IDENTIFICATION AND EVALUATION OF DROUGHT-ADAPTIVE TRAITS IN POTATO

Dissertation

by

Md Saiful Islam

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Supervisor: Univ. Prof. Dipl.-Ing. Dr. nat. techn. Hans-Peter Kaul

Advisor: Assoc. Prof. Dipl.-Ing. Dr. nat. techn. Ahmad M. Manschadi

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Universität für Bodenkultur Wien

University of Natural Resources and Life Sciences, Vienna

Department of Crop Sciences

Division of Agronomy

Declaration

I hereby confirm that the entire work of this thesis has been written by me. To best of my knowledge, I acknowledged all information, figures and data derived from other work, published or provided and their references are listed accordingly.

I hereby declare that I have not submitted this thesis to another University of Institution for obtaining any academic recognition.

Tulln, June 2017 Md Saiful Islam

Dedicated to my Father, who’s dream was it…….

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Abbreviations

UFT	Universitäts- und Forschungszentrum Tulln (University and Research Centre, BOKU, Tulln)
FAO	Food and Agriculture Organization
PSO	Principal Scientific Officer
Kcal	Kilo calorie
Kpa	Kilo pascal
CIP	International Potato Center
T	Transpiration
TE	Transpiration efficiency
TR	Transpiration ratio
NTR	Normalized transpiration
FTSW	Fraction of transpirable soil water
WUE	Water use efficiency
HI	Harvest index
LAI	Leaf area index
SD	Standard deviation
SEM	Standard error of means
WS	Water stress
WW	Well-watered
VPD	Vapor pressure deficit
DAP	Days after planting
DM	Dry mass/matter
TDM	Total dry matter
GDD	Growth degree days

Abstract

In response to drought, genotypic variations in potato, their interaction with the environment and management need to be evaluated. Considering transpiration efficiency (TE) as important trait for soil water saving and yield in potato, three glasshouse pot experiments were conducted with eleven genotypes collected from different countries. Contrasting genotypes for TE screened out in the glasshouse were tested for field performance once in Tulln and twice in Bangladesh. Plants were grown until the 9-12 leaf stage in pots filled with 6.0 kg substrate consisting of soil:sand:compost at 1:1:0.8 (v/v). At start of dry down treatment, all pots were brought to field capacity. Only one stem per plant was allowed in each pot by cutting additional stems at the base. Pots were then sealed by polyethylene bags to restrict water losses to transpiration (T). One set of plants was submitted to water stress (WS) and a 2nd set was kept well-watered (WW) near to field capacity. Daily T was measured gravimetrically. Dry down cycle was continued until T of all WS plants reached at 10% of WW plants. Glasshouse experiments in three different seasons showed variations in vapor pressure deficit (VPD).

WS plants during progressive soil drying consumed almost half the water of WW plants. Total T was significantly different among the genotypes. A wide range of Fraction of Transpirable Soil Water (FTSW) threshold among the genotypes (0.19 to 0.36) was narrowed down (0.19 to 0.29) under high VPD condition. Significant variations in TE among the genotypes increased under water stress and decreased at high VPD condition. Genotypes Desiree, Diego and Caesar had high TE values but were not good in saving water. Water saving properties of a genotype, therefore, may be more based on root characteristics or different traits, which opens up a new window of research on drought stress in potato.

1 Introduction

To assure food security for increasing population to 185 million by 2030 and 202 million by 2050 (FAOSTAT, 2016), Bangladesh needs to produce more food on less land in the future (Jahan et al., 2016). A small country with a total area of 14.84 million ha, where agricultural land as well as net cultivated area is declining by 0.27% annually over the period from 1976-77 to 2010-11 (Hasan et al., 2013), essentially requires a sustainable crop production system. In Bangladesh, production system is mostly dominated by rice with a net cropped area of 11.3 million ha (BBS, 2015) that accounts for about 75% of the total cultivated land. Although Bangladesh is a reserve of genetic diversity of about 5,000 species of higher plants (Khan, 1977) and there are more than 160 different crops presently grown in Bangladesh (Mondal, 1990) but 15 major crops cover about 98% of the total. Next to rice, potato (*Solanum tuberosum L*.) is the 2nd most important crop producing 9.4 million tons on a cultivated land of 0.49 million ha in 2014 (BBS, 2015).

