Comparative analysis of physiological and phenological traits of rice (*Oryza sativa*) under aerobic production systems in dry and wet tropics of Queensland, Australia

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Abstract

Aerobic rice is becoming a more promising rice cultivation system due to increasing water scarcity for irrigation and occurrence of drought, especially in Australia. Rice cultivation on aerobic soil under rainfed conditions has shown potential for successful rice cultivation in tropical climate. Strategic irrigation during the critical growth period can help reduce the water demand on farm. Central Queensland has an annual rainfall of ca. 800 mm, and about 600 mm occurs during the wet season from December to March; whereas parts of the wet tropical north Queensland receive ca. 3000 mm annual rainfall, and about 1893 mm during the wet season from December to March. The study was carried out at Alton Downs, central Queensland (dry tropics) and South Johnstone, north Queensland (wet tropics) to investigate the phenological, physiological and agronomical responses of 13 different rice varieties with a view to identifying suitable varieties for dry land cultivation. The objectives were to assess rice varieties under i) rainfed conditions in the wet and dry tropics, ii) rainfed conditions and strategic irrigation condition in the dry tropics, and to iii) identify the physiological, phenological and agronomical traits of rice adaptation under aerobic conditions in the dry and wet tropics. In the dry tropics, the strategic irrigation was provided by drip irrigation and was scheduled when the rice plants showed water deficit symptoms (corresponding to the refill point at 21 mm /100 mm soil water).

The average yield of rice varieties under strategic irrigation was significantly higher and the variety best yield (AAT 4) produced up to 5.23 t/ha in the year 2015 under strategic irrigation. The average yield of varieties was increased from 1.5 times (AAT 4) to 16.8 times (AAT 15) with strategic irrigation, as compared to rainfed conditions. The average water productivity was increased by 100 % in 2014 and by 110.3 % in 2015 using strategic irrigation as compared to rainfed. The average water productivity was 0.24 t/ML (in 2014) and 0.61 t/ML (in 2015) under strategic irrigation, whereas it was 0.12 t/ML (in 2014) and 0.29 t/ML (in 2015) under rainfed conditions. The high yielding varieties were early flowering types, which escaped the terminal drought caused by lower rainfall during the flowering stage, whereas the late varieties such as AAT 10, AAT 11 and AAT 15 were among the highest yielders in the wet tropics under rainfed conditions. The greater yield was associated with greater panicle fertility, leaf area

index , higher photosynthetic rate and water use efficiency during flowering, and one of the high yielding varieties (AAT 3) had the highest photosynthetic rate during the grain filling period in both strategic irrigation and rainfed conditions. Root dry weight and root weight density in the top soil layer at 0–15 cm were found to be related to yield under strategic irrigation, but the varietal characteristic of deep rooting was not correlated with yield. It is important to consider variations in flowering time, yield potential and drought patterns while developing varieties for aerobic conditions, as the drought reduced the panicle filling percentage to 1% under rainfed conditions.

The variety with most stable and consistent yield at Alton Downs was AAT 6, and had the lowest coefficient of variation across the years whereas the variety AAT 13 was found to be more responsive with better growing conditions at Alton Downs under rainfed conditions. The varieties when sown late, late flowering varieties were subjected to cold and terminal drought reducing the yield. AAT 6 and AAT 13 are both early flowering varieties.

In the wet tropical environment, the crop received rainfall until harvesting time. The favourable physiological characteristic of high yielding varieties such as AAT 4 and AAT 6 in the dry tropics was greater water use efficiency, and the agronomic characteristics were higher panicle fertility, higher effective tillers per plant and grains per panicle. In the wet tropics (South Johnstone), the high yielding variety AAT 10 was characterised by high harvest index, longest panicle length, higher effective tillers, higher panicle fertility and higher water use efficiency.

In South Johnstone, the days to flowering did not have any effect on the yield of varieties. The varieties those producing least yield under rainfed conditions at Alton Downs were among the highest yielders in South Johnstone. The high yielding varieties maintained greater effective tillers per plant, heavier 1000 grain weight, greater harvest index and fertility. Reliable soil moisture favoured photosynthetic rate and water use efficiency and the associated larger flag leaf area contributed significantly to higher yields at wet tropical South Johnstone as compared to dry tropical Alton Downs.

Strategic irrigation in dry tropical environments could allow plants to cope with water stress caused by less rainfall during the grain filling period. Similar yield was achieved under strategic irrigation for late flowering varieties as under rainfed conditions for early flowering varieties. The varieties responded with an average increase of 11.87 kg/ha and 15.80 kg/ha with each additional 1 mm water application in 2014 and 2015 respectively. This shows that there is great commercial scope for strategic irrigation during water deficit periods, created by little or no rainfall, during critical crop growth periods for rice in the dry tropical environment of central Queensland.

In conclusion, this thesis increases the understanding the role of strategic irrigation and varietal characteristics for rice cultivation under the dry tropical agro-ecological domain of central Queensland and the wet tropical conditions of north Queensland. Higher productivity of aerobic rice in dry tropical central Queensland is achieved with early flowering varieties, supported by strategic irrigation management during the water shortage periods, with higher water use efficiency, greater number of spikelets, higher panicle fertility. In the wet tropical environment of northern Queensland, yield variation between varieties was not significantly affected by the days to flowering. However, further study for selection of varieties from more diverse germplasm for plant water status and fertility, and different water management strategies under aerobic conditions needs, to be explored, to achieve the rice yield that can assure the commercial opportunity for rice production in the dry and wet tropical environments of Queensland, Australia.

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Declaration of authorship and originality

I, the undersigned author, declare that all of the research and discussion presented in this thesis is original work performed by the author. No content of this thesis has been submitted or considered either in whole or in part, at any tertiary institute or university for a degree or any other category of award. I also declare that any material presented in this thesis performed by another person or institute has been referenced and listed in the reference section.

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Sachesh Silwal Date

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List of Abbreviations

A	Photosynthetic rate
AAT	Australian Agricultural Technologies Limited
ANOVA	Analysis of variance
b	Regression coefficient
BOM	Bureau of Meteorology
C	Carbon
CEC	Cation exchange capacity
Chl	Chlorophyll
CID	Carbon isotope discrimination
CMS	Cell membrane stability
CV	Coefficient of variation
DAS	Days after seeding
E	Transpiration rate
EC	Electric conductivity
ET	Evapotranspiration
GDD	Growing degree days
gs	Stomatal conductance
HI	Harvest index
IRGA	Infrared gas analyser
LAI	Leaf area index
LSD	Least significant difference

LWP	Leaf water potential
N	Nitrogen
NERICA	New Rice for Africa
NSW	New South Wales
OM	Organic matter
OP	Osmotic potential
QLD	Queensland
QTL	Quantitative trait loci
RLD	Root length density
RWC	Relative water content
RWD	Root weight density
SPAD	Soil-Plant Analyses Development (SPAD) unit of Minolta camera
T	Transpiration rate
WUE	Water use efficiency

CHAPTER 1. GENERAL INTRODUCTION

Rice (*Oryza sativa*) is consumed as a staple food for one half of the 7 billion people in the world (Mohanty, 2013) and more than 90% of the world's rice is produced in Asia (Li and Xu, 2007). By 2025, the global population is projected to be 8.1 billion and the rice production needs to be increased by 40% over the next 10 years (United Nations, 2014). Globally, rice is grown on approximately 158 million hectares of land, producing 700 million tons annually (IRRI, 2010). Among rice growing regions, 45% of the area is in rainfed ecosystems, where the occurrence of drought severely restricts production and productivity (Maclean et al., 2002). An estimate by Evenson et al. (1996) showed that the world could lose 18 million tons of rice yield due to drought, or 4% of total production, worth US $ 3.6 billion at that time. Drought is the most important climatic hazard for rice production in rainfed areas, and affects an estimated 23 million ha of rainfed rice (Serraj et al., 2011). Water shortage and drought frequency are increasing in rice growing areas of Asia (Pandey et al., 2007). Declining access to water and increasing shortages have created much pressure on rice breeders to develop new rice varieties suitable for dry environments (Zhao et al., 2008).

Drought can be defined in three ways: meteorological drought, hydrological drought or agricultural drought (Pandey et al., 2007). Meteorological drought is defined as when the actual rainfall is below long term average. It considers rainfall only as a factor. Hydrological drought commences when surface and subsurface water resources are depleted due to low precipitation. Reasons for water resources depletion are a major concern. Agricultural drought is defined as when soil moisture is not sufficient in meeting crop water demand, leading to crop yield losses. Thus, agricultural drought is related to plant moisture stress. Another water shortage relates to the continued restriction to irrigation entitlements due to political changes (e.g., Murray-Darling Basin Plan in Australia), which has seen the global diversion of water from agriculture to other ends (environmental flows, urban requirements); hence, environmental hydrology is only the penultimate factor defining drought, for legislative restriction on water for productive uses is the paramount restriction.

Rice is a semi-aquatic plant from its evolutionary perspective (Bernier et al., 2008). Because of this, it is likely to have low adaptation to drought and to be sensitive to water deficit. However, flooded rice systems create environmental concerns, such as the emission of methane, off farm movements of nutrients and pesticides, and use of higher inputs. Aerobic rice will curb methane production as it discourages anaerobic fermentation of soil organic matter, and it improves water use efficiency (Shashidhar, 2008).

Aerobic rice is cultivated in non-flooded, non-puddled and well drained soils whereas flooded rice is grown in flooded, puddled and saturated soils (Peng et al., 2006). The aerobic system of rice cultivation is, in general, more productive than the flooded system in terms of water use efficiency. Between 1250 and 1666 litres of water are required to produce one kilogram of rice from the aerobic system (Xiaoguang et al., 2005), whereas the flooded system requires 2500–5000 litres of water to produce one kilogram of rice (Bouman and Tuong, 2001).

From a production perspective, moisture stress is the most important environmental stress that causes major yield loss in cereals. Yield loss due to drought is estimated at between 11% and 59% by Jongdee et al. (1997). Rainfed rice can be an alternative system of rice production, particularly in regions that receive an appreciable amount of summer rainfall (> 500 mm during growing season). Rainfed systems have the potential to save on stored water use for rice production significantly, compared to the conventional method of flooded rice cultivation (Huaqi et al., 2002). Global climate change and competing uses of water are the two emerging threats that will constrain crop yield increases, and rice is no exception. This is despite the fact that, in Australia, average irrigation water productivity in NSW has almost doubled from 1980 to 2000, as Australian growers use almost 50% less water than the world average in irrigation to grow one kilogram of rice. In the Murrumbidgee irrigation area, water use in irrigation to produce one kilogram of rice grain decreased from 2941 litres in 1980 to 1298 litres in 1999 (Humphreys et al., 2006), and then further decreased to 850 litres in 2015 (Dunn, 2016), due to the introduction of high yielding semi-dwarf varieties and their reduced water use.

With water saving irrigation practices, water productivity can be increased even further to produce one kilogram of rice using 526 litres of water, but yield will be decreased

(Bouman and Tuong, 2001). It will be difficult to produce more rice on the same land area. Rice in Australia is predominantly grown in puddled soil with ponded field. Around 30% of water input is required for puddling and transplanting (Gopal et al., 2010). In this context, adoption of new water saving agronomic practices and alternative technologies such as aerobic rice culture are crucial for yield improvement (Kato et al., 2009) in dry continent such as Australia. Water saving strategic irrigation, which is applied during the critical crop growth stages, has proven economically profitable in wheat in northern and western Syria with 200% more annual net profit per hectare as compared to rainfed production system (Oweis and Hachum, 2009). These techniques should conserve water and should be accomplished by development of suitable crop varieties with genetic traits for drought tolerance. The challenge is to find the right combination of agronomic practices and a suitable variety for particular drought conditions, whilst optimising weed and nutrient management (Dunn and Gaydon, 2011).

In this context, finding adaptive traits in new varieties for dynamic drought stress in relation to timing and intensity of stress will be crucial for yield improvement. Different genotypes exhibit different responses in adaptive plasticity in root growth or other physiological stresses depending on the type of drought stress (Kano et al., 2011). Finding such traits is essential in the context of unpredictable climatic stresses. Understanding of traits that help rice to cope with water stress at a particular growth stage every year (Cattivelli et al., 2008) helps farmers to manage crops under unpredictable drought at farm. Developing suitable variety for potential rainfed production is first step in establishing rice industry in target rainfed production domains. Rice industry in central and north Queensland will goffer farmers an alternative crop with good niche market of rainfed rice in Australia.

Selection for early varieties to escape cold and drought at flowering and maturity stages will be useful traits for drought escape in central Queensland, where the rainfall is limited to a 70.4 mm to 119.3 mm monthly average between November to April, as compared to northern Queensland where it is 190.7 mm to 552.9 mm during the same period (Figure 1.1) (Bureau of Meteorology, 2016a). The maximum and minimum temperatures during the summer season, November to April, are favourable for rice, with the average minimum temperature above 20°C and with the temperature going down after April with onset of winter (Figure 1.2) (Bureau of Meteorology, 2016a). Trials in these two environments will give an estimation of yield potential of varieties under rainfed conditions, as will strategic irrigation in central Queensland. Escape through earliness, although a quick fix to abiotic stress encountered globally, carries with it grain yield penalties. It is generally undesirable for long-term production and hence tolerance or resistance is the ultimate breeding objective.

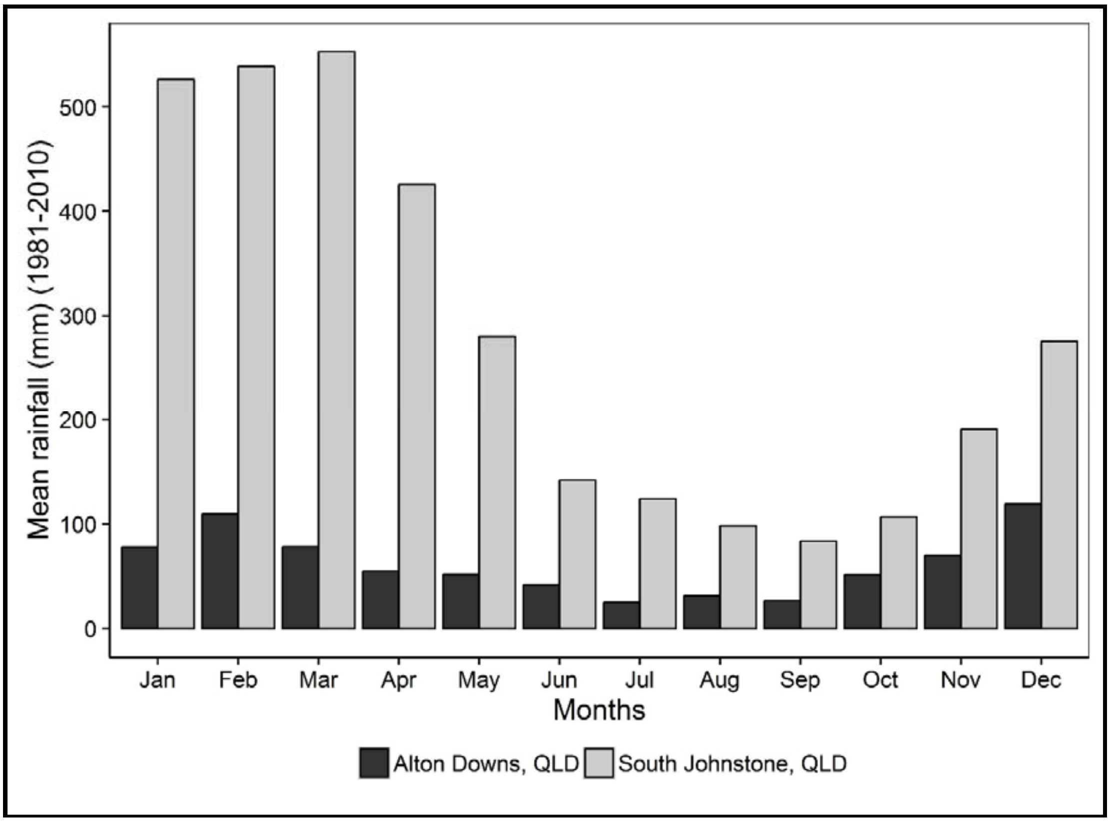

Figure 1.1 Mean monthly rainfall (1981–2010) at Alton Downs and South Johnstone.

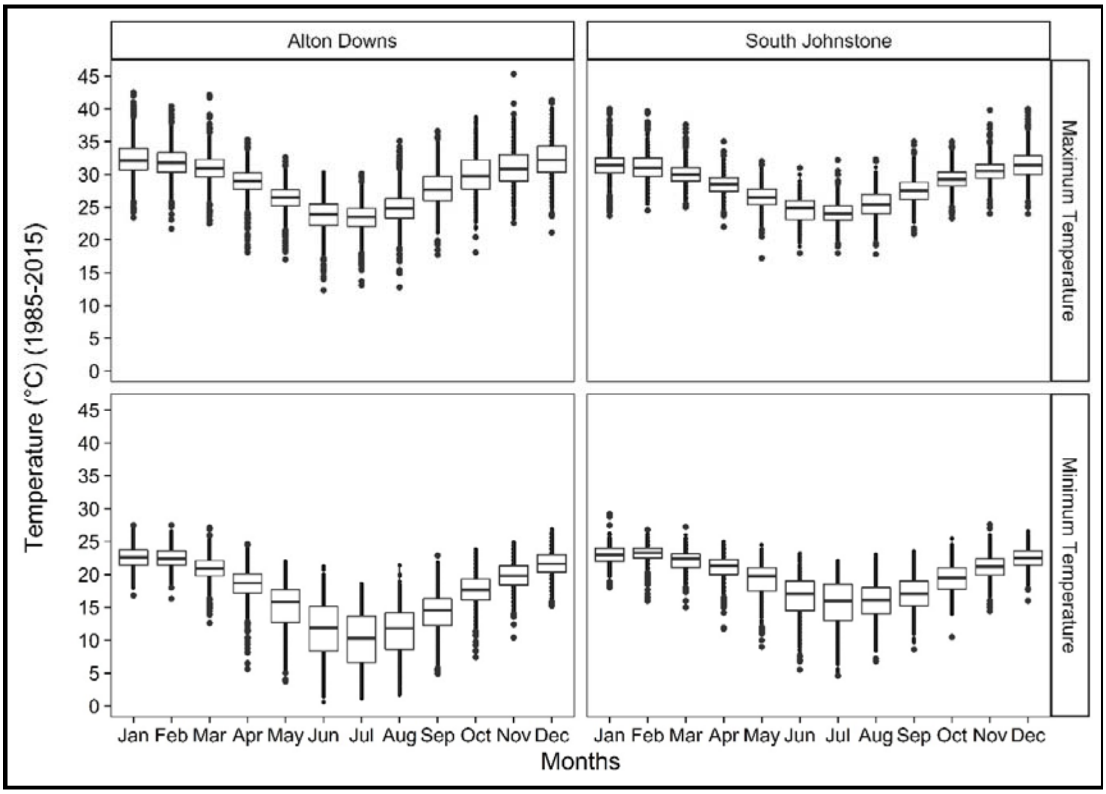

Figure 1.2 Mean monthly maximum and minimum temperatures (1981–2010) at Alton Downs and South Johnstone.

1.1. Rationale

Development of drought tolerant rice varieties will be critical in changing climatic conditions to improve rice production and ensure food security for water scarce areas. By 2035 an additional 116 million tons of rice will be needed annually to feed growing populations (Seck et al., 2012). For the development or improvement of rice for upland rice production systems, a better understanding of the nature of inheritance of different drought tolerance mechanisms is required. In addition, an understanding of physiology and their mode-of action is required to for screening of rice germplasm under drought. In addition, understanding of the role and correlation of secondary traits to drought is crucial for breeding new rice varieties for water limited environments. For instance, a decrease in stomatal conductance or an increase in photosynthetic activity can improve TE. Transpiration efficiency is defined as the ratio of biomass produced per unit of water transpired (Condon et al., 2002). Improvements in TE will ultimately improve agronomical water use efficiency and provide better tolerance to drought. However, it will to some extent negate evaporative cooling, a critical characteristic to prevent heat-induced sterility at anthesis.

Benchmarking of WUE associated with different varieties under rainfed systems can also be approached by modelling. The model of French and Schultz (1984) suggests that the upper limit of WUE in modern grain varieties to be 20 kg/ha/mm. However, Sadras and McDonald (2012) argued that current varieties have WUE closer to 25 kg/ha/mm. The French-Schulz model, when applied to the rainfed rice with 600 mm rain during the growing season, and with the WUE value updated to that of Sadras and McDonald (2012), can give as much as 6.1 ton/ha of rice considering 110 mm as evaporative loss and 0.5 HI. Theoretically, a sustainable rainfed rice system can be developed in the wet tropics provided the loss from soil due to run-off, deep drainage and evaporation can be controlled.

While the French-Schultz model analysis provides a basic guideline of possible yields in the wet tropics in Australia given good seasonal conditions and good soils, it has its own limitations when applied to the rice crop. More sophisticated analysis and modelling tools are available today, such as The Agricultural Production Systems Simulator (APSIM) (Holzworth et al., 2014) and ORZYA2000 (Xue et al., 2005).

Recent research on the understanding of crop physiology and genomics has guided crop breeding and selection of drought tolerance using new knowledge and tools. This research will have value for rice breeders, agronomists and growers with direct outputs, as varieties with suitable physio-morphological characters for dry regions of Queensland are identified.

Aerobic rice varieties have the combination of aerobic adaptation traits from traditional upland varieties and other production traits of input responsiveness, lodging tolerance and high HI of irrigated varieties (Atlin et al., 2006). Aerobic rice is already replacing irrigated rice in areas with limited water supplies, such as in northeast China (Bouman et al., 2006)

Characterisation of morphological, phenological and physiological traits that confer adaptation under drought conditions is essential for developing and identifying the appropriate varieties for the target production environment (Serraj et al., 2011).

1.2. Purpose of the research

This research is focused to evaluate the traits that underpin the combinations of mechanisms to adapt rice to rainfed and strategic irrigation growing conditions in Queensland, characterised by highly fluctuating soil moisture regime conditions associated with rainfall events.

This thesis focused on the field based screening of rice varieties under rainfed and strategic irrigation management to evaluate the varietal performance and the traits associated with their adaptation to rainfed and strategic irrigation in Queensland conditions. The objectives were to assess rice varieties under i) rainfed conditions in the wet and dry tropics, ii) rainfed conditions and strategic irrigation condition in the dry tropics, and to iii) identify the physiological, phenological and agronomical traits of rice adaptation under aerobic conditions in the dry and wet tropics. The thesis results are structured into i) comparative study of rice varieties under rainfed and strategic conditions (Chapter 3), ii) yield stability of rice varieties under rainfed conditions in central Queensland (Chapter 4), iii) performance evaluation of varieties in the wet and dry tropics of Queensland (Chapter 5) and iv) general discussion and conclusion (Chapter 6).

CHAPTER 2. LITERATURE REVIEW

2.1. Drought and its impact on rice yield

Drought affects 23 million ha of rainfed rice worldwide (Serraj et al., 2011). Crop productivity increase in dry land farming is a difficult task as drought resistance depends on many traits, and environmental factors are also involved along with their complex interactions (Reynolds and Tuberosa, 2008). As the current study is more focused on the understanding of physiological aspects of rice, the complex interactions of environmental influence on these traits cannot be ignored. Rice farming in the face of drought should be undertaken with drought resistant rice varieties combined with smart water saving agronomic practices (Pandey et al., 2007).

Rainfed rice is fully dependent on stored soil moisture and rainfall for its growth and development. Abiotic stresses such as drought cause a setback in grain yield, particularly if experienced during the reproductive stage (Hsiao et al., 1984; Saini et al., 1984). Rice plants have mechanisms to send signals to the shoot when they sense limited water availability in the root zone; these can be hydraulic or chemical or both. Plants then respond by showing adaptive signals such as stomatal closure and a decrease in gas exchange and leaf expansion (Tardieu and Davies, 1993). Drought has much more effect on rice plants during the flowering stage (terminal drought) than at other growth stages as it has a strong negative effect on grain formation (Boonjung and Fukai, 1996). Stress during that period upsets meiotic division and increases floral sterility, resulting in fewer filled grains in panicles(Saini and Westgate, 1999).

2.2. Drought research strategies

Earlier works on varietal development for rainfed rice involved the use of varieties developed for irrigated ecosystems. Varieties for irrigated rice crops were high yielding but poor performers when exposed to drought as they were developed without screening for drought tolerance (Verulkar et al., 2010). The mechanisms that decrease crop yield in drought conditions are reduced canopy absorption of photosynthetically active radiation (PAR), reduced harvest index (HI) and decreased radiation use efficiency (Earl and Davis, 2003).

Water uptake, water use efficiency (WUE) and HI play key roles in grain yield determination under moisture stress conditions (Condon et al., 2004). The physiological definition of WUE emphasises leaf gas exchange (A/T) as the basis of defining WUE (expressed as the moles of carbon gained in photosynthesis (A) divided by the total exchange of water used for transpiration (T)). The agronomical definition of WUE relates to the yield gained from the available water through irrigation and/or precipitation. Integrated physiological and genetic approaches to improve the yield of crops (Bernier et al., 2008; Subbarao et al., 1995) will be key for developing drought resistant rainfed varieties, as it gives a better understanding of the traits and their interrelationship with the environment. Bernier et al. (2009) identified quantitative trait loci (QTL), *qtl12.1*[1], responsible for improvement (7%) of grain yield under drought. Apparently, this small difference in water uptake with desired physiological traits can help to increase yield under field conditions. Identification and use of QTL for osmotic adjustment, relative water content, root traits, stomatal conductance and other WUE traits can help to increase yield under field condition. Although QTL for osmotic adjustment (Lilley and Ludlow, 1996; Price et al., 1997), relative water content (Lilley et al., 1996), root traits (McCough and Doerge, 1995) and cell membrane stability (Tripathy et al., 2000) linked to drought tolerance have been mapped. However, they are not repeatable over different environments and populations (Bernier et al., 2008). Therefore, they might not be suitable to achieve desired yield under different environmental conditions (Steele et al., 2007). Study of physiological responses of available germplasm to new environments is necessary to identify the suitable drought tolerant varieties.

Definition of drought resistance can also be determined by dehydration tolerance or dehydration avoidance in a physiological context (Levitt, 1972). Drought resistance mechanisms can be categorised according to Blum (2005) as i) dehydration avoidance (associated with traits such as leaf water potential, osmotic adjustment, cell membrane stability and transpiration efficiency); ii) enhanced soil moisture capture (associated with traits such as deep root systems, root number and root length density); and iii) reduced

[1] A section of DNA in rice chromosome identified as *qtl 12.1*

water use (associated with traits such as WUE/transpiration efficiency and reduced plant size).

When developing adaptation to drought in rice, the different approaches that plants use for drought resistance or tolerance need to be considered. It is important to understand how water deficits affect leaf gas exchange, photosynthesis and plant growth when developing drought phenotyping methods and identifying drought-resistant genotypes through physiological studies in the field (Serraj et al., 2008).

2.2.1. Dehydration avoidance

Plant capacity to maintain cellular hydration, or high plant water status under the influence of drought through increased water uptake or reduced transpiration, is termed dehydration avoidance (Levitt, 1972). To maintain cellular hydration, plants adopt different physiological mechanisms such as changes in leaf water potential, osmotic adjustment, cell membrane stability, transpiration efficiency or increased root capacity for efficient water uptake.

2.2.1.1. Leaf water potential

Under drought conditions genotypes able to maintain high leaf water potential (LWP) can grow better (Fukai and Cooper, 1995) and have positive influence on yields under terminal drought, as LWP is responsible for the panicle exertion (Pantuwan et al., 2002b). Leaf water potential is found to have negative phenotypic and genetic correlations with percent spikelet sterility at the flowering stage, affecting the grain yield (Jongdee et al., 2002). Genotypes with deeper root systems without restriction are able to maintain greater LWP, suggesting that well developed root systems support stable yield by maintaining plant water status (Kamoshita et al., 2008). Plants show leaf rolling and tip drying when they are exposed to drought conditions. Visual scores of leaf rolling and leaf tip drying are found to be highly correlated with LWP maintenance (O'Toole and Moya, 1978).

2.2.1.2. Osmotic adjustment

Osmotic adjustment is one of the adaptive processes to drought. Osmotic adjustment is a response to stress such as drought, and relates to the condition where solutes accumulate in cells to decrease osmotic potential (Turner et al., 1986). Delaying of leaf rolling is aided by osmotic adjustment in drought resistant rice and this helps to maintain gas exchange, resulting in delayed leaf death (Hsiao et al., 1984). In other words, it enhances dehydration avoidance (Blum, 2005) and delays the need for additional water to support yield under water stressed conditions. Babu et al. (1999) reported that osmotic adjustment in upland varieties was lacking or non-significant, and this was explained on the basis of selection for larger roots to extract deep moisture. Hence, there was no selection for osmotic adjustment for upland varieties.

2.2.1.3. Cell membrane stability

During drought, cell membranes are targeted first for injury due to water stress. Maintenance of cell membrane integrity and stability is vital for plant survival and stable yield production in plants (Bajji et al., 2002). Tripathy et al. (2000) reported that the cell membrane stability of plants was not related to relative water content in leaves during their QTL studies. The differences in cell membrane stability were due to the genetic difference between the varieties. Cell membrane stability (CMS) in plants is maintained by different physiochemical mechanisms such as the structure of the cell membrane and its protein arrangement, along with substances such as sugars, amino acids and anions (Bewley, 1979). Due to weak control over precision of field experimental conditions, precise measurement of CMS, LWP and osmotic potential is difficult. Because of this, integrated traits such as spikelet fertility are more reliable traits for drought stress tolerance under field conditions (Kamoshita et al., 2008).

2.2.1.4. Transpiration efficiency

Water use efficiency is the total water used to gain yield and was defined in terms of the physiological approach as the total carbon gained in photosynthesis as a function of the total exchange of water used for transpiration (Condon et al., 2004). Plants adapt to drought stress to increase their transpiration efficiency (TE) and reduce injury by reducing leaf area, plant size and leaf area index (LAI) (Mitchell et al., 1998). Transpiration efficiency is influenced by many physiological traits such as stomatal conductance, photosynthetic capacity and carbon discrimination (Xin et al., 2008). Stomatal control of WUE is indicated by the inverse relationship between mean transpiration rate and WUE in rice genotypes (Impa et al., 2005). Plants manipulate WUE or TE through senescence of older leaves under stress. They retain younger leaves to maintain cell turgidity, stomatal conductance and photosynthesis (Blum and Arkin, 1984). Higher moisture capture by roots is found to be associated with low WUE while reduced transpiration rate is found to be associated with higher WUE (Blum, 2005).

2.2.1.5. Root traits

Rice is a shallow rooted plant compared to other grain crops and water extraction is limited to 60 cm under aerobic conditions Fukai and Inthapan (1988b). Rice plants show steady growth in root length, total dry matter and root length density (RLD) up until the flowering stage (Yoshida and Hasegawa, 1982). Rice in the aerobic condition under direct sowing has a deeper root system than in lowland flooded conditions (Gowda et al., 2011).

Based on a previous study by Bernier et al. (2009), the most important traits for water consumption under drought conditions are deep root length (root length below 30 cm) and maximum rooting depth. Bernier et al. (2009) found that the QTL *qtl12.1* was responsible for improved root architecture. *Oryza sativa* L. has much diversity in root architecture and response to the soil environment (Gowda et al., 2011). Maximum root length and root number are important traits for grain yield improvement and panicle length under drought (Kanbar et al., 2009). Early studies on drought and rice roots emphasised the importance of root traits conferring deep and coarse root growth for the improvement of drought tolerance and for deeper hardpan penetration (Henry, 2013). Not all of the drought environments contain distinct hardpans, although they appear to be an artefact of highly mechanised agricultural systems. Gowda et al. (2011) argued that fine roots as a larger proportion of total root length are expected in helping crops to better water uptake by whole root systems. However, the relative contribution of fine roots over coarse roots is still not precisely determined. Deep rooting is widely targeted trait for rainfed conditions and other root traits will be understood with the improved understanding of plant-soil interactions.

Non-stage-specific drought resistance of the rice crop can be achieved through improvement of root traits. It has been achieved through conventional breeding for root related drought resistance and varieties were selected using participatory plant breeding approaches for the particular location (Shashidhar, 2008).

The current study will help to identify the variety exhibiting better root parameters adapted for rainfed and strategic irrigation conditions.

2.2.2. Chlorophyll Fluorescence

Approaches for measuring photosynthetic traits that are closely correlated with carbon exchange rate, such as chlorophyll content and chlorophyll fluorescence, estimate the environmental stress on growth and yield (Li et al., 2006). These parameters can be therefore used as surrogates for the evaluation of photosynthesis and yield performance of rice plants under water stress (Araus et al., 1998).

2.2.3. Carbon isotope discrimination

Scartazza et al. (1998) reported that during early grain filling, carbon isotope discrimination (CID) was found to be negatively correlated with WUE in rice (Farquhar and Richards, 1984) and integrates the long term photosynthesis and transpiration efficiency of the crop during its growth cycle. Physiologically, plant leaves discriminate stable carbon isotope ($\Delta^{13}C$) for better water use efficiency (Impa et al., 2005). Therefore, CID can be used as a surrogate for WUE in rice. In wheat, popular Australian varieties Drysdale and Rees were selected for CID to increase WUE (Richards, 2006; Richards et al., 2010). A similar approach can be applied to rainfed rice. Carbon isotope discrimination in leaf, stem or grain is useful parameter for WUE and photosynthetic parameters under water stress condition.

2.2.4. Leaf area index

Rice grain yield is directly related to LAI during the reproductive stage (Raboin et al., 2014; Tao et al., 2006). The leaf area index of varieties increases over time due to tillering, new leaf formation and leaf expansion (Tao et al., 2006), and this results in more photosynthesis for grain filling and increased panicle formation. Higher LAI during the reproductive stage is an important parameter for selection under aerobic conditions as LAI is restricted under water limited conditions compared to flooded systems (Sudhir et al., 2011). The LAI is also important for suppression of weed growth due to the negative relationship between rice and weed LAI (Raboin et al., 2014).

2.2.5. Spikelet fertility

Spikelet fertility is one of the best visual responses of rice under drought conditions. Water stress during the reproductive stage (terminal drought) reduces yield more than at other times because of the strong negative effect on grain formation (Boonjung and Fukai, 1996). Stress during that period upsets meiotic division and increases floral sterility resulting in fewer filled grains in panicles (Saini and Westgate, 1999). Spikelet fertility and yield are highly correlated with water stress during flowering (Garrity and O'Toole, 1994). Spikelet fertility or sterility is an indicator and target trait for the selection of drought adapted varieties under terminal drought (Yue et al., 2006a).

2.2.6. Yield

High yield with desirable traits is always the thrust of any breeding and selection program. Selection for yield is an efficient method to identify drought tolerant rice (Mishra et al., 2013). A number of studies have focused on secondary traits as a suitable predictor, although secondary traits have less broad sense heritability compared to yield under drought conditions and generally do not have strong correlation with yield (Atlin and Lafitte, 2002; Bernier et al., 2008). There have been drought tolerant rice varieties developed and released for cultivation using yield as the selection criteria (Kumar et al., 2008; Venuprasad et al., 2007). The selection environment needs to be defined and effective selection methods need to be identified for stable varieties due to high genotype by environment interactions for grain yield under fluctuating soil moisture and unpredictable rainfall in rainfed systems (Kumar et al., 2012).

2.3. Performance of aerobic rice

Aerobic rice varieties should have ability to maintain its steady growth in soils at moisture content at or below field capacity. There are already some varieties developed for aerobic system with such characteristics in different countries such as Han Dai 502 and Han Dao 297 in China; Pusa Hybrid 10, Praoagro 6111 (Hybrid) and IR55423-01 (Apo 1) in India; Apo (PSBRc9), UPLRi5 and PSBRc80 in Philippines (CPWF, 2013) and Talento and Soberana in Brazil (Prasad, 2011) with yield potential of up to 6.5 t/ha. Most of these varieties were derived from crosses between japonica and indica parents whereas the Chinese varieties were developed from crossing between high yielding low land varieties with upland types (IRRI, 2017).

Aerobic rice yields are correlated with the total seasonal water available, particularly from rainfall, and are very vulnerable to terminal drought during flowering (Serraj et al., 2011). For this reason, it is important to have information on target environment and phenological as well as phenotypic characters of available germplasm. The lowering of yield is not only related to water stress, but also to the timing of the stress as well. Therefore dependent on the timing of the drought during the crop phenological stage, drought is characterised as early (during vegetative stage), intermittent, and late or terminal (during panicle initiation) (Bernier et al., 2008). It is necessary to know the target environment and varieties to match with drought at different stages of crop growth.

There have been many studies related to supplementary irrigation to compensate for low or no rainfall during certain growth stages. Different researchers have achieved more than 8 t/ha yield from aerobic rice using sprinkler irrigation(Kato et al., 2009), centre pivot (Stevens et al., 2012), flooded irrigation (Shi et al., 2001), piped irrigation (Sudhir et al., 2011) or under rainfed condition (Matsunami et al., 2009) suggesting that aerobic rice is capable of achieving high yields similar to irrigated low land rice. Blackwell et al. (1985) studied rice under a sprinkler irrigation system in Australia at the Murrumbidgee Irrigation Area and achieved a yield of 5.8 t/ha and Fukai and Inthapan (1988a) achieved 6 t/ha in Redlands Bay, south-eastern Queensland using sprinkler irrigation. (Matsumoto et al., 2014) reported that with every additional 1 mm water applied, the NERICA[2] rice varieties under upland aerobic conditions increased their yield by 11–12 kg/ha, largely due to significant increases in grain filling percentage, number of panicles per m^2, higher grains per panicle and greater 1000 grain weight.

All of these studies have shown that with supplementary irrigation under aerobic systems there is potential to gain significant yield. Summer rainfall during December–March is ca. 600 mm at Alton Downs, central Queensland. This, as indicated earlier, could potentially lead to a yield of 6.1 t/ha if distributed optimally over the season. Rainfall, however, does not always concur with crop requirements. Small irrigation

[2] NERICA is abbreviation of New Rice for Africa representing a group of varieties developed through interspecific lines in 1999 for upland condition using *O. sativa* and *O. glaberrima*. http://www.africarice.org/publications/nerica-comp/module%202_Low.pdf

amounts to ensure that water is available in sufficient quantity throughout the growth cycle for the rice crop should increase the water productivity for aerobic rice production systems.

CHAPTER 3. PERFORMANCE OF RICE VARIETIES UNDER AEROBIC CONDITION WITH OR WITHOUT STRATEGIC IRRIGATION IN CENTRAL QUEENSLAND

Abstract

Recent breeding and agronomic research on aerobic rice has expanded our understanding of the response of rice varieties to different kinds of environment. Modern varieties adapted to aerobic conditions had expanded to different rice growing systems due to their plasticity to adapt in rainfed and irrigated conditions. A field experiment was conducted at Alton Downs, central Queensland during the 2014 and 2015 wet seasons with varieties seeded in a vertisol soil with the objective of assessing the field tolerance of rice varieties under rainfed conditions and strategic irrigation condition in the dry tropics. The performance of 13 varieties was tested using a strip plot design with two main plot irrigation treatments, a) strategic irrigation and b) rainfed conditions with 2 replications, and 13 varieties as sub-plots, to study yield and yield determining physiological, phenological and agronomic responses. During the experiment, the rainfall was very low, particularly during the latter stage of the crop, i.e., flowering and grain filling. Water scarcity at flowering time was a very important factor for yield. Earlier flowering varieties escaped the otherwise severe cold and drought stress during the flowering stage and had higher yield. The average yield of varieties was increased from 1.5 times (AAT 4) to 16.8 times (AAT 15) with strategic irrigation compared to rainfed conditions. The average water productivity was increased by 100% in 2014 and by 110.3% in 2015 with strategic irrigation when compared to rainfed. The yield advantage of strategic irrigation on late flowering varieties compared to rainfed varieties without irrigation showed the potential advantage of strategic irrigation to cope with terminal drought under Alton Downs conditions. The increase in yield was associated with greater panicle fertility, leaf area index (LAI) and water use efficiency (WUE) during flowering. It is important to consider variations in flowering time, yield potential and drought patterns while developing varieties for aerobic conditions.

Key words:
Rice, rainfed, drought, yield response, phenology

3.1. Introduction

Rice (*Oryza sativa* L.) is predominantly grown in tropical lowlands as a flood irrigated crop. In water scarce areas, the crop is also grown as upland rice (or aerobic rice) in many countries. Aerobic rice is grown in soil often kept below saturation for water content. The field is prepared as non-flooded and free-draining without puddling, and is unlike conventional rice farming. For such aerobic rice domains, developing and selecting high yielding rice varieties with drought-resistant traits of upland varieties can provide a good opportunity to achieve high yield under aerobic conditions (Lafitte et al., 2004).

Improving water productivity for rice production is a global driver for the rice industry. Control of irrigation in rice production systems has been seen as an effective way of improving water productivity. Aerobic rice has already shown promise with yields of 6–7 t/ha in China (Huaqi et al., 2002). Some improved aerobic good-yielding rice varieties have been identified (George et al., 2002; Lafitte et al., 2002) for the Huang-Huai-Hai River plains of China, with a yield of 7 t/ha on irrigated dryland (George et al., 2002). Despite being considered low yielding, aerobic rice can give high yield for adapted varieties with a high harvest index (HI) grown under nutrient deficient and/or drought stress.

Aerobic rice is, nevertheless, generally lower yielding than lowland rice. De Datta et al. (1973) tested IR20 under aerobic conditions with irrigation at the Philippines and achieved 55% more water savings than in traditional flooded systems, but yield was compromised down to 3.4 t/ha. Genetic diversity exists for water use efficiency (WUE); hence the yield penalty and reduced access to water can vary between varieties (Impa et al., 2005).

Water use efficiency is one of the major physiological traits used for identification and improvement of rice varieties under water limiting conditions. Genotypic variation for WUE in rice is necessary for selection, and fortunately in rice, there is much genetic variation for WUE (Impa et al., 2005). Water use efficiency in the physiological sense at the leaf level can be measured as the ratio of net photosynthesis rate (A) to stomatal conductance (gs) and by CID (Centritto et al., 2009; Dingkuhn et al., 1991). Carbon isotope discrimination is generally used as a measure of the longer-term integrative WUE, particularly in C_3 species (Xu et al., 2009).

It is essential to understand the effect and mechanisms of water deficit on leaf gas exchange, i.e., photosynthesis (A), transpiration (E) and on plant growth for targeted breeding and selection of tolerant varieties for dryland field conditions (Serraj et al., 2008). Different studies have reported that drought has a significant effect on the leaf photosynthesis rate, gs and E (Chaves, 1991; Lawlor and Cornic, 2002). The grain filling period is very important in terms of carbon storage for grain yield as most of the CO_2 assimilation from the photosynthetically active flag leaf is stored in mature grains (Murchie et al., 1999; Yoshida, 1981). Therefore, conditions that limit the photosynthetic rate of the flag leaf limit grain yield (Dingkuhn et al., 1989). The penalty of drought at the grain filling stage on yield is critical; hence, much varietal screening for drought tolerance is focused on terminal drought stress traits (Kashiwagi et al., 2013).

Australian Agricultural Technologies Limited (AAT) has obtained some improved tropical aerobic varieties bred in Australia (AAT 3, AAT 4, AAT 6, AAT 9, AAT 10, AAT 11, AAT 12, AAT 13, AAT 15, AAT 16, AAT 17, AAT 18 and AAT 19). The yield potential, water use efficiency, and water productivity of these AAT varieties under central Queensland conditions are not known. Preliminary trials conducted under controlled environments and in pots/tubs on assessment of coleoptile length, response to leaf blast (Challagulla et al., 2015) and response to drought, particularly on transpiration efficiency, leaf and root traits, suggest significant difference between these varieties. To extend the information on these varieties, and assess the field tolerance to drought, field experiments were carried out at Alton Downs, Queensland during 2014 and 2015 under strategic irrigation and rain-fed conditions. For the strategic irrigation, water input was supplied through a surface drip irrigation system, to provide limited supplemental irrigation when the rice plants exhibited water deficit and deficiency symptoms, approximately at the refill point of 21 mm per 100 mm of soil depth (Gardner et al., 1988).

