.9 C	22.6 DE	72.0 A	61.4 A
T51	*indica*	1.11 BCD	0.91 DEF	0.64 FG	1.37 DE	53.15 A	51.67 A	46.60 A	46.22 A	20.5 D	16.9 E	12.3 F	25.5 DE
LSD (0.05)		1.56	1.152	1.633	0.537	1.238	2.853	1.163	0.7135	7.07	10.33	5.379	9.053

Column means followed by the same letter are not significantly different at the 0.05 probability level.

[a] *,** significant at the 0.05 and 0.01 probability levels, respectively, indicates that diploid cultivars are significantly different from autotetraploid lines.

[b] LSD values are for the comparison of cultivars during each season.

There are many reasons, i.e., pollen abortion, embryo sac abortion, abnormal pollen mother cell meiosis and pollen sterility loci interaction, for low SS of autotetraploid rice. Some authors studied autotetraploid rices from the last twelve years and found a lot of variations among different materials for these abnormalities. Climatic factors also have pronounced effect on pollen and embryo sac fertility. Seed setting has a close relationship with these abnormalities and cultivars or hybrids with high SS depicted very low frequency of these abnormalities (Guo et al., 2006; Shahid et al., 2010; He et al., 2011a; He et al., 2011b). The present study also revealed that different autotetraploid cultivars showed great variation in SS, but seasons showed non-significant effect on SS of autotetraploid cultivars even though it was low in early seasons. So, there is a need to select cultivars with high SS for further studies and more number of autotetraploid cultivars should be developed to evolve autotetraploid varieties.

Our results further showed that autotetraploid rice is lodging free, which is an advantage over diploid rice cultivars that were susceptible to lodging during ES-2008. Morphologically, autotetraploid plants are short-statured with thick, compact and erect stem compared to diploid rice, which might have increased resistance against lodging in autotetraploid rice. Lodging had considerable detrimental effects on the grain yield due to the reduction of assimilate supply through vascular bundle (Kashiwagi et al., 2005). Moreover, the grain quality and aesthetic value reduced due to fungal growth (Kono, 1995).

Photothermal quotient

Photo-thermal quotient (PTQ, MJ m^{-2} d^{-1} $°C^{-1}$) was defined by Nix (1976) as the ratio of mean daily total incident solar radiation for an interval to the mean temperature minus a base temperature. Our results indicated linear relationship of yield and SS with PTQ in diploid and autotetraploid rice before and during anthesis. These results are in agreement with previous studies that PTQ prior to anthesis showed a positive linear relationship to grain yield (Nix, 1976; Islam and Morison, 1992; Ortiz-Monasterio et al., 1994). Solar radiation and temperature fluctuations tended to be negatively correlated; thereby, mutually reinforcing effects on yield determining traits (Fischer, 1985). Similar results were observed in the present study that both these negatively correlated factors had strong influence on yield and SS of diploid and autotetraploid rice.

Relationship of yield with dry matter and harvest index

Dry matter production in this study was highest during LS in both diploid and autotetraploid cultivars. It was noteworthy that yield of diploid cultivars showed correlation with DM, while autotetraploid showed with HI. Significant increase in yield occurred mainly due to the high HI, even though sometimes high amount of DM accumulated in wheat (Austin et al., 1989). In contrast to wheat, DM was the major contributor to increase the maize yield (Russell, 1991). Sinclair (1998) reported that yield increased due to HI which changed from 30 % to 50 % after green revolution, but now high yielding cultivars had achieved HI more than 50 %. It is an unconvincing way to increase the yield through increasing HI alone (Austin, 1994). Dry matter is the better predictor of yield than HI (Naylor et al., 1998); however, Peng et al. (2000) suggested that yield could be increased by increasing DM. HI was almost 50% in diploid cultivars, so the yield of diploid cultivars could be increased through increasing dry matter production, while HI could be major source to increase the grain yield of autotetraploid rice.

Materials and methods

Plant materials

A total of 10 autotetraploid cultivars, 8 of them were developed by colchicine treatment in our lab (State Key Laboratory for Conservation and Utilization of Subtropical Agro-bioresources, South China Agricultural University) from 8 diploid cultivars, and used for the comparative study of agronomic traits (Table 1). These diploid and autotetraploid cultivars were selected because of their contrasting agronomic traits and resistance to insect pests and diseases. Autotetraploid cultivars used in the study are genetically stable because they have been cultivated at our farm for the last 10-12 years.

Experimental site and crop management

Field experiments were conducted in early (1st March-July) and late seasons (26th July-Nov) during 2007 and 2008 at the experimental farm of South China Agricultural University, Guangzhou (23°16N, 113°8E and 18 m above sea level), China. The soil of the farm was sandy loam with pH 5.36, 22.0 g kg^{-1} organic matter, 105.7 mg kg^{-1} available N, 128.3 mg kg^{-1} available P and 112.5 mg kg^{-1} available K. Temperature, solar radiation and precipitation data were taken from the Guangzhou meteorological station.