Potato is produced in all continents except Antarctica (Rowe and Powelson, 2002) and is the world's third most important food crop. It is not only an important vegetable and cash crop in Bangladesh (Uddin et al., 2015) but also its demand is increasing permanently as one of the important food crops (Haque et al., 2012). Along with its flexibility for cultivation, potato provides a high amount of nutrients including carbohydrates, proteins, vitamin C, several forms of vitamin B, and minerals (Camire et al., 2009; White et al., 2009; Birch et al., 2012). Now potato is considered as an integral part of the global food system and it is the world's number one non-grain food commodity (Lutaladio et al., 2009), with a total production of 375 million tonnes in 2013. Its production has increased dramatically in developing countries in the past two decades (FAO, 2008), and has now overtaken that in the developed world (Birch et al., 2012). An improved production in Bangladesh was initiated in 1999, which reached now about 7-fold that of 1998 (FAOSTAT, 2016). According to FAO data (2013), Bangladesh represents the 7th position in global potato production with 9.4 million tons per year.

Potato grows in the cool season in Bangladesh and is regarded as a winter crop. Usually planting is done in October through November and harvest is in February through March (BBS, 2015). Optimum planting time in the northern region is 1st week of November, while

in the southern part it is extended from mid-November to the end of November (Khalil et al., 2014). Soon after the withdrawal of heavy monsoon rainfall from May to October (Barry and Chorley, 2009), Bangladesh passes through a long dry period (November to April). Like other winter crops, potato also goes with soil drying conditions from its early to advanced growth stages during the months of December to March when soil receives almost no precipitation (Rasid and Paul, 2013). Without sufficient irrigation soil drying leads potato growth at stake. Although deficit irrigation had a significant role in increasing water use efficiency and transpiration efficiency (Liu et al., 2006), however it affects physiological growth, biomass production and yield.

Potato crop is considered as sensitive to drought (Anithakumari et al., 2012; Obidiegwu et al., 2015). Drought affects crop growth and development but crops differ in responses to water deficit in many morphological and physiological aspects (Miller and Martin, 1987; Lahlou et al., 2003; Schafleitner et al., 2007; Anithakumari et al., 2012; Stark et al., 2013) and response to drought varies widely among cultivars (Martin and Miller, 1983; Stark et al., 1991; Shock and Feibert, 2002; Soltys-Kalina et al., 2016). Even a short period of water deficit can result in reduction of tuber production and tuber quality (Lynch et al., 1995; Dalla Costa et al., 1997; Deblonde and Ledent, 2001).

Drought tolerance in plants is a complex trait that involves morphological, physiological, and biochemical mechanisms (Soltys-Kalina et al., 2016). Cultivars within a similar maturity class can be affected differently by water stress (Stark et al., 2013). To adapt with different drought conditions, potato plants follow different strategies not to get tuber yield significantly affected (Deblonde and Ledent, 2001; Lahlou et al., 2003). Drought avoidance could be achieved by early maturing varieties before late season drought appears (Haverkort and Goudriaan, 1994). Drought acclimation in response to soil drying involves in a number of ways. Shifting assimilates from shoot to root has been reported by Khalil and Grace (1992), which is thought to reduce transpirational demand relative to water absorption (Pallardy, 1981). Osmotic adjustment by increasing the concentration of solutes in the symplast can also be a good strategy for extracting water from dry soil (Khalil and Grace, 1992). The turgor maintained at low water potential in tissues allows stomatal opening and cell expansion, root growth and maintenance of productivity (Kozlowski and Pallardy, 2002). The stomatal closure is one of the most well-known mechanisms of acclimation in response to a reduction

in soil water content (Khalil and Grace, 1992). In this case, a decline in leaf turgor is expected as a consequence of low water potential (Kramer, 1988) and a process of chemical signalling from root to leaves is involved (Yordanov et al., 2000). Another strategy for drought acclimation is osmoregulation relationship, between turgor maintenance and growth under water stress conditions (Wright et al., 1996). This one is considered to be an adaptive response of plants to maintain turgor, growth and yield during drought (Levy et al., 2006).

A putative trait to confer drought tolerance involves the response of transpiration rate to soil drying. In general, transpiration rate is unaffected by soil drying until the soil dries to a volumetric water content where the rate of water uptake from the soil becomes limited and controls transpiration rate (Ritchie, 1981). However, the restriction of transpiration as a drought avoidance mechanism may not be a realistic option for production systems. Yet, reduced transpiration leading to sub-optimal yield at relatively consistent production levels may be acceptable for subsistence farming in drought prone environments (Sinclair, 2011). Potato leaf growth and transpiration response to water deficits are a function of fraction of transpirable soil water (FTSW) where transpiration remains unaffected by water stress until a critical FTSW depending on the cultivar has been reached (Weisz et al., 1994).