3.2. Materials and Methods

3.2.1. Site description

The experiment was conducted over two years, during Jan–May in 2014 and Nov–March in the 2014/15 wet seasons at Alton Downs, Queensland (23^{o}18’14’’ S Latitude, 150^{o}21’24’’ E longitude, and 22 m above sea level). The soil of the experimental site was a heavy clay (self-mulching black cracking clay or vertisol). Soil chemical and nutritional characteristics are described in Table 3.1.

Table 3.1 Soil characteristics of the experimental site at Alton Downs

Parameter	Value
pH	6.6
Organic C (%)	1.57
Nitrate nitrogen (N)	2.1
Ammonium nitrogen (N)	23.8
Phosphorous (mg/kg)	2.0 (Morgan)
Potassium (mg/kg)	97
Organic matter (% OM)	2.8
EC (ds/m)	0.049
Cation exchange capacity (CEC)	60.19 (meq/100 g)

3.2.2. Weather and experimental conditions

The experimental site has a subtropical climate characterised by distinct wet and dry seasons. From December to March is the warm wet season, while from June to September it is cooler and drier. Total rainfall received during the experimental period was 639 mm and 593 mm for 2014 and 2014/15 seasons, respectively (Figure 3.1 and Figure 3.2), whereas the long term average annual rainfall is 800 mm (Bureau of Meteorology, 2016a). Rainfall data, and maximum and minimum air temperatures, were obtained from the Australian Bureau of Meteorology, Rockhampton Aerodrome weather station. Details of weather at the experimental site are presented in section 3.3.1.

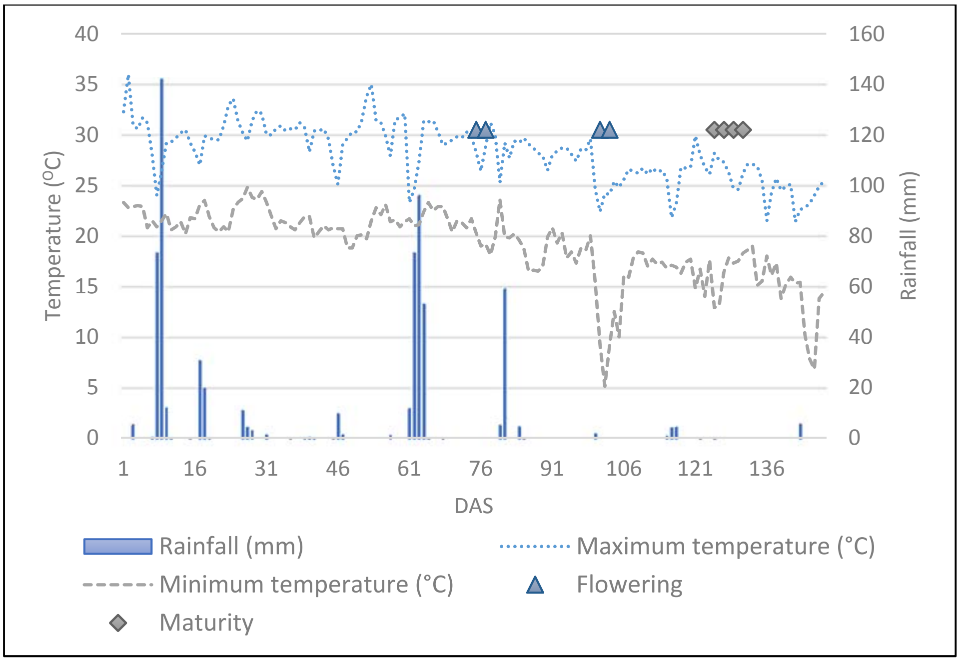

Figure 3.1 Rainfall and temperature in Alton Downs, QLD, 2014 during the rice growing period (Planting: 22 January 2014, Harvest: 28 June 2015).

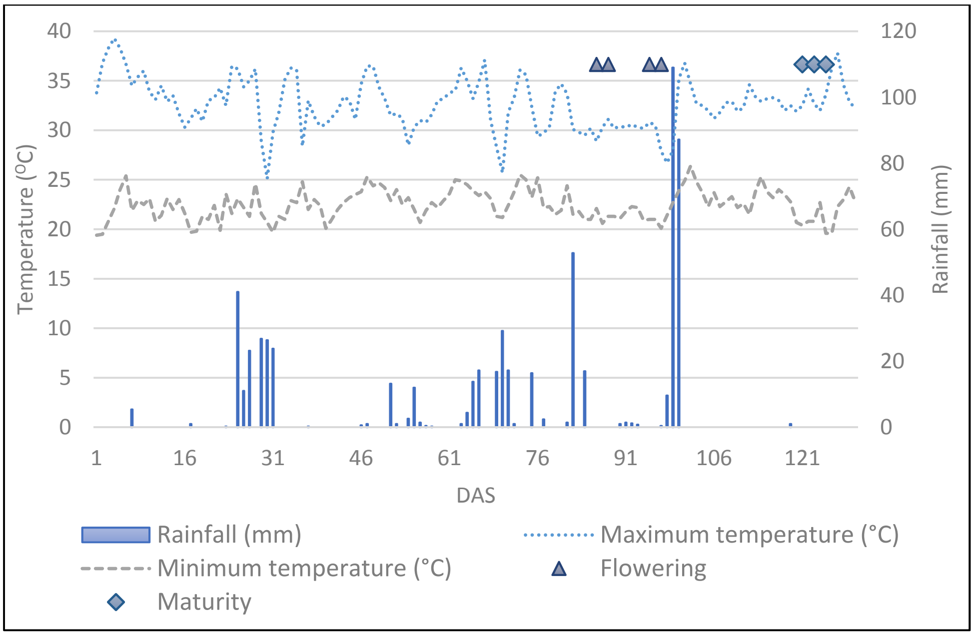

Figure 3.2 Rainfall and temperature in Alton Downs, QLD, 2014/15 during the rice growing period (Planting: 14 November 2014; Harvest: 23 March 2015).

3.2.3. Experimental design and treatments

The trial was set up as a strip-plot design (Gomez and Gomez, 1984). In a strip-plot design, the plots are in horizontal and vertical strips, and are perpendicular to each other. The two levels of irrigation (rainfed and strategic irrigation) was assigned as horizontal treatments and 13 varieties were assigned as vertical treatments. The experiment was conducted with two replications (blocks). Strategic irrigation (SI) was applied with drip irrigation when the soil moisture at 20–30 cm depth was below the refill value (21 mm/100 mm). Supplementary irrigation cumulative volume applied was 1.5 ML/ha in 2014 and 1.89 ML/ha in 2015. Each variety was planted in a 25 m × 3.75 m plot. In each plot 2 m × 1 m sample plots were marked for experimental data recording and sample plot harvest for yield assessment.

3.2.4. Crop management

The rice seeds were directly seeded in a well-prepared seed bed, at a rate of 40 kg/ha by a tractor mounted seed dibbler into the soil. Rows were 25 cm apart. The field was fertilised entirely as basal application with 100:29:76 kg NPK/ha using Crop King fertiliser before planting of the crop. During the 2014/15 season all the treatments received an initial irrigation of 0.79 ML to establish the crop.

Weeds in the experimental plots were controlled using commercial herbicides available on the market. A tank mix of Clomazone (Megister®) @ 0.4 L/ha plus pendimethalin Stomp® 440 @ 2.5 L/ha plus paraquat 250 g/L (Gramoxone® 250) @ 0.8 L/ha was applied as described by (Taylor, 2013) after sowing rice seeds, followed by initial irrigation in 2015 and rainfall in 2014. Similarly, Dicamba 500 g/L (Kamba®500) @ 0.4 to 0.56 L/ha was applied during the early tillering stage to control broad leaf weed growth. Intensive manual weeding was also performed on three occasions in both years, in order to control the weeds that were not controlled by herbicides.

3.2.5. Rice varieties

Seed samples of thirteen rice varieties were obtained from AAT (Australian Agricultural Technologies Ltd, Wee Waa). There were seven long grain and six medium grain type varieties in the trial (Table 3.2). These varieties were developed in north Queensland and the Northern Territory by Dr. Isaac Lasik from wild and cultivated germplasms of rice under the old defunct ‘Humpty Doo project’. The details of the pedigree of these varieties are maintained by AAT.

Table 3.2 Rice varieties used in the experiment

Varieties	Entry Name	Grain Type	Maturity
AAT 9	Linklatter B1	Long	Late
AAT 10	Dummeriney 11	Long	Late
AAT 11	Lasik IX	Long	Late
AAT 12	Inaminka MB	Long	Late
AAT 15	Lasik XII	Long	Late
AAT 16	Inaminka XB	Long	Late
AAT 18	Unnamed	Long	Late
AAT 3	Lasik VII	Medium	Early
AAT 4	Sunkiss PII	Medium	Early
AAT 6	Linklatter A1	Medium	Early
AAT 13	Lasix XB	Medium	Early
AAT 17	Inaminka XD	Medium	Early
AAT 19	Duminey	Medium	Early

3.2.6. Crop measurements

Grain yield was measured from whole plots (25 m × 3.75 m) using a plot rice harvester (Yanmar, Japan), and from the sample plot (2 m × 1 m) by manual harvesting using a sickle. The crop was harvested when grain moisture was ca. 14%. The sample plot was used to measure grain yield and all plant parameters were measured from five randomly selected hills within the sample plot areas. The sample plot harvest was threshed manually by hitting against the floor and the grain dried (as was the stems and chaff) and weighed to determine yield and HI. Grain yield was adjusted to 12% moisture content and presented as t/ha. Crop parameters (Section 0) were recorded following the International Rice Research Institute (IRRI) rice descriptor method (Bioversity International et al., 2007).

3.2.7. Parameters studied

Table 3.3 presents the variables that were recorded during the experiment. Details on specific procedures for each are presented in sections 0, 3.2.7.2, 3.2.7.3, 3.2.7.4 and 3.2.7.5.

Table 3.3 Variables recorded during the experiment at Alton Downs in 2014 and 2015.

Type	Variables and calculated parameters (units)
Growth	Plant height (cm) Flag leaf length (cm) Flag leaf breadth (cm) Flag leaf area (cm^2) Leaf area index (ratio)Days to flowering (no.) Days to maturity (no.)
Physiological	Chlorophyll content (SPAD value) Chlorophyll (Chl) fluorescence (Fv/Fm) Relative leaf water content, RWC (%) Electrolyte leakage (%) Osmotic potential (Mpa) Photosynthesis (µmol/m^2/sec) Stomatal conductance (mmol/m^2/sec) Leaf transpiration (mmol/ m^2/sec) WUEi or intrinsic water use efficiency (A/gs)/(µmol mol) WUE or water use efficiency (A/E) [(µmol CO_2)/(mmol H_2O)]
Root	Total length (cm) Total dry wt. (g)
Yield and yield contributing	Number of tillers (no.) Spikelet /panicle (number) 1000 grain wt. (g) Spikelet fertility (%) Grain yield (t/ha) Straw dry weight (t/ha) Harvest index (ratio)
Water and water productivity	Total irrigated water (ML/ha) Total rainfall (mm) Water productivity (t/ML)

3.2.7.1. Growth parameters

Plant height: Actual measurement for plant height (cm) was taken from soil surface to the tip of the tallest panicle (awns excluded). This was recorded 3 times at 85 days after sowing (DAS), 102 DAS and 133 DAS in 2014, and 3 times at 51 DAS, 79 DAS and 111 DAS in 2015.

Flag leaf length: Measurement of the length of the flag leaf (cm) was taken from the ligule to the tip of the blade, on five representative plants and average calculated to the nearest cm. Measurements were collected once at 7 days after anthesis.

Flag leaf width: Measurement of width (cm) at the widest portion of the flag leaf on five representative plants was taken once, 7 days after anthesis.

Flag leaf area: This was calculated in cm^2 from the formulae advocated by Palaniswamy and Gomez (1974).

$$Flag\ leaf\ area\ (FLA) = L \times B \times C \qquad \text{Equation 3.1}$$

Where,

L = length of flag leaf in centimetre

B = breadth of flag leaf from widest portion in centimetre

C = constant factor, which is 0.74 for flag leaf of rice.

Heading date (flowering date): The heading date was recorded when 50% of plants in a plot from the date of planting showed the panicle base emerged out of the flag leaf collar.

Maturity: The number of days from seeding to grain ripening was recorded as the maturity days (85% of grains on panicle were mature).

3.2.7.2. Physiological parameters

Leaf area index: A Ceptometer (model AccuPAR LP-80, Decagon Devices, Pullman, USA) was used to measure the light interception by the canopy and gave a further estimation of the leaf area index (LAI). The Ceptometer uses leaf angle distribution parameter χ in addition to above and below canopy readings of photosynthetically active radiation (PAR) to estimate LAI (Campbell, 1986). Measurements were recorded three times during each crop season, i.e., on 84 DAS, 103 DAS and 133 DAS in 2014, and on 82 DAS, 110 DAS and 123 DAS in 2014/15.

Leaf chlorophyll content (SPAD): A chlorophyll meter (SPAD-502, Soil-Plant Analysis Development Section, Minolta Camera Co., Osaka, Japan) was used to obtain chlorophyll values measured as SPAD units on the uppermost fully expanded leaf. SPAD readings were taken from three locations of each leaf. SPAD reading were recorded on three occasions on 85 DAS, 102 DAS and 133 DAS in 2014, and two occasions, on 79 DAS and 111 DAS in 2014/2015.

Chlorophyll fluorescence (Fv/Fm): Chlorophyll fluorescence parameters were recorded using a Chlorophyll Fluorometer (OS-30p) (Opti Science, USA) following the manufacturer's instruction. The parameters recorded were initial fluorescence (Fo), maximum fluorescence (Fm), variable fluorescence (Fv), and maximum quantum efficiency of photosystem II (Fv/Fm) on the fully expanded top leaf. The dark adaptation period was adjusted to 15 minutes for all measurements. One flag leaf from each plot was selected for measuring chlorophyll fluorescence and measurements were made on three occasions, on 85 DAS, 102 DAS and 133 DAS in 2014, and on 63 DAS, 82 DAS and 95 DAS in 2014/2015.

Electrolyte leakage: A leaf sample was harvested from five different plants for measurement of electrolyte leakage on 133 DAS in 2014 and 90 DAS in 2014/15 . The sampled leaves were washed quickly with deionised water and then a circular segment of 1 cm diameter from the centre of each leaf was taken. The five samples were then placed in a tube with 10 ml deionised water and initial electrical conductivity (EC1) was measured. The tubes were then placed in a dark room at 25°C for 24 hrs and another electrical conductivity was measured (EC2). Then the samples were autoclaved and cooled to 25°C for final electrical conductivity reading (EC3). The electrolyte leakage was calculated following the method of Bajji et al. (2002) and presented as Equation 3.2.

$$EC = \frac{EC2 - EC1}{EC3 - EC1} \times 100$$ Equation 3.2

Relative water content: For the measurement of relative water content (RWC), Leaf samples were taken from the second tiller of the sample plant on 133 DAS in 2014 and 90 DAS in 2014/15. The sampled leaves were immediately put in to a pre-weighed tube and kept in an esky with ice until it was taken to laboratory. The tubes were then weighed immediately for initial fresh weight (FW). The tubes with leaf sample were filled with distilled water and were kept overnight inside a dark box. After 24 hrs, the leaves were weighed to determine the turgid weight (TW) after wiping water from the leaf surface using paper towels. The leaves were dried at 70°C to for the dry mass (DW) estimation. The RWC was calculated following the method of Lafitte (2002) and presented as Equation 3.3.

$$RWC = \frac{(FW - DW)}{(TW - DW)} \times 100 \qquad \text{Equation 3.3}$$

Leaf gas exchange measurements: Leaf gas exchange parameters for assessment of net photosynthetic rate (A), stomatal conductance to CO_2 (gs) and leaf transpiration rate (E) were performed using a portable infrared gas analyser (IRGA) (ADC Bioscience, UK) on sunny days between 9 AM and 3 PM. Measurements were made on three occasions at 83 DAS, 103 DAS and 133 DAS in 2014, and four occasions at 51 DAS, 82 DAS, 95 DAS and 110 DAS in 2015. Each photosynthetic measurement was taken on fully expanded topmost leaves (3^{rd} or 4^{th} from apex) (Kumar et al., 2013a). Instantaneous water use efficiency (WUE) was calculated as the A to E ratio (WUE = A/E). Photosynthetic rate, gs, E, and WUE measured around flowering stage were used for correlation analysis with other parameters. photosynthetically active radiation (PAR), relative humidity (RH), air temperature, air CO_2 concentration and flow rate were recorded. Each of the measurements was made when net A and gs readings were stabilised on a sample plant. Instantaneous WUE was calculated as the ratio between A and E, and intrinsic WUE between A and gs (Medrano et al., 2015).

3.2.7.3. Root parameters

Root samples were collected from a random hill in the middle row of each sample plot, using a 4 cm diameter and 120 cm length sampling core on the second day of harvesting rice. The core samples were separated into depths of 0–15 cm, 15–30 cm, 30–60 cm and 60–100 cm. The roots were stored in a cold room (4°C) until each sample was washed. Soil samples were soaked in a sodium lignosulfonate solution (20 ml/l water) for 6 hours and placed over a 1 mm sieve to wash root samples with running water to remove the soil from roots. All samples were stored in a container with water until scanning. The scanner (HP ScanJet 8200) was set at 300 dpi for root imaging. Scanned root images were analysed for total root length and root diameter using Delta T software. After scanning, the roots were dried in an oven at 65°C to estimate dry weight.

Root morphological parameters such as root diameter (RD), root weight density (RWD) (mg cm^{-3}) and root length density (RLD) (mm cm^{-3}) were calculated using the formulae in equation 3.4 and 3.5 as described by Yang et al. (2004):

$$Root\ Length\ Density\ (RLD) = \frac{Root\ length}{Volume\ of\ soil\ core} \quad \text{Equation 3.4}$$

$$Root\ Weight\ Density\ (RWD) = \frac{Root\ weight}{Volume\ of\ soil\ core} \quad \text{Equation 3.5}$$

3.2.7.4. Yield parameters

Two days before the harvest, the frequency of effective tillers was estimated from the panicles per sample hill. Five samples hills per plot were marked for recording yield parameters such as tillers per plant, effective tillers per plant, plant height and panicle length. Five panicle samples were selected from those five hills and the grain from each of these panicles were collected in paper bags. The remaining grains from the five hills were threshed and collected in a large cotton bag. The grain samples were then air dried and weighed. The number of filled grains and unfilled grains were manually counted from sampled panicles. Postharvest data such as percentage filled grains, 1000 grain weight were measured following the method of Yoshida et al. (1976). For the remaining crop the total grain yield from the experimental plot was harvested, threshed and cleaned using a Yanmar rice combined harvester (Kubota Model Number AR90, Japan), followed by grain drying in air, and weighed. The grain harvest from each plot were weighed, and the moisture content assessed using a moisture meter (PFEUFFER HE 50, Germany), taking three moisture readings per plot. Grain weight was adjusted to 12% moisture content.

Spikelet fertility: The fertile spikelet counts were taken from the five sample panicles collected from the sample hills. Numbers of filled and unfilled spikelets were separated by water (floating are unfilled). Filled and unfilled spikelets were counted to determine the percent of filled florets, or spikelet fertility, and to determine spikelet fertility percentage.

1000 grain weight: Random samples of 1000 well-developed, whole grains were dried and weighed on an electronic balance to calculate the 1000 grain weight at 12% moisture.

Effective grains per panicle: The total number of effective grains was counted separately from the sample panicle of each tagged plant.

Harvest index: This was calculated as a ratio of grain yield to oven dried above ground crop biomass.

3.2.7.5. Water productivity

Water applications were measured by water meters when applied to the plots. Total water applied as irrigation water and rainfall were added to calculate total water input. Water productivity was then calculated using grain yield at 12% moisture divided by the total water input. Measurements from sample plots were used to derive correlation with other traits.

3.2.8. Data analysis

Microsoft Office Excel 2013 was used for data entry, recording, and data management.

ANOVA was undertaken as horizontal main plot (irrigation treatment) and vertical sub-plot (variety) in the same block and the interaction between the two according to (Gomez and Gomez, 1984). Therefore, when the experiment was repeated in the second year the error was divided in four levels, i.e., Year, Year × irrigation, Year × variety, and Year × irrigation × variety. All analysis was performed using GenStat 16th edition (VSN International, 2013). Interaction effects are presented and, where there was no interaction, only main effects are presented. Specific interaction effects are presented in graphs using R (R Core Team, 2016) package ggplot2 (Wickham, 2009) and Microsoft Office Excel 2013.

The means were compared by Fisher's protected 'Least Significant Difference' (LSD) test. The significance level was set at 5% in all comparisons.

3.3. Results

3.3.1. Weather parameters, irrigation inputs and soil moisture dynamics

The majority of rainfall during the 2014 season occurred during the first 85 DAS, but in 2015, it rained until 99 DAS. Severe Tropical Cyclone Marcia was a Category 3 cyclone when it hit Rockhampton, resulting in a rainfall peak of 109.4 mm on 98 DAS (20 February 2015) and 96 mm on 99 DAS. After this event, no rainfall was recorded at Alton

Downs during the crop period. Total rainfall received during the experimental period was 639 mm and 593 mm for 2014 and 2014/15 seasons, respectively and the long term average annual rainfall was 800 mm (Bureau of Meteorology, 2016a). Supplementary irrigation applied was 1.5 ML/ha, i.e., 150 mm in 2014, and 1.89 ML/ha, i.e., 189 mm in 2015, with the frequency of 14 times and 5 times in 2014 and 2015, respectively (Figure 3.3).

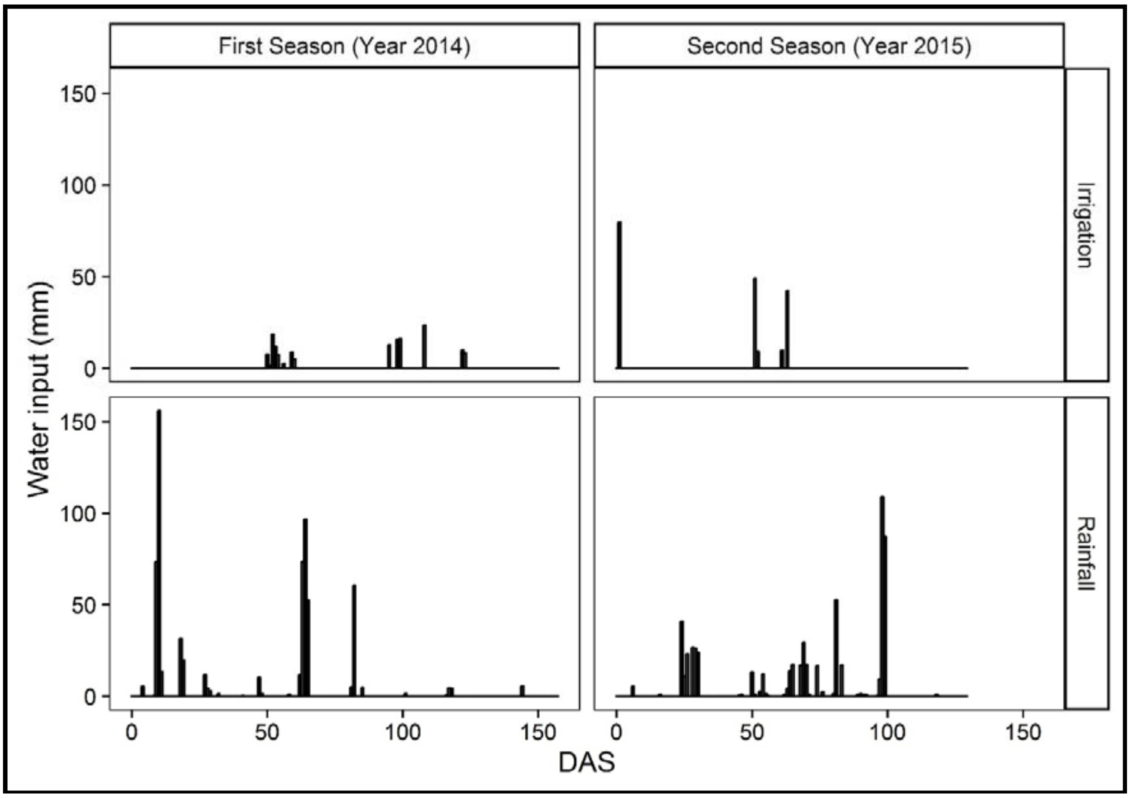

Figure 3.3 Rainfall (mm) and irrigation (mm) water volume applied to the crop during the crop period in 2014 and 2015.

The mean temperature during the experimental period in 2014 (22 January 2014 to 28 June 2014) and in 2015 (14 November 2014 to 23 March 2015) was 23.5°C and 27.5°C, respectively. Temperatures ranged from 5.1°C to 36°C in 2014, while in 2015, it ranged from 19.4°C to 39.3°C. The temperature gradually decreased from April to June (Figure 3.1 and Figure 3.2). Relative humidity averaged 70% and 68 % in 2014 and 2015, respectively, and ranged 16–100 % in 2014 and 18–100% in 2015. Evapotranspiration (ET_o) averaged 4.2 mm d^{-1} in 2014 and 5.9 mm d^{-1} in 2015. Evapotranspiration ranged from 1 to 8.4 mm d^{-1} and 1.7 to 8.3 mm d^{-1} in 2014 and 2015, respectively, during the growing period (Figure 3.4).

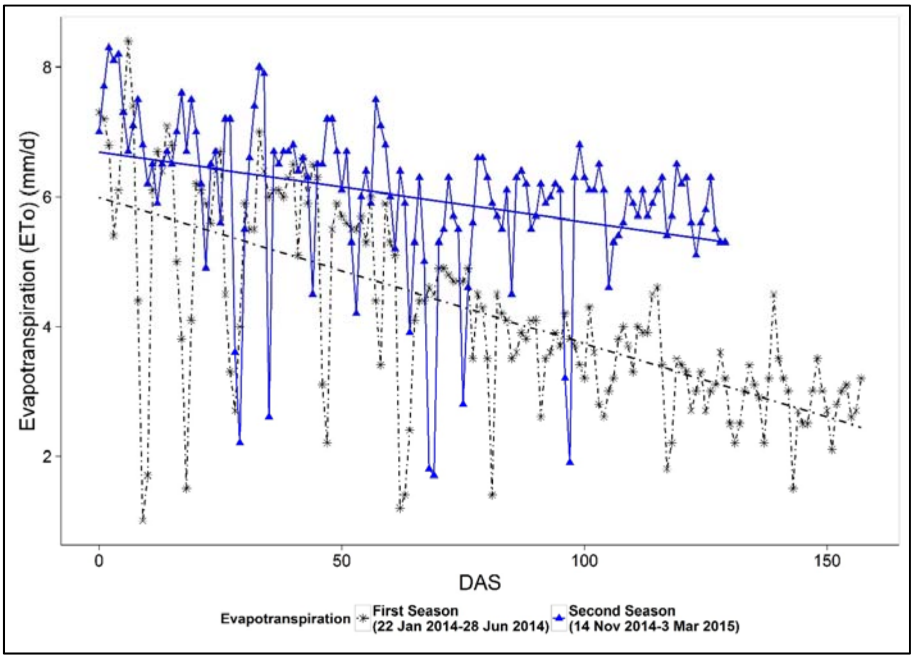

Figure 3.4 Reference evapotranspiration during the experimental period of 2014 and 2015 at Alton Downs.

Representative soil moisture measurements taken in January 2nd (49 DAS) and February 18th (96 DAS) of 2015 (active tillering) showed an increasing trend of soil moisture with the increased depth from 10 cm to 50 cm in both rainfed and strategic irrigation treatments in variety AAT 4 and AAT 12 (Figure 3.5). Soil moisture was measured using a calibrated Micro-Gopher system (Soil Moisture Technology, Australia), the probe of which consists of a capacitance sensor. Soil moisture extraction pattern for all the varieties are presented in Appendix A.

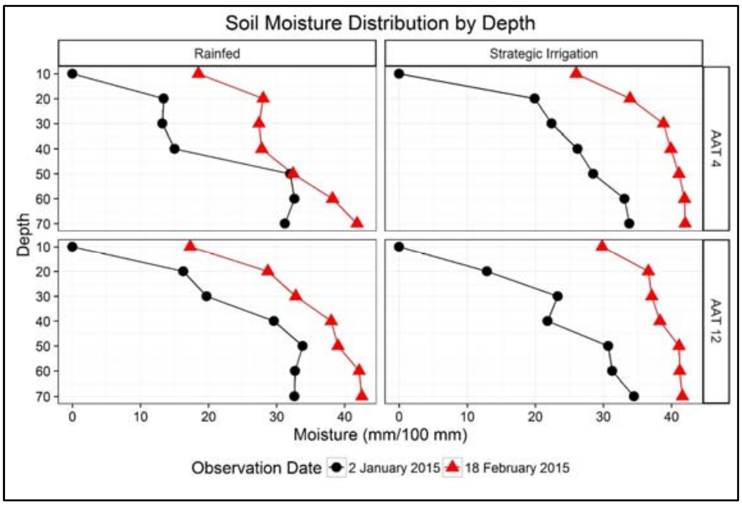

Figure 3.5 Soil moisture distribution by depths for varieties AAT 4 and AAT 12 in rainfed and strategic irrigation at Alton Downs, 2015.

3.3.2. Growth parameters

3.3.2.1. Days to flowering

Days to flowering of varieties differed significantly due to year of planting ($p < 0.001$) ($p<0.001$) (Table 3.4); mean days to flowering was significantly earlier in 2014 (90 DAS) than in 2015 (92 DAS) ($p = 0.002$) (Table 3.4). The early flowering (medium grain) varieties were AAT 3, AAT 4, AAT 6, AAT 13, AAT 17 and AAT 19, and flowered at 81–83 DAS, whereas the late flowering (long grain) varieties were AAT 9, AAT 10, AAT 11, AAT 12, AAT 15, AAT 16 and AAT 18, and flowered at 99 DAS. The late flowering coincided with a time when the temperature fell below 10°C in 2014 (Figure 3.1). All long grain type varieties were late for flowering compared to medium grain type varieties in both years (Table 3.4). The majority of rainfall during the 2014 season occurred at first 85 DAS but in 2015, it rained until 99 DAS.

Table 3.4 Days to flowering of varieties under strategic irrigation and rainfed conditions at Alton Downs, 2014 and 2015.

Varieties	Year 2014			Year 2015			Overall Mean (DAS)
	Rainfed (DAS)	Strategic irrigation (DAS)	Mean (DAS)	Rainfed (DAS)	Strategic irrigation (DAS)	Mean (DAS)	
AAT 9	102	102	102	96	96	96	99
AAT 10	102	102	102	96	96	96	99
AAT 11	102	102	102	96	96	96	99
AAT 12	102	102	102	96	96	96	99
AAT 15	102	102	102	96	96	96	99
AAT 16	102	102	102	96	96	96	99
AAT 18	102	102	102	96	96	96	99
AAT 3	76	76	76	87	87	87	82
AAT 4	76	76	76	87	87	87	82
AAT 6	76	76	76	87	87	87	82
AAT 13	76	76	76	87	87	87	82
AAT 17	79	78	78	87	87	87	83
AAT 19	79	79	79	87	87	87	83
Average	**90**	**90**	**90**	**92**	**92**	**92**	**91**
p-value and LSD at 5%							
Year (Y) 0.002 (0.25)	**Y×V**	<0.001 (0.43)		**Y×I×V**	0.478 (0.59)		
Variety(V) <0.001 (0.30)	**Y×I**	0.423 (0.23)					
Irrigation(I) 0.423 (0.25)	**V×I**	0.478 (0.42)					

3.3.2.2. Plant height at harvest

Mean plant height of varieties during maturity ranged from 72 cm (AAT 15) to 89 cm (AAT 4) in 2014 (Table 3.5), and from 90 cm (AAT 18) to 98 cm in 2015 (AAT 13) (Table 3.5). There was a significant effect of irrigation treatment ($p = 0.05$) with taller plants with strategic irrigation than in rainfed system. The average plant height of varieties in rainfed conditions was 77 cm and in strategic irrigation was 83 cm in 2014. In 2015, the plant height was 94 cm in rainfed conditions and 95 cm in strategic irrigation conditions.

Mean varietal difference was significant ($p < 0.001$) with variety AAT 4 (93 cm) being the tallest and AAT 16 (80 cm), the shortest. Average variety height was significantly greater in 2015 compared to 2014 ($p = 0.02$) (Table 3.5).

Table 3.5 Plant height of varieties under strategic irrigation and rainfed conditions at Alton Downs, 2014 and 2015.

Varieties	Year 2014			Year 2015			Overal l Mean
	Rainfed (cm)	Strategic irrigation (cm)	Mean (cm)	Rainfed (cm)	Strategic irrigation (cm)	Mean (cm)	
AAT 9	72	78	75	95	91	93	95
AAT 10	74	80	77	92	98	95	96
AAT 11	74	81	78	95	97	96	94
AAT 12	73	81	77	95	92	94	97
AAT 15	71	73	72	95	98	97	92
AAT 16	65	73	69	91	93	92	90
AAT 18	73	75	74	90	90	90	93
AAT 3	83	94	88	95	98	97	98
AAT 4	88	90	89	94	102	98	92
AAT 6	81	91	86	95	98	96	93
AAT 13	83	91	87	96	100	98	97
AAT 17	83	91	87	90	93	92	98
AAT 19	78	85	81	94	92	93	96
Average	**77**	**83**	**80**	**94**	**95**	**94**	**94**
p value and LSD $_{0.05}$							
Year 0.02 (8.906)	**Y×V**	0.052 (9.144)		**Y×I×V**	0.88 (11.002)		
Variety (V) <0.001 (5.87)	**V×I**	0.944 (7.356)					
Irrigation (I) 0.05 (4.165)	**Y×I**	0.139 (7.518)					

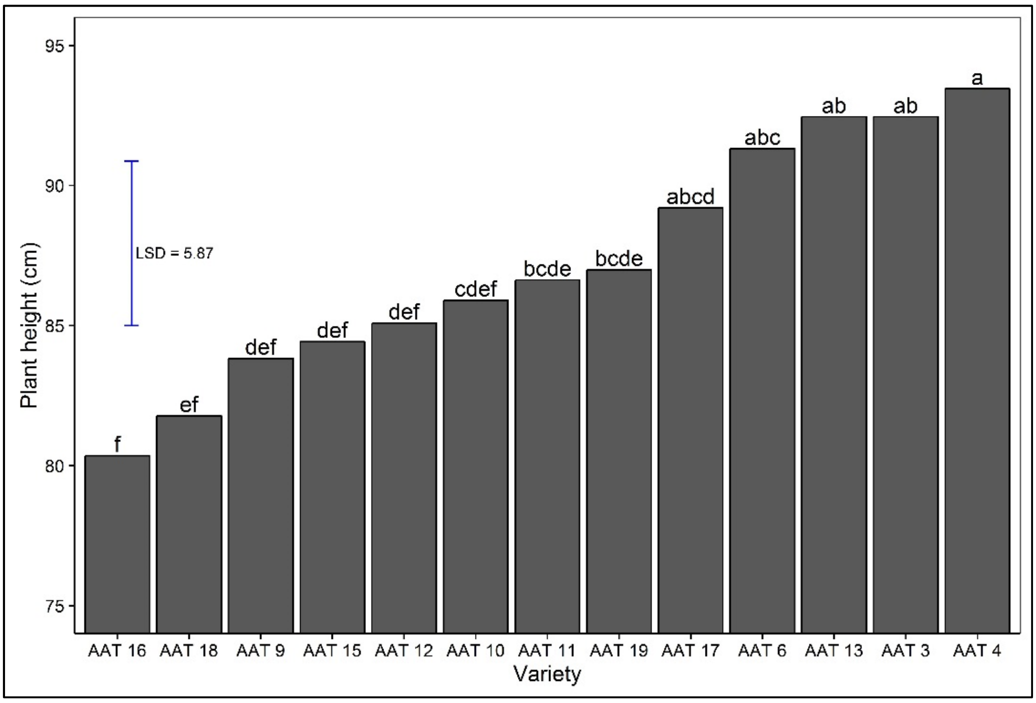

Figure 3.6 Plant height of rice varieties at Alton Downs, during 2014 and 2015.

3.3.2.3. Flag leaf length

Flag leaf length ranged from 22–37 cm across varieties. Average flag leaf length differed significantly ($p \leq 0.001$) between years, such that a longer flag leaf (28 vs 33 cm) was recorded in 2015, compared to 2014 (Table 3.6). Average flag leaf length of varieties depended significantly on the year of planting (Table 3.6) , i.e., there was a significant year x variety interaction ($p = 0.041$), as all varieties except AAT 10, AAT 11, and AAT 12 showed a significantly longer flag leaf in 2015 compared to 2014. The effect of irrigation treatment on the flag leaf length was not significant ($p = 0.495$) in either year (Table 3.6).

Table 3.6 Flag leaf length (cm) of varieties under strategic irrigation and rainfed conditions at Alton Downs, 2014 and 2015

	Year 2014			**Year 2015**			**Overall Mean**
Varieties	**Rainfed (cm)**	**Strategic irrigation (cm)**	**Mean (cm)**	**Rainfed (cm)**	**Strategic irrigation (cm)**	**Mean (cm)**	
AAT 9	34.02	26.56	30.29	33.40	35.28	34.34	32.32
AAT 10	30.93	27.72	29.33	30.75	32.05	31.40	30.36
AAT 11	33.06	31.39	32.23	33.15	32.25	32.70	32.46
AAT 12	31.79	31.46	31.63	34.45	33.93	34.19	32.91
AAT 15	26.77	24.30	25.54	34.95	31.35	33.15	29.34
AAT 16	24.62	23.70	24.16	31.00	29.90	30.45	27.31
AAT 18	29.12	25.53	27.33	33.75	31.93	32.84	30.08
AAT 3	21.72	30.46	26.09	33.15	30.05	31.60	28.85
AAT 4	26.47	26.78	26.63	30.50	31.70	31.10	28.86
AAT 6	24.37	28.60	26.49	31.05	32.30	31.68	29.08
AAT 13	29.31	26.74	28.03	33.80	31.43	32.62	30.32
AAT 17	23.86	25.59	24.73	33.60	32.75	33.18	28.95
AAT 19	25.02	25.88	25.45	36.60	33.03	34.82	30.13
Average	**27.77**	**27.29**	**27.53**	**33.09**	**32.15**	**32.62**	**30.07**
p- value and $LSD_{0.05}$							
Year	< 0.001 (0.37)	**Y×V**	0.041 (3.31)		**Y×I×V**	0.103 (5.08)	
Variety (V)	0.002 (2.43)	**V×I**	0.363 (3.84)				
Irrigation (I)	0.495 (3.71)	**Y×I**	0.819 (3.66)				

3.3.2.4. Flag leaf breadth

Flag leaf breadth ranged from 1.26 cm to 1.76 cm. Average flag leaf breadth was significantly higher in 2015 (1.62 cm), compared to 2014 (1.49 cm) ($p = 0.026$) (Table 3.7). However, flag leaf breadth was not higher for all varieties in 2015; one variety (AAT 16) had larger flag leaf breadth in 2014 as compared to 2015.

Irrigation showed a slight but not significant impact on flag leaf breadth ($p = 0.054$) (Table 3.7).

Table 3.7 Flag leaf breadth of varieties under strategic irrigation and rainfed conditions at Alton Downs, 2014 and 2015.

Varieties	Year 2014			Year 2015			Overall Mean
	Rainfed (cm)	Strategic irrigation (cm)	Mean (cm)	Rainfed (cm)	Strategic Irrigation (cm)	Mean (cm)	
AAT 9	1.38	1.76	1.57	1.63	1.73	1.68	1.63
AAT 10	1.36	1.65	1.51	1.54	1.59	1.57	1.54
AAT 11	1.36	1.68	1.52	1.58	1.53	1.56	1.54
AAT 12	1.39	1.67	1.53	1.62	1.61	1.62	1.57
AAT 15	1.48	1.65	1.56	1.60	1.65	1.63	1.59
AAT 16	1.54	1.75	1.64	1.61	1.61	1.61	1.63
AAT 18	1.36	1.71	1.54	1.63	1.69	1.66	1.60
AAT 3	1.31	1.46	1.39	1.58	1.63	1.61	1.50
AAT 4	1.39	1.46	1.43	1.54	1.58	1.56	1.49
AAT 6	1.26	1.48	1.37	1.51	1.54	1.53	1.45
AAT 13	1.35	1.55	1.45	1.66	1.64	1.65	1.55
AAT 17	1.30	1.53	1.42	1.71	1.70	1.71	1.56
AAT 19	1.39	1.46	1.43	1.69	1.67	1.68	1.55
Average	**1.37**	**1.60**	**1.49**	**1.61**	**1.63**	**1.62**	**1.55**
p- value and $LSD_{0.05}$							
Year	0.026 (0.09)	**Y×V**	0.017 (0.12)		**Y×I×V**	0.744 (0.17)	
Variety (V)	0.004 (0.08)	**V×I**	0.507 (0.13)				
Irrigation (I)	0.054 (0.13)	**Y×I**	0.075 (0.11)				

3.3.2.5. Flag leaf area

Flag leaf area of varieties ranged 35.1–48.8 cm^2 in 2014 and 48.3–58.6 cm^2 in 2015 (Table 3.8). Average flag leaf area differed significantly between varieties and years (p = 0.043) (Table 3.8), and the interaction between year x varieties was significant. The average flag leaf area was significantly larger in 2015, compared to 2014 (p = 0.003) (Table 3.8). Irrigation treatment did not significantly affect flag leaf area at harvest (Table 3.8), although it was greater with strategic irrigation in 2014. The significant year x variety interaction (p = 0.043) suggests that flag leaf area was larger in 2015 compared to 2014 for all varieties, but the difference between the years was significantly greater for most varieties, whereas, for varieties AAT 10, AAT 11 and AAT 12, the difference was not significant (Table 3.8).

Table 3.8 Flag leaf area (cm^2) of varieties under strategic irrigation and rainfed conditions at Alton Downs, 2014 and 2015.

Varieties	**Year 2014**			**Year 2015**			**Overall Mean**
	Rainfed	**Strategic irrigation**	**Mean**	**Rainfed**	**Strategic irrigation**	**Mean**	
AAT 9	47.14	46.57	46.86	54.64	61.20	57.92	52.39
AAT 10	42.11	45.74	43.93	47.37	51.07	49.22	46.57
AAT 11	44.85	52.75	48.80	52.36	49.41	50.89	49.84
AAT 12	44.26	52.48	48.37	55.95	54.58	55.27	51.82
AAT 15	39.64	40.07	39.86	55.91	51.75	53.83	46.84
AAT 16	37.51	41.47	39.49	49.93	48.16	49.05	44.27
AAT 18	39.68	43.66	41.67	55.35	53.96	54.66	48.16
AAT 3	28.48	44.49	36.49	52.59	48.97	50.78	43.63
AAT 4	37.08	39.10	38.09	46.94	50.01	48.48	43.28
AAT 6	30.70	42.33	36.52	46.91	49.74	48.33	42.42
AAT 13	39.47	41.51	40.49	56.11	51.58	53.85	47.17
AAT 17	30.95	39.26	35.11	57.53	55.67	56.60	45.85
AAT 19	34.81	37.78	36.30	61.98	55.16	58.57	47.43
Average	38.21	43.63	40.92	53.35	52.40	52.88	46.90
p- value and $LSD_{0.05}$							
Year	0.003 (2.93)	**Y×V**	0.043 (7.59)		**Y×I×V**	0.403 (10.52)	
Variety (V)	0.017 (5.5)	**V×I**	0.652 (8.21)				
Irrigation (I)	0.391 (8.87)	**Y×I**	0.262 (7.92)				

3.3.2.6. Leaf area index

The average LAI differed significantly across the growth period in both years (Table 3.9 and Table 3.10). In 2014, the varieties AAT 17 (3.06), AAT 11 (3.89) and AAT 11 (3.15) had the highest LAI on 84 DAS, 103 DAS and 133 DAS, respectively (Table 3.9). In 2015, the varieties AAT 17 (3.24), AAT 3 (3.81) and AAT 19 (3.24) had the highest LAI on 82 DAS, 110 DAS and 123 DAS, respectively (Table 3.10).