Randomized complete block design with three replications was used during each season. Plot size was 6.0 m × 4.0 m. Row-to-row and plant-to-plant distances were maintained at 20 cm and 16.6 cm, respectively. Pre-germinated seeds were sown in the trays filled with soil to get the uniform seedlings. Four-five leaf stage seedlings were transplanted to paddy field in all seasons. The experimental field was flooded after transplanting and 5-10cm water depth was maintained until 7 d before physiological maturity for each genotype. Phosphorus (90 kg P ha^{-1} as calcium super phosphate) and Zinc (5 kg Zn ha^{-1} as zinc sulfate heptahydrate) were applied as basal fertilizer. Potassium (150 kg K ha^{-1} as KCl) was applied in three splits (60% at basal, 20% at mid tillering and 20% at panicle initiation). Plants received a total of 180 kg N ha^{-1}, and Nitrogen was applied in the form of urea in four splits (60% at basal, 20% at mid tillering, 15% at panicle initiation, and 5% at flowering) to ensure N adequacy throughout the growing season. Basal fertilizers were incorporated in all plots one day before transplanting. The timing of N and P application was based on the growth stages. Mid-tillering is defined as midway between transplanting and panicle initiation. Panicle initiation was determined by dissecting six main stems in each plot every other day. Weeds, insect pests and diseases were intensively controlled to avoid the yield loss. Transplanting and harvesting was done manually.

Traits measurements

Central five rows (5.0 m^2) were selected for the measurements of yield and yield components. Plants were harvested when 95% of the grains had turned from green to yellow and data on various agronomic traits were recorded. Days to 50% flowering (Heading date, HD) were recorded on whole plot basis. Panicle length (PL, cm) was measured for all panicles of the plant and then mean value was used. Flag

Table 5. The relationship of yield and seed setting to mean temperature, mean solar radiation and mean photothermal quotient in the 50 days before and during reproductive stage.

Temporal Means	Yield		Seed setting rate	
	Dip[a]	Auto[b]	Dip	Auto
Daily mean temperature	-0.756	-0.683	-0.629	-0.622
Solar radiation	0.731	0.662	0.882	0.736
Photothermal quotient	0.905	0.807	0.965*	0.834
Solar radiation *vs.* daily mean temperature	-0.247	-0.247	-0.247	-0.247

[a]Denotes mean of diploid cultivars, [b]Denotes mean of autotetraploid cultivars.

Table 6. Correlation analysis among important traits of diploid and autotetraploid cultivar during four seasons.

Traits	HD	PL	FLA	NP	GP	FG	TGW	Yield	SS
HD		0.493	0.449	0.244	0.068	0.224	0.368	0.593*	-0.286
PL	0.177		0.671*	-0.043	0.508	0.142	0.295	0.464	0.626*
FLA	0.424	0.417		-0.456	0.37	-0.385	0.699*	0.125	-0.630*
NP	0.115	0.222	-0.404		-0.577*	0.55	-0.236	0.609*	0.126
GP	-0.004	0.734*	0.368	-0.354		0.217	-0.242	-0.062	-0.131
FG	-0.007	0.42	-0.456	0.743*	0.06		-0.689*	0.699*	0.505
TGW	0.58*	0.087	0.551	-0.066	-0.2	-0.349		0.006	-0.662*
Yield	0.052	0.428	-0.436	0.777**	0.01	0.988**	-0.219		0.094
SS	-0.061	0.224	-0.487	0.623*	-0.08	0.947**	-0.392	0.922**	

Diploid[a]

[a]Autotetraploid

*, ** represent significance at 0.05 and 0.01, respectively. [a]Lower half of the table relates to autotetraploid rice. [a]Upper half of the table relates to diploid rice. See Table 3 for traits abbreviations.

leaf area (FLA) was calculated according to Yoshida et al. (1976).

Plants were oven-dried at 70°C to achieve the constant weight to measure the dry matter production (DM), 1000-grain weight (TGW) and yield. Number of panicles per plant (NP), number of grains per panicle (GP, filled grains + unfilled grains/number of panicles), and filled grains per plant (FG) were counted manually. Ten grains were randomly selected and their length (GL) and width (GW) were measured with digital vernier caliper. Seed set ((SS% = Filled grains/total number of grains per plant) × 100) and harvest index ((HI= yield/dry matter production) × 100) were calculated in percentage.

Statistical analysis

The data were analyzed using SAS (SAS, 2003) and correlations were determined by SPSS. All the treatment means were compared by Duncan Multiple Range Test (DMRT) at the 5% significance level. Photothermal quotient (PTQ) was calculated before and during anthesis according to Fischer (1985).

$PTQ= \quad IRD/T_{Mean}-T_{base}$

Where, IRD is intercepted solar radiation, T_{Mean} is the daily mean temperature and T_{base} is the base temperature and for rice set to be 10 °C (Casanova et al., 2000).

Conclusions

This study was focused on the comparative performance of diploid and autotetraploid cultivars under different meteorological conditions (temperature, solar radiation and rainfall) in the field condition. This study revealed that climatic factors (solar radiation, temperature, especially photothermal quotient and rainfall) are responsible for the yield difference among seasons. Our results indicated that autotetraploid rice had an ideal plant type and more potential to increase crop productivity due to its longer and wider grains, longer panicles, enlarged stems, resistance to lodging, more 1000-grain weight, and shorter plants than their diploid counterparts. Doubling of rice chromosomes showed a strong influence on all the traits under study as compared to seasons. Higher yield but lower seed set percentage was produced by *indica* than *japonica* cultivars. Dry matter production showed a significant correlation with grain yield in diploid cultivars, while harvest index demonstrated significant correlation with grain yield of autotetraploid cultivars. Autotetraploid rice has sufficient amount of source; however, insufficient sink capacity is a yield limiting factor. It might have happened due to less partitioning of dry matter to developing panicles. Hence, there is a need to study the source-sink relationship to improve the yield and HI of autotetraploid rice. Autotetraploid cultivars (T2, T3, T5 and T47) should be used in hybrid rice breeding to exploit their potential and to take advantage of polyploidy and *indica-japonica* heterosis. It is concluded that autotetraploid cultivars are more stable than diploid cultivars across varying meteorological conditions and have high yield potential, but still need to improve seed set by breeding for commercial use.

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