Scientists in the previous decades started to use FTSW as a convenient tool for monitoring potato drought/water stress relationship (Muchow and Sinclair, 1991; Ray and Sinclair, 1997; Bindi et al., 2005; Davatgar et al., 2009). This approach has been widely used for the evaluation of plant response to water deficit. The FTSW threshold determines the timing of stomatal closure under water deficit in soil (Ray and Sinclair, 1997; Sinclair and Ludlow, 1986). Devi et al. (2009) reported that high FTSW threshold has been found in genotypes that were showing delayed wilting during a soil drying cycle. Such FTSW threshold has been determined for many annual agricultural crops, fruit crops and for some forest crops as well (Sinclair and Ludlow, 1986; Amir and Sinclair, 1991; Muchow and Sinclair, 1991; Ray and Sinclair, 1997; Ray and Sinclair, 1998; Bindi et al., 2005; Davatgar et al., 2009; Devi et al., 2009; Gholipoor et al., 2012) and variations were observed in FTSW threshold among cultivars of the same crop, such as soybean (Hufstetler et al., 2007), peanut (Devi et al., 2009), pearl millet (Kholova et al., 2010), sorghum (Gholipoor et al., 2012), potato (Bisognin et al., 2008; Lago et al., 2012; Anithakumari, 2012; Souza et al., 2014). The threshold for the decline in transpiration rate commonly occurs when FTSW declines to the range of 0.3 to 0.4

(Meyer and Green, 1981; Gollan et al., 1986; Sinclair and Ludlow, 1986; Rosenthal et al., 1987; Ray and Sinclair, 1997; Ray and Sinclair, 1998; Weisz et al., 1994; Sadras and Milroy, 1996) while other investigations found this value ranged among peanut genotypes from 0.43 to 0.47 in USA and that in India from 0.22 to 0.71 (Devi and Sinclair, 2011).

Another putative trait for drought-tolerance limits transpiration rate by having a decreased stomatal conductance under conditions when atmospheric vapour pressure deficit (VPD) is high (Tardieu et al., 1992). Without this sensitivity to VPD, plants would have continually increasing transpiration rates with increasing VPD (Sinclair and Bennett, 1998). Such sensitivity has been reported in many crops like soybean, sorghum, pearl millet, peanut etc. (Fletcher et al., 2007; Sinclair et al., 2008; Sadok and Sinclair, 2009; Devi et al., 2010; Gholipoor et al., 2010; Kholova et al., 2010). Unless transpiration is restricted by stomatal conductance, plant transpiration is anticipated to increase linearly with increases in the atmospheric VPD (Sinclair and Bennet, 1998). This response is particularly common under relatively low temperature (24.2^{o}C) conditions as reported by Devi and Sinclair (2011), while high temperature (32^{o}C) conditions yielded a breakpoint in this linear relationship. They hypothesized that under hotter temperatures water loss was restricted at high VPD but such restriction did not exist under lower temperatures due to enhanced stomatal opening at lower VPD (Devi and Sinclair, 2011).

In the agricultural context, farmers and breeders tend to define drought tolerant cultivars as those that maintain yield under drought conditions. Potential crop improvement mechanisms for drought tolerance include improvements in water use efficiency (WUE) and in harvest index (Muthoni and Kabira, 2016). Passioura (1996) defined grain yield as a partial function of WUE and dissected the potential yield under water-limited condition into several components:

$$Y = T \times WUE \times HI$$

Where Y is the yield, T is the amount of water transpired, WUE is the water use efficiency and HI is the harvest index (Blum, 2009). In other way, later above equation was expressed as (Passioura and Angus, 2010):

$$Y = T \times TE \times HI,$$

Where Y is the yield, T is water transpired, TE is transpiration efficiency for producing biomass (i.e., biomass divided by water transpired), and HI is the harvest index. Although these three components often interact, they are sufficiently independent to make it worthwhile considering them one by one (Passioura, 2007).

Since biomass production is tightly linked to transpiration, breeding for maximized soil moisture capture under drought is the most important target for yield improvement (Blum, 2009). Genotypes which perform better under water-deficit conditions are likely to achieve high transpiration efficiency (TE), as found in various studies for peanut (Devi et al., 2009; Krishnamurthy et al., 2007). Water conservation by restricting transpiration under continuous soil drying as well as elevated VPD conditions can result in prolonged crop growth during late season drought (Choudhary et al., 2013). Large genotypic variations were observed in restricting transpiration under high VPD in many legumes, such as chickpea (Zaman-Allah et al., 2011), soybean (Fletcher et al., 2007), cowpea (Belko et al., 2012) and in peanut (Devi et al., 2010). Similar studies have also been reported in wheat (Schoppach and Sadok, 2012), sorghum (Gholipoor et al., 2010) and pearl millet (Kholova et al., 2010). Relative differences among potato genotypes were evident in transpiration rates as observed in cv. Cara compared to cv. Desiree corresponding with their stomatal resistance (Levy et al., 1988).