There was no significant effect of irrigation treatment on LAI in either year, although in absolute terms there was an advantage with irrigation (Table 3.9 and Table 3.10).

Table 3.9 Leaf Area Index of varieties under strategic irrigation and rainfed conditions at Alton Downs in 2014.

Year 2014	**LAI (84 DAS)**			**LAI (103 DAS)**			**LAI (133 DAS)**		
Varieties	**Rainfed**	**Strategic irrigation**	**Mean**	**Rainfed**	**Strategic irrigation**	**Mean**	**Rainfed**	**Strategic irrigation**	**Mean**
AAT 9	1.82	2.22	2.02	2.88	3.24	3.06	2.15	3.20	2.67
AAT 10	2.41	2.49	2.45	3.79	3.57	3.68	2.54	3.40	2.97
AAT 11	2.14	2.54	2.34	3.07	3.89	3.48	2.48	3.81	3.15
AAT 12	2.23	3.21	2.72	3.34	4.45	3.89	2.29	3.75	3.02
AAT 15	2.08	2.29	2.19	2.58	2.67	2.63	2.44	3.41	2.92
AAT 16	2.26	2.57	2.41	2.84	3.64	3.24	2.47	3.71	3.09
AAT 18	2.10	2.45	2.27	2.68	3.30	2.99	2.20	3.58	2.89
AAT 3	1.63	2.43	2.03	2.28	2.83	2.55	1.90	3.07	2.48
AAT 4	1.97	1.79	1.88	2.36	2.49	2.42	2.14	2.84	2.49
AAT 6	1.86	2.74	2.30	2.96	3.43	3.20	2.40	3.36	2.88
AAT 13	2.35	3.15	2.75	2.54	3.35	2.95	2.21	3.14	2.67
AAT 17	2.89	3.23	3.06	2.76	3.87	3.32	2.40	3.56	2.98
AAT 19	2.62	2.45	2.54	2.82	3.53	3.17	2.18	3.21	2.69
Average	**2.18**	**2.58**	2.38	**2.84**	**3.40**	3.12	**2.29**	**3.39**	2.84
p- value and $LSD_{0.05}$									
Irrigation (I)	0.522 (5.4669)			0.193 (2.2448)			0.088 (1.9467)		
Variety (V)	0.058 (0.6329)			0.06 (0.827)			0.032 (0.3802)		
I*V	0.789 (1.7242)			0.845 (1.1287)			0.744 (0.6481)		

Table 3.10 Leaf Area Index (LAI) of varieties under strategic irrigation and rainfed conditions in Alton Downs at 2015.

Year 2015	**LAI (82 DAS)**			**LAI (110 DAS)**			**LAI (123 DAS)**		
Varieties	**Rainfed**	**Strategic irrigation**	**Mean**	**Rainfed**	**Strategic irrigation**	**Mean**	**Rainfed**	**Strategic irrigation**	**Mean**
AAT 9	2.33	3.01	2.67	2.27	3.22	2.74	1.37	2.60	1.98
AAT 10	2.08	3.07	2.58	2.14	4.11	3.12	1.24	3.05	2.14
AAT 11	1.94	3.52	2.73	2.80	3.95	3.37	1.30	2.82	2.06
AAT 12	2.31	3.00	2.66	1.92	3.90	2.91	1.85	3.07	2.46
AAT 15	1.93	3.42	2.68	1.67	4.42	3.04	1.37	2.51	1.94
AAT 16	2.18	3.03	2.60	1.68	4.00	2.84	1.08	2.22	1.65
AAT 18	2.10	2.83	2.46	1.89	3.73	2.81	1.23	2.71	1.97
AAT 3	2.60	3.40	3.00	3.30	4.32	3.81	1.73	3.99	2.86
AAT 4	2.33	3.56	2.94	2.53	3.57	3.05	1.84	3.94	2.89
AAT 6	2.37	3.59	2.98	2.42	3.30	2.86	1.47	4.89	3.18
AAT 13	2.42	3.33	2.88	2.67	2.95	2.81	1.90	4.30	3.10
AAT 17	2.66	3.81	3.24	2.66	3.28	2.97	1.91	4.19	3.05
AAT 19	2.56	3.59	3.08	2.74	3.55	3.15	1.79	4.69	3.24
Average	**2.29**	**3.32**	2.81	**2.36**	**3.71**	3.04	**1.54**	**3.46**	2.50
p- value and $LSD_{0.05}$									
Irrigation (I)	0.291 (6.43)			0.135 (2.49)			0.065 (3.7)		
Variety (V)	0.005 (0.32)			0.064 (0.82)			0.007 (0.57)		
I*V	0.495 (3.38)			0.358 (1.16)			0.185 (1.28)		

3.3.3. Physiological parameters

3.3.3.1. Leaf chlorophyll content (SPAD unit)

Neither variety nor irrigation had significant effect on leaf chlorophyll content expressed as SPAD readings in either year (data not presented). The leaf chlorophyll content was reduced significantly over time from flowering to grain filling to maturity (e.g., 47.4 at 85 DAS, to 46 at 102 Das to 34.6 at 133 DAS in 2014).

3.3.3.2. Leaf chlorophyll fluorescence

Neither varieties nor irrigation had significant influence on leaf fv/fm in either year (Table 3.11, data for 2014 not presented). However, at 63 DAS in 2015, the interaction effects of variety × irrigation was significant (Table 3.11). All varieties showed lower fv/fm with strategic irrigation on 63 DAS except variety AAT 16, as compared to rainfed.

Table 3.11 Leaf chlorophyll fluorescence (Fv/Fm) of varieties under strategic irrigation and rainfed conditions at Alton Downs in 2015.

Year 2015	**fv/fm 63 DAS**			**fv/fm 82 DAS**			**fv/fm 95 DAS**		
Varieties	**Rainfed**	**Strategic irrigation**	**Mean**	**Rainfed**	**Strategic irrigation**	**Mean**	**Rainfed**	**Strategic irrigation**	**Mean**
AAT 9	0.76	0.77	0.77	0.79	0.79	0.79	0.77	0.78	0.78
AAT 10	0.75	0.78	0.77	0.79	0.80	0.80	0.74	0.78	0.76
AAT 11	0.78	0.78	0.78	0.79	0.79	0.79	0.78	0.79	0.79
AAT 12	0.78	0.78	0.78	0.79	0.81	0.80	0.79	0.79	0.79
AAT 15	0.78	0.78	0.78	0.79	0.79	0.79	0.79	0.79	0.79
AAT 16	0.74	0.79	0.77	0.79	0.76	0.77	0.76	0.76	0.76
AAT 18	0.78	0.78	0.78	0.75	0.78	0.77	0.75	0.78	0.76
AAT 3	0.79	0.77	0.78	0.79	0.78	0.79	0.78	0.76	0.77
AAT 4	0.79	0.78	0.79	0.78	0.81	0.79	0.76	0.77	0.76
AAT 6	0.77	0.77	0.77	0.77	0.81	0.79	0.75	0.74	0.74
AAT 13	0.79	0.77	0.78	0.76	0.76	0.76	0.74	0.78	0.76
AAT 17	0.77	0.77	0.77	0.79	0.80	0.79	0.74	0.73	0.73
AAT 19	0.78	0.76	0.77	0.78	0.77	0.77	0.73	0.78	0.76
Average	**0.77**	**0.77**	0.77	**0.78**	**0.79**	0.78	**0.76**	**0.77**	0.77
p- value and $LSD_{0.05}$									
Irrigation (I)	0.766 (0.14)			0.492 (0.07)			0.28 (0.07)		
Variety (V)	0.964 (0.02)			0.139 (0.03)			0.16 (0.04)		
I*V	0.018 (0.04)			0.604 (0.04)			0.952 (0.06)		

3.3.3.3. Leaf relative water content

The leaf RWC for the varieties ranged from 86–120%. No significant genotypic and treatment effect on RWC was evident in either year (data not presented).

3.3.3.4. Leaf electrolyte leakage

Likewise, no significant genotypic and treatment effect on electrolyte leakage was recorded in either year (data not presented). Electrolyte leakage ranged from 10% to 18%.

3.3.3.5. Osmotic potential

Irrigation treatment and varieties did not show any significant effects on the osmotic potential (OP) before or during flowering, but after flowering at 116 DAS, varieties showed significant differences in OP in 2015 (Table 3.12). At 116 DAS, mean OP of rice varieties varied from -1.73 (variety AAT 9) to -2.26 MPa (variety AAT 3) with an overall mean of -2.00 MPa (Table 3.12).

Table 3.12 Osmotic potential (Op) of varieties under strategic irrigation and rainfed conditions in Alton Downs in 2015.

Year 2015	Op (MPa) (87 DAS)			Op (MPa) (116 DAS)		
Varieties	Rainfed	Strategic irrigation	Mean	Rainfed	Strategic irrigation	Mean
AAT 9	-1.63	-1.78	-1.70	-1.59	-1.87	-1.73
AAT 10	-1.85	-1.73	-1.79	-2.01	-2.02	-2.01
AAT 11	-1.84	-1.69	-1.76	-1.62	-2.09	-1.85
AAT 12	-1.63	-1.93	-1.78	-2.19	-2.09	-2.14
AAT 15	-1.64	-1.78	-1.71	-1.80	-1.98	-1.89
AAT 16	-1.59	-1.62	-1.60	-1.75	-2.12	-1.93
AAT 18	-1.70	-1.75	-1.72	-1.95	-2.05	-2.00
AAT 3	-1.97	-2.27	-2.12	-2.26	-2.26	-2.26
AAT 4	-2.30	-1.98	-2.14	-1.98	-2.15	-2.07
AAT 6	-2.03	-2.07	-2.05	-2.17	-1.90	-2.03
AAT 13	-2.15	-2.08	-2.11	-1.71	-1.83	-1.77
AAT 17	-2.08	-2.08	-2.08	-2.06	-2.28	-2.17
AAT 19	-1.85	-1.90	-1.87	-2.34	-1.88	-2.11
Average	**-1.86**	**-1.89**	-1.88	**-1.95**	**-2.04**	-2.00
p- value andLSD$_{0.05}$						
Irrigation (I)	0.878 (2.04)			0.119 (0.2)		
Variety (V)	0.137 (0.43)			0.05 (0.29)		
I*V	0.626 (0.65)			0.677 (0.48)		

3.3.3.6. Leaf gas exchange measurement

Leaf transpiration

Leaf transpiration rate across the varieties from 2014 ranged from 2.54 to 3.23, 1.91 to 2.52, and 1.18 to 2.31 mmol/m^2/s on 83 DAS, 103 DAS and 133 DAS, respectively. Similarly, for 2015 E ranged from 2.15 to 3.3, 2.97 to 4.05, 2.43 to 3.23, and 2.44 to 3.63 mmol /m^2 s on 51 DAS, 82 DAS, 95 DAS and 110 DAS, respectively.

Varieties and irrigation treatment did not have any significant effect on E at any stage in either year, except irrigation at 103 DAS in 2014, i.e., during the flowering period (p = 0.009) (Table 3.13), where surprisingly transpiration was lower in the strategic irrigation treatment.

Table 3.13 Leaf transpiration rate (E) (mmol/ m^2/ s) of varieties under strategic irrigation and rainfed conditions at Alton Downs in 2014.

Year 2014	**E (83 DAS)**			**E (103 DAS)**			**E (133 DAS)**		
Varieties	**Rainfed**	**Strategic irrigation**	**Mean**	**Rainfed**	**Strategic irrigation**	**Mean**	**Rainfed**	**Strategic irrigation**	**Mean**
AAT 9	2.70	2.60	2.70	2.10	2.00	2.00	1.90	2.20	2.00
AAT 10	3.70	1.90	2.80	2.20	2.20	2.20	2.10	1.80	2.00
AAT 11	3.30	1.80	2.50	2.50	2.20	2.40	1.40	1.50	1.40
AAT 12	3.80	2.70	3.20	2.40	1.90	2.10	1.60	1.80	1.70
AAT 15	3.20	2.30	2.70	2.20	2.30	2.30	1.90	1.40	1.60
AAT 16	4.10	2.60	3.40	3.00	2.10	2.50	1.90	1.90	1.90
AAT 18	3.00	2.60	2.80	2.60	1.90	2.20	1.80	0.90	1.40
AAT 3	3.20	3.20	3.20	2.50	2.20	2.30	1.30	1.50	1.40
AAT 4	2.70	2.80	2.80	2.10	2.20	2.10	1.90	2.70	2.30
AAT 6	2.90	3.30	3.10	2.10	2.40	2.20	0.80	1.50	1.20
AAT 13	3.80	2.50	3.10	2.70	1.80	2.30	1.50	1.60	1.50
AAT 17	3.10	2.60	2.80	2.50	1.60	2.00	1.80	1.20	1.50
AAT 19	2.60	2.90	2.80	2.40	1.40	1.90	1.40	1.30	1.40
Average	**3.20**	**2.60**	2.90	**2.40**	**2.00**	2.20	**1.60**	**1.60**	1.60
o- value and$LSD_{0.05}$									
Irrigation (I)	0.471 (7.57)			0.009 (0.0684)			0.383 (0.1075)		
Variety (V)	0.915 (1.168)			0.528 (0.5026)			0.088 (0.1075)		
I*V	0.43 (2.331)			0.606 (0.7985)			0.89 (1.1414)		

Stomatal conductance

Stomatal conductance across the varieties from 2014 ranged from 0.06 to 0.09, 0.05 to 0.07, and 0.02 to 0.04 mol /m^2 /s on 83 DAS, 103 DAS and 133 DAS, respectively. Similarly, from 2015, the gs ranged from 0.05 to 0.08, 0.11 to 0.19, 0.05 to 0.13, and 0.05 to 0.09 mol /m^2 /s on 51 DAS, 82 DAS, 95 DAS and 110 DAS, respectively.

Neither variety nor the irrigation treatment had any significant effect on gs in any stage (data not presented), although there was a tendency ($p = 0.051$) for gs to be higher in the strategic irrigation treatment at 95 DAS in 2015 (0.12 mol /m^2 /s vs 0.05 mol /m^2 /s for the rainfed treatment).

Leaf photosynthetic rate

Leaf photosynthetic rate across the varieties for 2014 ranged from 9.84 to 18.1, 6.32 to 9.64, and 3.39 to 6.73 µmol/m^2/ s on 83 DAS, 103 DAS and 133 DAS, respectively (Table 3.14 and Table 3.15). Similarly, for 2015, A ranged from 6.68 to 10.75, 11.58 to 18.74, 6.22 to 10.2, and 4.7 to 8.04 µmol/m^2/ s on 51 DAS, 82 DAS, 95 DAS and 110 DAS, respectively.

Nevertheless, A of the varieties and irrigation treatments did not vary significantly except for between irrigation treatments during flowering at 95 DAS of 2015 (p = 0.004) (Table 3.15), and at the later maturity stage at 133 DAS in 2014 (p = 0.017) (Table 3.14), when the rate was greater for the strategic irrigation treatment.

Table 3.14 Leaf photosynthetic rate (A) (µmol/m²/ s) of varieties under strategic irrigation and rainfed conditions at Alton Downs in 2014.

Year 2014	**A (83 DAS)**			**A (103 DAS)**			**A (133 DAS)**		
Varieties	**Rainfed**	**Strategic irrigation**	**Mean**	**Rainfed**	**Strategic irrigation**	**Mean**	**Rainfed**	**Strategic irrigation**	**Mean**
AAT 9	9.90	9.80	9.80	7.00	9.50	8.30	2.80	6.90	4.80
AAT 10	10.80	9.80	10.30	6.80	9.20	8.00	3.20	5.80	4.50
AAT 11	14.00	11.70	12.80	7.70	8.40	8.10	4.40	4.80	4.60
AAT 12	14.70	13.50	14.10	6.10	7.40	6.80	3.20	5.20	4.20
AAT 15	16.40	12.60	14.50	8.20	11.10	9.60	2.00	5.80	3.90
AAT 16	14.00	12.00	13.00	7.30	6.90	7.10	3.50	5.00	4.30
AAT 18	13.50	15.00	14.20	8.70	8.80	8.80	4.00	2.70	3.40
AAT 3	11.10	17.80	14.50	9.50	7.90	8.70	3.50	7.70	5.60
AAT 4	10.00	11.70	10.80	9.10	9.40	9.20	3.70	9.80	6.70
AAT 6	13.80	18.10	15.90	5.20	7.40	6.30	0.90	8.30	4.60
AAT 13	14.90	11.60	13.20	6.30	7.20	6.80	4.40	5.80	5.10
AAT 17	14.70	13.40	14.00	8.60	6.40	7.50	4.00	4.40	4.20
AAT 19	14.70	14.90	14.80	9.70	6.80	8.30	2.60	5.20	3.90
Average	**13.20**	**13.20**	13.20	**7.70**	**8.20**	7.90	**3.30**	**6.00**	4.60
p- value and LSD $_{0.05}$									
Irrigation (I)	0.964 (7.77)			0.591 (8.264)			0.017 (0.938)		
Variety (V)	0.356 (5.127)			0.402 (2.905)			0.455 (2.554)		
I*V	0.643 (6.725)			0.844 (4.576)			0.168 (3.412)		

Table 3.15 Leaf photosynthetic rate (A) (µmol/m²/ s) of varieties under strategic irrigation and rainfed conditions at Alton Downs in 2015.

Year 2015	**A (51 DAS)**			**A (82 DAS)**			**A (95 DAS)**			**A (110 DAS)**		
Varieties	**Rainfed**	**Strategic irrigation**	**Mean**	**Rainfed**	**Strategic irrigation**	**Mean**	**Rainfed**	**Strategic irrigation**	**Mean**	**Rainfed**	**Strategic irrigation**	**Mean**
AAT 9	9.20	9.00	9.10	15.60	10.70	13.20	4.50	8.40	6.50	6.20	7.00	6.60
AAT 10	6.80	7.60	7.20	13.00	12.90	12.90	4.50	9.10	6.80	6.50	7.80	7.10
AAT 11	10.10	6.10	8.10	14.10	12.40	13.20	5.30	8.90	7.10	6.30	7.20	6.80
AAT 12	8.70	7.90	8.30	13.40	14.40	13.90	3.60	8.90	6.20	6.10	5.40	5.80
AAT 15	5.60	7.20	6.40	11.20	12.00	11.60	4.10	10.50	7.30	5.50	4.80	5.20
AAT 16	9.10	12.40	10.80	14.40	14.40	14.40	4.30	8.70	6.50	5.70	8.20	7.00
AAT 18	9.70	7.90	8.80	15.80	16.40	16.10	2.50	12.10	7.30	6.60	6.30	6.40
AAT 3	6.50	7.80	7.20	13.90	17.00	15.40	3.20	13.90	8.50	3.60	5.80	4.70
AAT 4	7.40	8.90	8.10	14.80	10.90	12.80	2.60	15.30	9.00	5.60	6.80	6.20
AAT 6	7.00	8.10	7.60	17.70	16.80	17.20	3.40	15.10	9.30	5.10	7.00	6.00
AAT 13	8.00	6.00	7.00	18.80	18.60	18.70	4.50	15.90	10.20	6.90	5.40	6.20
AAT 17	6.50	6.90	6.70	14.50	15.70	15.10	3.20	10.80	7.00	7.60	8.50	8.00
AAT 19	8.50	6.80	7.70	13.70	13.00	13.40	3.30	14.20	8.80	6.90	6.30	6.60
Average	**7.90**	**7.90**	**7.90**	**14.70**	**14.20**	**14.50**	**3.80**	**11.70**	**7.70**	**6.10**	**6.70**	**6.40**
p - value and LSD$_{0.05}$												
Irrigation (I)	0.967 (4.54)			0.914 (40.89)			0.004 (0.55)			0.618 (11.22)		
Variety (V)	0.444 (3.46)			0.568 (6.5)			0.878 (5.53)			0.875(3.71)		
I*V	0.623 (4.42)			0.952 (12.6)			0.099 (6.15)			0.538 (4.49)		

3.3.4. Root characteristics

Root parameters were only measured in 2015 and differed among irrigation treatment and varieties (Table 3.16). At shallowest depth (0–15 cm), a significant effect of irrigation treatment was recorded for root length (RL) ($p = 0.042$) and RLD ($p = 0.042$) in 2015 (Table 3.16). Root length and RLD were higher for the strategic irrigation as compared to the rainfed treatment (460 cm vs 653 cm and 76.7 mm/cm^3 vs 108.9 mm/cm^3 for RL and RLD, respectively).

A significant effect of varieties on RL ($p < 0.001$), RLD (< 0.001), RD ($p = 0.036$), root dry weight (RDW) ($p = 0.002$) and RWD (0.002) at depth 30–60 cm was observed in 2015 (Table 3.16) but was not significant at other depths. Differences between varieties are presented in Figure 3.7 and Figure 3.9.

Table 3.16 Analysis of variance p values for root length, root length density, root diameter, root dry weight, and root weight density between irrigated and rainfed treatment in 2015 at Alton Downs.

			Soil depth (cm)			
Root Parameters	**Source of variation**	**Total**	**0–15**	**15–30**	**30–60**	**60–100**
		P values				
Root Length (RL)(mm)	Irrigation (I)	0.403	0.042	0.713	0.419	0.72
	Variety (V)	0.135	0.109	0.598	< 0.001	0.497
	IxV	0.513	0.425	0.128	0.335	NA
Root Length Density (RLD) (mm/cm^3)	Irrigation (I)	0.341	0.042	0.713	0.419	0.72
	Variety (V)	0.19	0.109	0.598	< 0.001	0.497
	IxV	0.52	0.425	0.128	0.335	NA
Root Diameter (RD) (mm)	Irrigation (I)	0.872	0.2	0.75	0.698	0.394
	Variety (V)	0.847	0.301	0.245	0.036	0.483
	IxV	0.112	0.469	0.08	0.827	NA
Root Dry Weight (RDW) (mg)	Irrigation (I)	0.22	0.176	0.74	0.825	0.401
	Variety (V)	0.162	0.27	0.173	0.002	0.84
	IxV	0.57	0.411	0.07	0.81	NA
Root Weight Density (RWD) (mg/cm^3)	Irrigation (I)	0.21	0.176	0.74	0.825	0.401
	Variety (V)	0.195	0.27	0.173	0.002	0.84
	IxV	0.524	0.411	0.07	0.81	NA

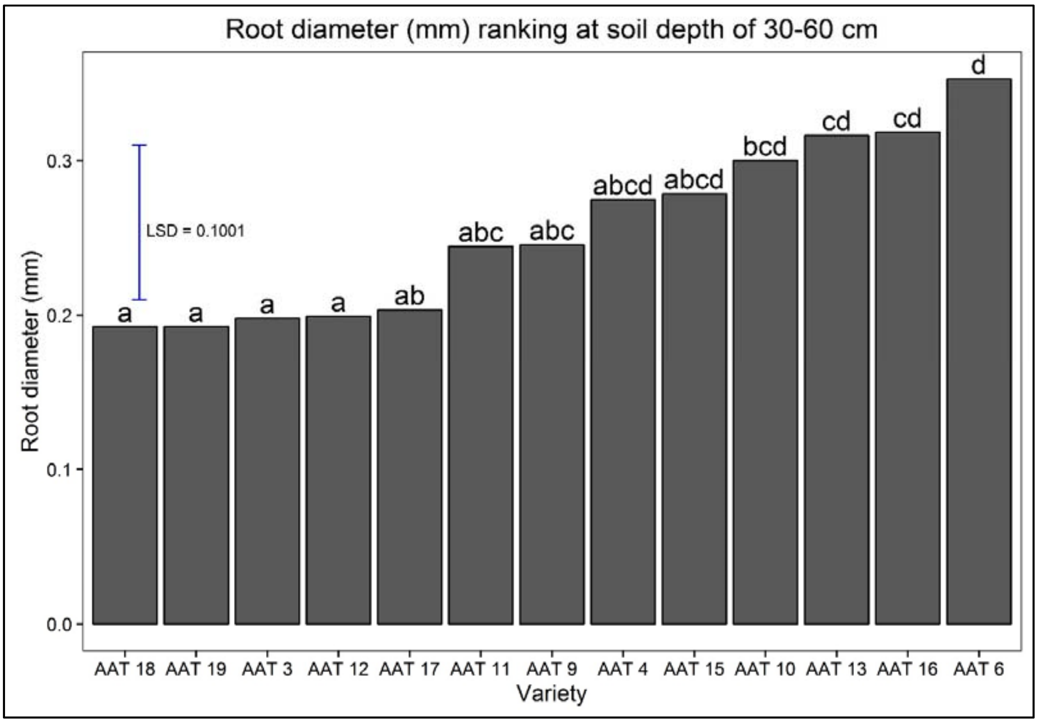

Figure 3.7 Root diameter ranking at 30–60 cm soil depth in year 2015

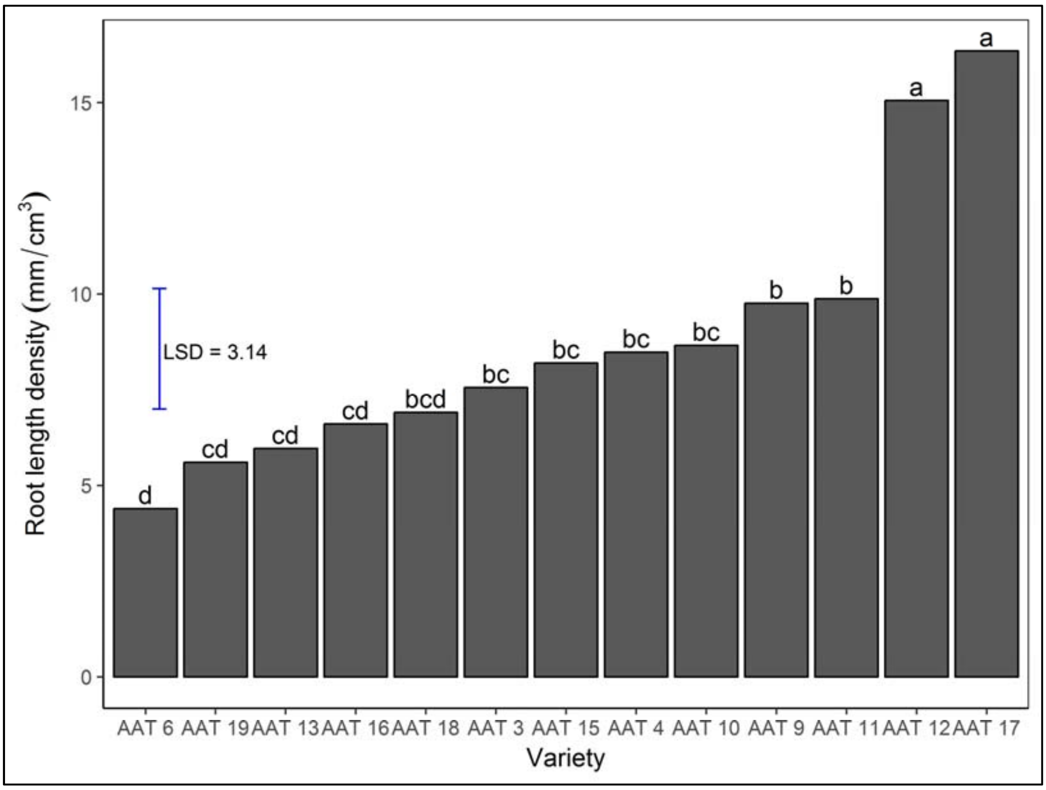

Figure 3.8 Root length density ranking at 30–60 cm soil depth in year 2015

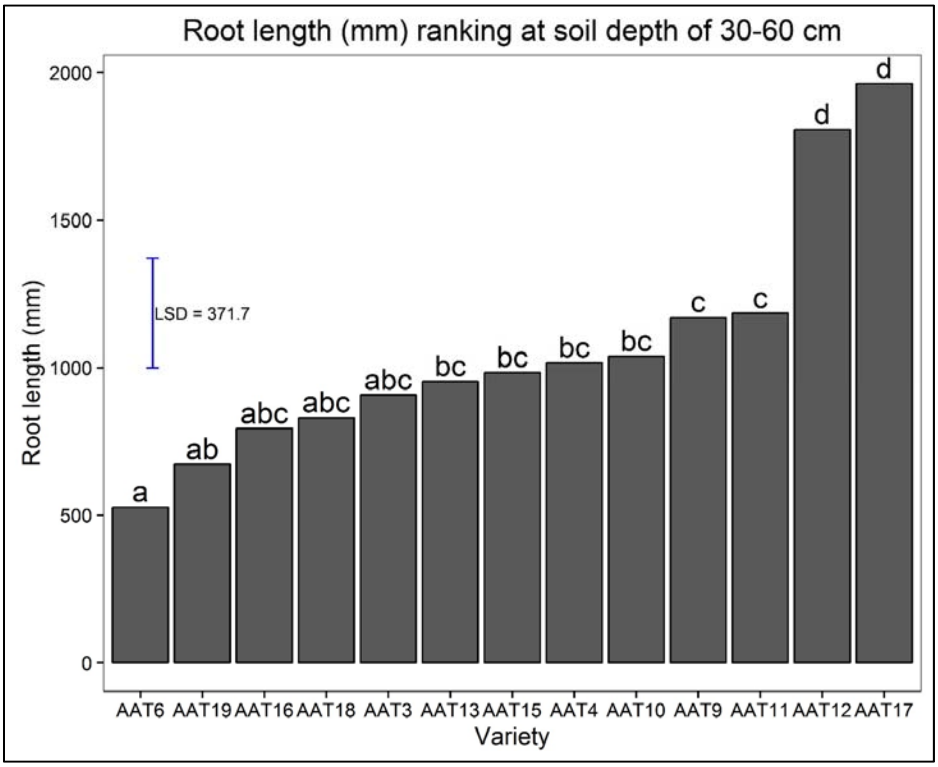

Figure 3.9 Root length ranking at 30–60 cm soil depth average in year 2015

Root dry weight distribution (%) at 0–15 cm, 15–30 cm and 30–60 cm depth was significantly affected by the irrigation treatment (Table 3.17). At 0–15 cm, strategic irrigation had 76.6% of total RDW as compared to 58.7% under rainfed conditions (Figure 3.10). For 15–30 cm and 30–60 cm depths, the RDW percentage was significantly higher in the rainfed system than in strategic irrigation (Figure 3.10). Under rainfed systems, the plant invested heavily in root biomass at 15–60 cm depth while under irrigation, investment was active in the top layer of soil at 0–15 cm depth (Figure 3.10).

Table 3.17 Analysis of variance p values for distribution of root length, root length density, root dry weight and root weight density between irrigated and rainfed treatment in 2015 at Alton Downs.

Root Parameters	**Source of variation**	**Soil depth (cm), p values**			
		0–15	**15–30**	**30–60**	**60–100**
Root Length (RL) distribution %	Irrigation (I)	0.368	0.400	0.153	0.822
	Variety (V)	0.092	0.671	0.359	0.388
	IxV	0.053	0.290	0.260	0.094
Root Length Density (RLD) distribution %	Irrigation (I)	0.367	0.400	0.153	0.822
	Variety (V)	0.144	0.671	0.359	0.388
	IxV	0.096	0.290	0.260	0.094
Root Dry Weight (RDW) distribution %	Irrigation (I)	0.019	0.003	0.041	0.114
	Variety (V)	0.081	0.192	0.043	0.475
	IxV	0.305	0.150	0.370	0.286
Root Weight Density (RWD) distribution %	Irrigation (I)	0.028	0.017	0.051	0.105
	Variety (V)	0.053	0.098	0.033	0.470
	IxV	0.302	0.200	0.373	0.311

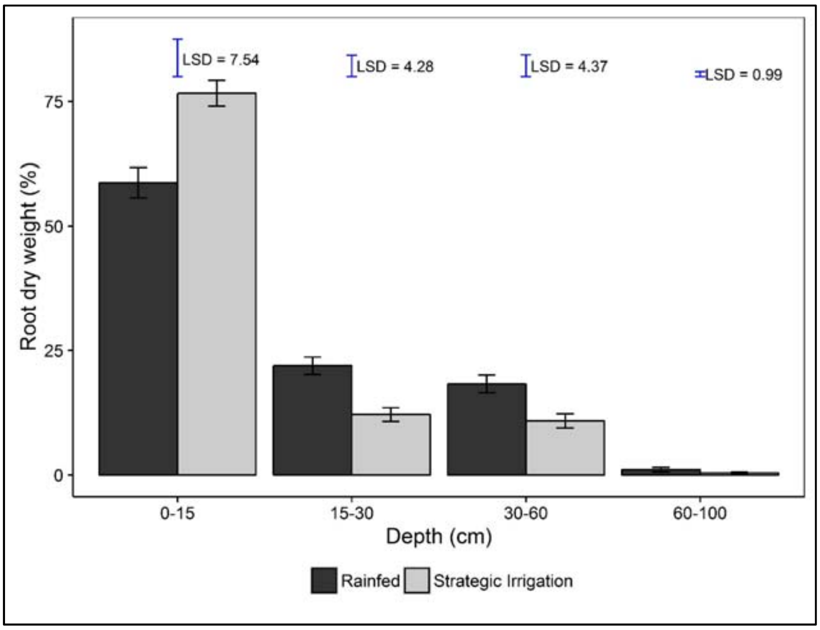

Figure 3.10 Root dry weight distribution at different depth under irrigated and rainfed treatments, Alton Downs 2015.

3.3.5. Yield and yield components

3.3.5.1. Whole plot yield

Grain yield from whole plot machine harvest across rice varieties ranged from 0.04 t/ha (AAT 15) to 2.06 t/ha (AAT 6) under rainfed conditions and 0.36 t/ha (AAT 9) to 2.83 t/ha (AAT 6) under strategic irrigation conditions, with a mean of 0.69 t/ha under rainfed and 1.73 t/ha under irrigated conditions in 2014 (Table 3.18). In 2015, the grain yield from whole plot machine harvest across rice varieties ranged from 0.79 t/ha (AAT 18) to 3.00 t/ha (AAT 19) under rainfed conditions and 3.44 t/ha (AAT 6) to 5.46 t/ha (AAT 19) under strategic irrigation conditions, with a mean of 1.92 t/ha and 4.75 t/ha under rainfed and irrigated conditions, respectively (Table 3.18).

The effect of irrigation on yield depended on year of planting ($p = 0.011$) (Table 3.18) as the yield difference with strategic irrigation was significantly higher than the rainfed irrigation in 2015 as compared to 2014.

The effect of varieties on yield depended on the year of planting ($p \leq 0.001$) (Table 3.18), as all varieties showed significant difference in whole plot yield between years except AAT 6 (Table 3.18 and Figure 3.11).

The year x irrigation effect was due to fact that the yield difference between the irrigated and rainfed crop in year 2014 was not significant. Whereas in 2015, the strategic irrigation produced significantly higher yield compared to the rainfed (Figure 3.11).

Table 3.18 Whole plot yield (t/ha) of varieties under strategic irrigation and rainfed conditions at Alton Downs, 2014 and 2015.

Varieties	Year 2014			Year 2015		
	Rainfed (t/ha)	**Strategic irrigation (t/ha)**	**Mean (t/ha)**	**Rainfed (t/ha)**	**Strategic irrigation (t/ha)**	**Mean (t/ha)**
AAT 9	0.10	0.36	0.23	1.74	4.43	3.08
AAT 10	0.29	1.22	0.75	1.63	4.94	3.29
AAT 11	0.21	1.56	0.88	1.73	4.55	3.14
AAT 12	0.09	1.51	0.80	1.56	4.24	2.90
AAT 15	0.04	0.81	0.43	1.01	4.55	2.78
AAT 16	0.13	1.27	0.70	0.84	4.58	2.71
AAT 18	0.07	0.96	0.51	0.79	4.32	2.56
AAT 3	1.33	2.11	1.72	2.93	5.27	4.10
AAT 4	1.32	2.21	1.76	2.72	5.25	3.98
AAT 6	2.06	2.83	2.45	1.59	3.44	2.52
AAT 13	1.72	2.62	2.17	2.70	5.44	4.07
AAT 17	1.03	2.42	1.72	2.74	5.32	4.03
AAT 19	0.56	2.56	1.56	3.00	5.46	4.23
Average	**0.69**	**1.73**	**1.21**	**1.92**	**4.75**	**3.34**
p- value and $LSD_{0.05}$						
Year	0.003 (0.478)	**Y×V**	< 0.001 (0.645)		**Y×I×V**	0.344 (0.915)
Variety (V)	< 0.001 (0.448)	**V×I**	0.448 (0.642)			
Irrigation (I)	0.002 (0.416)	**Y×I**	0.011 (0.412)			

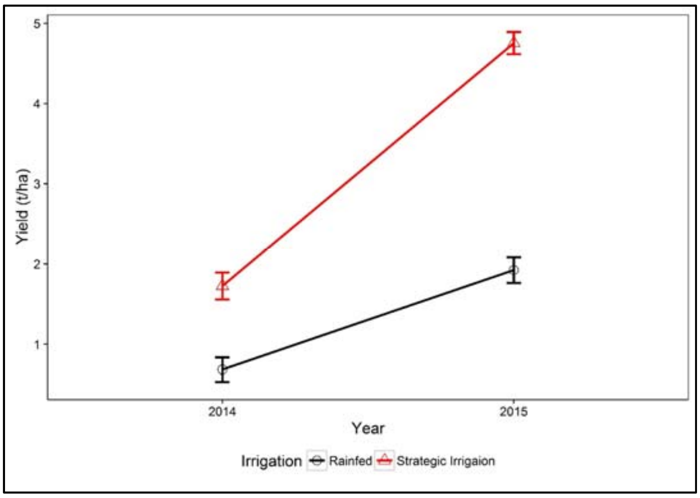

Figure 3.11 Average whole plot yield (t/ha) under rainfed and strategic condition at Alton Downs in 2014 and 2015.

3.3.5.2. Sample plot yield

Grain yield from sample plot harvest across rice varieties in 2014 ranged from 0.10 t/ha (AAT 9 and AAT 18) to 3.85 t/ha (AAT 4) under rainfed conditions and 1.34 t/ha (AAT 15) to 4.68 t/ha (AAT 13) under strategic irrigation conditions, with a mean of 1.43 t/ha under rainfed and 3.21 t/ha under irrigated conditions (Table 3.19). In 2015, the grain yield from sample plot harvest across rice varieties ranged from 0.24 t/ha (AAT 15) to 2.72 t/ha (AAT 6) under rainfed conditions and 3.32 t/ha (AAT 18) to 5.23 t/ha (AAT 4) under strategic irrigation conditions, with a mean of 1.38 t/ha and 4.22 t/ha under rainfed and irrigated conditions, respectively (Table 3.19).

Yield with strategic irrigation was significantly higher than under rainfed conditions in both years (Table 3.19).

The effect of varieties on yield depended on the year of planting (Table 3.19); most varieties had higher yields in 2015 with the exception of AAT 3, AAT 13 and AAT 17.

Table 3.19 Sample plot yield (t/ha) of varieties under strategic irrigation and rainfed conditions at Alton Downs, 2014 and 2015.

Varieties	2014			2015		
	Rainfed	Strategic irrigation	Mean	Rainfed	Strategic irrigation	Mean
AAT 9	0.10	3.03	1.57	0.82	3.81	2.31
AAT 10	0.84	2.38	1.61	1.14	4.38	2.76
AAT 11	0.49	3.08	1.79	0.61	3.90	2.25
AAT 12	0.26	2.81	1.53	0.79	3.66	2.23
AAT 15	0.11	1.34	0.72	0.24	4.36	2.30
AAT 16	0.12	2.24	1.18	0.59	4.06	2.33
AAT 18	0.10	1.81	0.96	0.42	3.32	1.87
AAT 3	2.12	4.20	3.16	1.94	3.90	2.92
AAT 4	3.85	3.48	3.67	2.10	5.23	3.67
AAT 6	2.71	4.48	3.60	2.72	4.62	3.67
AAT 13	2.19	4.68	3.44	2.02	4.58	3.30
AAT 17	2.99	4.57	3.78	1.94	4.06	3.00
AAT 19	2.71	3.64	3.18	2.64	4.95	3.80
Average	**1.43**	**3.21**	**2.32**	**1.38**	**4.22**	**2.80**
p- value and $LSD_{0.05}$						
Year	0.107 (0.735)	**Y×V**	0.002 (0.756)		**Y×I×V**	0.109 (1.147)
Variety (V)	< 0.001 (0.485)	**V×I**	0.178 (0.815)			
Irrigation (I)	0.006 (0.747)	**Y×I**	0.093 (0.676)			

3.3.5.3. Harvest Index

Harvest index from the sample plot harvest ranged from 0.02 (AAT 9, AAT 15, AAT 16 and AAT 18) to 0.49 (AAT 4) across varieties under rainfed conditions, and 0.15 (AAT 15) to 0.51 (AAT 6) under strategic irrigation conditions, with a mean of 0.22 under rainfed and 0.36 under irrigated conditions in 2014 (Table 3.20). In 2015, the HI from sample plot harvest across rice varieties ranged from 0.14 (AAT 18) to 0.43 (AAT 16) under rainfed conditions and 0.36 (AAT 6) to 0.53 (AAT 3) under strategic irrigation conditions, with a mean of 0.29 and 0.46 under rainfed and irrigated conditions, respectively (Table 3.20).

Harvest index between varieties depended on the irrigation treatment ($p < 0.001$) (Table 3.20). Varieties showed significantly greater HI with strategic irrigation as compared to rainfed except for AAT 4, AAT 6 and AAT 17.

Similarly, the HI of varieties depended on the year of experiment, i.e a significant Y x V interaction ($p < 0.001$) (Table 3.20). All late varieties (AAT9, AAT10, AAT11, AAT12, AAT15, AAT16, AAT) had significantly higher average HI in 2015 compared to 2014, whereas the difference in HI between two years for early varieties did not vary significantly except for AAT 6, for which the HI in 2015 (0.33) was significantly reduced compared to Hi in 2014 (0.47).

There were significant differences in HI among varieties ($p < 0.001$) (Table 3.20). AAT 15 had the lowest HI and AAT 6 had the highest HI. AAT 15, AAT 18 and AAT 16 had significantly lower HI than AAT 17, AAT 13, AAT 3, AAT 19, AAT 4 and AAT 6 (Figure 3.12).

Table 3.20 Harvest index (HI) of varieties under strategic irrigation and rainfed conditions at Alton Downs, 2014 and 2015.

Varieties	**2014**			**2015**		
	Rainfed	**Strategic irrigation**	**Mean**	**Rainfed**	**Strategic irrigation**	**Mean**
AAT 9	0.02	0.31	0.16	0.27	0.45	0.36
AAT 10	0.13	0.30	0.21	0.25	0.44	0.34
AAT 11	0.08	0.34	0.21	0.31	0.45	0.38
AAT 12	0.05	0.29	0.17	0.25	0.45	0.35
AAT 15	0.02	0.15	0.09	0.18	0.44	0.31
AAT 16	0.02	0.24	0.13	0.15	0.44	0.29
AAT 18	0.02	0.19	0.10	0.14	0.45	0.29
AAT 3	0.41	0.49	0.45	0.39	0.53	0.46
AAT 4	0.49	0.46	0.47	0.41	0.50	0.45
AAT 6	0.42	0.51	0.47	0.31	0.36	0.33
AAT 13	0.39	0.48	0.44	0.36	0.52	0.44
AAT 17	0.41	0.47	0.44	0.43	0.46	0.45
AAT 19	0.39	0.45	0.42	0.40	0.52	0.46
Average	0.22	0.36	0.29	0.29	0.46	0.38
p- value and $LSD_{0.05}$						
Year	0.054 (0.041)	**Y×V**	< 0.001 (0.06)		**Y×I×V**	0.12 (0.093)
Variety (V)	< 0.001 (0.042)	**V×I**	< 0.001 (0.068)			
Irrigation (I)	0.007 (0.063)	**Y×I**	0.157 (0.052)			

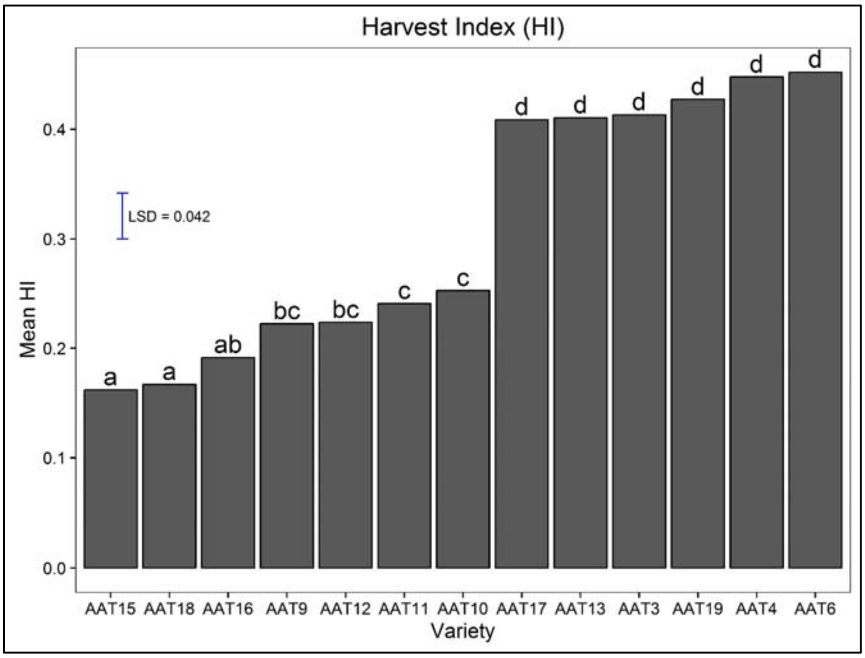

Figure 3.12 Variety ranking for harvest index, means of varieties across years 2014 and 2015.

3.3.5.4. Yield attributing parameters

Spikelets per panicle

Spikelets per panicle from the sample plot harvests ranged across the varieties from 81 (AAT 19) to 220 (AAT 9) under rainfed conditions and 109 (AAT 6) to 222 (AAT 18) under strategic irrigation conditions, with a mean of 136 under rainfed and 153 under irrigated conditions in 2014 (Table 3.21). In 2015, the spikelets per panicle ranged across varieties from 74 (AAT 18) to 118 (AAT 11) under rainfed conditions and 115 (AAT 4) to 193 (AAT 11) under strategic irrigation conditions, with a mean of 102 and 144 under rainfed and irrigated conditions, respectively (Table 3.21).

Difference between varieties in spikelets per panicles depended on the year of experiment ($p = 0.004$), as all varieties showed significantly fewer spikelets per panicle in 2015, except for varieties AAT 3, AAT 4, AAT 6, AAT 13, AAT 17 and AAT 19 (Table 3.21). Similarly, year of experiment ($p = 0.045$) and irrigation treatment ($p = 0.033$) showed significant effects on spikelets per panicle (Table 3.21).

Table 3.21 Total spikelets per panicle of varieties under strategic irrigation and rainfed conditions in Alton Downs, 2014 and 2015.

Varieties	Year 2014			Year 2015		
	Rainfed	Strategic irrigation	Mean	Rainfed	Strategic irrigation	Mean
AAT 9	220	150	185	101	187	144
AAT 10	145	179	162	88	172	130
AAT 11	169	189	179	118	193	156
AAT 12	142	189	165	102	170	136
AAT 15	153	169	161	108	154	131
AAT 16	170	175	172	115	137	126
AAT 18	204	222	213	74	153	114
AAT 3	100	129	114	106	123	115
AAT 4	100	128	114	101	115	108
AAT 6	91	109	100	103	117	110
AAT 13	107	125	116	106	109	107
AAT 17	90	110	100	102	123	113
AAT 19	81	116	98	105	124	114
Average	**136**	**153**	**145**	**102**	**144**	**123**
p- value and LSD $_{0.05}$						
Year 0.045 (20.03)	**Y×V**	0.004 (33.85)		**Y×I×V**	0.368 (55.61)	
Variety (V) < 0.001 (23.99)	**V×I**	0.796 (39.11)				
Irrigation (I) 0.033 (23.48)	**Y×I**	0.145 (20.11)				

1000 grain weight

The 1000 grain weight across rice varieties in 2014 ranged from 15.8 g (AAT 15) to 29.4 g (AAT 4) under rainfed conditions and 18.1 g (AAT 9) to 27.9 g (AAT 18) under strategic irrigation conditions, with a mean of 22.6 g under rainfed and 23.5 g under irrigated conditions (Table 3.22). In 2015, the 1000 grain weight from sample plot harvest across rice varieties ranged from 17.7 g (AAT 18) to 26.3g (AAT 3) under rainfed conditions and 19.8 g (AAT 16) to 29.5 g (AAT 3) under strategic irrigation conditions, with a mean of 22.1 g and 24.6 g under rainfed and strategic irrigated conditions, respectively (Table 3.22).

The 1000 grain weight of varieties was significantly affected by the irrigation treatment and year of experiment (p = 0.006) (Table 3.22). The three-way interaction (YxIxV) was due to the fact that some varieties responded significantly differently over the two years to irrigation treatment. In 2014, AAT 11, AAT15 and AAT16 recorded significantly greater 1000 seed weight in strategic irrigation as compared to rainfed irrigation, whereas in 2015, AAT3, AAT13 and AAT 17 recorded significantly greater 1000 seed weight in strategic irrigation as compared to rainfed irrigation (Table 3.22).

Table 3.22 Varietal 1000 grain weight (g) under strategic irrigation and rainfed conditions in Alton Downs, 2014 and 2015.

Varieties	2014			2015		
	Rainfed	**Strategic irrigation**	**Mean**	**Rainfed**	**Strategic irrigation**	**Mean**
AAT 9	18.7	18.1	18.4	19.5	21.4	20.4
AAT 10	21.3	23.2	22.3	18.8	21.7	20.3
AAT 11	18.2	22.5	20.3	18.8	22.3	20.6
AAT 12	20.4	21.3	20.8	21.2	21.7	21.5
AAT 15	26.2	26.3	26.3	24.9	29.0	27.0
AAT 16	15.8	19.9	17.8	18.3	20.2	19.2
AAT 18	19.4	20.7	20.0	17.7	21.0	19.3
AAT 3	26.7	26.5	26.6	26.3	29.5	27.9
AAT 4	29.4	27.0	28.2	25.9	28.1	27.0
AAT 6	24.7	27.9	26.3	26.0	28.7	27.3
AAT 13	26.2	26.3	26.3	24.9	29.0	27
AAT 17	27.3	24.6	25.9	25.4	28.2	26.8
AAT 19	29.0	26.0	27.5	25.7	29.0	27.4
Average	**22.6**	**23.5**	**23.1**	**22.1**	**24.6**	**23.4**
p- value and $LSD_{0.05}$						
Year 0.428 (1.426)	**Y×V**	7.66 (2.803)		**Y×I×V**	0.006 (3.232)	
Variety (V) < 0.001 (2.009)	**V×I**	0.033 (2.294)				
Irrigation (I) 0.009 (0.723)	**Y×I**	0.04 (1.191)				

Panicle filling (fertility) percentage

Panicle fertility from sample plot harvest across rice varieties ranged from 1% (AAT 15) to 91% (AAT 4) under rainfed conditions and 27% (AAT 9) to 85 % (AAT 6) under strategic irrigation conditions, with a mean of 41.8% under rainfed and 57.4 % under irrigated conditions in year 2014. In 2015, the panicle filling percentage ranged across varieties from 17.9% (AAT 18) to 60.8% (AAT 11) under the rainfed conditions and 44.9% (AAT 4) to 70.3% (AAT 13) under strategic irrigation, with a mean of 42.6 % and 57.8 % under rainfed and irrigated conditions, respectively.

Fertility percentage of varieties depended significantly on the year of experiment (p = 0.006). The fertility percentage of varieties AAT 9, AAT 10, AAT 11, AAT 12, AAT 15 and AAT 16 was higher in 2015 than in 2014 (Figure 3.13).

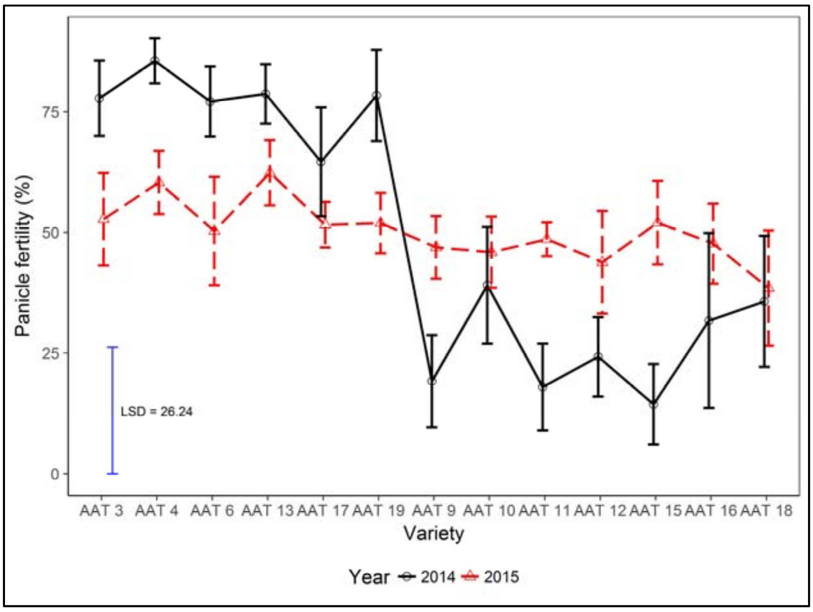

Figure 3.13 Panicle fertility percentage of varieties in years 2014 and 2015.

Effective tillers

Effective tiller counts per plant from sample plot harvest across rice varieties ranged from 3.1 (AAT 15) to 8.9 (AAT 4) under rainfed conditions and 4.4 (AAT 15) to 9.4 (AAT 3) under strategic irrigation with a mean of 5.4 under rainfed and 7.3 under strategic irrigated conditions in year 2014 (Table 3.23). In 2015, the effective tillers per plant ranged from 1.3 (AAT 18) to 6.2 (AAT 4) under rainfed conditions and 3.5 (AAT 16) to 8.1 (AAT 3) under strategic irrigation, with a mean of 4 and 5.6 under rainfed and strategic irrigated conditions, respectively (Table 3.23).

Strategic irrigation had significantly greater number of the effective tillers per plant (p = 0.048) as compared to rainfed conditions (Table 3.23).

Significantly more effective tillers per plant (p = 0.018) were recorded in 2014 (7.3) as compared to 2015 (4.8) (Table 3.23). Moreover, varieties AAT 3 and AAT 4 recorded significantly more effective tillers per plant (p = 0.007) (Table 3.23) compared to other varieties.

Table 3.23 Effective tillers of varieties under strategic irrigation and rainfed conditions at Alton Downs, 2014 and 2015.

Varieties	2014			2015		
	Rainfed	Strategic irrigation	Mean	Rainfed	Strategic irrigation	Mean
AAT 9	4.0	7.3	5.7	3.2	5.9	4.6
AAT 10	5.0	7.9	6.5	3.7	4.7	4.2
AAT 11	3.8	6.3	5.0	5.6	6.3	6.0
AAT 12	4.9	7.7	6.3	4.1	4.9	4.5
AAT 15	3.1	4.4	3.7	2.3	5.0	3.7
AAT 16	3.9	5.0	4.5	3.2	3.5	3.4
AAT 18	4.6	7.1	5.9	1.3	5.5	3.4
AAT 3	7.5	9.4	8.5	4.4	8.1	6.3
AAT 4	8.9	9.3	9.1	6.2	6.6	6.4
AAT 6	5.8	9.0	7.4	5.4	5.9	5.7
AAT 13	5.8	6.9	6.4	3.7	5.2	4.5
AAT 17	5.8	8.5	7.2	4.2	6.2	5.2
AAT 19	4.5	6.4	5.5	4.8	4.9	4.9
Average	**5.2**	**7.3**	**6.3**	**4.0**	**5.6**	**4.8**

p- value and LSD 0.05					
Year	0.018 (0.862)	**Y×V**	0.81 (2.637)	**Y×I×V**	0.968 (3.645)
Variety (V)	0.007 (1.921)	**V×I**	0.904 (2.643)		
Irrigation (I)	0.048 (1.812)	**Y×I**	0.59 (1.526)		

3.3.6. Water Productivity

3.3.6.1. Whole plot water productivity:

Whole plot water productivity varied significantly by the year, variety, year x variety, irrigation, and Y x irrigation (Table 3.24). Water productivity was generally higher for 2015 (0.45 t/ML) as compared to 2014 (0.18 t/ML) for all varieties, except for AAT 6. Water productivity in 2014 did not vary significantly between irrigation types but in 2015, water productivity was significantly higher for strategic irrigation compared to the rainfed ($LSD_{0.05}$ = 0.13, Table 3.24).

Table 3.24 Whole plot water productivity (t/ML) of varieties under strategic irrigation and rainfed conditions at Alton Downs, 2014 and 2015.

Varieties	2014			2015		
	Rainfed (t/ML)	Strategic irrigation (t/ML)	Mean (t/ML)	Rainfed (t/ML)	Strategic irrigation (t/ML)	Mean (t/ML)
AAT 9	0.02	0.05	0.03	0.26	0.57	0.41
AAT 10	0.05	0.17	0.11	0.24	0.63	0.44
AAT 11	0.04	0.22	0.13	0.26	0.58	0.42
AAT 12	0.02	0.21	0.11	0.23	0.54	0.39
AAT 15	0.01	0.11	0.06	0.15	0.58	0.37
AAT 16	0.02	0.18	0.10	0.13	0.59	0.36
AAT 18	0.01	0.14	0.07	0.12	0.55	0.33
AAT 3	0.24	0.30	0.27	0.43	0.67	0.55
AAT 4	0.24	0.31	0.27	0.40	0.67	0.54
AAT 6	0.37	0.40	0.38	0.24	0.44	0.34
AAT 13	0.31	0.37	0.34	0.40	0.69	0.55
AAT 17	0.18	0.34	0.26	0.41	0.68	0.54
AAT 19	0.10	0.36	0.23	0.45	0.70	0.57
Average	**0.12**	**0.24**	**0.18**	**0.29**	**0.61**	**0.45**

p- value and LSD 0.05					
Year	0.005 (0.08)	**Y×V**	< 0.001 (0.091)	**Y×I×V**	0.516 (0.134)
Variety (V)	< 0.001 (0.061)	**V×I**	0.242 (0.093)		
Irrigation (I)	0.005 (0.067))	**Y×I**	0.023 (0.13)		

3.3.6.2. Sample plot water productivity:

Sample plot water productivity of rice varieties in 2014 ranged from 0.02 t/ML (AAT 18) to 0.69 t/ML (AAT 4) under rainfed conditions and 0.19 t/ML (AAT 15) to 0.66 t/ML (AAT 13) under strategic irrigation, with a mean of 0.26 t/ML under rainfed and 0.45 t/ML under irrigated conditions (Table 3.25). In 2015, the sample plot water productivity of rice varieties ranged from 0.04 t/ML (AAT 15) to 0.40 t/ML (AAT 6) under rainfed conditions and 0.42 t/ML (AAT 18) to 0.67 t/ML (AAT 4) under strategic irrigation, with a mean of 0.21 t/ML under rainfed and 0.54 t/ML under irrigated conditions (Table 3.25).

Varietal sample plot water productivity depended significantly on the year of experiment ($p < 0.001$) (Table 3.25). Varieties AAT 10, AAT 15, AAT 16 and AAT 18 showed significantly higher water productivity in 2015 than in 2014, and AAT 3, AAT 4, AAT 6 and AAT 13 showed lower water productivity in 2015 than in 2014. Varieties AAT 9, AAT 11, and AAT 12 did not show any significant difference in water productivity between years.

Strategic irrigation significantly increased the water productivity, with water productivity across the year being higher in strategic irrigation (0.49 t/ML) as compared to rainfed conditions (0.23 t/ML) ($LSD_{0.05}$ = 0.104, Table 3.25).

The varietal water productivity depended significantly on the irrigation treatment (p = 0.017) (Table 3.25). All varieties recorded increased water productivity across the years with strategic irrigation, except for AAT 4.

Table 3.25 Sample plot water productivity (t/ML) of varieties under strategic irrigation and rainfed conditions at Alton Downs, 2014 and 2015.

Varieties	2014			2015		
	Rainfed	Strategic irrigation	Mean	Rainfed	Strategic irrigation	Mean
AAT 9	0.02	0.43	0.22	0.12	0.49	0.30
AAT 10	0.15	0.34	0.24	0.17	0.56	0.36
AAT 11	0.09	0.44	0.26	0.09	0.50	0.29
AAT 12	0.05	0.40	0.22	0.12	0.47	0.29
AAT 15	0.02	0.19	0.10	0.04	0.56	0.30
AAT 16	0.02	0.32	0.17	0.09	0.52	0.30
AAT 18	0.02	0.26	0.14	0.06	0.42	0.24
AAT 3	0.38	0.59	0.49	0.29	0.50	0.39
AAT 4	0.69	0.49	0.59	0.31	0.67	0.49
AAT 6	0.49	0.63	0.56	0.40	0.59	0.50
AAT 13	0.39	0.66	0.53	0.30	0.58	0.44
AAT 17	0.53	0.64	0.59	0.29	0.52	0.40
AAT 19	0.49	0.51	0.50	0.39	0.63	0.51
Average	**0.26**	**0.45**	**0.35**	**0.21**	**0.54**	**0.37**

p- value and LSD $_{0.05}$

Year	0.576 (0.112)	**Y×V**	< 0.001 (0.11)	**Y×I×V**	0.103 (0.167)
Variety(V)	< 0.001 (0.069)	**V×I**	0.017 (0.117)		
Irrigation (I)	0.008 (0.104)	**Y×I**	0.107 (0.099)		

3.4. Discussion

3.4.1. Relationship of phenology with yield and yield contributing characters

Varietal performance varied between years irrespective of irrigation methods. The effect of varieties on yield depended on year of planting (p=0.002) (Table 3.19), as all of the long grain varieties AAT 10, AAT 15 and AAT 16, showed significant increase in yield from 2014 to 2015 whereas some medium grain varieties (AAT 3, AAT 13 and AAT 17) showed a decrease in yield between the same years (Table 3.19). This year-to-year difference was partially due to the variation in planting time, which ultimately affected crop phenology. Rice flowering under long day conditions is delayed by the genes such as Hd1, Hd5, Hd6 and Hd16 and OsPhyB, OsCOL4 and SNB inhibits flowering irrespective of day length (Lee and An, 2015). Flowering signals are produced only after sufficient vegetative growth (Song et al., 2012). Due to these physiological effects, later varieties are more sensitive to photoperiod when planted early (i.e., before the middle of summer). Phenological development is very important for yield determination of the rice crop. Under long day and low temperature conditions the Ghd7 gene in rice is upregulated and causes delayed flowering (Song et al., 2012). The time of planting particularly affected the time of flowering with respect to both temperature and water availability at that time with the exposure to terminal drought. Growing degree days (GDD) showed greater difference between early varieties and late varieties in the later sowing of 2014 (early varieties = 1225.2 GDD, late varieties = 1564.85 GDD) as compared to the earlier sowing in 2015 (early varieties = 1554.05 GDD, late varieties = 1695.5 GDD). Earlier sowing [before the summer solstice] would be expected to delay flowering, leading to a greater number of GDD for a flowering event than if sown after the solstice. This was not so for the present data set. The greater difference of GDD in 2014 between early varieties and late varieties can be attributed to the interactin between the greater exposure to the low temperature and long day conditions caused by late planting as compared to 2015. Early varieties required more GDD in 2015 (1554.05 GDD) compared to 2014 (1225.2 GDD) for flowering. Here the photoperiod is interacting with temperature. These early varieties holds unique attributes of lower GDD requirement when planted early for flowering. Further studies on the genetics of these germplasm on photoperiod and temperature may reveal the mechanisms for control of flowering date and interaction between them. Drought may also play a part in the delay in flowering.

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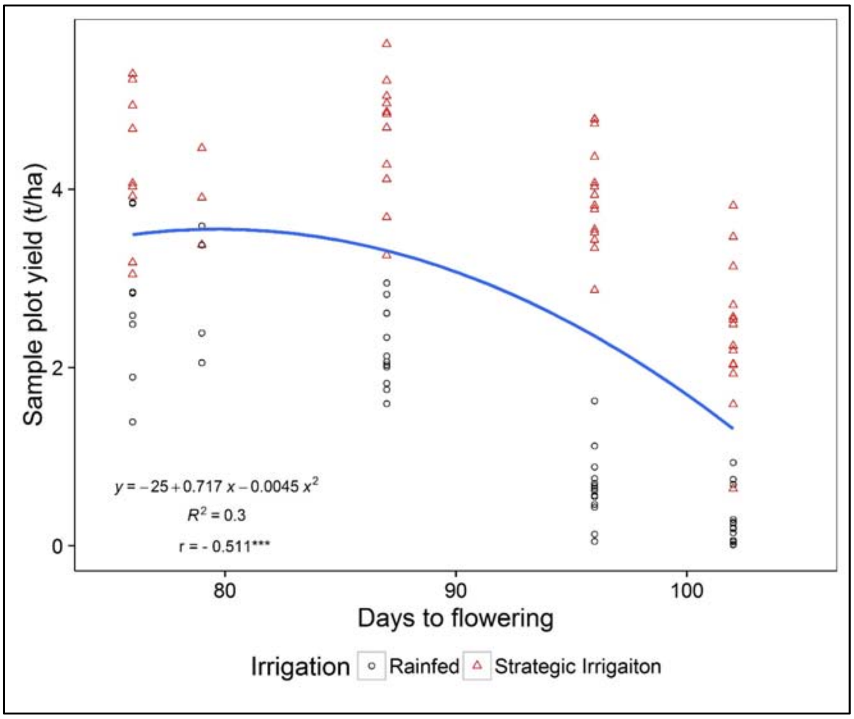

Figure 3.14 Relationship between yield and days to flowering at Alton Downs in 2014 and 2015. Here R^2 represents multiple R-squared value and r explains correlation coefficient between yield and days to flowering.

Later flowering showed a yield penalty in both irrigated and rainfed systems, although under rainfed conditions delayed flowering had a more prominent effect on productivity (Figure 3.14). The late planting in 2014 exposed the varieties to low temperatures (below 15^{o}C for 7 days from 101 DAS to 107 DAS and below 10^{o}C for 4 days and below 5^{o}C for 1 days within the same period) during flowering (Figure 3.1 and Table 3.4), resulting in less grain set and subsequent yield loss. In addition to the low temperature, the flowering time in 2014 coincided with the drought period (Figure 3.3), causing more severe terminal drought, as there was no rain for 11 days before flowering for varieties flowering in 76 days (medium grain types), and 20 days of no rain for the varieties flowering in 102 days (long grain types). Rice require above 22°C during anthesis for pollen fertility (Yoshida, 1978). When rice is exposed to low temperatures it negatively affects the fertility of panicles and results in lower grain setting per panicle (Gunawardena et al., 2003) , and since pollination of all spikelets in a panicle takes about one week even a short period of low temperature can negatively affect fertility. Rice varieties with delayed flowering time are vulnerable as such varieties are likely to be subjected to lower soil moisture during flowering and grain filling, which also hampers panicle exertion, panicle fertility and grain filling (Fukai, 1999). This is in accordance with other studies investigating the interrelationship between yield and days to flowering (Pantuwan et al., 2002c). When there is occurrence of late season drought, as in 2014, early flowering varieties have an advantage over late varieties. The varieties with delayed flowering were more susceptible to drought stress and recorded greater decreases in grain yield and HI, compared to their performance with strategic irrigation and rainfed condition. A strong negative correlation (r = - 0.86***) was evident between grain yield and HI (Table 3.26) across the experiment. Prolonged drought resulted in greater yield loss and decreased HI in late varieties as compared to early varieties.

Even though there was a stronger negative correlation between grain yield and days to flowering in the rainfed treatment (r=-0.88***), as compared to the strategic irrigation (r=-0.58***), the irrigation treatment did not influence days to flowering in contrast to findings of Pantuwan et al. (2002c), who reported that the drought stress has a large influence in delaying flowering time.

3.4.2. Relationship between physiological traits, yield and yield contributing characters

Apart from the varietal effect on days to flowering and on yield performance, the latter also depended on LAI (Table 3.27) across the years. Grain yield of varieties was directly correlated with LAI during the reproductive stage (r = 0.44 ***). This observation is in accordance with Raboin et al. (2014) and Tao et al. (2006), who reported that LAI was directly related to rice grain yield. Rice varieties showed strong correlation between yield and LAI in 2015 (r = 0.79***) (Table 3.33) but no correlation in 2014 (Table 3.32). This is because the effect of terminal drought in late varieties was severe in 2014, which affected the grain set. Hence, the effect of LAI was less in 2014 as compared to 2015. Varieties with higher LAI have a comparative advantage when planted earlier in the Alton Downs conditions.

Varietal flag leaf parameters (length, breadth and area) depended on year and all of them were positively correlated with days to flowering, total water input, intrinsic WUE (WUEi) and A (Table 3.28). Flag leaf area is considered important for yield as it determines the photosynthetic output by influencing the photosynthetic area. Flag leaf area and its component length and breadth was correlated with water input and negatively with WUE during the flowering stage (Table 3.28). Smaller leaves have higher A during the flowering stage (Table 3.28). Yue et al. (2006b) also reported the significant correlation between yield and flag leaf area, but such a relationship was not noted in this experiment (Table 3.28).

There was significant correlation between yield and physiological parameters, such as A (r = 0.60***), gs (r = 0.50***) and E (r = 0.40***) (Table 3.27) across the year. Water use efficiency was associated with a high A (r = 0.79***) and a high WUE was less affected by variation in E (Table 3.27). There was a correlation between A and gs (r = 0.57***), with a typical hyperbolic relationship when all the data are pooled together from strategic irrigation and rainfed treatments (Table 3.27 and Figure 3.17) during the flowering stage, showing that declining gs has a limiting effect on A (Thompson et al., 2007). Centritto et al. (2009) reported that drought stress is significantly correlated with the effects on A, as genotypes with higher photosynthesis and conductance were more productive under all moisture conditions. One of the high yielding varieties, AAT 3, had a higher A during the flowering and grain filling period in both strategic irrigation and rainfed treatments.

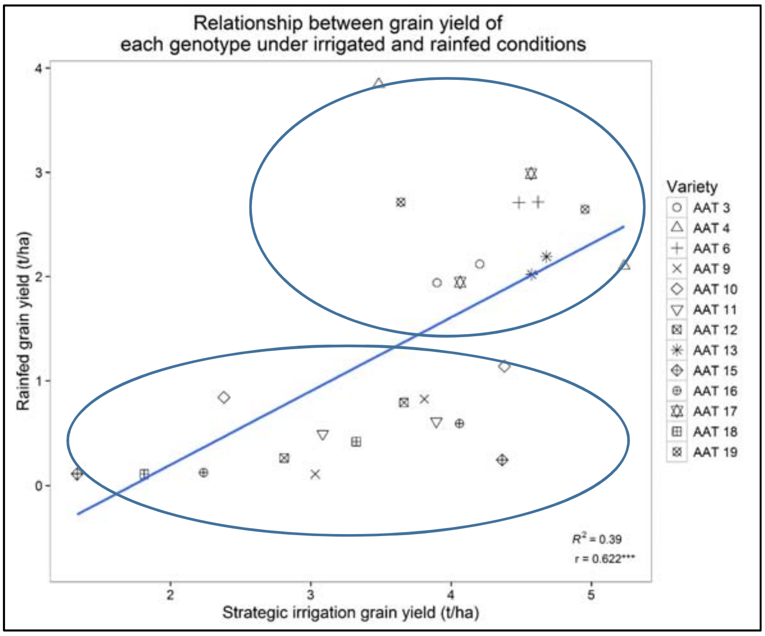

Figure 3.15 Relationship between grain yield of each variety under irrigated and rainfed conditions in 2014 and 2015 at Alton Downs, Queensland. Upper ellipsoid is early varieties (Cluster A), lower is late varieties (Cluster B). Harvest data from 2 m^2 sampling plots.

Grain yield under rainfed and strategic irrigation was closely correlated (r = 0. 62***) (Figure 3.15). Some of the varieties produced high yields under both irrigation treatments whereas others only performed well under irrigated conditions; therefore, response to irrigation varied according to varieties.

Grain yield of varieties under strategic irrigation increased by 1.5 (AAT 4) to 16.8 (AAT 15) times that of rainfed systems (Figure 3.16). In 2014, the yield gain with strategic irrigation ranged between 0.6 (AAT 4) to 3.9 (AAT 9) times as compared to 1.7 (AAT 6) to 18 (AAT 15) times in 2015 (Figure 3.16). Varieties AAT 3, AAT 4, AAT 6, AAT 13, AAT 17 and AAT 19 had less than the mean yield increment (2.6 times) with strategic irrigation whereas other varieties gained more than 6 times their rainfed yield with strategic irrigation (Figure 3.16). When the data from 2014 and 2015 are compared, varieties AAT 3, AAT 4, AAT 6, AAT 13, AAT 17 and AAT 19 produced grain yields from 1.94 t/ha to 3.85 t/ha and 3.64 t/ha to 5.24 t/ha in rainfed and strategic irrigation systems, respectively, and others produced at the range of 0.24 t/ha to 1.14 t/ha and 1.34 t/ha to 4.38 t/ha in rainfed and strategic irrigation systems, respectively (Table 3.19). The yield gained from strategic irrigation was similar to that of Bouman et al. (2005), who recorded a yield of 4.0–5.7 t/ha under aerobic conditions in the dry season. During wet seasons with supplemental irrigation by sprinkler irrigation (Kato et al., 2009), centre pivot (Stevens et al., 2012), flooded irrigation (Shi et al., 2001), piped irrigation (Sudhir et al., 2011) or under rainfed condition (Matsunami et al., 2009) yields of more than 8 t/ha have been recorded, albeit with soil moisture content maintained at close to field capacity.

The data clearly formed two separate clusters of varieties yielding more than 1.94 under rainfed conditions (cluster A with varieties, AAT 3, AAT 4, AAT 6, AAT 13, AAT 17 and AAT 19) and less than 1.94 under rainfed conditions (cluster B with varieties AAT 9, AAT 10, AAT 11, AAT 12, AAT 15, AAT 16 and AAT 18). Cluster A varieties produced better in both conditions, but cluster B varieties were highly susceptible under rainfed conditions, resulting in less than 1.14 t/ha, and produced up to 18 times higher yields with strategic irrigation. The average yield of early flowering varieties (cluster A) under rainfed conditions was 2.76 t/ha and 2.23 t/ha in 2014 and 2015, respectively, while late flowering varieties (cluster B) produced 2.38 t/ha and 3.93 t/ha with strategic irrigation in 2014 and 2015, respectively. The yield advantage of strategic irrigation on late flowering varieties as compared to rainfed varieties without irrigation was greater in 2015. The low temperature had additional impact on yield loss on top of terminal drought in 2014.Fukai and Inthapan (1988a) also reported similar results in yield penalty with exposure to low temperatures with late planting on rice under south-eastern Queensland conditions. Rice needs above 22°C during anthesis for pollen fertility (Yoshida, 1978). During 2015, rice varieties were not exposed to cold (Figure 3.2) but were exposed to terminal drought only. The response of late flowering varieties showed that they have similar yield potential to early flowering varieties under Alton Downs conditions provided that cold and drought stress are escaped.

The impact of a short rainfall window created drought, and the decreasing ambient temperature from May caused exposure to cold injury during the flowering stage of the 2014 crop. The timing of drought during the flowering stage had an effect on spikelet sterility and grain filling. The correlation between spikelet fertility and grain yield was highly significant (0.62***), which ultimately affected HI (Table 3.26). Spikelet sterility of up to 73% has been reported by Cruz and O'Toole (1984) while Jongdee et al. (2002) reported up to 98% sterility due to terminal drought. Boonjung and Fukai (1996) reported up to 73% yield reduction of the crop caused by lower spikelet fertility when exposed to terminal drought. The lower spikelet fertility could be due to lower assimilate for grain setting and a high proportion of abortion. Lanceras et al. (2004) argued that lower spikelet fertility was due to slower panicle exertion with low carbohydrate accumulation (Saini and Lalonde, 1997).

The higher panicle fertility and higher assimilation in grains ultimately results in higher biomass and therefore contributes to yield (Boonjung and Fukai, 1996). In general, HI decreased sharply under rainfed conditions as compared to strategic irrigation at Alton Downs. It is important to note that the early varieties AAT 3, AAT 4, AAT 6, AAT 13, AAT 17 and AAT 19 showed the highest HI in both irrigation treatments as their early flowering allowed them to escape the effects of drought during grain formation. A similar relationship of reduction in HI with the onset of terminal drought in late flowering varieties was reported by Pantuwan et al. (2002c), showing a subsequent reduction in yield.

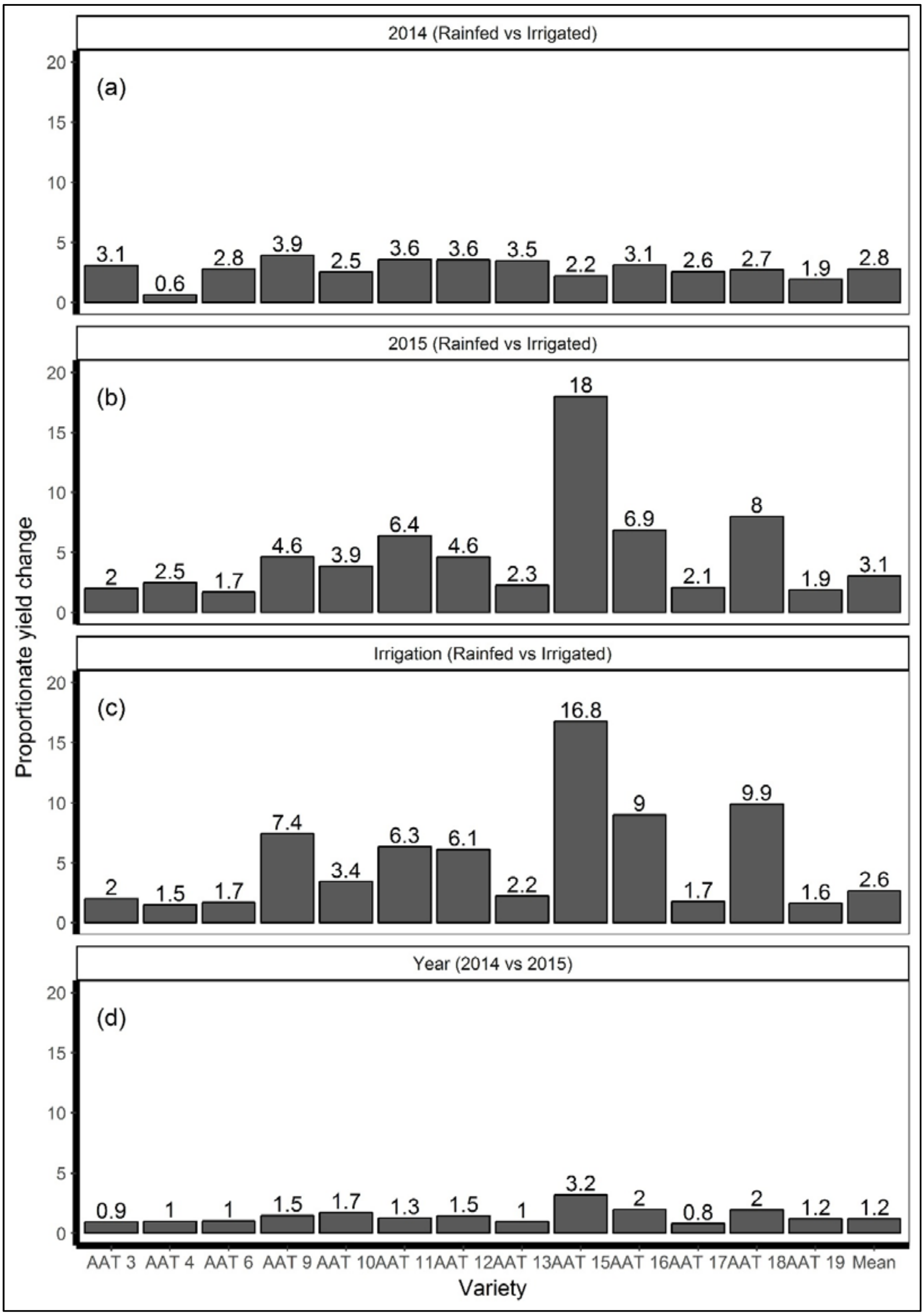

Figure 3.16 Yield difference of varieties under a) Rainfed vs strategic irrigated conditions in year 2014, b) Rainfed vs strategic irrigated conditions in year 2015, c) Rainfed vs irrigated conditions in two years and d) Year (2014 vs 2015).

Table 3.26 Correlation between phenology, yield, and yield contributing characters from the two years trial.

	Plot yield	HI	Days to flowering	Plant height (cm)	Tillers/Plant	Effective Tillers/Plant	Panicle length	Spikelets/Panicle	Filled grains/Panicle	Unfilled grains/Panicle	1000 grain wt
Plot yield	-										
HI	0.86***	-									
Days to flowering	-0.51***	-0.68***	-								
Plant height (cm)	0.51***	0.61***	-0.37***	-							
Tillers/ plant	0.14^{ns}	0.14^{ns}	-0.32***	-0.06 ^{ns}	-						
Effective Tillers/ plant	0.49***	0.45***	-0.40***	0.13 ^{ns}	0.78***	-					
Panicle length	0.44***	0.36***	-0.28**	0.12 ^{ns}	0.57***	0.61***	-				
Spikelets/Panicle	-0.08^{ns}	-0.33***	0.58***	-0.35***	0.13^{ns}	0.17^{ns}	0.35***	-			
Filled grains/ Panicle	0.68***	0.73***	-0.26**	0.62***	0.11^{ns}	0.39***	0.36***	0.11^{ns}	-		
Unfilled grains/ Panicle	-0.32**	-0.48***	0.72***	-0.19 ^{ns}	-0.28***	-0.32***	-0.10^{ns}	0.63***	-0.20*	-	
1000 grain wt	0.65***	0.73***	-0.77***	0.39***	0.29**	0.46***	0.45***	-0.40***	0.42***	-0.59***	-
Fertility %	0.62***	0.75***	-0.72***	0.44***	0.35***	0.50***	0.36***	-0.32***	0.69***	-0.79***	0.71***

*p < 0.05, **p < 0.01, ***< 0.001, ns = not significant

Table 3.27 Correlation between yield and physiological parameters from the two year trial.

	Plot yield	Straw yield	HI	Tillers/Plant	Effective tillers/Plant	LAI	Water productivity (t/ML)	Days to flowering	WUE	WUEi	A	gs
Plot yield	-											
Straw yield	0.04^{ns}	-										
HI	0.86***	-0.33***	-									
Tillers/ plant	0.14^{ns}	-0.14^{ns}	0.14^{ns}	-								
Effective tillers/ plant	0.47***	-0.10^{ns}	0.45***	0.80***	-							
LAI	0.44***	0.56***	0.13^{ns}	0.10^{ns}	0.21*	-						
Water productivity (t/ML)	0.96***	-0.07^{ns}	0.86***	0.24*	0.54***	0.35***	-					
Days to flowering	-0.51***	0.60***	-0.68***	-0.32***	-0.41***	0.15^{ns}	-0.65***	-				
WUE	0.44***	0.08^{ns}	0.30**	0.43***	0.48***	0.37***	0.49***	-0.33***	-			
WUEi	0.18^{ns}	-0.07^{ns}	0.14^{ns}	0.44***	0.40***	0.13^{ns}	0.28**	-0.34***	0.83***	-		
A	0.60***	0.00^{ns}	0.45***	0.34***	0.42***	0.44***	0.62***	-0.48***	0.79***	0.50***	-	
gs	0.50***	0.06^{ns}	0.39***	0.02^{ns}	0.14^{ns}	0.32***	0.41***	-0.18^{ns}	0.16^{ns}	-0.30**	0.57***	-
E	0.40***	-0.11^{ns}	0.35***	0.02^{ns}	0.08^{ns}	0.22*	0.37***	-0.34***	0.02^{ns}	-0.21*	0.60***	0.75***

*p < 0.05, **p < 0.01, ***< 0.001, ns = not significant

Table 3.28 Correlation between flag leaf parameters and other parameters during the flowering stage.

	Flag leaf area	Flag leaf breadth	Flag leaf length
Flag leaf area	-		
Flag leaf breadth	0.73***	-	
Flag leaf length	0.89***	0.34***	-
Days to flowering	0.32**	0.35***	0.25*
Total spikelets	0.06^{ns}	0.24*	-0.04 ^{ns}
Water input	0.52***	0.60***	0.32***
Effective tillers per plant	-0.24*	-0.01 ^{ns}	-0.32**
Panicle fertility (%)	-0.20*	-0.07 ^{ns}	-0.25*
Water use efficiency (WUE) during flowering	-0.50***	-0.19 ^{ns}	-0.56***
Intrinsic water use efficiency (WUEi) during flowering	-0.54***	-0.31**	-0.55***
A (Flowering)	-0.38***	-0.25**	-0.36***
gs (Flowering)	0.07 ^{ns}	0.01 ^{ns}	0.10 ^{ns}
E (Flowering)	-0.01 ^{ns}	-0.17 ^{ns}	0.08 ^{ns}
Yield	0.06 ^{ns}	0.18 ^{ns}	-0.04 ^{ns}
Water productivity	-0.08 ^{ns}	0.04 ^{ns}	-0.17 ^{ns}

*p < 0.05, **p < 0.01, ***< 0.001, ns = not significant

Root ideotypes representing greater root length density and deeper root systems are considered as target traits for drought tolerance (Henry, 2013). (Chang and Vergara, 1975) reported that a long and deep root system correlated with drought tolerance in upland or aerobic rice varieties. Although the varieties under study at Alton Downs in 2015 were also deep rooted and had their root systems deeper than 60 cm (Table 3.16), the varieties with longer root length and greater root length density at depth did not always show significant correlations to yield (Table 3.29). Indeed, root characteristics such as RDW and RWD at 0–15 cm were more closely correlated with yield, HI and water productivity across the rainfed conditions and strategic irrigation (Table 3.29) but not under strategic irrigation (Table 3.30) or rainfed conditions (Table 3.31). The strong correlation between RDW and RWD at 0–15 cm (r = 0.80***) is due to the significant effect of irrigation on RDW and RWD distribution at 0–15 cm soil depth (Table 3.17 and Figure 3.10). At 0–15 cm, the irrigated crop root could access more moisture due to drip irrigation, receiving 1.89 ML/ha more than from rainfed conditions (Figure 3.3). This favoured yield for the crop by expanding its roots for better water extraction in the top soil, resulting in a significant contribution to yield (r = 0.56*) under strategic irrigation.

Kato et al. (2007) argued that the limitation of assimilates accumulation under drought would probably hinder the transportation to roots and subsequently suppress root development. This response of rice plants in the field suggests that the adaptive response of root, such as deep rooting and large root length density, is important in rice varieties (Lilley and Fukai, 1994a).

Table 3.29 Correlation between root parameters and yield, HI and water productivity at Alton Downs under rainfed conditions and strategic irrigation.