Cabello et al. (2013) screened out drought tolerant germplasms from a set of 918 potato accessions provided by CIP (International Potato Center) gene bank based on yield under drought and irrigated conditions. Advanced clones of CIP showed minimum yield reduction under severe water deficit and higher drought tolerance index (Sharma et al., 2011). The European Cultivated Potato Database (Retrieved from http://www.europotato.org/display_character.php?char_no=107&character=Drought%20resistance on 15 August, 2016) indexed 458 varieties as drought resistant of which 4.4% were recorded as very high resistant to drought, 12.9% were found as high to very high resistant, 44.3% appeared with high resistance while only 38.4% showed moderate to very low resistance. Gastelo et al. (2014) reported that 21 CIP clones were found drought tolerant and late blight resistant for highland tropics while 24 accessions were found drought tolerant and virus resistant in lowland subtropics.

In previous decades scientists invested a lot of efforts in crop improvement programs largely based on Genotype (G) × Environment (E) interactions (G x E) (Manschadi, et al., 2006), however management factors (M) received very little attention. Fischer (2009) pointed out and discussed about the contributions of G, G x M, and M to grain yield in Australia. Manschadi et al. (2014) explained P-efficiency as a complex multi-genic trait governed by interactions between genetic, environmental and management factors (G × E × M) for crop yield. Taking into account and considering TE as an important trait for yield, soil water conservation and drought tolerance for potato, a number of experiments were undertaken for examining T-efficient genotypes under controlled environment in the glasshouse, and screened out genotypes were exposed to ambient environment in the field for better understanding of the contribution of TE for secured potato production under water limited management. The study was focused on the following hypotheses:

- ✓ Genetic variation exists in transpiration response of potato genotypes to continuous soil drying.
- ✓ Potato genotypes are capable of restricting transpiration rate in response to soil drying.
- ✓ Transpiration-efficient genotypes conserve soil water, which would be available later in the season for tuber production.
- ✓ Higher TE produces higher potato tuber yield.

2 Review of literature

2.1 The potato: a high potential crop

Potato (*Solanum tuberosum* L.) is the most important non-grain food crop in the world, ranking third in total production producing more dry matter, edible energy, and edible protein in less duration of time than cereals (Kawar, 2016). The crop stands out for its productive water use, it yields more food per unit of water. Its nutritional productivity, especially for high calories per unit water applied in cultivation, make the crop important as it produces 5600 kilo calories (kcal) of dietary energy, compared to 3860 in maize, 2300 in wheat and just 2000 in rice per cubic meter of water applied (Renault and Wallender, 2000). As the global population expands towards 10 billion, a total expected to be reached between 2050 and 2100, it is essential to create sustainable farming systems capable of being maintained within increasingly apparent environmental limits (Underwood et al., 2013). Advances in crop yields and productivity are paramount in raising food availability and preparing the global food systems fitting well for the decades to come, potato can make an important contribution in a sustainable way (Gastello et al., 2014).

2.1.1 The history and origin of potato

Ancient history says that earliest evidences for potato were discovered in Chilca Canyon, in the south-central area of coastal Peru, dating to the Neolithic period (Engel, 1970) about 8000 years ago. Landrace potatoes are today widely distributed from western Venezuela to northern Argentina with another group of landraces in coastal Chile (Spooner et al., 2010). Together with a number of plant species potato had already been domesticated by the end of the last Ice age (Spooner et al., 2014). The primary domestication of potatoes in the Andean uplands likely occurred around the Lake Titicaca (Hawkes, 1944; Spooner et al., 2005) and Spanish explorers are known to have brought potato in the tropical lowlands of the Magdalena River Valley (at present-day Colombia) in 1536 (Spooner et al., 2014). In the 1570s, cultivated potato was introduced into Europe and from there distributed throughout the world. Now potatoes are grown in 149 countries from latitudes of 65°N to 50°S and altitudes ranging from sea level to 4000 m, demonstrating that the versatility and adaptability of the crop is very wide in many environmental conditions. It is not known exactly when potato was introduced in the Indian subcontinent but assumed that at the beginning of the 17th century, the Portuguese navigators first brought potato to India