	Yield (t/ha)	Water productivity (t/ML)	Straw yield (t/ha)	Harvest index (HI)	Irrigation (ML/ha)	Total water input (rainfall + irrigation) (ML/ha)
RDW (whole profile)	0.53*	0.43^{ns}	0.31^{ns}	0.64*	0.79***	0.79***
RDW (0–15)	0.56*	0.47*	0.30^{ns}	0.67*	0.80***	0.80***
RDW (15–30)	-0.17^{ns}	-0.22^{ns}	0.07^{ns}	-0.17^{ns}	-0.03^{ns}	-0.03^{ns}
RDW (30–60)	0.04^{ns}	-0.01^{ns}	0.16^{ns}	0.08^{ns}	0.21^{ns}	0.21^{ns}
RDW (60–100)	-0.15^{ns}	-0.18^{ns}	-0.11^{ns}	-0.04^{ns}	0.00^{ns}	0.00^{ns}
RD (whole profile)	0.11^{ns}	0.07^{ns}	0.43^{ns}	0.09^{ns}	0.27^{ns}	0.27^{ns}
RD (0–15)	0.26^{ns}	0.18^{ns}	0.31^{ns}	0.18^{ns}	0.48*	0.48*
RD (15–30)	0.12^{ns}	0.16^{ns}	0.07^{ns}	0.05^{ns}	-0.01^{ns}	-0.01^{ns}
RD (30–60)	-0.16^{ns}	-0.13^{ns}	-0.05^{ns}	-0.19^{ns}	-0.28^{ns}	-0.28^{ns}
RD (60–100)	-0.07^{ns}	-0.10^{ns}	0.05^{ns}	-0.03^{ns}	0.11^{ns}	0.11^{ns}
RLD (whole profile)	-0.12^{ns}	-0.19^{ns}	-0.06^{ns}	0.07^{ns}	0.16^{ns}	0.16^{ns}
RLD (0–15)	0.12^{ns}	0.06^{ns}	-0.02^{ns}	0.23^{ns}	0.34^{ns}	0.34^{ns}
RLD (15–30)	-0.38^{ns}	-0.39^{ns}	-0.10^{ns}	-0.25^{ns}	-0.29^{ns}	-0.29^{ns}
RLD (30–60)	-0.32^{ns}	-0.40^{ns}	0.05^{ns}	-0.11^{ns}	-0.01^{ns}	-0.01^{ns}
RLD (60–100)	-0.25^{ns}	-0.32^{ns}	0.09^{ns}	-0.14^{ns}	0.07^{ns}	0.07^{ns}
RL (whole profile)	-0.15^{ns}	-0.22^{ns}	-0.05^{ns}	0.05^{ns}	0.15^{ns}	0.15^{ns}
RL (0–15)	0.12^{ns}	0.06^{ns}	-0.02^{ns}	0.23^{ns}	0.34^{ns}	0.34^{ns}
RL (15–30)	-0.38^{ns}	-0.39^{ns}	-0.10^{ns}	-0.25^{ns}	-0.29^{ns}	-0.29^{ns}
RL (30–60)	-0.32^{ns}	-0.40^{ns}	0.05^{ns}	-0.11^{ns}	-0.01^{ns}	-0.01^{ns}
RL (60–100)	-0.25^{ns}	-0.32^{ns}	0.09^{ns}	-0.14^{ns}	0.07^{ns}	0.07^{ns}
RWD (whole profile)	0.54*	0.44^{ns}	0.31^{ns}	0.65*	0.80***	0.80***
RWD (0–15)	0.56*	0.47*	0.30^{ns}	0.67*	0.80***	0.80***
RWD (15–30)	-0.17^{ns}	-0.22^{ns}	0.07^{ns}	-0.17^{ns}	-0.03^{ns}	-0.03^{ns}
RWD (30–60)	0.04^{ns}	-0.01^{ns}	0.16^{ns}	0.08^{ns}	0.21^{ns}	0.21^{ns}
RWD (60–100)	-0.15^{ns}	-0.18^{ns}	-0.11^{ns}	-0.04^{ns}	0.00^{ns}	0.00^{ns}

*p < 0.05, **p < 0.01, ***< 0.001, ns = not significant

Table 3.30 Correlation between root parameters and yield, HI and water productivity at Alton Downs under strategic irrigation.

	Yield (t/ha)	Water productivity (t/ML)	Straw yield (t/ha)	Harvest index (HI)
RDW (whole profile)	-0.59^{ns}	-0.60^{ns}	-0.49^{ns}	0.39^{ns}
RDW (0–15)	-0.60^{ns}	-0.62^{ns}	-0.50^{ns}	0.44^{ns}
RDW (15–30)	0.10^{ns}	0.12^{ns}	0.00^{ns}	-0.20^{ns}
RDW (30–60)	-0.18^{ns}	-0.18^{ns}	0.02^{ns}	-0.20^{ns}
RDW (60–100)	-0.06^{ns}	-0.06^{ns}	-0.67*	0.53^{ns}
RD (whole profile)	-0.45^{ns}	-0.46^{ns}	0.34^{ns}	-0.17^{ns}
RD (0–15)	-0.37^{ns}	-0.38^{ns}	-0.40^{ns}	0.52^{ns}
RD (15–30)	0.03^{ns}	0.06^{ns}	0.00^{ns}	-0.11^{ns}
RD (30–60)	0.43^{ns}	0.42^{ns}	0.61^{ns}	-0.29^{ns}
RD (60–100)	-0.71*	-0.70*	-0.48^{ns}	0.29^{ns}
RLD (whole profile)	-0.61^{ns}	-0.63^{ns}	-0.42^{ns}	0.42^{ns}
RLD (0–15)	-0.64^{ns}	-0.66^{ns}	-0.45^{ns}	0.43^{ns}
RLD (15–30)	-0.25^{ns}	-0.26^{ns}	-0.21^{ns}	0.23^{ns}
RLD (30–60)	-0.43^{ns}	-0.46^{ns}	-0.12^{ns}	0.20^{ns}
RLD (60–100)	-0.54^{ns}	-0.54^{ns}	-0.59^{ns}	0.38^{ns}
RL (whole profile)	-0.60^{ns}	-0.63^{ns}	-0.42^{ns}	0.41^{ns}
RL (0–15)	-0.64^{ns}	-0.66^{ns}	-0.45^{ns}	0.43^{ns}
RL (15–30)	-0.25^{ns}	-0.26^{ns}	-0.21^{ns}	0.23^{ns}
RL (30–60)	-0.43^{ns}	-0.46^{ns}	-0.12^{ns}	0.20^{ns}
RL (60–100)	-0.54^{ns}	-0.54^{ns}	-0.59^{ns}	0.38^{ns}
RWD (whole profile)	-0.59^{ns}	-0.61^{ns}	-0.50^{ns}	0.41^{ns}
RWD (0–15)	-0.60^{ns}	-0.62^{ns}	-0.50^{ns}	0.44^{ns}
RWD (15–30)	0.10^{ns}	0.12^{ns}	0.00^{ns}	-0.20^{ns}
RWD (30–60)	-0.18^{ns}	-0.18^{ns}	0.02^{ns}	-0.20^{ns}
RWD (60–100)	-0.06^{ns}	-0.06^{ns}	-0.67*	0.53^{ns}

*p < 0.05, **p < 0.01, ***< 0.001, ns = not significant

Table 3.31 Correlation between root parameters and yield, HI and water productivity at Alton Downs under rainfed conditions.

	Yield (t/ha)	Water productivity (t/ML)	Straw Yield (t/ha)	Harvest Index (HI)
RDW (whole profile)	-0.29^{ns}	-0.28^{ns}	-0.10^{ns}	0.03^{ns}
RDW (0–15)	-0.05^{ns}	-0.04^{ns}	-0.26^{ns}	0.14^{ns}
RDW (15–30)	-0.39^{ns}	-0.39^{ns}	0.27^{ns}	-0.21^{ns}
RDW (30–60)	-0.30^{ns}	-0.31^{ns}	0.08^{ns}	-0.03^{ns}
RDW (60–100)	-0.32^{ns}	-0.31^{ns}	0.35^{ns}	-0.26^{ns}
RD (whole profile)	-0.07^{ns}	-0.08^{ns}	0.59^{ns}	-0.36^{ns}
RD (0–15)	-0.21^{ns}	-0.22^{ns}	0.48^{ns}	-0.55^{ns}
RD (15–30)	0.31^{ns}	0.31^{ns}	0.25^{ns}	0.18^{ns}
RD (30–60)	0.03^{ns}	0.04^{ns}	-0.26^{ns}	0.14^{ns}
RD (60–100)	-0.12^{ns}	-0.14^{ns}	0.60^{ns}	-0.39^{ns}
RLD (whole profile)	-0.40^{ns}	-0.40^{ns}	0.04^{ns}	-0.28^{ns}
RLD (0–15)	-0.19^{ns}	-0.19^{ns}	-0.23^{ns}	-0.19^{ns}
RLD (15–30)	-0.26^{ns}	-0.27^{ns}	0.34^{ns}	-0.12^{ns}
RLD (30–60)	-0.57^{ns}	-0.57^{ns}	0.22^{ns}	-0.23^{ns}
RLD (60–100)	-0.54^{ns}	-0.54^{ns}	0.71*	-0.50^{ns}
RL (whole profile)	-0.46^{ns}	-0.46^{ns}	0.09^{ns}	-0.31^{ns}
RL (0–15)	-0.19^{ns}	-0.19^{ns}	-0.23^{ns}	-0.19^{ns}
RL (15–30)	-0.26^{ns}	-0.27^{ns}	0.34^{ns}	-0.12^{ns}
RL (30–60)	-0.57^{ns}	-0.57^{ns}	0.22^{ns}	-0.23^{ns}
RL (60–100)	-0.54^{ns}	-0.54^{ns}	0.71*	-0.50^{ns}
RWD (whole profile)	-0.24^{ns}	-0.23^{ns}	-0.14^{ns}	0.06^{ns}
RWD (0–15)	-0.05^{ns}	-0.04^{ns}	-0.26^{ns}	0.14^{ns}
RWD (15–30)	-0.39^{ns}	-0.39^{ns}	0.27^{ns}	-0.21^{ns}
RWD (30–60)	-0.30^{ns}	-0.31^{ns}	0.08^{ns}	-0.03^{ns}
RWD (60–100)	-0.32^{ns}	-0.31^{ns}	0.35^{ns}	-0.26^{ns}

*p < 0.05, **p < 0.01, ***< 0.001, ns = not significant

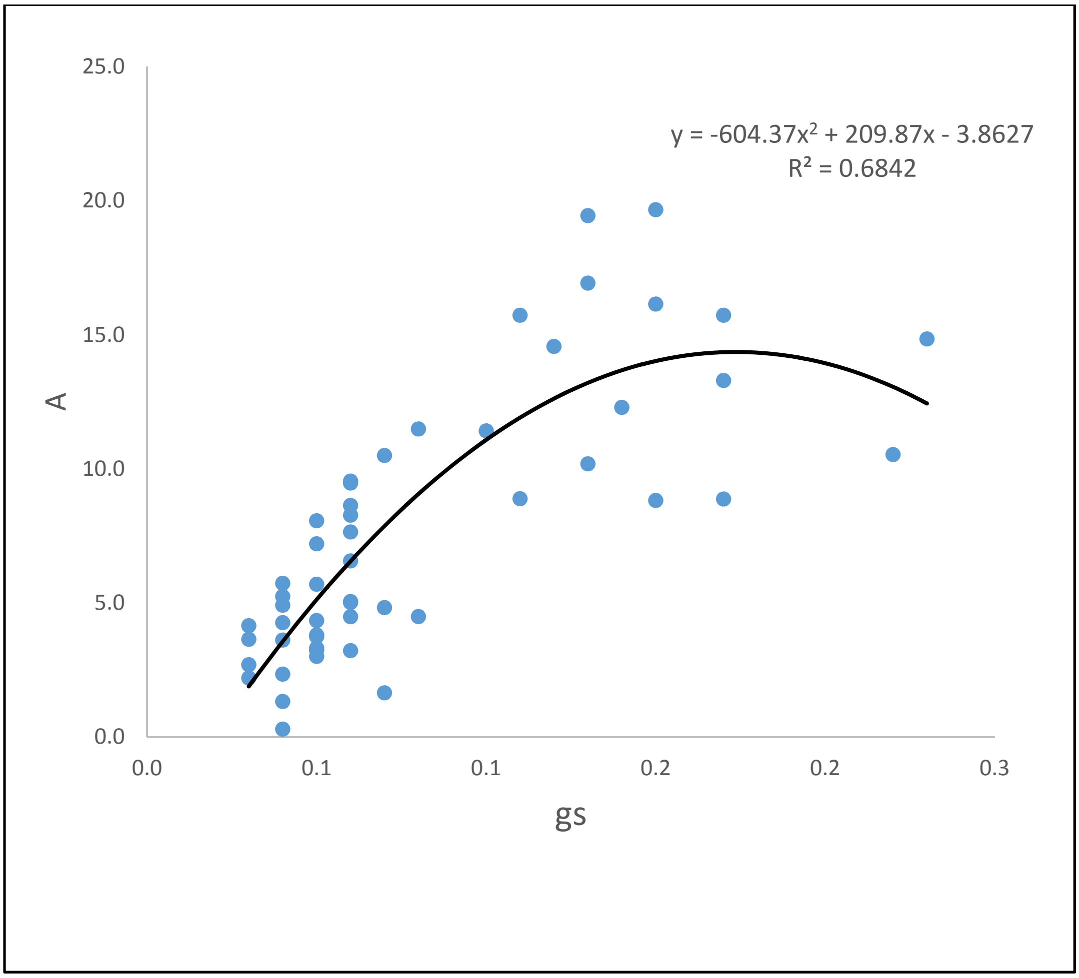

Figure 3.17 Relationship between stomatal conductance (gs) and photosynthesis (A) during the flowering stage (95 DAS) in 2015.

Table 3.32 Correlation between yield, phenology, yield contributing traits, and physiological parameters in 2014.

	Yield	Harvest index (HI)	Days to flowering	Plant height	Tillers/plant	Effective tillers/plant	Panicle length	Spikelets/ panicle	Filled grains/ panicle	Unfilled grains/ panicle	1000 grain wt.	Fertility %	LAI	WUE	WUEi	A	gs
Harvest index (HI)	0.93***	--															
Days to flowering	-0.69***	-0.84***	--														
Plant height	0.86***	0.85***	-0.75***	--													
Tillers/plant	0.30*	0.37**	-0.38**	0.58***	--												
Effective tillers/plant	0.64***	0.64***	-0.45***	0.75***	0.70***	--											
Panicle length	0.41**	0.43**	-0.31*	0.62***	0.60***	0.57***	--										
Spikelets/ panicle	-0.44**	-0.60***	0.74***	-0.44*	-0.14^{ns}	-0.10^{ns}	0.10^{ns}	--									
Filled grains/ panicle	0.75***	0.77***	-0.54***	0.72***	0.35*	0.66***	0.51***	-0.19^{ns}	--								
Unfilled grains/panicle	-0.65***	-0.77***	0.80***	-0.66***	-0.28*	-0.40**	-0.26^{ns}	0.74***	-0.66***	--							
1000 grain wt.	0.72***	0.84***	-0.83***	0.73***	0.37**	0.51***	0.43**	-0.64***	0.70***	-0.83***	--						
Fertility %	0.73***	0.84***	-0.80***	0.75***	0.38**	0.55***	0.43**	-0.54***	0.87***	-0.9***	0.90***	--					
LAI	0.00^{ns}	-0.24^{ns}	0.54***	-0.18^{ns}	-0.29*	-0.19^{ns}	-0.03^{ns}	0.39**	-0.11^{ns}	0.42**	-0.29*	-0.37**	--				
WUE	0.53***	0.57***	-0.48***	0.45***	0.21^{ns}	0.33*	0.26^{ns}	-0.26^{ns}	0.50***	-0.45***	0.40**	0.52***	-0.22^{ns}	--			
WUEi	0.35*	0.45***	-0.44**	0.34*	0.31*	0.30*	0.24^{ns}	-0.28*	0.32*	-0.37**	0.34*	0.40**	-0.29*	0.88***	--		
A	0.64***	0.69***	-0.74***	0.60***	0.20^{ns}	0.29*	0.28*	-0.52***	0.49***	-0.61***	0.64***	0.65***	-0.29*	0.62***	0.42**	- -	
gs	0.28*	0.29*	-0.39**	0.27^{ns}	-0.06^{ns}	0.02^{ns}	0.02^{ns}	-0.28*	0.22^{ns}	-0.29*	0.36**	0.31*	-0.07^{ns}	-0.17^{ns}	-0.43**	0.55 ***	- -
E	0.27*	0.33*	-0.51***	0.29*	0.02^{ns}	0.02^{ns}	0.06^{ns}	-0.42**	0.14^{ns}	-0.35*	0.44**	0.34*	-0.19^{ns}	-0.17^{ns}	-0.29*	0.64 ***	0.9 ***

*p < 0.05, **p < 0.01, ***< 0.001, ns = not significant

Table 3.33 Correlation between yield, phenology, yield contributing traits, and physiological parameters in 2015.

	Yield	Harvest index (HI)	Days to flowering	Plant height	Tillers/plant	Effective tillers/plant	Panicle length	Spikelets/ panicle	Filled grains/ panicle	Unfilled grains/ panicle	1000 grain wt.	Fertility %	LAI	WUE	WUEi	A	gs
Harvest index (HI)	0.81***	- -															
Days to flowering	-0.34*	-0.42**	- -														
Plant height	0.25^{ns}	0.06^{ns}	-0.18^{ns}	- -													
Tillers/plant	0.18^{ns}	0.26^{ns}	-0.22^{ns}	0.27^{ns}	- -												
Effective tillers/plant	0.48***	0.55***	-0.37**	0.26^{ns}	0.91***	- -											
Panicle length	0.60***	0.56***	-0.27^{ns}	0.25^{ns}	0.45***	0.60***	- -										
Spikelets/ panicle	0.47***	0.37**	0.33*	0.14^{ns}	0.27^{ns}	0.38**	0.60***	- -									
Filled grains/ panicle	0.66***	0.66***	0.03^{ns}	0.21^{ns}	0.49***	0.63***	0.60***	0.79***	- -								
Unfilled grains/panicle	0.09^{ns}	-0.05^{ns}	0.40**	-0.06^{ns}	-0.10^{ns}	-0.02^{ns}	0.34*	0.68***	0.13^{ns}	- -							
1000 grain wt.	0.58***	0.63***	-0.9***	0.23^{ns}	0.31*	0.52***	0.52***	-0.08^{ns}	0.22^{ns}	-0.27^{ns}	- -						
Fertility %	0.53***	0.63***	-0.28*	0.27^{ns}	0.51***	0.58***	0.32*	0.23^{ns}	0.75***	-0.50***	0.41**	- -					
LAI	0.79***	0.64***	-0.42**	0.36**	0.26^{ns}	0.49***	0.64***	0.28*	0.47***	-0.02^{ns}	0.67***	0.42**	- -				
WUE	0.73***	0.62***	-0.12^{ns}	0.12^{ns}	0.24^{ns}	0.44**	0.52***	0.44***	0.61***	0.05^{ns}	0.38**	0.47***	0.71***	- -			
WUEi	0.33*	0.24^{ns}	-0.02^{ns}	0.07^{ns}	0.06^{ns}	0.18^{ns}	0.26^{ns}	0.16^{ns}	0.21^{ns}	0.06^{ns}	0.19^{ns}	0.16^{ns}	0.41**	0.58***	- -		
A	0.74***	0.57***	-0.20^{ns}	0.17^{ns}	0.25^{ns}	0.44**	0.51***	0.37**	0.53***	0.03^{ns}	0.44**	0.43**	0.77***	0.90***	0.46***	- -	
gs	0.62***	0.48***	-0.08^{ns}	0.11^{ns}	0.27^{ns}	0.41**	0.43**	0.46***	0.52***	0.15^{ns}	0.25^{ns}	0.33*	0.52***	0.63***	-0.13^{ns}	0.76***	- -
E	0.48***	0.32*	-0.14^{ns}	0.16^{ns}	0.23^{ns}	0.32*	0.34*	0.19^{ns}	0.29*	0.02^{ns}	0.27^{ns}	0.26^{ns}	0.54***	0.43**	0.12^{ns}	0.75***	0.7***

*p < 0.05, **p < 0.01, ***< 0.001, ns = not significant

3.5. Conclusion

Adapting rainfed rice systems to a dry land system is quite challenging. The soil type, pattern of rainfall and weather conditions determine whether a rainfed rice production system can be effective and successful. The crop needs to be planted in a soil profile full of moisture in the warm window throughout the crop season. In the trial site at Alton Downs, central Queensland, rainfall generally commences in January, and so early planting is often compromised by a lack of early rainfall. Planting rice varieties early with the onset of rainfall during November significantly increased the chance of producing better yield from varieties as compared to late planting during January. The increases in yield were associated with greater panicle fertility, LAI, water productivity and associated effects through higher HI, higher effective tiller number per plant, larger panicle length, total filled grains per panicle and greater grain density. Greater WUE during flowering time was closely correlated with total yield, resulting in higher filled grains per panicle and higher 1000 grain weights. The experiment was not able to show the relationship of total root length to yield of rice, but the total RDW and RWD in the top soil layer of 0–15 cm showed some correlation with yield in the strategically irrigated treatment. The current research suggests that varieties with short maturity duration such as AAT 3, AAT 4, AAT 6 AAT 13, AAT 17 and AAT 19 are better for Alton Downs when there is a short window of rainfall. They avoid later drought through early flowering and maturity. Short duration varieties with higher panicle fertility, HI and LAI can be used as selection criteria for better-adapted varieties for central Queensland. Varieties with higher LAI have a comparative advantage when planted earlier in the Alton Downs conditions. All medium grain varieties with short maturity duration performed well under both the rainfed and irrigated conditions. The response to irrigation was particularly outstanding for late maturity varieties such as AAT 9, AAT 10, AAT 11, AAT 12, AAT 15, AAT 16, AAT 16 and AAT 18, where response to strategic irrigation resulted in yield increase up to 18 times compared to rainfed treatment.

This results demonstrate an opportunity for developing a rainfed rice production system using strategic irrigation, particularly in central QLD, where window for general rainfed rice planting is constrained by late onset of summer rain (on set of wet season generally starts in January), and dry spells during the wet season can be profound. The yield advantage of strategic irrigation on late flowering varieties as compared to early flowering rainfed varieties without irrigation was greater in 2015, showing the potential advantage of strategic irrigation as it allows rice to cope with terminal drought in the Alton Downs conditions. These results show that the central Queensland region which has low rainfall environments can support a viable rice industry with suitable rice varieties adapted to rainfed and strategic irrigation.

CHAPTER 4. PERFORMANCE OF RICE VARIETIES UNDER RAINFED CONDITIONS IN CENTRAL QUEENSLAND

Abstract

Year-to-year variation of yield can cause rainfed rice farming to be unpredictable and risky. Varieties with suitable phenology and better stability are needed to be selected for particular environments. Rainfall patterns during the flowering period play an important role in yield variation under rainfed conditions. Hence, the industry will need to identify more widely adapted rainfed upland varieties, and also explore new potential rice growing areas for rainfed production such as found in central and north Queensland, Australia. A field experiment was conducted during the 2013, 2014 and 2015 wet seasons with varieties seeded in a vertisol soil at Alton Downs, central Queensland. The objective of this study was to evaluate varieties provided by Australian Agricultural Technologies Limited (AAT) for yield stability under rain fed conditions. The performance of varieties was tested in a randomised complete block design with two replications of each variety under rainfed conditions to determine yield and yield determining physiological, phenological and agronomic responses. Rainfall was very low during the flowering and grain filling stages in 2013 and 2014, exposing the crop to terminal drought, and temperatures were below 15°C during flowering. The results suggested that phenology has a significant impact on the yield and yield contributing characters such as effective tillers per plant. Early varieties escaped the cold and drought during the flowering stage, making them better adapted for the dry tropical environment of Alton Downs. Among the early varieties, AAT 6 had the smallest coefficient of variation across the years, showing it to be the most consistent yielder under all conditions, whereas AAT 13 showed a tendency to respond with better yield when conditions were more favourable.

Key words:

Drought, yield variability, rainfed rice, aerobic rice

4.1. Introduction

Rainfed rice systems are known to have much variation in terms of water availability and soil characteristics (Kumar et al., 2008), and drought is generally the main reason for yield reduction in rainfed systems. Development of drought tolerant rice varieties for different kinds of drought environments is still in its infancy (Kumar et al., 2013b). Drought is one of the most damaging abiotic stresses and reduces the yield of rice by 15–50 % (Srividhya et al., 2011). Global yield reduction due to drought accounts for 18 million tonnes annually (O'Toole, 2004). When there is water deficiency during reproductive stages the yield is reduced significantly, even with moderate stress (Venuprasad et al., 2007).

Rice is sensitive to moisture fluctuation from year to year. Yield stability of varieties from year to year under rainfed production system is important to maintain productivity in any water limited rice growing environment. Different researchers have focused on secondary traits (rather than on yield *per se*) for selection of drought tolerant varieties under natural drought stress conditions (Fukai et al., 1999; Jongdee et al., 2002; Pantuwan et al., 2002b; Price et al., 2002) but it is also understood that these secondary traits generally have lower heritability compared to yield under stress and generally are often not highly correlated to yield (Atlin and Lafitte, 2002). This is due to the stronger association of yield with maturity (earliness confers avoidance) than with traits important for plant-water relations responsible for tolerance (Witcombe et al., 2008). Therefore, direct selection for yield under rainfed conditions and testing of yield stability over the year is often advocated by conventional plant breeders.

However, there are few studies on rice varietal selection and evaluation under natural stress environments for yield (Venuprasad et al., 2007). A tolerant variety Mansara was developed through selection for yield under rainfed conditions in Nepal (Sthapit et al., 2010). Similarly, IRRI has developed and released 17 drought tolerant varieties for Asia and Africa in the last decade using the method of direct selection for yield under water stress conditions (Kumar et al., 2014).

Studies on leaf blast (Challagulla et al., 2015) and preliminary trials on assessment of coleoptile length and response of varietal root traits were carried out under controlled environment in central Queensland in 2013. Preliminary results suggested a significant difference between the varieties tested in larger concrete tubs during wet season in dry tropics (Rockhampton), Queensland (Bhattarai, 2013). Central Queensland region receives about 900 mm of annual rainfall and it receives about 700 mm during the wet season (Dec–May) and it may be possible to develop a rainfed rice system in this region. Finding a suitable stable variety for that window during the wet season is crucial. With the possibility of developing rainfed rice systems in central Queensland, this study aimed to evaluate varieties provided by Australian Agricultural Technologies Limited (AAT) for yield stability under rain fed conditions in central Queensland, Australia.

4.2. Materials and Methods

4.2.1. Site description

The experiment was conducted over three year's wet seasons, during Feb–July in 2013, Jan–May in 2014 and Nov–March in 2014/15 wet seasons at Alton Downs, Queensland (23°18'14'' S Latitude, 150°21'24'' E Longitude, and 22 m above sea level).

The soil of the experimental site was a heavy clay (self-mulching black cracking clay or vertisol). Soil chemical and nutritional characteristics were: pH 6.6, organic C (%): 1.57, total N (%): 0.1, available P-Morgan (mg/kg):2.0, available K (meq/100 g): 0.25, organic matter (% OM): 2.8, EC (ds/m): 0.049 and cation exchange capacity (CEC) (meq 100/ g): 60.19.

4.2.2. Weather and experimental conditions

The experimental site has a subtropical climate characterised by distinct wet and dry seasons. From December to March it is warm and wet while from June to September it is cooler and drier. Rainfall data, and maximum and minimum air temperatures, were obtained from the Australian Bureau of Meteorology, Rockhampton Aerodrome weather station. Total rainfall received during the experimental period was 565 mm, 639 mm and 593 mm for 2013, 2014 and 2014/15 seasons, respectively, and the long term average annual rainfall was 800 mm (Bureau of Meteorology, 2016a). Details of weather at the experimental site are presented in section 4.3.1.

4.2.3. Experimental design and treatments

The experiment was set up as a randomised complete block design (RCBD) with two replications of each variety. Each variety was planted in a 25 m × 3.75 m plot. In each plot a 2 m × 1 m sample plot was marked for experimental data recording and sample plot harvest for yield assessment.

4.2.4. Crop management

The rice seeds were directly seeded in a well-prepared seed bed, at a rate of 40 kg/ha by a tractor mounted seed dibbler into the soil. Rows were 25 cm apart. The field was fertilised entirely as basal application with 100:29:76 kg NPK/ha using Crop King fertiliser before planting of the crop. During the 2014/15, season all of the treatments received an initial irrigation of 0.79 ML to establish the crop.

Weeds in the experimental plots were controlled using commercial herbicides available on the market. A tank mix of Clomazone (Megister®) @ 0.4 L/ha plus pendimethalin Stomp® 440 @ 2.5 L/ha plus paraquat 250 g/L (Gramoxone® 250) @ 0.8 L/ha was applied as described by (Taylor, 2013) after sowing rice seeds, followed by initial irrigation in 2015 and rainfall in year 2014. Similarly, Dicamba 500 g/L (Kamba®500) @ 0.4 to 0.56 L/ha was applied during the early tillering stage to control broad leaf weed growth. Intensive manual weeding was also performed in 2013, 2014 and 2015, on three occasions each year, in order to control the weeds that were not controlled by herbicides.

4.2.5. Rice varieties

Australian Agricultural Technologies Limited (AAT) provided seeds of thirteen rice varieties for study. Table 4.1 presents the varieties used during the experiment. Details on the varietal pedigree and development are presented in Chapter 3.

Table 4.1 Rice varieties used in the experiment

Varieties	Entry Name	Grain Type
AAT 9	Linklatter B1	Long
AAT 10	Dummeriney 11	Long
AAT 11	Lasik IX	Long
AAT 12	Inaminka MB	Long
AAT 15	Lasik XII	Long
AAT 16	Inaminka XB	Long
AAT 18	Unnamed	Long
AAT 3	Lasik VII	Medium
AAT 4	Sunkiss PII	Medium
AAT 6	Linklatter A1	Medium
AAT 13	Lasix XB	Medium
AAT 17	Inaminka XD	Medium
AAT 19	Duminey	Medium

4.2.6. Crop measurements

Grain yield was measured from the sample plot (2 m^2) by manual harvesting using a sickle. The crop was harvested when grain moisture was ca. 14%. The sample plot was used to measure yield and all plant parameters were measured from five randomly selected hills within the sample plot areas. The sample plot harvest was threshed manually by hitting against the floor and the grain was dried (as was the stems/chaffs) and weighed to determine yield and HI. Grain yield was presented at 12% moisture. Crop parameters were recorded following the IRRI rice descriptor method (Bioversity International et al., 2007).

4.2.7. Parameters studied

Table 4.2 presents the variables that were recorded during the experiment. Details on specific procedures for each are presented in Chapter 3.

Table 4.2 Variables recorded during the experiment at Alton Downs

Type	Variable and calculated parameters (units)
Growth	Plant height (cm) Days to flowering (no.)
Physiological	Photosynthesis (µmol/m^2/sec) Stomatal conductance (mmol/m^2/sec) Leaf transpiration (mmol/ m^2/sec)
Yield and yield contributing	Number of tillers (no.) per plant Effective tillers (no.) per plant Grain yield (t/ha) Harvest index (HI) (ratio)
Water and water productivity	Total rainfall (mm) (including 79 mm in 2014 irrigation) Water productivity (t/ML)

4.2.8. Data analysis

Microsoft Office Excel 2013 was used for data entry and recording.

The ANOVA was performed with varieties as treatment and replication as blocks. Therefore, when repeating the experiment in three years the error is divided in two groups of blocks, i.e., Year, Year × Block. All the analyses were performed using GenStat 16th edition (VSN International, 2013) and R (R Core Team, 2016). Interaction effects are presented and, where there was no interaction, only main effects are presented. Specific interaction effects are presented in graphs using R (R Core Team, 2016) package ggplot2 (Wickham, 2009) and Microsoft Office Excel 2013.

The means were compared by Fisher's protected 'Least Significant Difference' test. The significance level was set at 5% in all comparisons. Simple pair-wise correlations, and linear and polynomial regression were performed where appropriate to examine interrelationships between variables.

4.3. Results

4.3.1. Experimental environment and weather

The total rainfall in 2013 was 565 mm and most of the rainfall occurred before 101 days after sowing (DAS). The majority of rainfall during the 2014 season occurred during the first 85 DAS but in year 2015, it rained until 99 DAS. Severe Tropical Cyclone Marcia was a Category 3 cyclone when it hit in Rockhampton, resulting in a rainfall peak of 109.4 mm on 98 DAS (20 February 2015) and 96 mm on 99 DAS. After this event in 2015, no rainfall was recorded at Alton Downs during the crop period (Figure 4.1), where slight rainfall occurred beyond 100 DAS in 2013 and 2014.

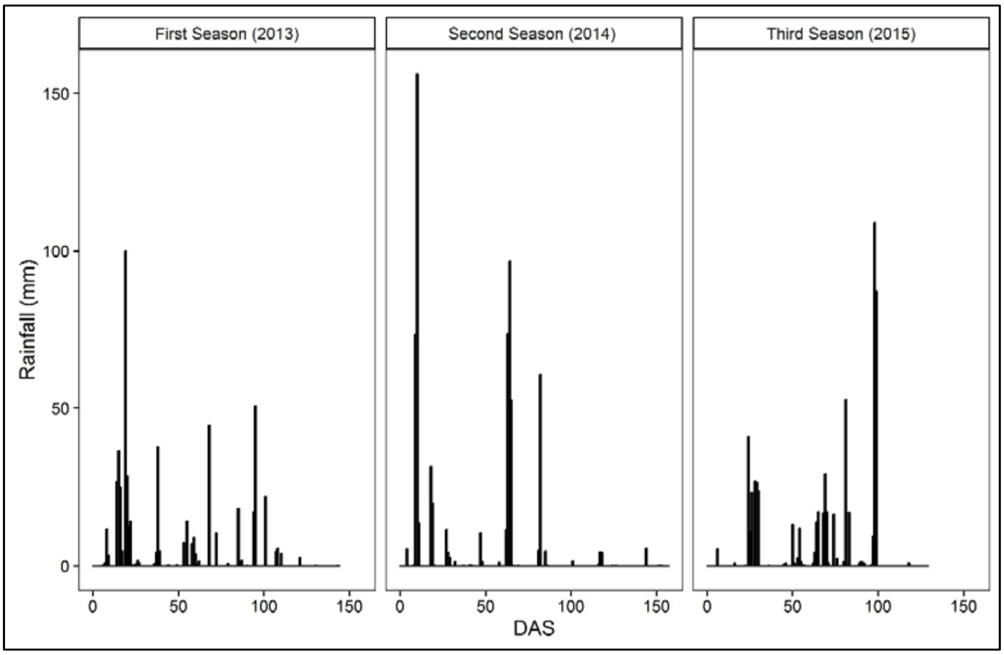

Figure 4.1 Rainfall during the experimental periods at Alton Downs.

The mean temperatures during the experimental period in 2013 (11 February 2013 to 7 July 2013), 2014 (22 January 2014 to 28 June 2014) and in 2015 (14 November 2014 to 23 March 2015) were 22°C, 23.5°C and 27.5°C, respectively. Temperatures ranged from 5.8°C to 34.7°C in 2013, from 5.1°C to 36°C in year 2014 and from 19.4°C to 39.3°C in 2015. The temperature gradually decreased from April to June (Figure 4.2). Relative humidity averaged 72%, 70% and 68% in 2013, 2014 and 2015, respectively, and it ranged from 17% to 100 % in 2013, 16% to 100% in 2014, and 18% to 100% in 2015. Evapotranspiration averaged 3.6 mm/day in 2013, 4.2 mm/day in 2014 and 5.9 mm/day in 2015. Evapotranspiration ranged from 1 to 7 mm/day, 1 to 8.4 mm/day and 1.7 to 8.3 mm/day in 2013, 2014 and 2015, respectively, during the growing period. Average ET_o was higher in 2015 as compared to 2013 and 2014 (Figure 3.4).

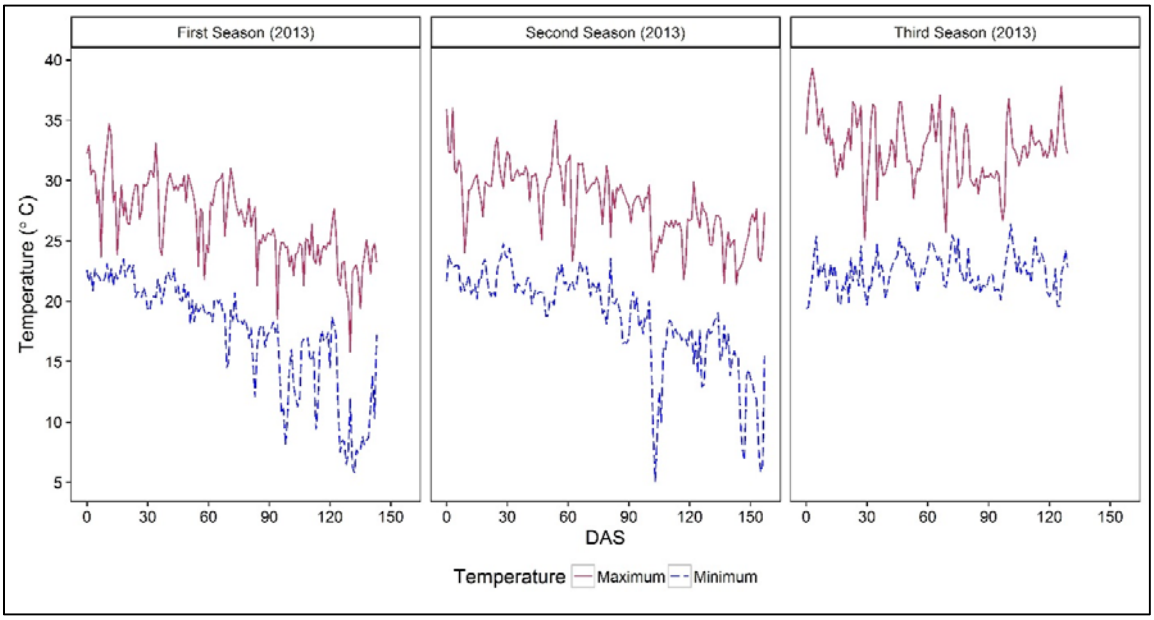

Figure 4.2 Maximum and minimum temperature during the experimental period of 2013, 2014 and 2015 at Alton Downs.

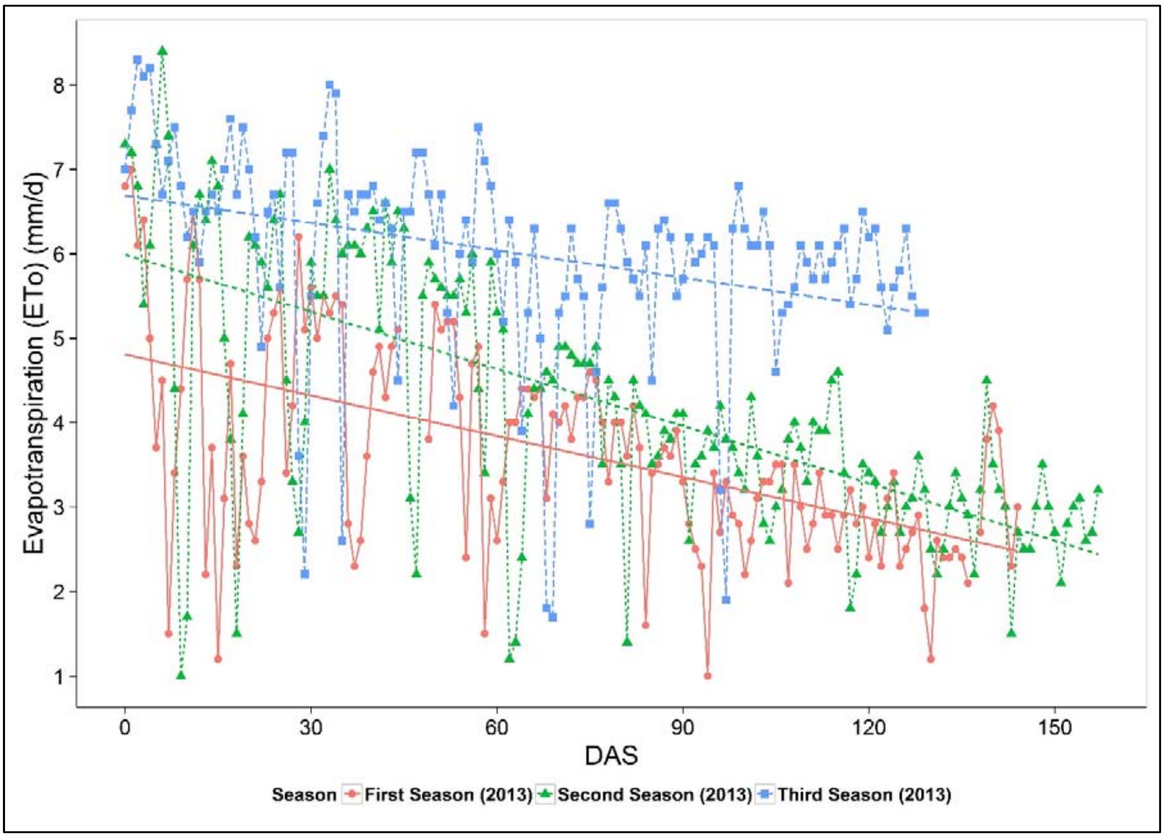

Figure 4.3 Reference evapotranspiration (ET_o) during the experimental period of 2013, 2014 and 2015 at Alton Downs.

4.3.2. Growth parameters

4.3.2.1. Days to flowering

Days to flowering ranged across varieties from 80.0 to 93.0 DAS in 2013, 76 to 102 DAS in 2014 and 87 to 96 DAS in 2015 (Table 4.3). The average days to flowering were 90.5 DAS in 2014, 91.8 DAS in 2015 and 86.9 DAS in 2013.

The varieties showed significant year x variety interaction ($p \leq 0.001$, $LSD_{0.05} = 1.7$) (Table 4.3). Varieties AAT 9, AAT 10, AAT 11, AAT 12, AAT 15, AAT 16 and AAT 18 were late flowering varieties and the differences of flowering days for 2013 to 2014 were significantly higher than for the early flowering varieties AAT 3, AAT 4, AAT 6, AA T 13, AAT 17 and AAT 19. While in 2015 the days to flowering was significantly late for early flowering varieties than in 2014.

The late flowering coincided with the time when the temperature fell below 15^{o}C in 2013 and 2014 (Table 4.3). All long grain type varieties were late for flowering compared to medium grain type varieties (Table 4.3 and Table 3.2). The majority of rainfall during the 2013, 2014 and 2015 occurred during the first 101 DAS, 85 DAS and 99 DAS, respectively. Early varieties received rainfall during the reproductive stage whereas later varieties suffered terminal drought due to lack of rainfall in year 2014 and 2015.

Table 4.3 Days to flowering of varieties under rainfed conditions at Alton Downs in 2013, 2014 and 2015

Variety	Grain Type	2013	2014	2015	Average
AAT 9	Long	93.0	102.0	96.0	97.0
AAT 10	Long	91.0	102.0	96.0	96.3
AAT 11	Long	92.0	102.0	96.0	96.7
AAT 12	Long	90.5	102.0	96.0	96.2
AAT 15	Long	91.5	102.0	96.0	96.5
AAT 16	Long	91.0	102.0	96.0	96.3
AAT 18	Long	92.0	102.0	96.0	96.7
AAT 3	Medium	82.0	76.0	87.0	81.7
AAT 4	Medium	81.0	76.0	87.0	81.3
AAT 6	Medium	83.0	76.0	87.0	82.0
AAT 13	Medium	81.5	76.0	87.0	81.5
AAT 17	Medium	81.5	79.0	87.0	82.5
AAT 19	Medium	80.0	79.0	87.0	82.0
Average		**86.9**	**90.5**	**91.8**	**89.7**
			P-value	LSD at 0.05	
	Year		< 0.001	0.399	
	Variety		< 0.001	0.983	
	Year*Variety		< 0.001	1.703	

4.3.2.2. Plant height

Mean plant height of varieties at harvest ranged from 71.0 cm (AAT 15) to 92.5 cm (AAT 12) in 2013, 64.5 cm (AAT 16) to 87.8 cm (AAT 4) in 2014, and from 89.9 cm (AAT 18) to 96.4 cm in 2015 (AAT 13) (Table 4.4).

Variety effect on plant height was significantly affected by year of planting because there was a significant year x variety interaction ($p = 0.046$) (Table 4.4). All the varieties were significantly taller in year 2015 than in year 2014 except AAT 4 and AAT 17 while for year 2013 and 2014 only AAT 11 and AAT 12 showed significant reduction in plant height. Variety AAT 3 was the tallest variety (87.7 cm), whereas AAT 16 was the shortest variety (76.4 cm) among the 13 varieties tested (Table 4.4).

Table 4.4 Plant height (cm) of varieties under rainfed conditions at Alton Downs in 2013, 2014 and 2015.

Variety	**Flowering**	**2013**	**2014**	**2015**	**Average**
AAT 9	Late	75.5	71.8	94.9	80.7
AAT 10	Late	83.0	73.6	91.9	82.8
AAT 11	Late	84.5	74.4	94.8	84.6
AAT 12	Late	92.5	72.9	94.6	86.7
AAT 15	Late	71.0	70.9	95.1	79.0
AAT 16	Late	74.0	64.5	90.7	76.4
AAT 18	Late	73.5	72.7	89.9	78.7
AAT 3	Early	85.0	83.1	94.9	87.7
AAT 4	Early	79.5	87.8	93.8	87.0
AAT 6	Early	80.0	81.3	94.9	85.4
AAT 13	Early	76.5	83.3	96.4	85.4
AAT 17	Early	78.5	83.1	90.3	84.0
AAT 19	Early	75.5	77.9	93.9	82.4
Average		79.2	76.7	93.5	83.1
			P-value	LSD at 0.05	
	Year		0.01	7.43	
	Variety		0.005	5.79	
	Year*Variety		0.046	10.032	

4.3.3. Physiological parameters

4.3.3.1. Leaf gas exchange measurement

Leaf photosynthesis

There was no significant effect of year, variety or year x variety on leaf photosynthetic rate during the heading stage (data not presented). Leaf photosynthetic rate ranged from 5.78 to 12.86 in 2013, 6.13 To 14.85 in 2014 and 2.51 To 5.27 µmol /m^2/ s in 2015.

Leaf transpiration

There was no significant effect of year, variety or year x variety on leaf transpiration rate during heading stage (data not presented). Leaf transpiration rate ranged from 1.34 to 2.27 in 2013, 2.07 To 3.76 in 2014 and 1.55 To 3.18 mmol /m^2/ s in 2015.

Stomatal conductance

There was no significant effect of year, variety or year x variety on leaf stomatal conductance during heading stage (data not presented). Stomatal conductance rate ranged from 0.05 to 0.11 in 2013, 0.05 To 0.12 in 2014 and 0.03 To 0.07 mol/m^2/ s in 2015.

Water use efficiency

There was no significant effect of year, variety or year x variety on water use efficiency during heading stage (data not presented). Water use efficiency ranged from 4.03 to 6.96 in 2013, 2.42 To 6.05 in 2014 and 1.03 To 2.04 µmol CO2/mmol H2O in 2015.

4.3.4. Yield and yield components

4.3.4.1. Sample plot yield

Grain yield of rice varieties ranged from 0.00 t/ha (all late flowering varieties) to 3.39 t/ha (AAT 19) in 2013. In 2014, yield ranged from 0.10 t/ha (AAT 18) to 3.85 t/ha (AAT 4) with a mean of 1.43 t/ha (Table 4.5). In 2015 the grain yield across rice varieties ranged from 0.24 t/ha (AAT 15) to 2.72 t/ha (AAT 6) under rainfed conditions with a mean of 1.38 t/ha (Table 4.5).

The yield performance of varieties depended on year of planting ($p < 0.001$) (Table 4.5) as some varieties showed significant increase in yield from 2014 to 2015 while varieties

AAT 13, AAT 17, AAT 19, AAT 3 and AAT 4 showed a decrease in yield over the same period (Table 4.5).

Table 4.5 Yield (t/ha) of varieties under rainfed condition at Alton Downs in 2013, 2014 and 2015.

Variety	Flowering	2013	2014	2015	Average
AAT 9	Late	0.00	0.11	0.83	0.31
AAT 10	Late	0.00	0.84	1.14	0.66
AAT 11	Late	0.00	0.49	0.61	0.37
AAT 12	Late	0.00	0.26	0.79	0.35
AAT 15	Late	0.00	0.11	0.24	0.12
AAT 16	Late	0.00	0.12	0.59	0.24
AAT 18	Late	0.00	0.10	0.42	0.17
AAT 3	Early	2.74	2.12	1.94	2.27
AAT 4	Early	2.80	3.85	2.10	2.92
AAT 6	Early	2.90	2.71	2.72	2.78
AAT 13	Early	3.04	2.19	2.02	2.42
AAT 17	Early	3.25	2.99	1.95	2.73
AAT 19	Early	3.39	2.72	2.65	2.92
Average		1.39	1.43	1.38	1.40
			P-value	LSD at 0.05	
	Year		0.956	0.526	
	Variety		<0.001	0.435	
	Year*Variety		<0.001	0.75	

4.3.4.2. Whole plot yield

Grain yield of rice varieties ranged from 0.00 t/ha (all late flowering varieties) to 2.73 t/ha (AAT 4) in 2013. In 2014 yield ranged from 0.05 t/ha (AAT 15) to 2.06 t/ha (AAT 6) with a mean of 0.69 t/ha (Table 4.6). While in 2015 the grain yield across rice varieties ranged from 0.29 t/ha (AAT 18) to 2.26 t/ha (AAT 4) under rainfed condition with a mean of 1.19 t/ha (Table 4.6).

The yield performance of varieties depended on year of planting ($p<0.001$) as all the varieties showed significant increase in yield from 2014 to 2015 except AAT 6, AAT 16 and AAT 18 while from 2013 to 2014 varieties AAT 4, AAT 17 and AAT 19 had significant yield reduction (Table 4.6).

Table 4.6 Yield (t/ha) of varieties (machine harvest) under rainfed condition at Alton Downs in 2013, 2014 and 2015

Variety	Flowering	2013	2014	2015	Average
AAT 9	Late	0.00	0.10	1.74	0.61
AAT 10	Late	0.00	0.29	1.64	0.64
AAT 11	Late	0.00	0.21	1.73	0.65
AAT 12	Late	0.00	0.09	1.56	0.55
AAT 15	Late	0.00	0.05	1.01	0.35
AAT 16	Late	0.00	0.13	0.84	0.32
AAT 18	Late	0.00	0.07	0.79	0.29
AAT 3	Early	1.09	1.33	2.93	1.78
AAT 4	Early	2.73	1.32	2.72	2.26
AAT 6	Early	1.98	2.06	1.60	1.88
AAT 13	Early	2.08	1.72	2.71	2.17
AAT 17	Early	1.92	1.03	2.75	1.90
AAT 19	Early	2.49	0.56	3.00	2.02
Average		**0.95**	**0.69**	**1.92**	**1.19**
			P-value	LSD at 0.05	
	Year		0.008	0.496	
	Variety		<0.001	0.425	
	Year*Variety		<0.001	0.736	

4.3.4.3. Biomass yield

Biomass ranged from 5.34 t/ha (AAT 11) to 9.56 t/ha (AAT 6) with a mean of 8.21 t/ha in 2013 (Table 4.7). In 2014 it was higher and ranged from 4.91 t/ha (AAT 9) to 7.90 t/ha (AAT 4) with mean of 6.26 t/ha. While in 2015 the biomass yield ranged from 4.51 t/ha (AAT 11) to 7.25 t/ha (AAT 19) under rainfed conditions with a mean of 5.83 t/ha.

Biomass yield differed significantly between varieties (p=0.004) with AAT 19 with the highest biomass yield (7.58 t/ha) and AAT 11 recording the lowest (5.35 t/ha).

Table 4.7 Biomass yield (t/ha) of varieties under rainfed condition at Alton Downs in 2013, 2014 and 2015

Variety	Flowering	2013	2014	2015	Average
AAT 9	Late	7.35	4.91	5.54	5.93
AAT 10	Late	6.65	6.58	6.17	6.46
AAT 11	Late	5.34	6.21	4.51	5.35
AAT 12	Late	8.63	5.67	5.49	6.59
AAT 15	Late	8.23	6.42	4.87	6.50
AAT 16	Late	8.13	6.26	5.36	6.58
AAT 18	Late	8.03	6.00	5.18	6.40
AAT 3	Early	9.52	5.07	6.60	7.06
AAT 4	Early	8.52	7.90	6.02	7.48
AAT 6	Early	9.56	6.53	6.23	7.44
AAT 13	Early	9.37	5.69	6.88	7.32
AAT 17	Early	8.90	7.20	5.73	7.28
AAT 19	Early	8.54	6.97	7.25	7.58
Average		8.21	6.26	5.83	6.77
			P-value	LSD at 0.05	
	Year		0.078	2.199	
	Variety		0.004	1.083	
	Year*Variety		0.083	2.373	

4.3.4.4. Harvest Index (HI)

Harvest index (HI) of the rice varieties ranged from 0.00 (all late flowering varieties) to 0.50 (AAT 19) in year 2013 (Table 4.8) with a mean of 0.20. In 2014, HI ranged from 0.02 (AAT 15) to 0.49 (AAT 4), with a mean of 0.22. In 2015, HI ranged from 0.14 (AAT 18) to 0.43 (AAT 17) with a mean of 0.45 (Table 4.8).

The effect of varieties on HI depended on year of planting ($p < 0.001$) (Table 4.8). In 2013, none of the late varieties produced grain; hence, their HI was 0.00. All the varieties showed significant increase in HI from 2014 to 2015 except AAT 11, AAT 12, AAT 13 and AAT 3 while varieties AAT 4 and AAT 6 showed a decrease in HI over the same period (Table 4.8).

Table 4.8 Harvest index (HI) of varieties under rainfed condition at Alton Downs in 2013, 2014 and 2015.

Variety	Flowering	2013	2014	2015	Average
AAT 9	Late	0.00	0.02	0.27	0.10
AAT 10	Late	0.00	0.13	0.25	0.12
AAT 11	Late	0.00	0.08	0.31	0.13
AAT 12	Late	0.00	0.05	0.25	0.10
AAT 15	Late	0.00	0.02	0.18	0.07
AAT 16	Late	0.00	0.02	0.15	0.06
AAT 18	Late	0.00	0.02	0.14	0.05
AAT 3	Early	0.38	0.41	0.39	0.39
AAT 4	Early	0.42	0.49	0.42	0.44
AAT 6	Early	0.40	0.42	0.31	0.38
AAT 13	Early	0.42	0.39	0.36	0.39
AAT 17	Early	0.46	0.41	0.43	0.44
AAT 19	Early	0.50	0.39	0.40	0.43
Average		0.20	0.22	0.30	0.24
			P-value	LSD at 0.05	
	Year		0.025	0.057	
	Variety		<0.001	0.034	
	Year*Variety		<0.001	0.059	

4.3.4.5. Tillers per plant

Tillers per plant ranged from 4.5 (AAT 19) to 15.5 (AAT 3) in 2013, with an average of 8.0 (Table 4.9). In 2014, it ranged from 5.1 (AAT 15) to 9.3 (AAT 4 and AAT 11), with an average of 7.8. In 2015, the tillers per plant ranged from 2.7 (AAT 18) to 7.5 (AAT 11), with an average of 5.4.

The average number of tillers differed significantly between varieties ($p \leq 0.001$); AAT 3 had the highest number of tillers (10.0) and AAT 15 showed the least (4.5). Between years, 2013 produced the highest average number of tillers per plant (8.0), which did not differ from that of 2014 (7.8), but 2015 produced the least (5.4) (Table 4.9).

Table 4.9 Tillers per plant of varieties under rainfed conditions at Alton Downs in 2013, 2014 and 2015.

Variety	Flowering	2013	2014	2015	Average
AAT 9	Late	7.5	7.6	5.2	6.8
AAT 10	Late	10.5	7.2	5.1	7.6
AAT 11	Late	10.5	9.3	7.5	9.1
AAT 12	Late	12.0	8.6	6.1	8.9
AAT 15	Late	5.0	5.1	3.4	4.5
AAT 16	Late	6.0	5.5	5.6	5.7
AAT 18	Late	6.0	7.1	2.7	5.3
AAT 3	Early	15.5	9.0	5.6	10.0
AAT 4	Early	7.0	9.3	7.1	7.8
AAT 6	Early	7.5	7.8	6.1	7.1
AAT 13	Early	6.0	8.9	4.8	6.6
AAT 17	Early	6.5	8.9	4.5	6.6
AAT 19	Early	4.5	7.6	5.9	6.0
Average		8.0	7.8	5.4	7.1
			P-value	LSD at 0.05	
	Year		0.022	1.613	
	Variety		<0.001	2.228	
	Year*Variety		0.073	3.859	

4.3.4.6. Effective tillers

Effective tillers per plant ranged between varieties from 0.0 (AAT 9) to 6.0 (AAT 3) in 2013, with an average of 2.6 (Table 4.10). In 2014, it ranged from 3.1 (AAT 15) to 8.9 (AAT 4), with average of 5.3 (Table 4.10). In 2015 the effective tillers per rice plant ranged across varieties from 1.3 (AAT 18) to 6.2 (AAT 4), with an average of 4 (Table 4.10).

The average number of effective tillers differed significantly between varieties ($p \leq 0.001$); AAT 4 had the highest (6.9) and AAT 15 had the least (2.0). Between years, 2013 produced the least number of effective tillers (2.6) compared to the other years (Table 4.10).

Table 4.10 Effective tillers per plant for varieties under rainfed conditions at Alton Downs in 2013, 2014 and 2015.

Variety	Flowering	2013	2014	2015	Average
AAT 9	Late	0.0	4.0	3.2	2.4
AAT 10	Late	1.0	5.1	3.7	3.3
AAT 11	Late	1.0	3.8	5.6	3.5
AAT 12	Late	1.0	4.9	4.1	3.3
AAT 15	Late	0.5	3.1	2.3	2.0
AAT 16	Late	1.0	3.9	3.2	2.7
AAT 18	Late	1.0	4.6	1.3	2.3
AAT 3	Early	6.0	7.6	4.4	6.0
AAT 4	Early	5.5	8.9	6.2	6.9
AAT 6	Early	4.0	5.8	5.4	5.1
AAT 13	Early	4.5	5.8	3.7	4.7
AAT 17	Early	5.0	5.8	4.2	5.0
AAT 19	Early	3.5	5.8	5.3	4.9
Average		2.6	5.3	4.0	4.0
			P-value	LSD at 0.05	
	Year		0.005	0.857	
	Variety		<0.001	1.837	
	Year*Variety		0.650	3.1	

4.3.5. Water productivity

Sample plot water productivity ranged from 0.00 t/ML to 0.62 t/ML in 2013 (Table 4.11). In 2014, it was higher and ranged from 0.02 t/ML (AAT 18) to 0.69 t/ML (AAT 4), with a mean of 0.26 t/ML. In 2015, the water productivity ranged from 0.04 t/ML (AAT 15) to 0.41 t/ML (AAT 6) under rainfed conditions, with a mean of 0.21 t/ML.

Varietal water productivity depended significantly on the year of experiment ($p < 0.001$) (Table 4.11) as the varieties AAT 3 and AAT 4 had significantly less water productivity in 2015 compared to 2014, and the varieties AAT 4 and AAT 10 had significantly greater water productivity in 2014 than in 2013. Varieties AAT 13 and AAT 19 had significantly less water productivity in 2014 and 2015 than in 2013 (Table 4.11).

Table 4.11 Water productivity (t/ML) of varieties under rainfed condition at Alton Downs in 2013, 2014 and 2015.

Variety	Flowering	2013	2014	2015	Average
AAT 9	Late	0.00	0.02	0.12	0.05
AAT 10	Late	0.00	0.15	0.17	0.11
AAT 11	Late	0.00	0.09	0.09	0.06
AAT 12	Late	0.00	0.05	0.12	0.06
AAT 15	Late	0.00	0.02	0.04	0.02
AAT 16	Late	0.00	0.02	0.09	0.04
AAT 18	Late	0.00	0.02	0.06	0.03
AAT 3	Early	0.50	0.38	0.29	0.39
AAT 4	Early	0.51	0.69	0.32	0.51
AAT 6	Early	0.53	0.49	0.41	0.47
AAT 13	Early	0.56	0.39	0.30	0.42
AAT 17	Early	0.60	0.53	0.29	0.47
AAT 19	Early	0.62	0.49	0.40	0.50
Average		0.26	0.26	0.21	0.24
			P-value	LSD at 0.05	
	Year		0.28	0.092	
	Variety		<0.001	0.074	
	Year*Variety		<0.001	0.128	

4.4. Discussion

Days to flowering showed a significant strong negative correlation with yield (r = -0.80***) under rainfed conditions across the years (Table 4.12) and individually in each year separately for 2013 (r = -0.95***, Table 4.13), 2014 (r = -0.91***, Table 4.14) and 2015 (r =-0.89***, Table 4.15). As the days to flowering increased the yield of the variety decreased. Coefficient of variation of mean yield of varieties was 113 %, 95% and 63 % in year 2013, 2014 and 2015, respectively. This year-to-year variability was due to the variability of flowering time and the effect of terminal drought and cold. Late flowering varieties were exposed to terminal drought and low temperatures at later stages, as reported in Chapter 3, with its effect on panicle fertility, grain setting and 1000 grain weight in year 2014. The late maturing varieties were not able to produce any yield in 2013 (Table 4.5) due to the later sowing date and the consequent exposure to low temperatures below 15°C during flowering (Figure 4.2). Fukai (1999) reported that terminal drought has a significant negative effect on the panicle fertility and grain yield, and below 22°C rice suffers severe yield loss due to the chilling effect (Yoshida, 1978).

Higher yield in early varieties reflects a degree of drought avoidance rather than drought tolerance as these varieties flowered and produced grain before commencement of water stress as described by Levitt (1972). Boyer and Westgate (2004) also reported the terminal drought stress increased pollen sterility leading to decreased yield. Similar decrease in yield of late varieties was found in chickpea (Soltani and Sinclair, 2012) where the early genotypes were superior to late genotypes due to drought avoidance during flowering and grain filling stage.

The effective tillers number per plant was significantly correlated to yield across the years (r= 0.43***, Table 4.12), and in 2013 (r = 0.85***, Table 4.13), 2014 (r= 0.59**, Table 4.14) and 2015 (r = 0.52**, Table 4.15). Effective tillers per plant was more strongly correlated to yield in 2013 than in later years. In 2013, late flowering varieties were exposed to the cold temperatures and late varieties, although producing more tillers than in later years (Table 4.10) were unable to produce panicles and those that produced panicles did not produce yield in that year. Increased effective tillers per plant can improve yield but it has always been a major hurdle for better yield in upland varieties (Matsumoto et al., 2014). Notably from the current trials, early varieties were high in effective tillers per plant and had higher yield across the trials.

Yield has significant correlation with A around flowering time (r=0.40***) across the year as well as in year 2014 (r=0.67***) but was not significant in 2013 and 2015 (Table 4.12). Water productivity was significantly correlated with WUE during flowering (r= 0.47***) across years (Table 4.12). Similarly, WUE was significantly correlated with A (r= 0.79***) across years (Table 4.12) and in 2013 (r = 0.79***), 2014 (r = 0.62***) and 2015 (r = 0.81***). Water use efficiency and water productivity are both ratios and depend on their numerator and denominator dynamics (Blum, 2005). The photosynthetic parameters were not significantly different between varieties and between the years. Yield showed significant interaction with year and variety (Table 4.5). However, the varieties which recorded higher photosynthetic rate (e.g., AAT 11 and AAT 13), did not have significant correlation with yield and water productivity due to the effect of terminal drought. The significant negative correlation between yield and flowering date suggests that the less stress to early varieties contributed to better translocation of assimilates to grain sinks while late varieties, being stressed, were unable to translocate to the sink due to stress condition at later stages. This is as reported in chapter 3 under rainfed and strategic irrigation where the late flowering varieties had significantly higher panicle sterility due to exposure to terminal drought. Higher panicle sterility reduces the sink capacity resulting in lower yield (Boonjung and Fukai, 1996).

Biomass has significant correlation with yield (r = 0.43***), water productivity (r = 0.47***), photosynthetic rate (r = 0.29**), stomatal conductance (r = 0.23*) and water use efficiency (r= 0.46***) but significant negate correlation with days to flowering (r = -39***) and transpiration efficiency (r = -0.30**) across the year (Table 4.12). Interestingly biomass yield was not correlated with photosynthetic rate, transpiration rate, stomatal conductivity and water use efficiency when analysed separately for 2013, 2014 and 2015 while biomass was significantly correlated with the yield in 2013 (r = 0.60**), 2014 (r = 0.48*) and 2015 (r = 0.74***) (Table 4.13, Table 4.14 and Table 4.15). Photosynthesis is the major factor for biomass and partitioning of biomass into grain determines yield (Farooq et al., 2009). Yield is strongly correlated with HI in 2013 (r = 0.99***), 2014 (r = 0.96***), 2015 (r = 0.75***) and across the year (r = 0.89***). The significant varietal difference in biomass yield (Table 4.7) and the strong correlation with yield suggests the varieties with higher biomass are also highest yielders such as AAT 19 which has highest mean yield (2.92 t/ha) with highest biomass (7.58 t/ha) with one of the highest HI (0.43). Cao et al. (2002) studied the relationship between biomass and yield under alternate wetting and drying system and conventional irrigated system where the higher yields were associated with higher harvest index but not with biomass while under the flooded and aerobic system Peng et al. (2006) reported the yield difference more to biomass than harvest index.

In the two seasons where late varieties did produce some yield, yield of late varieties (long grain type) such as AAT 9, AAT 10, AAT 11, AAT 12, AAT 15, AAT 16 and AAT 18 was limited to less than 1.14 t/ha while earlier varieties (medium grain type) such as AAT 3, AAT 4, AAT 6, AAT 13, AAT 17 and AAT 19 produced more than 1.94 t/ha (Table 4.5 and Figure 4.4). The highest yield was obtained from AAT 4 with 3.85 t/ha in year 2014 and across the years it yielded 2.92 t/ha which is the highest overall average while AAT 6 showed less deviation from mean yield with an average of 2.78 t/ha (Figure 4.4). Both the varieties AAT 4 and AAT 6 are early flowering varieties (Table 4.3). Jongdee et al.

(1997) also reported that early sowing contributed to increased yield through escape of terminal drought for rainfed lowland rice.

Table 4.12 Correlation between phenological, physiological and agronomical characters of varieties under rainfed conditions at Alton Downs averaged over the years 2013, 2014 and 2015.

	Yield (t/ha)	HI	Water productivity	Plant height	Tillers/ plant	Effective tillers/ plant	Days to flowering	A	E	gs	WUE
HI	0.89***	-									
Water productivity	0.99***	0.87***	-								
Plant height	0.13ns	0.35**	0.04ns	-							
Tillers/ plant	0.22ns	0.13ns	0.26*	-0.13ns	-						
Effective tillers/plant	0.43***	0.41***	0.43***	0.01ns	0.63***	-					
Days to flowering	-0.80***	-0.77***	-0.59***	-0.17ns	-0.21ns	-0.42***	-				
A	0.40***	0.26*	0.48***	-0.46***	0.34**	0.25*	-0.45***	-			
E	0.00ns	0.05ns	0.00ns	0.00ns	-0.09ns	0.11ns	-0.12ns	0.30*	-		
gs	0.34**	0.27*	0.38**	-0.26*	0.14ns	0.18ns	-0.32**	0.44***	0.57***	-	
WUE	0.39**	0.24ns	0.47***	-0.39**	0.47***	0.17ns	-0.33**	0.79***	-0.27*	0.07ns	
Biomass (t/ha)	0.43***	0.20ns	0.47***	-0.18ns	0.20ns	-0.06ns	-0.39***	0.29**	-0.30**	0.23*	0.46***

*p < 0.05, **p < 0.01, ***< 0.001, ns = not significant

Table 4.13 Correlation between phenological, physiological and agronomical characters of varieties under rainfed conditions at Alton Downs in 2013.

	Yield	HI	Water productivity	Plant height	Tillers/ plant	Effective tillers/ plant	Days to flowering	A	E	gs	WUE
HI	0.99***	-									
Water productivity	1.00***	0.99***	-								
Plant height	-0.01ns	-0.02ns	-0.01ns	-							
Tillers/ plant	-0.11ns	-0.12ns	-0.11ns	0.65***	-						
Effective tillers/plant	0.85***	0.87***	0.85***	-0.03ns	0.12ns	-					
Days to flowering	-0.95***	-0.97***	-0.95***	0.02ns	0.06ns	-0.91***	-				
A	0.23ns	0.25ns	0.23ns	-0.23ns	-0.29ns	0.21ns	-0.23ns	-			
E	0.38ns	0.42*	0.38ns	-0.38ns	-0.34ns	0.44*	-0.44*	0.38ns	-		
gs	0.30ns	0.30ns	0.30ns	0.00ns	0.12ns	0.40*	-0.30ns	-0.10ns	0.67***	-	
WUE	0.10ns	0.09ns	0.10ns	0.01ns	0.04ns	0.06ns	-0.05ns	0.79***	-0.19ns	-0.43*	
Biomass (t/ha)	0.60**	0.55**	0.60**	-0.01ns	0.01ns	0.50**	-0.54**	0.11ns	-0.14ns	-0.01ns	0.22ns

*p < 0.05, **p < 0.01, ***< 0.001, ns = not significant

Table 4.14 Correlation between phenological, physiological and agronomical characters of varieties under rainfed conditions at Alton Downs in 2014.

	Yield	HI	Water productivity	Plant height	Tillers/ plant	Effective tillers/ plant	Days to flowering	A	E	gs	WUE
HI	0.96***	-									
Water productivity	1.00***	0.96***	-								
Plant height	0.84***	0.85***	0.84***	-							
Tillers/ plant	0.34	0.40*	0.34	0.61***	-						
Effective tillers/plant	0.59**	0.64***	0.59**	0.68***	0.55**	-					
Days to flowering	-0.91***	-0.97***	-0.91***	-0.81***	-0.36	-0.59**	-				
A	0.67***	0.68***	0.67***	0.49*	0.04	0.10	-0.74***	-			
E	0.40*	0.38	0.40*	0.24	-0.27	-0.05	-0.43*	0.61***	-		
gs	0.33	0.32	0.33	0.19	-0.27	-0.07	-0.37	0.57**	0.97***	-	
WUE	0.44*	0.51**	0.44*	0.35	0.30	0.20	-0.55**	0.62***	-0.20	-0.20	
Biomass (t/ha)	0.48*	0.28ns	0.48*	0.31ns	-0.02ns	0.03ns	-0.19ns	0.25ns	0.26ns	0.18ns	0.01ns

*p < 0.05, **p < 0.01, ***< 0.001, ns = not significant

Table 4.15 Correlation between phenological, physiological and agronomical characters of varieties under rainfed conditions at Alton Downs in 2015.

	Yield	HI	Water productivity	Plant height	Tillers/ plant	Effective tillers/ plant	Days to flowering	A	E	gs	WUE
HI	0.75***	-									
Water productivity	0.99***	0.76***	-								
Plant height	-0.04ns	-0.07ns	-0.04ns	-							
Tillers/ plant	0.19ns	0.26ns	0.20ns	0.37ns	-						
Effective tillers/plant	0.52**	0.56**	0.52**	0.22ns	0.89***	-					
Days to flowering	-0.89***	-0.80***	-0.89***	-0.11ns	-0.16ns	-0.47*	-				
A	-0.16ns	-0.17ns	-0.16ns	-0.06ns	0.20ns	0.16ns	0.26ns	-			
E	-0.10ns	0.06ns	-0.09ns	-0.12ns	0.26ns	0.21ns	0.27ns	0.40*	-		
gs	-0.14ns	-0.01ns	-0.14ns	0.26ns	0.29ns	0.15ns	0.16ns	0.24ns	0.63***	-	
WUE	-0.10ns	-0.20ns	-0.10ns	0.02ns	0.07ns	0.05ns	0.11ns	0.81***	-0.18ns	-0.16ns	
Biomass (t/ha)	0.74***	0.43*	0.74***	0.17ns	0.09ns	0.25ns	-0.66***	-0.25ns	-0.26ns	-0.18ns	-0.12ns

*p < 0.05, **p < 0.01, ***< 0.001, ns = not significant

The varietal stability across the years can be measured by three different approaches (Lin et al., 1986). A variety is defined as stable when i) the variation (coefficient of variation) of varieties between years is low (Type I stability), ii) the response of varieties to year is parallel to the response of all varieties in the trial (Type II stability), or iii) the deviation from the mean regression coefficient for each variety regression coefficient is minimal when the variety mean is regressed over trial mean (Type III stability). The second and third approach can be explained using the Eberhart and Russell (1966) model.

A variety is stable if the coefficient of variation (CV) between years is low, as it measures the genotype's homeostasis. The CV of varieties ranged from 3.9 % to 144.9 % (Table 4.16). The varieties with higher CV means they are not stable yielding across years. Late flowering varieties have CV higher than 88.1% across years, and they can be classified as unstable varieties. Variety AAT 6 had the lowest CV of 3.9 % and can be classified as the most stable variety, followed by AAT 19 as the second most stable with at 14.1 %. A late maturing variety has a higher CV due to its exposure to severe cold in year 2013 and mild cold in 2014 in addition to terminal drought during flowering in 2014 and 2015. This resulted in severe environment in 2013 followed by less severe environment in 2014 and more favourable in 2015. Early flowering varieties such as AAT 6 did not suffer cold and terminal drought in all three years. Type I stability i.e. CV is found negatively correlated with varietal mean yield (Costa and Bollero, 2001) and in the 3 year rainfed trial CV has also shown strong negative correlation with yield (r = - 0.95***, Table 4.17).

The Eberhart and Russell (1966) model was applied to test the varietal stability against the environment mean to see the varietal response to the given environment. According to Eberhart and Russell (1966) a variety is stable if it is responsive to favourable environment conditions, when mean variety yield is regressed against site yield, with a regression coefficient (*b*) of 1.0 or greater and with low deviations from the mean regression (sd=0). Varieties AAT 10, AAT 12, AAT 15, AAT 3, AAT 17 and AAT 19 had significant deviation from the mean regression (Table 4.16). This suggestes that these varieteis do not respond significantly with the better environment and cannot be classified as stable. As Costa and Bollero (2001) indicated in stability analysis of barley measured by regression, the rice varieties (AAT 9, AAT 11, AAT 16, AAT 18, AAT 4, AAT 6 and AAT 13) that have no significant difference from 1.0 have genetic potential for better yield under improved growing conditions at Alton Downs. Varieties AAT 4 and AAT 11 have high *b* values and no significant difference from 1.0, and AAT 4 has the lowest sd between these two varieties. These varieties responded with better yield under improved environment conditions and AAT 4 was most responsive to favourable environmental conditions according to the Eberhart and Russell stability concept as it would be categorised as an unstable variety with a high CV of 30.1%.

Table 4.16 Means, coefficient of variation (CV), slope (b) and sd of slope from grain yield of varieties tested at Alton Downs in 2013, 2014 and 2015.

Variety	**Yield (t/ha)**	**CV %**	Slope (b)	Standard deviation
AAT 9	0.31	144.9	-10.80	0.191
AAT 10	0.66	89.5	0.81**	0.628
AAT 11	0.37	88.1	1.36	0.137
AAT 12	0.35	115.2	-6.76*	0.199
AAT 15	0.12	103.9	-1.41**	-0.043
AAT 16	0.24	132.3	-6.74	0.070
AAT 18	0.17	124.8	-4.27	0.002
AAT 3	2.27	18.6	-1.29*	0.285
AAT 4	2.92	30.1	34.85	-0.022
AAT 6	2.78	3.9	-1.34	-0.047
AAT 13	2.42	22.7	-2.96	0.521
AAT 17	2.73	25.3	14.95**	0.605
AAT 19	2.92	14.1	-3.39*	0.255

Significantly different from 1.0 at $^{*}p < 0.05$, $^{**}p < 0.01$

Table 4.17 Correlation coefficients between the mean yield and stability parameters of varieties tested at Alton Downs in 2013, 2014 and 2015

	CV (%)	Slope (b)	Standard deviation	Yield (t/ha)
CV (%)	-			
Slope (b)	-0.46^{ns}	-		
Standard deviation	-0.24^{ns}	-0.01^{ns}	-	
Yield (t/ha)	-0.95***	0.53^{ns}	0.23^{ns}	-

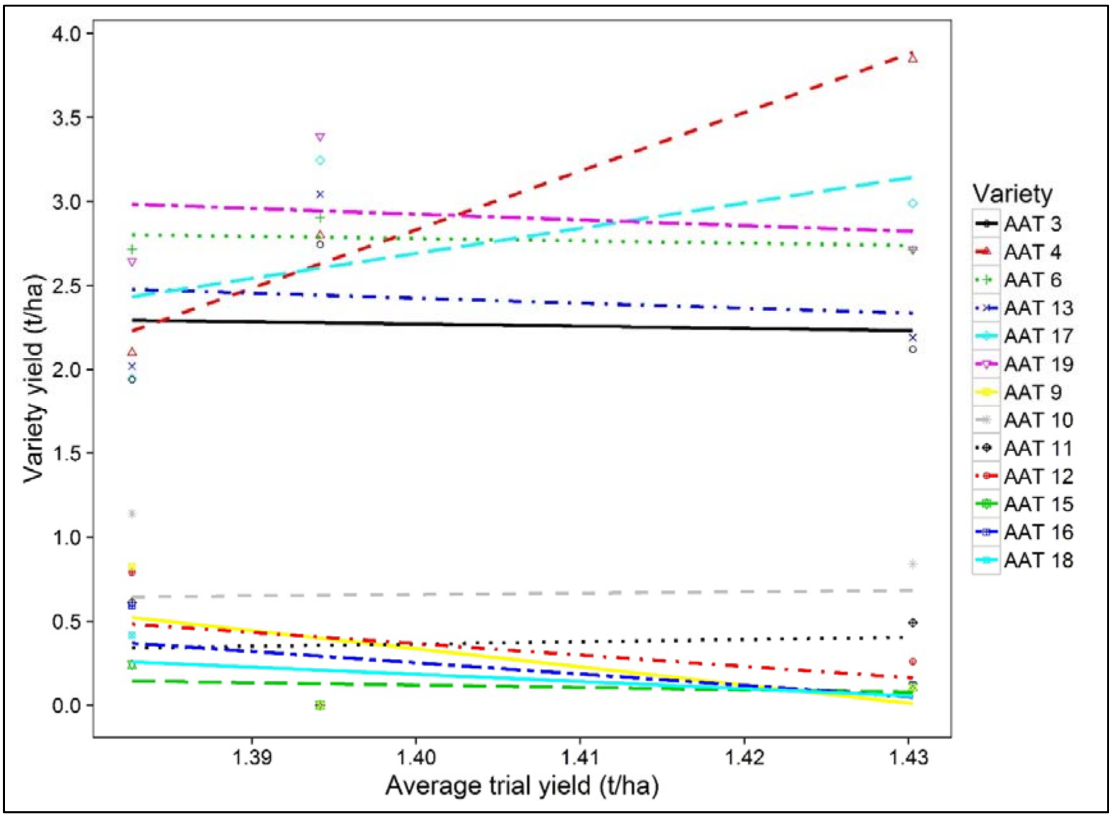

Figure 4.4 Yield of varieties across the years 2013, 2014 and 2015.

While due to the late flowering varieties not producing any grain in 2013 and being subjected to cold and terminal drought the difference in mean yield of good years and bad years is very narrow between 1.38 t/ha and 1.43 t/ha (Table 4.19). Therefore, it is not representative to the domain potential. To dissect the stability of domain suitable early flowering varieties were analysed for type II and type III stability separately using Eberhart and Russell stability model (Table 4.18).

When early varieties were analysed for their yield stability using regression across the years separately against the trial mean, AAT 4, AAT 13 and AAT 17 had higher *b* value (i.e. they do better in better years compared to the average performance between years). Variety AAT 4 had significant deviation from mean slope 1 (Table 4.18). While the regression slope of AAT 17 and AAT 13 were not significantly deviated but AAT 17 has more standard deviation than AAT 13. Therefore, the variety AAT 13 can be defined as the most stable variety across the year which gave good yield across the years and better yield when the environment (year) was favourable (Table 4.18 and Figure 4.5).

Table 4.18 Means, slope (b) and sd of slope from grain yield (t/ha) of early flowering varieties tested at Alton Downs in 2013, 2014 and 2014.

SN	**Varieties**	**2013**	**2014**	**2015**	**Mean yield**	**Slope (b)**	**sd-slope**
1	AAT 13	3.04	2.19	2.02	2.42	1.14	0.048
2	AAT 17	3.25	2.99	1.95	2.73	1.68	-0.105
3	AAT 19	3.39	2.71	2.65	2.92	0.81	-0.003
4	AAT 3	2.74	2.12	1.94	2.27	1.91	-0.039
5	AAT 4	2.80	3.85	2.10	2.91	1.23**	0.918
6	AAT 6	2.90	2.71	2.72	2.78	0.19	-0.112
	Mean yield	**3.02**	**2.76**	**2.23**	2.67		

Significantly different from 1.0 at **p<0.01

Table 4.19 Means, slope (b) and sd of slope from grain yield of late flowering varieties tested at Alton Downs in 2013, 2014 and 2014.

Varieties	**2013**	**2014**	**2015**	**Mean yield**	**Slope (b)**	**sd-slope**
AAT 10	0.00	0.84	1.14	0.66	1.68	0.050
AAT 11	0.00	0.49	0.61	0.37	0.89	0.006
AAT 12	0.00	0.26	0.79	0.35	1.21	-0.021
AAT 15	0.00	0.11	0.24	0.12	0.36	-0.026
AAT 16	0.00	0.12	0.59	0.24	0.91	-0.013
AAT 18	0.00	0.10	0.42	0.17	0.63	-0.022
AAT 9	0.00	0.10	0.83	0.31	1.28	0.017
Average	**0.00**	**0.20**	**0.58**	0.26		

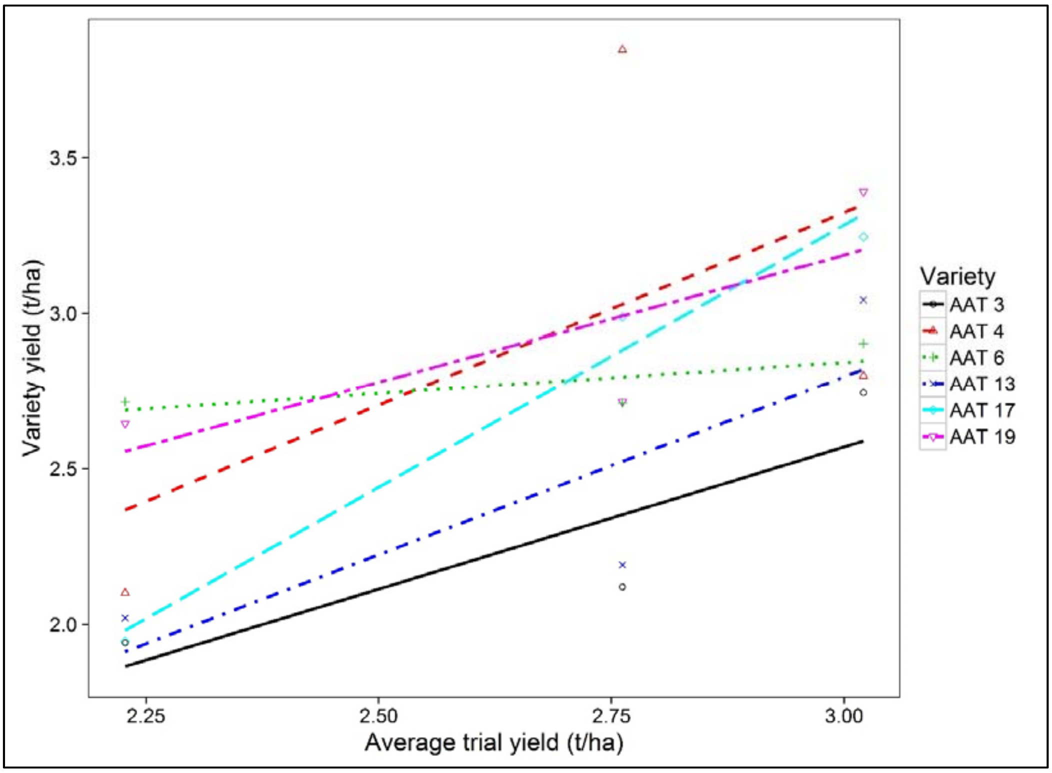

Figure 4.5 Average of early flowering varieties across the years 2013, 2014 and 2015.

4.5. Conclusion

The rainfall pattern during the flowering stage caused terminal drought to the late flowering varieties during the grain filling period after March in Alton Downs. The temperature was also unfavourable for late flowering varieties exposing them to temperatures below 15°C during the flowering stage in 2013 and 2014. Hence, phenology had significant impact on the yield and yield contributing characters, such as effective tillers, under rainfed conditions in central Queensland. Varieties with early flowering, such as AAT 3, AAT 4, AAT 6, AAT 13, AAT 17 and AA 19, escaped the drought and cold (during 2013 and 2014), which resulted in their better yield as compared to the late varieties. Late flowering varieties AAT 9, AAT 10, AAT 11, AAT 12, AAT 15, AAT 16 and AAT 18 did not produced any grain in year 2013, and while in year 2014 and 2015 were significantly lower yielding than early flowering varieties. AAT 6 had the lowest CV across the years, showing it to be the most consistent yielder under all the conditions at Alton Downs. Variety AAT 4 had better regression slope more than and close to 1.0 with lowest deviations from mean regression when compared with all the varieties tested. However, among the early varieties, when analysed separately, AAT 13 showed good potential under better growing conditions.

Varieties AAT 4 and AAT 13 were found to be consistently high yielding under rainfed conditions and can be considered as stable varieties for rainfed cultivation. However, this interpretation is based on short-term study of three seasons; hence, a rigorous assessment for varietal stability under irrigated conditions in central Queensland conditions is suggested. Field evaluation of varieties for stability under strategic irrigation can offer more choices to growers for choice of varieties based on the availability of water for a particular rice growing season.

CHAPTER 5.PERFORMANCE OF RICE VARIETIES UNDER RAINFED CONDITION IN WET AND DRY TROPICS OF QUEENSLAND

Abstract

Rainfed rice systems are becoming more relevant in the context of the seasonal unpredictability of rainfall and declining access to irrigation water for the rice industry in Australia. Field experiments were conducted during the 2015 wet season at Alton Downs, central Queensland (dry tropics) and South Johnstone, north Queensland (wet tropics), to compare varietal performance in the drier and wetter tropics. The yield performance of varieties was evaluated and related to yield determining physiological, phenological and agronomic traits. At Alton Downs the rainfall was very low during the flowering and grain filling stages, which exposed the late flowering crop to terminal drought. In contrast, in the wet tropics of South Johnstone, the rainfall amount and distribution exceeded well above the crop evapotranspiration demand during the experiment. The results suggest that the earlier varieties such as AAT 4 and AAT 6 were higher yielders under Alton Downs conditions, but the late flowering and least yielding varieties under Alton Downs conditions, such as AAT 15 and AAT 18, were among the highest yielders in South Johnstone, with their yields greater by 6–20 fold that of Alton Downs. The greater yield of these later varieties at South Johnstone was due to the higher effective tiller number per plant, heavier 1000 grain weight, and greater harvest index, and higher panicle fertility and higher number of grains per panicle. Additionally, the enhanced leaf photosynthetic rate and WUE were coupled with increased flag leaf area, which had a significant contribution to yield under favourable soil moisture conditions in the wet tropical environment of South Johnstone.

Key words:

Drought, tropical, rice, rainfed, upland

5.1. Introduction

Rice is adapted to diverse environments such as in tropical lowlands in flooded conditions and in upland rainfed conditions in aerobic soils with little or no puddled water (Acuña et al., 2008). The rainfed system is prone to intermittent and terminal drought due to the unpredictability of rainfall for meeting crop water demand throughout the growing season. For this reason, the primary objective of any rainfed rice research programme is to identify varieties with yield stability across the different likely scenarios of drought environments.

When a target environment for drought testing has low or no rainfall during and after flowering, terminal drought stress ensues. Terminal drought can cause delay in anthesis and/or cessation of flowering and/or cause spikelet sterility (Saini and Westgate, 1999). Different drought resistance or tolerance mechanisms and associated traits have been identified in rice, such as those involving i) drought escape through selection of suitable phenology, ii) dehydration avoidance, iii) dehydration tolerance, and iv) drought recovery (Fukai and Cooper, 1995). To date there are no definitive and effective approaches for selection for drought stress tolerance at the reproductive stage (Venuprasad et al., 2007). Direct selection for yield is often considered the best approach during varietal screening as it integrates the overall physiological and phenological responses of crops in any particular environment, but this approach is prone to significant genotype by environment interaction (Lafitte and Courtois, 2002). The sporadic nature and unpredictability of drought stress are reasons for ineffective selection under natural stress in any rice production environment (Venuprasad et al., 2007). Therefore, varieties selected in one environment may not be adapted to other rice growing environments (Acuña et al., 2008). Varieties can have different physiological adaptations for yield responses in different rice growing environments.

Preliminary trials that assessed coleoptile length, response to leaf blast (Challagulla et al., 2015) and response to drought, particularly on transpiration efficiency conditioned by leaf and root traits, suggest a significant difference between the varieties in this study. The central Queensland region receives about 900 mm of annual rainfall of which about 700 mm falls during the wet season (Dec–May), whereas in South Johnstone of north Queensland the rainfall is about 3322 mm annually, of which 2600 mm falls during the summer season (Dec–May) (Bureau of Meteorology, 2016b). An understanding of varietal response under diverse agroclimatic environments can provide a useful understanding of the physiological, phenological and agronomic characteristics that underpin the genetic potential of the varieties tested for adaptation in the target rainfed environment. This chapter aims to investigate the physiological, phenological and agronomical traits that confirm yield responses of varieties in different rice growing environments representing dry and wet tropical environments of Queensland, Australia.

5.2. Materials and Methods

5.2.1. Site description

The experiment was conducted in two locations, during December, 2014 to March, 2015 in the wet tropics at South Johnstone, Queensland (17°36′29′′ S Latitude, 145°59′49′′ E Longitude, and 18 m above sea level), and during November, 2014 to March, 2015 in the dry tropics of Alton Downs, Queensland (23°18′14′′ S Latitude, 150°21′24′′ E Longitude, and 22 m above sea level).

The soil of the Alton Downs site was a heavy clay (self-mulching black cracking clay or vertisol) whereas the soil of South Johnstone was a clay loam. Soil chemical and nutritional characteristics are described in Table 5.1.

Table 5.1 Soil chemical and nutritional characteristics of experiment sites at Alton Downs and South Johnstone.

Parameter	Alton Downs	South Johnstone
pH	6.6	5.2
Organic C (%)	1.57	2.7
Nitrate nitrogen (N)	2.1	23.0
Ammonium nitrogen (N)	23.8	2.8
Phosphorous (mg/kg)	2.0 (Morgan)	12 (Colwell)
Potassium (mg/kg)	97	130
Organic matter (%OM)	2.8	4.6
EC (ds/m)	0.049	0.06
Cation exchange capacity (CEC)	60.19 (meq/100 g)	2.6 (meq/100 g)

5.2.2. Weather and experimental condition

The experimental site at Alton Downs has a subtropical climate characterised by distinct wet and dry seasons. From December to March is the warm wet season and from June to September it is cooler and drier. In contrast, the experimental site in South Johnstone has a tropical maritime climate characterised by high summer dominant rainfall with warm winters and a hot and humid summer.

Rainfall data and maximum and minimum air temperatures were obtained from the Australian Bureau of Meteorology, Rockhampton Aerodrome weather station and South Johnstone experimental station, Department of Agriculture, Fisheries and Forestry. Total rainfall received during the experimental period was 593 mm and 839 mm for Alton Downs and South Johnstone, respectively. Details of weather of the experimental site are presented in section 5.3.1. The rainfall recorded in South Johnstone during the rice season was about one third of the long-term average rainfall for the same period.

5.2.3. Experimental design and treatments

The experimental was set up as a randomised complete block design (RCBD) to compare varieties with two replications at Alton Downs and 3 replications at South Johnstone. At Alton Downs, each variety was planted in 25 m × 3.75 m plot. In each plot a 2 m × 1 m sample plot was marked for recording of experimental data and sample plot harvest for yield assessment. In South Johnstone, each variety was planted in smaller 3 m x 2 m plots for the recording of experimental data and harvest data were derived from the whole plot.

5.2.4. Crop management

The rice seeds were directly seeded in well a prepared seedbed, at a rate of 40 kg/ha. Seed were sown by tractor mounted seed dibbler at Alton Downs and manually by using a hoe in South Johnstone. Rows were 25 cm apart. The fields were fertilised with 100:29:76 kg NPK/ha using Crop King fertiliser entirely as basal application before planting of the crop.

Weeds in the experimental plots were controlled using commercial herbicides available on the market. A tank mix of Clomazone (Megister®) @ 0.4 L/ha plus pendimethalin (Stomp® 40) @ 2.5 L/ha plus paraquat 250 g/L (Gramoxone® 250) @ 0.8 L/ha was applied as described by (Taylor, 2013) after sowing rice. Similarly Dicamba 500 g/L (Kamba®500) @ 0.4 to 0.56 L/ha was applied during the early tillering stage to control broad leaf weed growth. Intensive manual weeding was also performed on three occasions at both sites in order to control the weeds that were not controlled by herbicides.

5.2.5. Rice varieties

Australian Agricultural Technologies Limited provided seeds of thirteen rice varieties for study. Table 5.2 presents the varieties used during the experiment. Details on the varietal pedigree and development are presented in Chapter 3.

Table 5.2 Rice varieties used in the experiment

Variety Code	Variety Name	Grain Type
AAT 9	Linklatter B1	Long
AAT 10	Dummeriney 11	Long
AAT 11	Lasik IX	Long
AAT 12	Inaminka MB	Long
AAT 15	Lasik XII	Long
AAT 16	Inaminka XB	Long
AAT 18	Unnamed	Long
AAT 3	Lasik VII	Medium
AAT 4	Sunkiss PII	Medium
AAT 6	Linklatter A1	Medium
AAT 13	Lasix XB	Medium
AAT 17	Inaminka XD	Medium
AAT 19	Duminey	Medium

5.2.6. Crop measurements

Grain yield was measured from the sample plot by manual harvesting using a sickle. The crop was harvested when grain moisture was ca. 14%. The sample plots were used to measure yield and all plant parameters were measured from five randomly selected hills within the sample plot areas. The sample plot harvests were threshed manually by hitting against the floor and the grain dried (as was the stems/chaffs) and weighed to determine yield and HI. Grain yield was presented at 12% moisture. Crop parameters were recorded following the IRRI rice descriptor method (Bioversity International et al., 2007).

5.2.7. Parameters studied

Table 5.3 presents the variables that were recorded during the experiment. Details on specific procedures for each are presented in Chapter 3.

Table 5.3 Variables recorded during the experiment at Alton Downs and South Johnstone in 2015.

Type	**Parameters (units)**
Growth	Plant height (cm) Flag leaf length (cm) Flag leaf breadth (cm) Flag leaf area (cm^2) Days to flowering (no.)
Physiological	Chlorophyll (Chl) fluorescence (Fv/Fm) Photosynthesis (A) ($\mu mol/m^2/s^1$) Leaf transpiration (E) ($mmol/m^2/s^1$) Stomatal conductance (gs) ($mol/m^2/s^1$) WUEi or intrinsic water use efficiency (A/gs) (µmol mol) WUE or water use efficiency (A/E) [(µmol CO_2)/(mmol H_2O)]
Yield and yield attributing	Panicle length (cm) Number of effective tillers (no.) Spikelet /panicle (number) 1000 grain wt. (g) Spikelet fertility (%) Grain yield (t/ha) Harvest index (HI) (ratio)
Water and water productivity	Total rainfall (mm) Water productivity (t/ML)(yield/rainfall)

5.2.8. Data analysis

Microsoft Office Excel 2013 was used for data entry and recording.

Using ANOVA, the experiment was analysed with varieties and location as treatments and replication within each location as blocks. The error was divided in two groups of blocks; i.e., Location, Location x Block. All the analyses were performed using GenStat 16th edition (VSN International, 2013). Interaction effects are presented first and where there was no significant interaction effect, only main effects are presented. Specific interaction effects are presented in graphs using R (R Core Team, 2016) package ggplot2 (Wickham, 2009) and Microsoft Office Excel 2013.

The means were compared by Fisher's protected 'Least Significant Difference' test. The level of significance was set at 5% in all comparisons. Simple pair-wise correlations were performed where appropriate to examine interrelationship between variables.

5.3. Results

5.3.1. Experimental environment and weather

The rainfall at Alton Downs ceased after 99 DAS while in South Johnstone it rained until harvest time (Figure 5.1). Severe Tropical Cyclone Marcia was a Category 3 cyclone which hit Rockhampton on 98 DAS (20 February 2015), resulting in rainfall peaks of 109.4 mm on 98 DAS and 96 mm on 99 DAS. After this event, no further rainfall was recorded at Alton Downs before harvest (Figure 5.1). Total rainfall received during the experimental period was 593 mm and 839.2 mm for Alton Downs and South Johnstone, respectively.

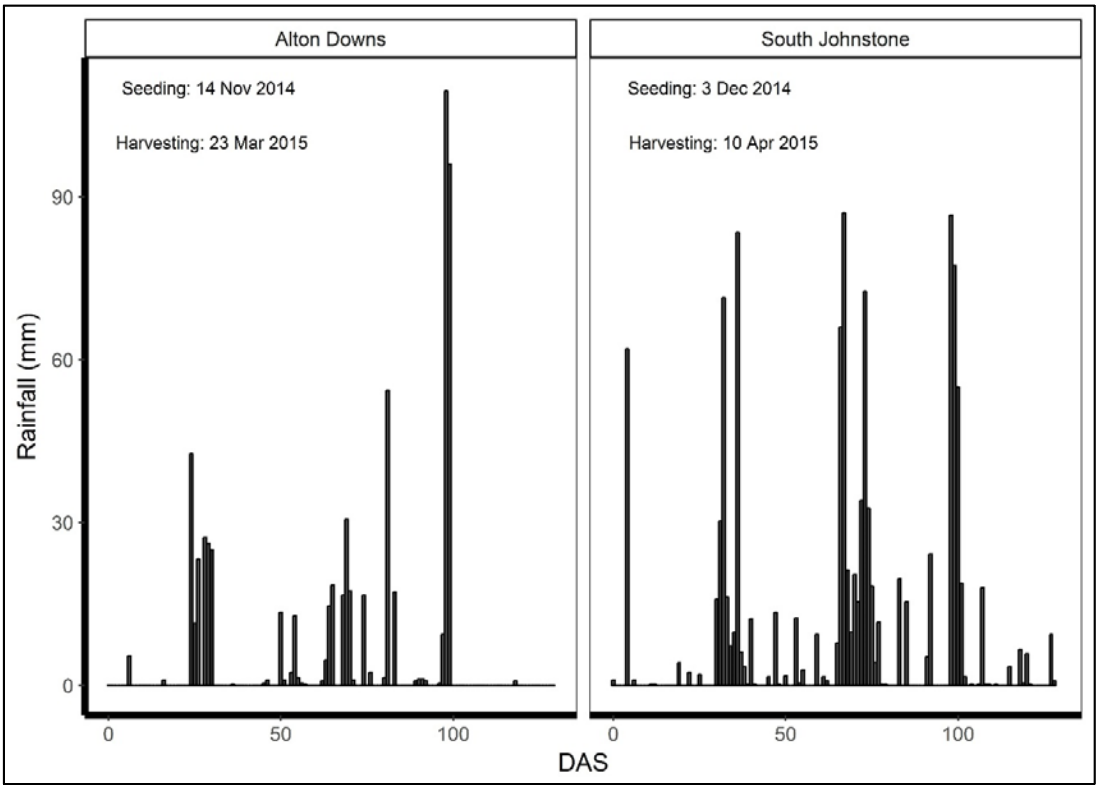

Figure 5.1 Rainfall during experimental period at Alton Downs and South Johnstone.

The mean temperature during the experiment period at Alton Downs (14 November 2014 to 23 March 2015) was 27.5°C and at South Johnstone was 27.3°C. Temperature ranged from 19.4°C to 39.3°C at Alton Downs and from 19.4°C to 37.1°C at South Johnstone (Figure 5.2). Relative humidity averaged 68% and 77% at Alton Downs and South Johnstone, respectively, ranging from 18% to 100% at Alton Downs and 19% to 99 % at South Johnstone. Daily ET_o averaged 5.9 mm/day at Alton Downs and 4.7 mm/day at South Johnstone. Evapotranspiration ranged from 1.7 to 8.3 mm/day and 1.4

to 6.8 mm/day at Alton Downs and South Johnstone, respectively, during the growing period. Average ET_o remained high at Alton Downs as compared to South Johnstone (Figure 5.3).

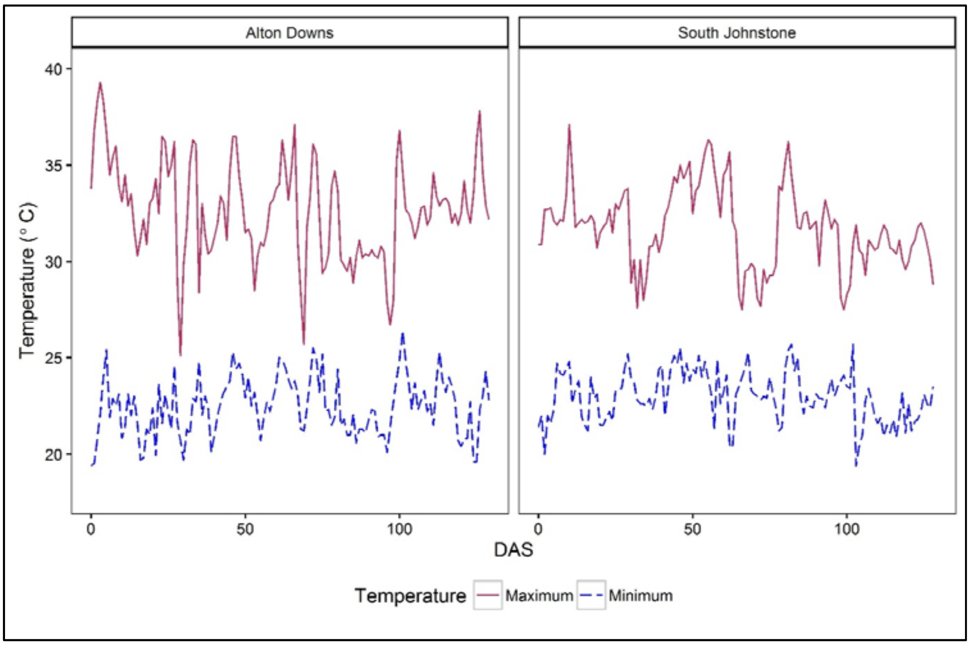

Figure 5.2 Daily maximum and minimum temperatures for the experimental sites Alton Downs and South Johnstone.

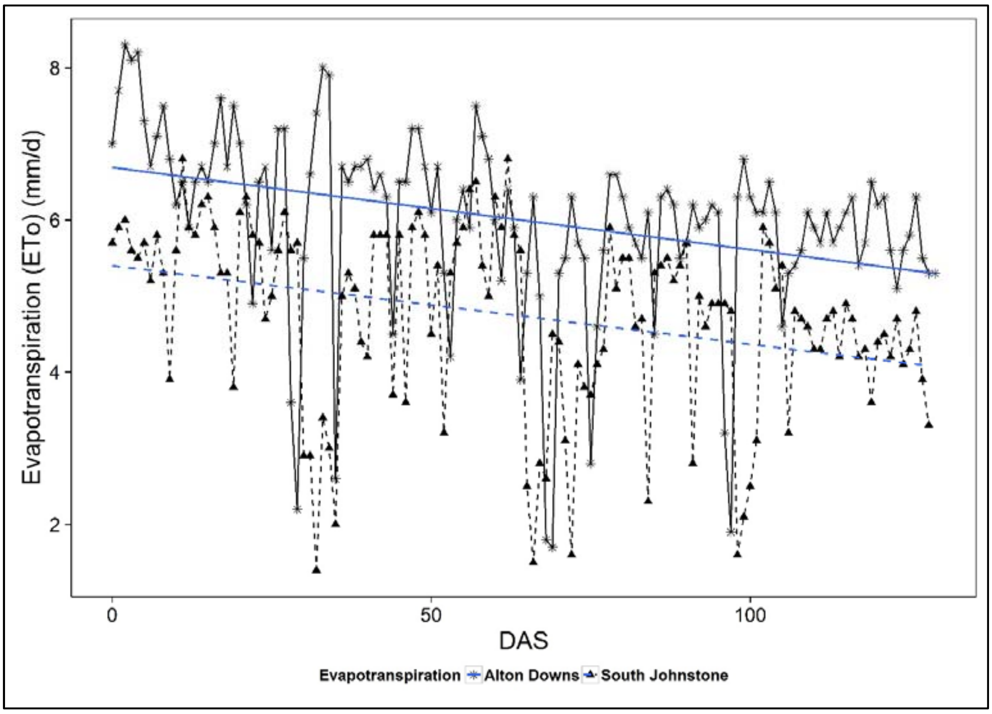

Figure 5.3 Reference evapotranspiration (ET_o) during the experiment at Alton Downs and South Johnstone.

5.3.2. Growth parameters

5.3.2.1. Days to flowering

Days to flowering of varieties differed significantly ($p < 0.001$) due to location of planting, variety and their interaction (Table 5.4). Flowering was significantly later at South Johnstone (94.1 DAS) than at Alton Downs (91.8 DAS), although for the varieties AAT 3, AAT 6, AAT 13, AAT 17 and AAT 19, the difference in flowering time between locations was not significant (Table 5.4). The early flowering varieties, AAT 3, AAT 4, AAT 6, AAT 13, AAT 17 and AAT 19, flowered on average at 88 DAS, whereas the late flowering varieties, AAT 9, AAT 10, AAT 11, AAT 12, AAT 15, AAT 16 and AAT 18, flowered between 97 DAS and 98 DAS (Table 5.4).

Table 5.4 Days from sowing to flowering of varieties at Alton Downs and South Johnstone

Variety	Alton Downs	South Johnstone	Average
AAT 9	96.0	98.0	97.2
AAT 10	96.0	100.0	98.4
AAT 11	96.0	99.3	98.0
AAT 12	96.0	99.7	98.2
AAT 15	96.0	99.0	97.8
AAT 16	96.0	99.3	98.0
AAT 18	96.0	99.7	98.2
AAT 3	87.0	88.0	87.6
AAT 4	87.0	88.7	88.0
AAT 6	87.0	88.0	87.6
AAT 13	87.0	88.0	87.6
AAT 17	87.0	88.0	87.6
AAT 19	87.0	88.0	87.6
Average	91.8	94.1	93.2
		P-value	LSD at 0.05
Location		< 0.001	0.21
Variety		< 0.001	0.88
Location*Variety		< 0.001	1.23

5.3.2.2. Plant height

Plant height of rice varieties at Alton Downs ranged from 96.4 cm (AAT 15) to 89.9 cm (AAT 18) with a mean of 93.5 cm, and plant height at South Johnstone ranged from 90.2 cm (AAT 16) to 108 cm (AAT 17) with a mean of 99.4 cm (Table 5.5). In general, plant height increased in the wet tropical environments by 3%.

The effect of variety on plant height depended on location of planting (interaction effect, $p = 0.011$) (Table 5.5), showing strong location x variety interaction. The varieties AAT 3, AAT 4, AAT 6 and AAT 17 showed significant increase in plant height at South

Johnstone as compared to Alton Downs, whereas varieties AAT 11, AAT 15 and AAT 16 were shorter at South Johnstone as compared to Alton Downs (Table 5.5).

Table 5.5 Plant height (cm) during harvest of rice varieties under rainfed conditions at Alton Downs and South Johnstone.

Variety	**Alton Downs**	**South Johnstone**	**Average**
AAT 9	94.9	96.5	95.8
AAT 10	91.9	99.4	96.4
AAT 11	94.8	91.6	92.9
AAT 12	94.6	99.8	97.7
AAT 15	95.1	91.1	92.7
AAT 16	90.7	90.2	90.4
AAT 18	89.9	94.9	92.9
AAT 3	94.9	105.1	101.0
AAT 4	93.8	104.4	100.2
AAT 6	94.9	105.9	101.5
AAT 13	96.4	103.2	100.5
AAT 17	90.3	108.0	100.9
AAT 9	94.9	96.5	95.8
Average	93.5	99.4	97.1
		P-value	LSD at 0.05
Location		0.073	6.898
Variety		< 0.001	5.29
Location*Variety		0.011	8.67

5.3.2.3. Flag leaf length

Flag leaf length ranged from 30.5 cm (AAT 4) to 36.6 cm (AAT 19) at Alton Downs with a mean of 33.1 cm. Flag leaf length at South Johnstone ranged from 26.3 cm (AAT 13) to 39.5 cm (AAT 11), with a mean of 32 cm (Table 5.6).

The effect of variety on flag leaf length depended on location of planting (interaction effect, $p \leq 0.001$) (Table 5.6) as one half of the varieties showed significant increase in flag leaf length at South Johnstone as compared to Alton Downs, whereas varieties AAT 3, AAT 4, AAT 6, AAT 17 and AAT 19, the earlier flowering varieties, showed shorter flag leaf length at South Johnstone as compared to Alton Downs (Table 5.6).

Table 5.6 Flag leaf length (cm) of varieties tested at Alton Downs and South Johnstone

Variety	Alton Downs	South Johnstone	Average
AAT 9	33.40	38.57	35.99
AAT 10	30.75	35.43	33.09
AAT 11	33.15	39.47	36.31
AAT 12	34.45	35.49	34.97
AAT 15	34.95	32.73	33.84
AAT 16	31.00	32.97	31.99
AAT 18	33.75	34.90	34.33
AAT 3	33.15	30.10	31.63
AAT 4	30.50	27.13	28.82
AAT 6	31.05	26.87	28.96
AAT 13	33.80	26.33	30.07
AAT 17	33.60	29.50	31.55
AAT 19	36.60	26.53	31.57
Average	33.09	32.00	32.55
		P-value	LSD at 0.05
Location		0.413	1.147
Variety		< 0.001	1.205
Location*Variety		< 0.001	2.028

5.3.2.4. Flag leaf breadth

Flag leaf breadth ranged from 1.5 cm (AAT 6) to 1.7 cm (AAT 13, AAT 17 and AAT 19) at Alton Downs, with a mean of 1.6 cm. Flag leaf length in South Johnstone ranged from 1.8 cm (AAT 17) to 1.9 cm (AAT 15), with a mean of 1.8 cm (Table 5.7).

Average flag leaf breadth of varieties at Alton Downs (1.6 cm) was significantly smaller as compared to South Johnstone (1.8 cm) (p=0.007) (Table 5.7), but differences between varieties and their interaction with location were not significant.

Table 5.7 Flag leaf breadth (cm) of varieties tested at Alton Downs and South Johnstone

Variety	Alton Downs	South Johnstone	Average
AAT 9	1.60	1.83	1.72
AAT 10	1.55	1.86	1.71
AAT 11	1.60	1.79	1.70
AAT 12	1.60	1.82	1.71
AAT 15	1.60	1.88	1.74
AAT 16	1.60	1.83	1.71
AAT 18	1.60	1.86	1.73
AAT 3	1.60	1.85	1.72
AAT 4	1.55	1.83	1.69
AAT 6	1.50	1.77	1.64
AAT 13	1.70	1.85	1.77
AAT 17	1.70	1.77	1.73
AAT 19	1.70	1.81	1.75
Average	1.61	1.83	1.72
		P-value	LSD at 0.05
Location		0.007	0.106
Variety		0.764	0.104
Location*Variety		0.511	0.16

5.3.2.5. Flag leaf area

Flag leaf area ranged from 34.5 cm^2 (AAT 6) to 46.1 cm^2 (AAT 19) across varieties at Alton Downs, with a mean of 39.5 cm^2. Flag leaf area at South Johnstone ranged from 35.5 cm^2 (AAT 6) to 52.4 cm^2 (AAT 11), with a mean of 43.4 cm^2 (Table 5.8).

The effect of variety on flag leaf area depended on location of planting (interaction, $p \leq 0.001$) (Table 5.8); some varieties showed significant increase in flag leaf area at South Johnstone as compared to Alton Downs, others, such as AAT 3, AAT 4 and AAT 6, showed non-significant increases, and varieties AAT 13, AAT 17 and AAT 19 showed decreased flag leaf area at South Johnstone as compared to Alton Downs (Table 5.8).

Table 5.8 Flag leaf area (cm^2) varieties tested at Alton Downs and South Johnstone

Variety	Alton Downs	South Johnstone	Average
AAT 9	39.68	52.36	46.02
AAT 10	35.31	48.77	42.04
AAT 11	39.25	52.40	45.83
AAT 12	40.90	47.95	44.43
AAT 15	41.38	45.59	43.49
AAT 16	36.70	44.77	40.74
AAT 18	40.19	48.15	44.17
AAT 3	39.41	41.52	40.47
AAT 4	34.96	36.92	35.94
AAT 6	34.47	35.49	34.98
AAT 13	42.52	36.00	39.26
AAT 17	42.27	38.35	40.31
AAT 19	46.12	35.57	40.85
Average	39.47	43.37	41.42
		P-value	LSD at 0.05
Location		0.143	1.978
Variety		< 0.001	2.499
Location*Variety		< 0.001	3.99

5.3.3. Physiological parameters

5.3.3.1. Leaf chlorophyll (Chl) fluorescence

Chlorophyll fluorescence measured on the flag leaf of the rice varieties ranged from 0.74 (AAT 10) to 0.79 (AAT 12) at Alton Downs, with a mean of 0.77 and fv/fm at South Johnstone ranged from 0.49 (AAT 17) to 0.79 (AAT 16), with a mean of 0.70. There was no significant location, variety or location x variety effect on fv/fm (data not presented).

5.3.3.2. Leaf gas exchange

Leaf Photosynthesis

Leaf photosynthetic rate at grain filling stage ranged from 2.52 (AAT 6) to 5.28 µmol m^{-2} s^{-1} (AAT 11) at Alton Downs with a mean of 3.76 µmol/m^2/s and at South Johnstone A ranged from 10.49 (AAT 18) to 15.42 µmol/m^2/s (AAT 17), with a mean of 12.55 µmol/m^2/s (Table 5.9).

Average A of varieties at South Johnstone was, therefore, significantly higher than that at Alton Downs ($p \leq 0.001$) (Table 5.9), but no significant differences were found between varietal means nor between varieties across location.

Table 5.9 Leaf photosynthetic rate (A, µmol/m^2/s) of varieties tested at Alton Downs and South Johnstone during grain filling stage.

Variety	**Alton Downs**	**South Johnstone**	**Average**
AAT 9	4.49	12.62	8.55
AAT 10	4.49	11.46	7.98
AAT 11	5.28	11.11	8.19
AAT 12	3.56	12.78	8.17
AAT 15	4.07	13.16	8.61
AAT 16	4.30	10.99	7.65
AAT 18	2.52	10.49	6.50
AAT 3	3.18	12.76	7.97
AAT 4	2.63	12.69	7.66
AAT 6	3.43	12.90	8.16
AAT 13	4.46	12.24	8.35
AAT 17	3.17	15.42	9.29
AAT 19	3.32	14.46	8.89
Average	3.76	12.55	8.15
		P-value	LSD at 0.05
Location		< 0.001	0.659
Variety		0.921	3.297
Location*Variety		0.834	4.589

Leaf transpiration

Leaf transpiration rate of rice varieties during the grain filling stage ranged from 1.55 (AAT 3) to 3.18 mmol/m^2/s (AAT 9) at Alton Downs, with a mean of 2.47 mmol/m^2/s and at South Johnstone E ranged from 4.02 (AAT 18) to 4.75 mmol/m^2/s (AAT 15), with a mean of 4.51 mmol/m^2/s (Table 5.10).

As for photosynthetic rate, average E of varieties at South Johnstone was significantly higher than those of Alton Downs ($p = 0.006$) (Table 5.10), but differences between varieties, nor their interaction with location, were significant.

Table 5.10 Leaf transpiration rate (E, mmol/m^2/s) of varieties tested at Alton Downs and South Johnstone during grain filling stage.

Variety	Alton Downs	South Johnstone	Average
AAT 9	3.18	4.75	3.96
AAT 10	2.61	4.48	3.54
AAT 11	3.01	4.36	3.69
AAT 12	2.96	4.22	3.59
AAT 15	2.17	4.75	3.46
AAT 16	2.33	4.65	3.49
AAT 18	1.99	4.02	3.01
AAT 3	1.55	4.74	3.14
AAT 4	2.48	4.42	3.45
AAT 6	2.52	4.52	3.52
AAT 13	2.80	4.65	3.72
AAT 17	2.36	4.34	3.35
AAT 19	2.19	4.71	3.45
Average	2.47	4.51	3.49
		P-value	LSD at 0.05
Location		0.006	0.935
Variety		0.887	0.858
Location*Variety		0.707	1.19

Stomatal conductance

Leaf stomatal conductance during the grain filling stage ranged from 0.03 (AAT 3) to 0.07 mol/m^2/s (AAT 9) at Alton Downs, with a mean of 0.05 mol/m^2/s and in South Johnstone gs ranged from 0.11 (AAT 3) to 0.14 mol/m^2/s (AAT 18), with a mean of 0.12 mol/m^2/s (Table 5.11).

Average leaf gs at South Johnstone was significantly higher as compared to Alton Downs ($p = 0.003$) (Table 5.11).

Table 5.11 Leaf stomatal conductance (gs, mol/m^2/s) of varieties tested at Alton Downs and South Johnstone during grain filling stage.

Variety	Alton Downs	South Johnstone	Average
AAT 9	0.07	0.12	0.10
AAT 10	0.05	0.11	0.08
AAT 11	0.06	0.13	0.09
AAT 12	0.05	0.12	0.09
AAT 15	0.05	0.13	0.09
AAT 16	0.05	0.13	0.09
AAT 18	0.04	0.11	0.07
AAT 3	0.03	0.14	0.09
AAT 4	0.06	0.11	0.08
AAT 6	0.05	0.13	0.09
AAT 13	0.05	0.11	0.08
AAT 17	0.05	0.11	0.08
AAT 19	0.04	0.13	0.09
Average	0.05	0.12	0.09
		P-value	LSD at 0.05
Location		0.003	0.025
Variety		0.999	0.043
Location*Variety		0.990	0.062

Water use efficiency at flowering

Water use efficiency of rice varieties ranged from 1.03 (AAT 4) to 2.04 µmol CO_2/mmol H_2O (AAT 3) at Alton Downs, with a mean of 1.54 µmol CO_2/mmol H_2O and at South Johnstone the WUE ranged from 2.35 (AAT 16) to 3.56 µmol CO_2/mmol H_2O (AAT 17), with a mean of 2.79 µmol CO_2/mmol H_2O (Table 5.12). Differences between varieties were not significant, but average WUE of varieties at South Johnstone was significantly higher as compared to Alton Downs (p = 0.003) (Table 5.12).

Table 5.12 Water use efficiency (µmol CO_2/mmol H_2O) of varieties tested at Alton Downs and South Johnstone.

Variety	**Alton Downs**	**South Johnstone**	**Average**
AAT 9	1.41	2.62	2.01
AAT 10	1.72	2.61	2.16
AAT 11	1.85	2.57	2.21
AAT 12	1.20	3.11	2.16
AAT 15	1.86	2.80	2.33
AAT 16	1.85	2.35	2.10
AAT 18	1.32	2.58	1.95
AAT 3	2.04	2.63	2.34
AAT 4	1.03	2.87	1.95
AAT 6	1.36	2.88	2.12
AAT 13	1.63	2.62	2.13
AAT 17	1.22	3.56	2.39
AAT 19	1.58	3.10	2.34
Average	1.54	2.79	2.17
		P-value	LSD at 0.05
Location		0.003	0.453
Variety		0.919	0.665
Location*Variety		0.225	0.964

Intrinsic water use efficiency at flowering

Intrinsic water use efficiency of rice varieties ranged from 56.8 (AAT 4) to 106.1 µmol /mol (AAT 11) at Alton Downs, with a mean of 81.8 µmol mol^{-1}, and at South Johnstone the WUEi ranged from 84.1 (AAT 16) to 135.5 µmol/ mol (AAT 17), with a mean of 105.7 µmol/mol (Table 5.13).

Average WUEi of varieties at South Johnstone was significantly higher as compared to Alton Downs (p = 0.03) (Table 5.13).

Table 5.13 Intrinsic water use efficiency (µmol/mol) of varieties tested at Alton Downs and South Johnstone WUEi.

Variety	Alton Downs	South Johnstone	Average
AAT 9	65.4	104.7	85.1
AAT 10	102.9	102.1	102.5
AAT 11	106.1	100.1	103.1
AAT 12	71.1	113.3	92.2
AAT 15	88.2	102.9	95.6
AAT 16	96.7	84.1	90.4
AAT 18	74.1	98.6	86.3
AAT 3	105.8	92.6	99.2
AAT 4	56.8	111.7	84.3
AAT 6	58.3	101.9	80.1
AAT 13	89.2	108.1	98.6
AAT 17	58.3	135.5	96.9
AAT 19	90.7	118.0	104.4
Average	81.8	105.7	93.7
		P-value	LSD at 0.05
Location		0.033	20.31
Variety		0.986	37.93
Location*Variety		0.436	54.03

5.3.4. Yield and yield components

5.3.4.1. Yield

Grain yield of rice varieties ranged from 0.24 t/ha (AAT 15) to 2.72 t/ha (AAT 6) at Alton Downs, with a mean of 1.38 t/ha, and grain yield at South Johnstone ranged from 3.2 t/ha (AAT 16) to 5.7 t/ha (AAT 10), with a mean of 4.66 t/ha. The rainfed rice yield was 3.38 times higher in the wet tropical environment of South Johnstone compared to the dry tropical environment of Alton Downs.

The effect of variety on yield depended on location of planting ($p \leq 0.001$) (Table 5.14) and on the significant location x variety interaction ($p < 0.001$). All varieties showed significant increases in yield at South Johnstone as compared to Alton Downs as the difference in yield between late flowering varieties is higher as compared to early flowering varieties. At Alton Downs, the late flowering varieties such as AAT 15, AAT 16, AAT 18, AAT 10, AAT 11, AAT 12 and AAT 13 were lower yielding compared to early flowering varieties but they yielded the same or even higher at South Johnstone than the earlier flowering varieties (Table 5.14 and Figure 5.4).

Table 5.14 p-values of source of variation for yield of varieties under rainfed conditions at Alton Downs and South Johnstone.

Source of variation	P-value	LSD at 0.05
Location	<0.001	0.522
Variety	0.006	0.702
Location*Variety	<0.001	1.027

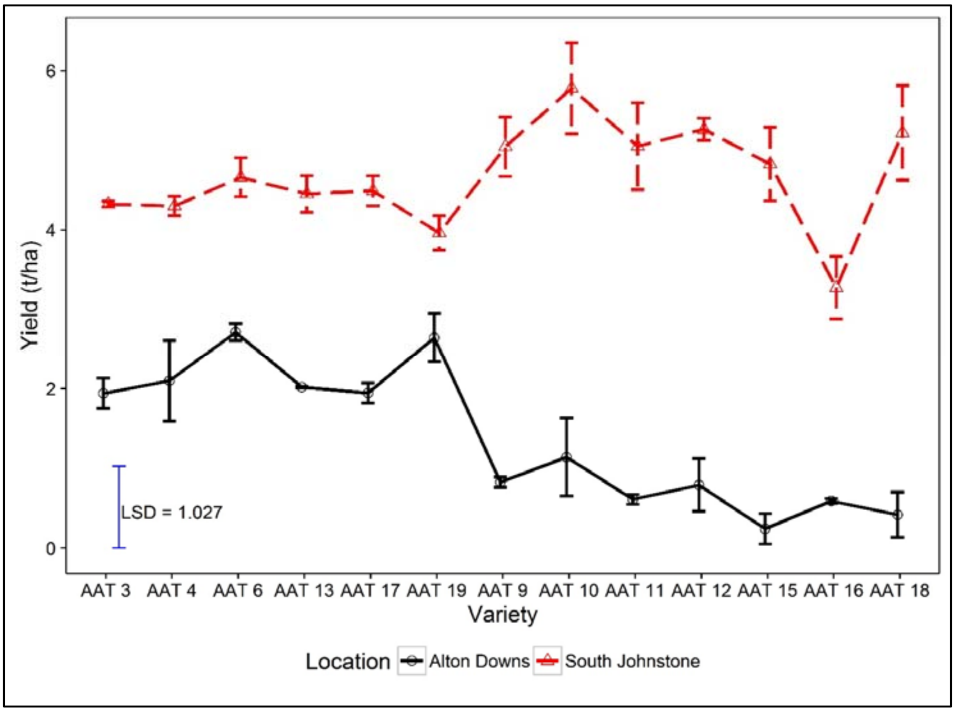

Figure 5.4 Yield of varieties under rainfed conditions at Alton Downs and South Johnstone

5.3.4.2. Harvest Index

The HI of rice varieties ranged from 0.14 (AAT 18) to 0.43 (AAT 17) at Alton Downs, with a mean of 0.30, and at South Johnstone, ranged from 0.37 (AAT 16) to 0.53 (AAT 11), with a mean of 0.45 (Table 5.15).

The effect of variety on HI depended on location of planting ($p < 0.001$) (Table 5.15) as all varieties showed significant increase in HI when grown at South Johnstone as compared to Alton Downs except AAT 3, AAT 4, AAT 17 and AAT 19, for which, although HI was greater at South Johnstone, the difference was not significant (Table 5.15).

Table 5.15 Harvest index (HI) of varieties under rainfed conditions at Alton Downs and South Johnstone.

Variety	Alton Downs	South Johnstone	Average
AAT 9	0.27	0.52	0.42
AAT 10	0.25	0.51	0.41
AAT 11	0.31	0.53	0.44
AAT 12	0.25	0.51	0.41
AAT 15	0.18	0.43	0.33
AAT 16	0.15	0.37	0.28
AAT 18	0.14	0.44	0.32
AAT 3	0.39	0.43	0.41
AAT 4	0.42	0.43	0.42
AAT 6	0.31	0.42	0.38
AAT 13	0.36	0.46	0.42
AAT 17	0.43	0.44	0.44
AAT 19	0.40	0.42	0.41
Average	0.30	0.45	0.37
		P-value	LSD at 0.05
Location		0.003	0.055
Variety		< 0.001	0.044
Location*Variety		< 0.001	0.072

5.3.4.3. Yield contributing parameters

Panicle length

Panicle length ranged from 16.5 cm (AAT 15) to 19.8 cm (AAT 3) between varieties at Alton Downs, with a mean of 18.3 cm, while panicle length in South Johnstone ranged from 19.2 (AAT 13) to 24.1 (AAT 10), with a mean of 21.4 cm (Table 5.16).

Panicle length differed between varieties depending on location of planting (interaction $p < 0.001$) (Table 5.16); all the varieties showed significant increase in panicle length when tested at South Johnstone as compared to Alton Downs except AAT 4, AAT 13 and AAT 19, for which the difference was not significant (Table 5.16).

Table 5.16 Panicle length of varieties under rainfed condition at Alton Downs and South Johnstone.

Variety	Alton Downs	South Johnstone	Average
AAT 9	18.39	22.30	20.7
AAT 10	17.69	24.13	21.6
AAT 11	18.90	23.73	21.8
AAT 12	19.70	23.15	21.8
AAT 15	16.45	21.20	19.3
AAT 16	16.71	20.07	18.7
AAT 18	16.48	22.60	20.2
AAT 3	19.75	19.60	19.7
AAT 4	19.30	20.60	20.1
AAT 6	18.20	20.33	19.5
AAT 13	18.77	19.20	19.0
AAT 17	19.15	21.47	20.5
AAT 19	18.25	19.27	18.9
Average	18.29	21.36	19.82
		P-value	LSD at 0.05
Location		0.005	1.313
Variety		< 0.001	1.129
Location*Variety		< 0.001	1.787

Spikelets per panicle

Spikelets per panicle ranged from 73.6 (AAT 18) to 118.4 (AAT 11) between varieties under Alton Downs conditions, with a mean of 102.1, while spikelets per panicle at South Johnstone ranged from 111 (AAT 19) to 182.6 (AAT 16), with a mean of 146.9 (Table 5.17). Differences between locations, varieties and their interaction were significant. Varieties differed significantly in average spikelets per panicle ($p \leq 0.001$); variety AAT 16 recorded the highest number of spikelets per panicle (155) and AAT 19 recorded the lowest number (108) (Table 5.17).

However, varietal difference in spikelets per panicles of varieties depended on the growing location ($p = 0.002$) as all the varieties showed significantly more spikelets per panicle at South Johnstone than at Alton Downs, except the early varieties AAT 3, AAT 4, AAT 6, AAT 13 and AAT 17 (Table 5.17).

Table 5.17 Number of spikelets per panicle of varieties under rainfed condition at Alton Downs and South Johnstone.

Variety	**Alton Downs**	**South Johnstone**	**Average**
AAT 9	101	166	140
AAT 10	88	169	136
AAT 11	118	169	149
AAT 12	102	167	141
AAT 15	108	170	145
AAT 16	115	183	155
AAT 18	74	171	132
AAT 3	106	119	114
AAT 4	101	120	113
AAT 6	103	113	109
AAT 13	106	117	112
AAT 17	102	137	123
AAT 19	105	111	108
Average	102	147	129
		P-value	LSD at 0.05
Location		0.011	24.96
Variety		< 0.001	23.17
Location*Variety		0.002	35.99

1000 grain weight:

The 1000 grain weight ranged from 17.68 (AAT 18) to 26.28 (AAT 3) under Alton Downs conditions, with a mean of 22.12, and in South Johnstone it ranged across varieties from 20.77 (AAT 16) to 29.57 (AAT 6), with a mean of 25.5 (Table 5.18).

Both growing location and variety influenced 1000 grain weight. Averaged over varieties, 1000 grain weight was greater at South Johnstone compared to that at Alton Downs.

Across varieties a significant difference was evident with variety AAT 6 (27.78) having the highest average 1000 grain weight and AAT 16 (19.87) having the lowest average 1000 grain weight (Table 5.18).

Table 5.18 1000 grain weight (g) of varieties under rainfed condition at Alton Downs and South Johnstone.

Variety	**Alton Downs**	**South Johnstone**	**Average**
AAT 9	19.45	24.35	22.39
AAT 10	18.84	23.97	21.92
AAT 11	18.81	22.93	21.28
AAT 12	21.24	23.25	22.45
AAT 15	18.26	21.79	20.38
AAT 16	18.97	20.77	20.05
AAT 18	17.68	22.26	20.43
AAT 3	26.28	28.20	27.43
AAT 4	25.93	28.39	27.41
AAT 6	25.99	29.57	28.14
AAT 13	24.94	28.16	26.87
AAT 17	25.44	29.17	27.68
AAT 19	25.74	28.85	27.61
Average	22.12	25.51	23.82
		P-value	LSD at 0.05
Location		0.002	0.974
Variety		< 0.001	1.429
Location*Variety		0.315	2.071

Panicle filling (fertility) percentage

Only growing location affected panicle filling percentage, with fertility being greater at South Johnstone (73.9 %) compared to Alton Downs (42.6 %, $LSD_{0.05}$ = 7.67) (Table 5.19). Although differences were greater between varieties at Alton Downs than at South Johnstone, differences between varieties were not significant (Table 5.19).

Table 5.19 Panicle filling percentage (fertility %) of varieties under rainfed condition at Alton Downs and South Johnstone.

Variety	**Alton Downs**	**South Johnstone**	**Average**
AAT 9	43.8	68.8	58.8
AAT 10	44.0	74.2	62.1
AAT 11	52.3	75.3	66.1
AAT 12	31.2	68.1	53.4
AAT 15	39.3	71.3	58.5
AAT 16	42.1	69.6	58.6
AAT 18	17.9	70.7	49.6
AAT 3	36.4	80.2	62.7
AAT 4	60.8	82.5	73.8
AAT 6	42.9	78.4	64.2
AAT 13	54.5	71.9	65.0
AAT 17	45.6	70.9	60.8
AAT 19	43.4	79.0	64.8
Average	42.6	73.9	61.4
		P-value	LSD at 0.05
Location		< 0.001	7.67
Variety		0.104	13.25
Location*Variety		0.419	18.96

Effective tillers

Effective tillers per plant across rice varieties ranged from 1.3 (AAT 18) to 6.2 (AAT 4) under Alton Downs conditions, with an average of 4.0, and at South Johnstone the number of effective tillers per plant of varieties ranged from 2.8 (AAT 18) to 5.8 (AAT 12), with a mean of 4.2 (Table 5.20).

Only the effect of recorded variety was significant; AAT 4 (5.6) had the highest effective tillers per plant and AAT 18 (2.2) had the least number of effective tillers per plant (Table 5.20).

Table 5.20 Effective tillers (number per plant) of varieties under rainfed condition at Alton Downs and South Johnstone.

Variety	Alton Downs	South Johnstone	Average
AAT 9	3.2	3.8	3.6
AAT 10	3.7	5.1	4.6
AAT 11	5.6	4.9	5.2
AAT 12	4.1	5.8	5.1
AAT 15	2.3	2.9	2.6
AAT 16	3.2	3.3	3.3
AAT 18	1.3	2.8	2.2
AAT 3	4.4	4.2	4.3
AAT 4	6.2	5.2	5.6
AAT 6	5.4	4.1	4.6
AAT 13	3.7	4.0	3.9
AAT 17	4.2	4.0	4.1
AAT 19	5.3	4.5	4.8
Average	4.0	4.2	4.1
		P-value	LSD at 0.05
Location		0.503	0.646
Variety		0.012	1.776
Location*Variety		0.821	2.493

5.3.5. Water productivity

Rice water productivity ranged between varieties from 0.04 t/ML (AAT 15) to 0.41 t/ML (AAT 6) under Alton Downs conditions, with a mean of 0.21 t/ML, and at South Johnstone water productivity of varieties ranged from 0.29 (AAT 16) to 0.51 (AAT 10), with a mean of 0.41 (Table 5.21).

Water productivity differences between varieties depended significantly on the location of experiment ($p = 0.001$) (Table 5.21); all varieties showed significantly higher water productivity at South Johnstone as compared to Alton Downs except AAT 3, AAT 4, AAT 6 and AAT 13, for which the differences between sites were not significant, and for AAT 19, which had lower water productivity at South Johnstone as compared to Alton Downs (Table 5.21).

Table 5.21 Water productivity (t/ML) of varieties under rainfed condition at Alton Downs and South Johnstone.

Variety	Alton Downs	South Johnstone	Average
AAT 9	0.12	0.45	0.32
AAT 10	0.17	0.51	0.38
AAT 11	0.09	0.45	0.31
AAT 12	0.12	0.47	0.33
AAT 15	0.04	0.43	0.27
AAT 16	0.09	0.29	0.21
AAT 18	0.06	0.46	0.30
AAT 3	0.29	0.38	0.35
AAT 4	0.32	0.38	0.36
AAT 6	0.41	0.41	0.41
AAT 13	0.30	0.40	0.36
AAT 17	0.29	0.40	0.36
AAT 19	0.40	0.35	0.37
Average	0.21	0.41	0.33
		P-value	LSD at 0.05
Location		0.001	0.051
Variety		< 0.001	0.07
Location*Variety		< 0.001	0.102

5.4. Discussion

Within this discussion section, interrelationships between different physiological and agronomic traits at two contrasting rainfed rice production environments are interpreted.

5.4.1. Relationship of phenology with yield and yield attributing characters

Yield of varieties when tested at the two different locations, South Johnstone and Alton Downs, showed significant location x variety interaction ($p \leq 0.001$) (Table 5.14). The varieties responded differently at the two locations; the lowest yielding late flowering varieties at Alton Downs were the highest yielding varieties at South Johnstone. Varieties such as AAT 9, AAT 10, AAT 11, AAT 12, AAT 15 and AAT 18, which recorded lowest yield in Alton Downs, were among the top yielders at South Johnstone (Table 5.14). Yields were greater in South Johnstone by 1.5 to 20.1 times as compared to Alton Downs (Figure 5.5). This increase in yield of varieties at South Johnstone can be attributed to significant higher panicle fertility percentage ($p \leq 0.001$), 1000 grain weight ($p = 0.002$), number of grains per panicle, panicle length ($p = 0.005$) and HI (0.003) as compared to Alton Downs. The correlations analysis revealed that yield was significantly correlated with panicle length (r = 0.78***), spikelets per panicle (r = 0.62***), panicle fertility (r = 0.76***), filled grains per panicle (r = 0.79***) and 1000 grain weight (r =

0.53***) across locations (Table 5.22). Yield was not correlated with tillering capacity across locations.

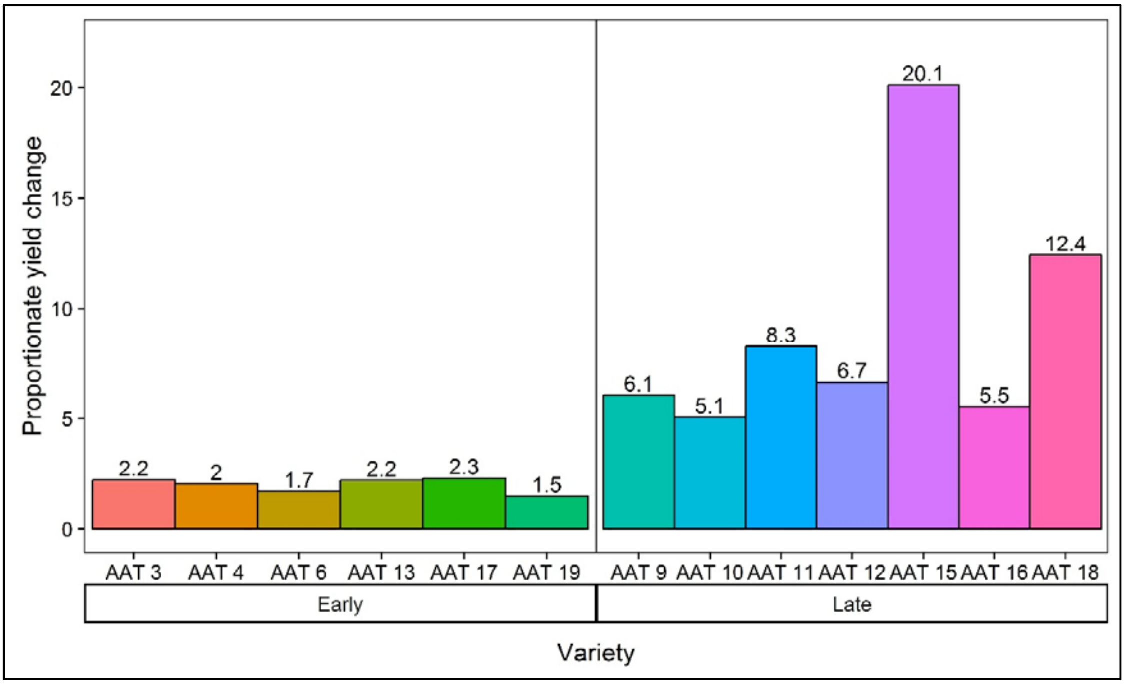

Figure 5.5 Yield gain of varieties in terms of proportion at South Johnstone as compared to Alton Downs.

Panicle fertility of varieties was strongly correlated with yield (r = 0.76***) across locations (Table 5.22) but not at Alton Downs (Table 5.24) or South Johnstone separately (Table 5.23). The strong across location correlation was due to significant differences in average panicle fertility between the two locations ($p \leq 0.001$). Only growing location affected panicle filling percentage, with fertility being greater at South Johnstone (73.9 %) as compared to Alton Downs (42.6 %, $LSD_{0.05} = 7.67$) (Table 5.19). Although differences were greater between varieties at Alton Downs than at South Johnstone, differences were not significant (Table 5.19).

The yield potential of late flowering varieties such as AAT 9, AAT 10, AAT 11, AAT 15 and AAT 18 was expressed only when they were grown at South Johnstone, most likely due to availability of rainfall throughout the growing period (Figure 5.1). At Alton Downs, late flowering varieties did not receive rain after flowering, whereas at South Johnstone rain continued until harvesting. Lack of rainfall in the reproductive phase resulted in severe yield reduction in late flowering varieties at Alton Downs, as they were exposed to terminal drought, consistent with the previous study as reported by Pantuwan et al. (2002a). This is supported by the positive correlation (r = 0.35*) of days to flowering with yield at South Johnstone (Table 5.23) in contrast to the stronger negative correlation (r = - 0.89***) of days to flowering with yield at Alton Downs (Table 5.24).

Days to flowering showed significant negative correlation (r = -0.47*) with effective tillers per plant at Alton Downs (Table 5.24) but was non-significant at South Johnstone (Table 5.23) or across both locations (Table 5.22). However, effective tillers per plant showed a positive correlation (r = 0.52**) with yield at Alton Downs (Table 5.24) but non-significant relationships at South Johnstone (Table 5.23) and across locations (Table 5.22). Effective tillers per plant is reported as a main bottleneck for higher yield in upland varieties (Matsumoto et al., 2014). Under drought, the varieties with better ability to produce effective tillers, such as AAT 4 and AAT 6, produced better yield at Alton Downs. The trait 1000 grain weight was correlated with yield (r = 0.53**) across locations and very strongly at Alton Downs (r = 0.88***), but not at South Johnstone. Early varieties have significantly higher 1000 grain weight in both locations individually, and in the average of both locations. It seems that earliness has a phenological advantage over late flowering varieties at Alton Downs because the former varieties had higher 1000 grain weight, but at South Johnstone there was no correlation between yield and 1000 grain weight as there was no drought stress until maturity. The variation for 1000 grain weight between varieties was less at South Johnstone than that at Alton Downs.

All the early flowering varieties had high values for effective tillers per plant at Alton Downs, but late flowering varieties lacked yield stability because of their inability to produce effective tillers that produced grains. Higher yield in early varieties reflects some degree of drought avoidance at Alton Downs, as these varieties produced grain before commencement of water stress, as described by Levitt (1972), whereas the same late varieties which produced poorly at Alton Downs did not suffer any kind of stress at South Johnstone. Acuña et al. (2008) also reported a similar result of better yield in a wet environment without terminal drought as compared to a dry environment with terminal drought. Soltani and Sinclair (2012) also reported that early genotypes of chickpea were superior to late genotypes when genotypes were exposed to drought during flowering, and a similar result of high spikelet sterility and yield decrease with terminal drought was reported in rice (Lafitte, 2002; Lilley and Fukai, 1994b; Pantuwan et al., 2002a).

Table 5.22 Correlation between phenology, yield and yield contributing characters of varieties at South Johnstone and Alton Downs.

	Days to flowering	Yield (t/ha)	HI	Water Productivity (t/ML)	Tillers per plant	Effective tillers per plant	Plant height	Panicle length	1000 grian wt	Grains per panicle	Panicle filling percentage (Fertility %)
Days to flowering	-										
Yield (t/ha)	0.14^{ns}	-									
HI	0.02^{ns}	0.85***	-								
Water Productivity (t/ML)	-0.01^{ns}	0.95***	0.86***	-							
Tillers per plant	-0.21^{ns}	-0.09^{ns}	0.05^{ns}	-0.02^{ns}	-						
Effective tillers/ plant	-0.24^{ns}	0.17^{ns}	0.34**	0.27*	0.89***	-					
Plant height	-0.39**	0.42***	0.26*	0.34**	0.16 ^{ns}	0.19 ^{ns}	-				
Panicle length	0.41***	0.78***	0.76***	0.72***	0.09^{ns}	0.29*	0.20 ^{ns}	-			
1000 grain wt	-0.71***	0.53***	0.54***	0.59***	0.11^{ns}	0.30*	0.64***	0.21^{ns}	-		
Grains per panicle	0.38**	0.79***	0.68***	0.67***	-0.02^{ns}	0.17 ^{ns}	0.26*	0.79***	0.19^{ns}	-	
Panicle filling percentage (Fertility %)	0.00^{ns}	0.76***	0.68***	0.66***	0.11^{ns}	0.28*	0.50***	0.58***	0.51***	0.84***	-
Spikelets/ panicle	0.60***	0.62***	0.53***	0.52***	-0.08^{ns}	0.07 ^{ns}	0.01 ^{ns}	0.78***	-0.08^{ns}	0.89***	0.52***

*p < 0.05, **p < 0.01, ***< 0.001, ns = not significant

Table 5.23 Correlation between phenology, yield and yield contributing characters of varieties at South Johnstone.

	Days to flowering	Yield (t/ha)	HI	Tillers/ plant	Effective Tillers/ plants	Panicle length	Plant height	Spikelets/panicle	Grains per panicle	1000 grain wt
Days to flowering	-									
Yield (t/ha)	0.35*	-								
HI	0.35*	0.65***	-							
Tillers/plant	-0.20^{ns}	0.10^{ns}	0.23^{ns}	-						
Effective Tillers/plants	-0.13^{ns}	0.10^{ns}	0.28^{ns}	0.93***	-					
Panicle length	0.67***	0.56***	0.61***	0.16^{ns}	0.21^{ns}	-				
Plant height	-0.70***	0.12^{ns}	-0.11^{ns}	0.24^{ns}	0.19^{ns}	-0.26^{ns}	-			
Spikelets/ panicle	0.83***	0.19^{ns}	0.23^{ns}	-0.13^{ns}	-0.08^{ns}	0.66***	-0.58***	-		
Grains per panicle	0.69***	0.16^{ns}	0.14^{ns}	-0.14^{ns}	-0.03^{ns}	0.59***	-0.40*	0.85***	-	
1000 grain wt	-0.92***	-0.13^{ns}	-0.19^{ns}	0.21^{ns}	0.14^{ns}	-0.52***	0.80***	-0.83***	-0.69***	-
Panicle filling percentage (Fertility %)	-0.43**	-0.12^{ns}	-0.22^{ns}	0.20^{ns}	0.21^{ns}	-0.24^{ns}	0.40*	-0.43**	0.06^{ns}	0.44**

*p < 0.05, **p < 0.01, ***< 0.001, ns = not significant

Table 5.24 Correlation between phenology, yield and yield contributing characters of varieties at Alton Downs.

	Days to flowering	Yield (t/ha)	HI	Tillers/ plant	Effective Tillers/ plants	Panicle length	Plant height	Spikelets/panicle	Grains per panicle	1000 grain wt
Days to flowering	-									
Yield (t/ha)	-0.89***	-								
HI	-0.80***	0.75***	-							
Tillers/plant	-0.16^{ns}	0.19^{ns}	0.26^{ns}	-						
Effective Tillers/plants	-0.47*	0.52**	0.56**	0.89***	-					
Panicle length	-0.44^{ns}	0.46*	0.59**	0.55**	0.66***	-				
Plant height	-0.11^{ns}	-0.04^{ns}	-0.07^{ns}	0.37^{ns}	0.22^{ns}	0.26^{ns}	-			
Spikelets/ panicle	-0.09^{ns}	0.06^{ns}	0.08^{ns}	0.47*	0.42*	0.45*	0.52**	-		
Grains per panicle	-0.30^{ns}	0.31^{ns}	0.42*	0.66***	0.66***	0.50**	0.31^{ns}	0.70***	-	
1000 grain wt	-0.94***	0.88***	0.79***	0.22^{ns}	0.51**	0.57**	0.06^{ns}	0.17^{ns}	0.31^{ns}	-
Panicle filling percentage (Fertility %)	-0.28^{ns}	0.31^{ns}	0.41*	0.60**	0.59**	0.33^{ns}	0.29^{ns}	0.50**	0.93***	0.24^{ns}

*p < 0.05, **p < 0.01, ***< 0.001, ns = not significant

5.4.2. Relationship of physiological traits with yield and HI

Yield, HI and water productivity are significantly correlated with physiological parameters such as WUE, WUEi, A, gs and E across the locations (Table 5.25) but the correlation was not significant for varieties separately at Alton Downs (Table 5.27) or South Johnstone (Table 5.26). Similar correlation was found in the study conducted by Centritto et al. (2009), with a typical hyperbolic relationship between photosynthesis and gs. There was significant location effect on all physiological parameters studied (Section 5.3.3.2) and the yields of varieties were also significantly higher at South Johnstone as compared to Alton Downs (Table 5.14 and Figure 5.4). Degenkolbe et al. (2009) reported the down regulation of photosynthesis genes in both sensitive and tolerant varieties to prevent photodamage under drought stress during water shortages. The rice growing environment at South Johnstone is favourable for efficient photosynthate assimilation, resulting in high economic yield across all varieties. However, the leaf A at Alton Downs was not correlated with yield, as photosynthate assimilation and favourable conditions for translocation to sink was limited by moisture stress. Photosynthesis alone cannot be taken into consideration in isolation as the yield determining factor Centritto et al. (2009). Photosynthesis interacts with plant water status and escape or avoidance mechanisms (e.g., earliness at Alton Downs). Water use efficiency was significantly correlated with water productivity (r = 0.54***) across the locations but the correlation was not significant at Alton Downs (Table 5.27) or South Johnstone (Table 5.26). The WUE between the varieties were not significantly different between the varieties within each location, but the WUE was significantly higher at South Johnstone as compared to Alton Downs (Table 5.12). Hsiao et al. (2007) has reported positive correlation between WUE and water productivity. With the increased availability of additional water, water productivity and HI showed positive response as compared to low rainfall water (Oweis et al., 2000). Better availability of water contributed to increased water productivity and WUE at South Johnstone as compared to Alton Downs.

Flag leaf area was significantly correlated with higher yield across locations (r = 0.39**, Table 5.25) and at South Johnstone (r = 0.41**, Table 5.26) but not at Alton Downs (Table 5.27). Yue et al. (2006b) also reported a significant correlation between yield and flag leaf area. Flag leaf area is important for yield as it determines the photosynthetic output by influencing the photosynthetic area. The alleles responsible for the increased leaf area are closely linked with grain yield in the same genomic locations (Li et al., 1998). Therefore, selecting varieties with larger flag leaf area can also contribute to the higher yield of varieties.

Table 5.25 Correlation between yield, harvest index (HI) and physiological traits at Alton Downs and South Johnstone under rainfed conditions.

	Yield (t/ha)	HI	Water Productivity (t/ML)	Flag leaf length	Flag leaf breadth	Flag leaf area	Fv/Fm	WUE	WUEi	A	gs
Yield (t/ha)	-										
HI	0.85***	-									
Water Productivity (t/ML)	0.95***	0.86***	-								
Flag leaf length	0.01^{ns}	0.10^{ns}	0.05	-							
Flag leaf breadth	0.74***	0.61***	0.61***	0.09^{ns}	-						
Flag leaf area	0.39**	0.39**	0.35**	0.87***	0.57***	-					
Fv/Fm	-0.21^{ns}	-0.20^{ns}	-0.16^{ns}	0.26*	-0.18 ^{ns}	0.14 ^{ns}	-				
WUE	0.69***	0.49***	0.54***	-0.18^{ns}	0.54***	0.12 ^{ns}	-0.26*	-			
WUEi	0.36**	0.28*	0.27*	-0.17 ^{ns}	0.20^{ns}	-0.05 ^{ns}	-0.27*	0.78***	-		
A	0.76***	0.57***	0.60***	-0.19 ^{ns}	0.72***	0.20 ^{ns}	-0.28*	0.88***	0.51***	-	
gs	0.67***	0.50***	0.53***	-0.09 ^{ns}	0.72***	0.29*	-0.12 ^{ns}	0.59***	0.06^{ns}	0.86***	-
E	0.70***	0.55***	0.54***	-0.14 ^{ns}	0.74***	0.25*	-0.21 ^{ns}	0.60***	0.20^{ns}	0.90***	0.93***

*p < 0.05, **p < 0.01, ***< 0.001, ns = not significant

Table 5.26 Correlation between yield, harvest index (HI) and physiological traits at South Johnstone under rainfed conditions.

	Yield (t/ha)	HI	Water Productivity (t/ML)	Flag leaf length	Flag leaf breadth	Flag leaf area	Fv/Fm	WUE	WUEi	A	gs
HI	0.65***	-									
Water Productivity (t/ML)	1.00***	0.65***	-								
Flag leaf length	0.42**	0.52***	0.42**	-							
Flag leaf breadth	0.10^{ns}	-0.04^{ns}	0.10^{ns}	0.21^{ns}	-						
Flag leaf area	0.41**	0.46**	0.41**	0.97***	0.44**	-					
Fv/Fm	0.02^{ns}	-0.11^{ns}	0.02^{ns}	0.25^{ns}	0.03^{ns}	0.25^{ns}	-				
WUE	0.10^{ns}	-0.03^{ns}	0.10^{ns}	-0.12^{ns}	-0.20^{ns}	-0.17^{ns}	-0.17^{ns}	-			
WUEi	0.12^{ns}	0.21^{ns}	0.12^{ns}	-0.17^{ns}	-0.30^{ns}	-0.24^{ns}	-0.32*	0.71***	-		
A	-0.10^{ns}	-0.27^{ns}	-0.10^{ns}	-0.16^{ns}	0.08^{ns}	-0.13^{ns}	-0.14^{ns}	0.65***	0.21^{ns}	-	
gs	-0.13^{ns}	-0.30^{ns}	-0.13^{ns}	0.04^{ns}	0.31^{ns}	0.13^{ns}	0.13^{ns}	-0.05^{ns}	-0.63***	0.59***	-
E	-0.24^{ns}	-0.30^{ns}	-0.24^{ns}	-0.08^{ns}	0.34*	0.02^{ns}	-0.01^{ns}	-0.13^{ns}	-0.46**	0.66***	0.86***

*p < 0.05, **p < 0.01, ***< 0.001, ns = not significant

Table 5.27 Correlation between yield, harvest index (HI) and physiological traits at Alton Downs under rainfed conditions.

	Yield (t/ha)	HI	Water Productivity (t/ML)	Flag leaf length	Flag leaf breadth	Flag leaf area	Fv/Fm	WUE	WUEi	A	gs
HI	0.75***	-									
Water Productivity (t/ML)	1.00***	0.76***	-								
Flag leaf length	-0.04^{ns}	0.00^{ns}	-0.04^{ns}	-							
Flag leaf breadth	0.10^{ns}	0.19^{ns}	0.10^{ns}	0.70***	-						
Flag leaf area	0.03^{ns}	0.09^{ns}	0.03^{ns}	0.94***	0.90***	-					
Fv/Fm	0.22^{ns}	0.40*	0.22^{ns}	0.23^{ns}	0.12^{ns}	0.19^{ns}	-				
WUE	-0.10^{ns}	-0.20^{ns}	-0.10^{ns}	-0.19^{ns}	-0.19^{ns}	-0.21^{ns}	-0.03^{ns}	-			
WUEi	-0.09^{ns}	-0.12^{ns}	-0.09^{ns}	-0.12^{ns}	-0.15^{ns}	-0.16^{ns}	-0.04^{ns}	0.90***	-		
A	-0.16^{ns}	-0.17^{ns}	-0.16^{ns}	-0.17^{ns}	-0.10^{ns}	-0.17^{ns}	-0.04^{ns}	0.81***	0.77***	-	
gs	-0.14^{ns}	-0.01^{ns}	-0.14^{ns}	-0.13^{ns}	0.01^{ns}	-0.08^{ns}	0.07^{ns}	-0.16^{ns}	-0.40*	0.24^{ns}	-
E	-0.10^{ns}	0.06^{ns}	-0.09^{ns}	-0.01^{ns}	0.04^{ns}	0.01^{ns}	0.00^{ns}	-0.18^{ns}	-0.09^{ns}	0.40*	0.63***

*p < 0.05, **p < 0.01, ***< 0.001, ns = not significant

5.5. Conclusion

A variety selected in one particular environment suffer much loss when planted in another environment with different rainfed conditions. As an example, a variety producing more than 5 t/ha in the South Johnstone environment produced less than 0.5 t/ha at Alton Downs (e.g., AAT 11, AAT 12 and AAT 18). The more than 5 fold yield difference in these varieties between the two growing environments suggests that the genetic potential of these varieties was not expressed at Alton Downs. The greater yield of AAT 10 and AAT 11 at South Johnstone is due to the fact that in the wet tropics the favourable environment offered these varieties favourable factors to allow them to perform better. It is necessary to evaluate varieties in different kinds of rice growing systems to evaluate their adaptability. Varieties AAT 4, AAT 6 and AAT 19 were consistent yielders in both locations, producing highest yields when exposed to terminal drought at Alton Downs. The early flowering varieties showed greater adaptation in the dry tropical environment, whereas the adaptation of late flowering varieties was not compromised under the wet tropical environment of South Johnstone These varieties could be considered as more widely adapted than other tested varieties as they had the lowest yield reduction between South Johnstone and Alton Downs. The findings of this research suggest that physiological potentials of late flowering varieties were not realised in Alton Downs due to drought during flowering and grain filling stages.

Yield attributing traits behaved differently in different rice growing environments. The higher overall yield at South Johnstone was associated with high panicle fertility percentage and 1000 grain weight, HI, effective tillers per plant, larger panicle length, total filled grains per panicle and greater density grain (1000 grain weight). Water use efficiency had a positive impact on total yield, contributing assimilates that resulted in higher numbers of filled grains per panicle and higher 1000 grain weights at South Johnstone in contrast to a non-significant relationship at Alton Downs.

Growers in the wet tropics have a better choice of varieties with AAT 10 and AAT 11 as long grain varieties and AAT 4, AAT 6 and AAT 19 as medium grain varieties as compared to only medium grain varieties for the drier tropics of central Queensland for rainfed production. Further investigation on the performance of these varieties with multiple years in different locations is suggested to better comprehend their response to environments (G x E interactions) for commercial cultivation of rainfed rice crop in Queensland, Australia.

CHAPTER 6. GENERAL DISCUSSION AND CONCLUSION

Aerobic rice culture has the potential to reduce the demand for irrigation water input in rice farming without yield penalty (Bouman et al., 2007). Rainfed rice cultivation could provide opportunities to make a quantum jump in attaining water productivity in rice farming, particularly in areas such as central Queensland. The growing demand of water for flooded rice farming has created more attention in aerobic rice culture in Australia. The risk of severe water stress in rice farming in rainfed systems can be minimised by incorporating strategic irrigation, where irrigation water is provided to the plant when the crop water demand is not met by rainfall. This approach has shown great potential under rainfed conditions for a number of crops such as chickpea (Oweis et al., 2004) and wheat (Oweis and Hachum, 2003). Strategic irrigation has highlighted that better water management can help plants cope with the terminal drought in the dry tropics such as found at Alton Downs in central Queensland, Australia. Under strategic irrigation the rice crop has achieved up to 5.23 t/ha (AAT 4) at Alton Downs (November sowing) which compares well with 5.78 t/ha at the wetter and more uniformly distributed rainfall site at South Johnstone, also in Queensland. But this is still less than Blackwell et al. (1985) achieved (5.8 t/ha) under a sprinkler irrigation system in Australia at the Murrumbidgee Irrigation Area and Fukai and Inthapan (1988a) achieved (6 t/ha) with sprinkler irrigation at Redlands Bay, south-eastern Queensland. There is, therefore, still more research scope in central Queensland to reach the record yield of 8 t/ha as reported by different researchers under sprinkler irrigation (Kato et al., 2009), centre pivot (Stevens et al., 2012), flooded irrigation (Shi et al., 2001), piped irrigation (Sudhir et al., 2011) or even under rainfed conditions (Matsunami et al., 2009) with more water.

The proportionate yield gain with strategic irrigation compared to rainfed conditions across the years 2014 and 2015 at Alton Downs in central Queensland for the rice varieties trialled was from 1.5 fold (AAT 4) to 16.8 fold (AAT 15). The yield of rice with every 1 mm of strategic water application was increased by 11.87 kg/ha in 2014 and 15.80 kg/ha in 2015, with the range of -2.41 kg/ha (AAT 4) to 19.49 kg/ha (AAT 9) in 2014 and 10.60 kg/ha (AAT 6) to 22.95 kg/ha (AAT 15) in 2015 (Table 6.1). In general the yield increase per mm of strategic irrigation was greater for the later varieties. Under greenhouse conditions in Uganda, Matsumoto et al. (2014) reported that the yield increase with 1 mm in NERICA rice was 11–12 kg/ha.

Table 6.1 Yield gain with strategic irrigation at Alton Downs in 2014 and 2015.

		Yield gain (kg/ha/mm)	
Flowering	**Variety**	**2014**	**2015**
Late	AAT 9	19.49	16.64
Late	AAT 10	10.27	18.08
Late	AAT 11	17.28	18.31
Late	AAT 12	17.00	16.00
Late	AAT 15	8.19	22.95
Late	AAT 16	14.10	19.33
Late	AAT 18	11.39	16.19
Early	AAT 3	13.89	10.90
Early	AAT 4	-2.41	17.45
Early	AAT 6	11.81	10.60
Early	AAT 13	16.59	14.25
Early	AAT 17	10.53	11.80
Early	AAT 19	6.18	12.86
Average		11.87	15.80

With the varieties with similar and higher than 11–12 kg/ha per 1 mm water application at Alton Downs, the earlier planting (in 2015) showed better strategic irrigation water utilisation for most varieties compared to the later planting in 2014, where variety AAT 4 showed negative gain per unit of water application. The high yield gained per unit water application by some varieties shows that there is great commercial scope for strategic irrigation during the water deficit periods created by little or no rainfall, especially that leading to terminal drought.

Average yield of early flowering varieties (AAT 3, AAT 4, AAT 6, AAT 13, AAT 17 and AAT 19) under rainfed conditions was 2.76 t/ha in 2014 and 2.23 t/ha in 2015, whereas late flowering varieties (AAT 9, AAT 10, AAT 11, AAT 12, AAT 15, AAT 16 and AAT 18) with strategic irrigation produced 2.38 t/ha in 2014 and 3.93 t/ha in 2015. Strategic irrigation enabled the late varieties to cope with terminal drought in 2015 in contrast to 2014, when late varieties had to contend with both low temperatures and terminal drought. Fukai and Inthapan (1988a) also reported similar effects of late planting in south-eastern Queensland on exposure to low temperatures of late flowering varieties resulting in low yield. Maintenance of temperatures above 22°C during anthesis is critical for rice pollen fertility (Yoshida, 1978). During 2015, the late flowering varieties were not exposed to a cold periods during anthesis (Figure 3.2) and were exposed only to terminal drought. The response of late flowering varieties to strategic irrigation at Alton Downs in 2015 showed that they have similar yield potential to the early flowering varieties. Late flowering varieties, such as AAT 10, AAT 12 and AAT 18, out-yielded the early flowering varieties at South Johnstone (Figure 4.4), where there was no water stress (nor cold stress) across the growth period.

Williams et al. (2001) argued that reduction in crop duration by 20 days can save up to 10% irrigation water under flooded irrigation systems in NSW, Australia, but under rainfed and aerobic systems in the Queensland tropics, short duration varieties can save even more water. Short duration varieties help escape drought. Drought escape is the best strategy to minimise the yield reduction due to drought, to ensure the best utilisation of available water during a wet-season (Fukai et al., 1999) and to lead to yield stability across years. The varieties tested in the current trials were distinguished by two flowering groups (within each of which varieties had quite similar maturity dates). Under the Alton Downs conditions the early flowering varieties had more adaptive advantage to late flowering varieties in escaping the terminal drought. The development of early maturing varieties of rice has contributed to the increase of water productivity by up to a threefold difference (Farooq et al., 2009).Therefore, there is further scope for testing and/or developing short duration varieties to escape the terminal drought and to save water. Short duration varieties can make for a more efficient farming system WUE with the chance of establishing winter crops after rice without losing soil moisture.

Boyer and Westgate (2004) related drought stress during the grain filling period to pollen sterility, leading to decreased yield. However, water stress down regulates the photosynthesis genes in rice varieties (Degenkolbe et al., 2009) and carbohydrate synthesis during the grain filling period by the flag leaf is very important for yield determination and any factor that hinders the photosynthetic rate results in yield reduction (Dingkuhn et al., 1989). Values for the leaf gas exchange parameters such as photosynthetic rate, stomatal conductance, transpiration rate and WUEi were higher at South Johnstone as compared to Alton Downs. A significant positive correlation between yield and A was evident at South Johnstone (r=0.76***, an asymptotic relationship, Figure 6.1) and a similar relationship was noted at Alton Downs with rainfed conditions and strategic irrigation trial in 2015 (r=0.74***, again an asymptotic relationship, Figure 6.2), with the average yield of 4.22 t/ha under strategic irrigation at Alton Downs and 4.66 t/ha at South Johnstone in comparison to the rainfed yield at Alton Downs with of 1.38 t/ha.

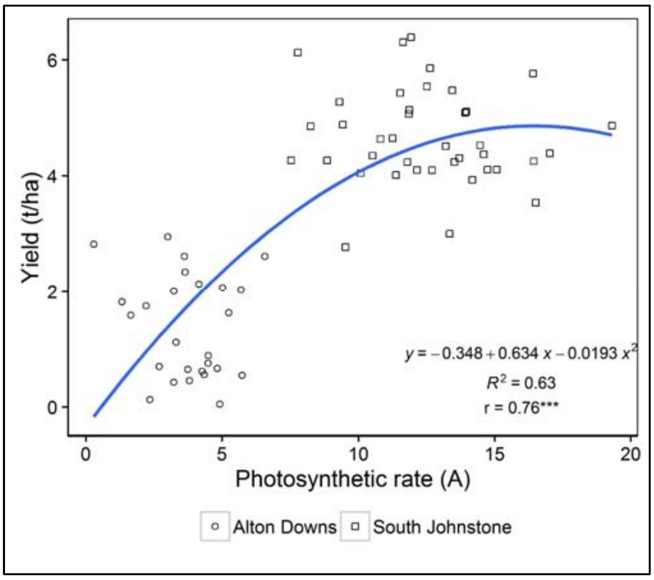

Figure 6.1 Relationship between photosynthetic rate (A) and yield at Alton Downs and South Johnstone in 2015.

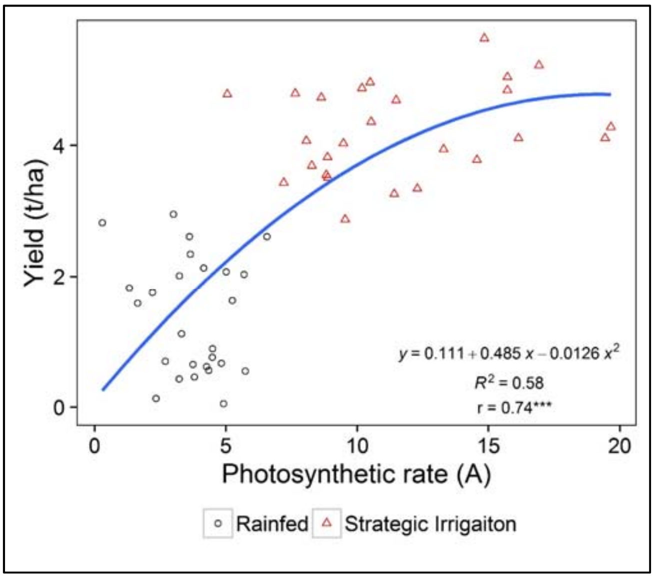

Figure 6.2 Relationship between photosynthetic rate (A) and yield under rainfed conditions and strategic irrigation at Alton Downs in 2015.

Grain yield is determined mainly by the rate of photosynthesis (producing biomass) and HI (partitioning of biomass to grain). Most of the yield gains from recent research were achieved through increased HI (Farooq et al., 2009). Varieties that can produce more grain yield from total biomass are therefore more desirable. From the current study, the early flowering varieties had better HI as compared to the late flowering varieties under drought (Table 3.20) and HI showed a strong correlation with yield in all the experimental conditions (Table 3.32 and Table 3.33).

Leaf area index prior to the reproductive stage is important for rice grain yield as it represents increased tillering, new leaf formation and leaf expansion (Raboin et al., 2014; Tao et al., 2006), which contribute to more photosynthetic activity for grain filling and increased panicle formation. The LAI in the Alton Downs experiment under strategic irrigation and rainfed conditions were significantly correlated with yield, WUE and A (Table 3.27). Leaf area index, therefore, has been shown as an important parameter for selection under the rice aerobic system (Sudhir et al., 2011).

Under rainfed conditions at Alton Downs yield attributes were significantly correlated with yields. The yield of varieties were significantly correlated with panicle fertility (r = 62***) at Alton Downs across the strategic irrigation and rainfed treatments, with significant interaction on year of planting (Table 4.5). Late flowering varieties had significantly lower fertility percentages as compared to early flowering varieties in 2014, whereas in 2015 the opposite was so (Figure 3.13). The significant reduction of panicle fertility in 2014 can be related to the cold stress during flowering. Similar reduction of sterility was also reported by Gunawardena et al. (2003), notably with a decrease in sterility with exposure to cold temperature. The varieties with higher fertility had higher yields in the Alton Downs trial (Table 3.32, r = 0.73*** and Table 3.33, r = 0.53***). All the early flowering varieties at Alton Downs under rainfed conditions had significantly higher panicle fertility compared to late varieties as the late varieties were exposed to terminal drought. This result is similar to the those of Srividhya et al. (2011) and Jongdee et al. (2002) where significant reduction of spikelet fertility was found (with reduction of 20–98 %), which depended up on the days to drought exposure before flowering. Higher sterility in late varieties exposed to drought has been reported to be due to slower panicle exertion (Lanceras et al., 2004) in addition to the identified low carbohydrate accumulation in pollen and low enzymatic activity of starch synthase and ADP-glucose phosphorylase (Saini and Lalonde, 1997). Nevertheless, Kobata et al. (1994) argued that the sterility was not due to the lack of assimilate, but because of dehydration of the root zone. As tolerance of spikelet fertility to drought is an ideal character for the adaptation of rice under terminal drought in rainfed systems, the physiological mechanisms of higher spikelet fertility still needs to be investigated.

In the experiments under rainfed conditions and strategic irrigation the number of effective tillers produced by each plant was significantly correlated to the grain yield (Table 3.26, r = 0.49***; Table 3.27, r = 0.43***). Grain yield in rice is therefore dependent on effective tillers produced by each plant (Fageria, 2007). Strategic irrigation significantly increased the effective tillers per plant compared to rainfed conditions (Table 3.23). The number of effective tillers is determined by the environment favourable for tiller bud initiation during the plant development stages (Fageria, 2007). Zhang et al. (2009) reported that tiller development or abortion was affected by water availability during the crop growth period. Therefore, plants that can produce more effective tillers per plant are better for drought adaptation under aerobic and rainfed systems.

Varieties of rice, being mostly a drought avoider (Centritto et al., 2009), that can maintain higher water status during flowering and grain filling produce better yield (Serraj et al., 2008). Bernier et al. (2009) reported deeper root length as an important trait for water absorption to maintain the required plant water status. Of interest, there was, however, no significant correlation between the deep root trait recorded in the field and yield of rainfed rice under the Alton Downs condition when measured during 2015 (Table 3.29). However, the RDW at 0–15 cm depth showed significant correlation with yield (Table 3.29, r = 0.56*) under strategic irrigation. Similarly, a preliminary trial in 1.5 m tall and 15 cm diameter PVC columns was conducted in 2014, with the same varieties as tested in the field, under field capacity and half of field capacity to determine root length, root volume and root dry weight (unpublished data). The correlation analysis between root parameters at field capacity and yield with strategic irrigation (Alton Downs), as well as between half field capacity and rainfed yields (Alton Downs), showed surprisingly strong negative correlations (Table 6.2 and Table 6.3). This contrasts with previous studies (Bernier et al., 2009; Chang and Vergara, 1975; Henry, 2013), where deep rooting was positively correlated with drought adaptation; i.e., yield under rainfed conditions or drought. Similarly, the rooting characteristic under field capacity in PVC columns did not show a significant relationship with yield under strategic irrigation in the field (Table 6.3). Varieties under Alton Downs conditions were better favoured by investing in root biomass in the upper part of the soil profile than deeper, as there was not much moisture difference beyond 20 cm depth under strategic irrigation due to drip irrigation (Figure 3.5 variety AAT 4 was the early flowering and AAT 12 the late flowering). Strategic drip irrigation receiving 1.89 ML/ha more water than rainfed conditions (Figure 3.3) which mostly favoured the crop accessing more moisture at 0-15 cm. In Australia, deep percolation has historically been considered as unfavourable due to potential recharge and the raising of salty ground water (P Snell, personal communication, 29 December 2014); hence, for ponded crops deep roots are considered to be of little value.

Table 6.2 Correlation between yield under rainfed conditions at Alton Downs and root parameters at half field capacity in PVC column.

	Root parameters under half field capacity		
Variety yield under rainfed condition (t/ha)	Root Length (cm)	Root Dry Weight (g)	Root Volume (cc)
2014	-0.78**	-0.81***	-0.74**
2015	-0.80**	-0.77**	-0.65*
Average	-0.80***	-0.81***	-0.72**

*p < 0.05, **p < 0.01, ***< 0.001, ns = not significant

Table 6.3 Correlation between yield under strategic irrigation conditions at Alton Downs and root parameters at field capacity in PVC column.

	Root parameters under field capacity		
Variety yield under strategic irrigation (t/ha)	Root Length (cm)	Root Dry Weight (g)	Root Volume (cc)
2014	-0.42^{ns}	-0.56*	-0.34^{ns}
2015	-0.13^{ns}	-0.17^{ns}	-0.18^{ns}
Average	-0.39^{ns}	-0.51^{ns}	-0.34^{ns}

*p < 0.05, **p < 0.01, ***< 0.001, ns = not significant

Varieties with the characteristics of efficient photosynthesis, high HI, enhanced root characteristics at shallow depth, higher panicle fertility, LAI and effective tillers will be ideal for tropical Queensland. Different strategies of breeding, such as using molecular tools to dissect out contributions of individual traits, need to be used to combine the genes responsible for improving the WUE and drought tolerance in rice.

Varieties such as AAT 6 and AAT 13 showed stability over varying planting dates and drought conditions (over three seasons) of Alton Downs in central Queensland. Development of a rice industry with suitable varieties such as AAT 6 and AAT 13 for the central Queensland region can give better opportunity to the growers as an alternative crop in vertisols by adapting rainfed rice to the local climatic conditions and prevailing cropping systems, which can significantly contribute to local economy and job.

With strategic irrigation in the dry tropics, rice varieties can give significant yield improvements for both late and early varieties. Varieties were highly responsive to additional/supplementary water application with an average increase of 11.87 kg/ha and 15.80 kg/ha for each mm of supplemental irrigation in 2014 and 2015 respectively. This shows significant scope for commercial production of rice farming under strategic irrigation especially during water deficit periods. Therefore, further research on varietal development and water management strategies for aerobic rice in central Queensland is suggested to achieve the commercial success on rice cultivation in the dry and wet tropics of Queensland, Australia.

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Appendix A

Soil Moisture measurements of varieties under rainfed conditions and strategic irrigation at Alton Downs in 2015