(Wustman et al., 2011). The first mention of potato in the Indian history is that a British Ambassador received a banquet of potato at Ajmer which was described in Edward Terry's voyage published in 1655. Fryers travel records during the period 1672-81 also described that potato was grown among other vegetables in the Gardens of Surat and in Karnataka in 1675. British traders are known to have introduced potato into Bengal where it is locally called Alu. It has also been mentioned in the old documents that good potatoes were produced in 1842 in the immediate vicinity of Kolkata and still finer ones in the hills of Cherrapunjee (Sharma, 2008) adjacent to the north eastern border of Bangladesh.

2.1.2 Biodiversity

Potato belongs to the family *Solanaceae* which comprises 3000–4000 species within about 90 genera (Machida-Hirano, 2015). Solanaceae Source (2017) shows that cultivated potato and its wild relatives are within the largest genus *Solanum* with 3000–4000 species, while Olmstead et al. (2008) reported that around 100 genera and 2500 species are currently recognised within this family. Cultivated potatoes can be classified as landraces, native varieties (grown in Latin America) or improved varieties (that are grown worldwide). Potato cultivars and landraces are highly diverse with a variety of tuber shapes, skin and flesh colours (Photo 2.1). Others also have diversity in ploidy level which may be diploid (2n = 2x = 24), triploid (2n = 3x = 36), tetraploid (2n = 4x = 48), pentaploid (2n = 5x = 60) or hexaploid (2n = 6x = 72) with a base chromosome number of n = 12 (Machida-Hirano, 2015; Srivastava et al., 2016). Hawkes (1990) reported seven cultivated potato species and later on Spooner et al. (2007) described four (Table 2.1), namely (i) *S. tuberosum,* with two groups *Andigenum* (diploids, triploids, and tetraploids) and *Chilotanum* (tetraploids), (ii) *S. ajanhuiri* (diploid), (iii) *S. juzepczukii* (triploid), (iv) *S. curtilobum* (pentaploid) (Spooner et al., 2007; Ovchinnikova et al., 2011). Recently Srivastava et al. (2016) reviewed works on potato worldwide and described in their book chapter that Potato has six cultivated species, 225 wild relatives and 110 wild tuber-bearing species.

Photo 2.1: Tubers of different genotypes of potato

Table 2.1: Classification of cultivated potato

Ploidy level	As of Hawkes (1990)		As of Spooner et al. (2007) and Ovchinnikova et al. (2011)	
	Species	**Sub species**	**Species**	**Group**
2x	*S. ajanhuiri*		*S. ajanhuiri*	
2x	*S. stenotomum*	*stenotomum*	*S. tuberosum*	Andigenum group
2x	*S. stenotomum*	*goniocalyx*	*S. tuberosum*	
4x	*S. tuberosum*	*andigenum*	*S. tuberosum*	
4x	*S. tuberosum*	*hygrothermicum*	*S. tuberosum*	
4x	*S. phureja*	*estradae*	*S. tuberosum*	
4x	*S. tuberosum*	*tuberosum*	*S. tuberosum*	Chilotanum group
3x	*S. chaucha*			
3x	*S. juzepczukii*		*S. juzepczukii*	
5x	*S. curtilobum*		*S. curtilobum*	
Source: Adapted from Spooner et al. (2014)				

2.1.3 Morphology

The potato is a herbaceous plant with a wide variation in growth among the species. Stems are semi erect, erect, and trailing on the ground, or bent up at the apex and grow in rosette or semi-rosette pattern. Leaves are compound in shape, consist of a midrib and several leaflets and they are arranged spirally on the stem (Huaman, 1986). Potato plants may develop from true seed or vegetatively propagated from tubers. Plants grown from seed produce a slender tap root with lateral branches. Plants from tubers form adventitious roots at the base of each sprout and, later, at the nodes of the underground part of each stem (Photo 2.2). Occasionally, roots may also grow on stolons. In comparison with other crops, the potato root system is weak and shallow (Levy et al. 2013), spreading mostly in the plough layer down to 30 cm in soil (Iwama, 2008). Tubers are the underground harvest product of potato, not coming from roots but from the lateral underground buds (Photo 2.3) developed at the base of the main stem (Fernie and Willmitzer, 2001). Later in development, the stem produces inflorescences usually divided into two branches and forming a cymose. It consists of bisexual complete flowers, which upon fertilization form a berry with numerous true botanical seeds (Huaman, 1986).

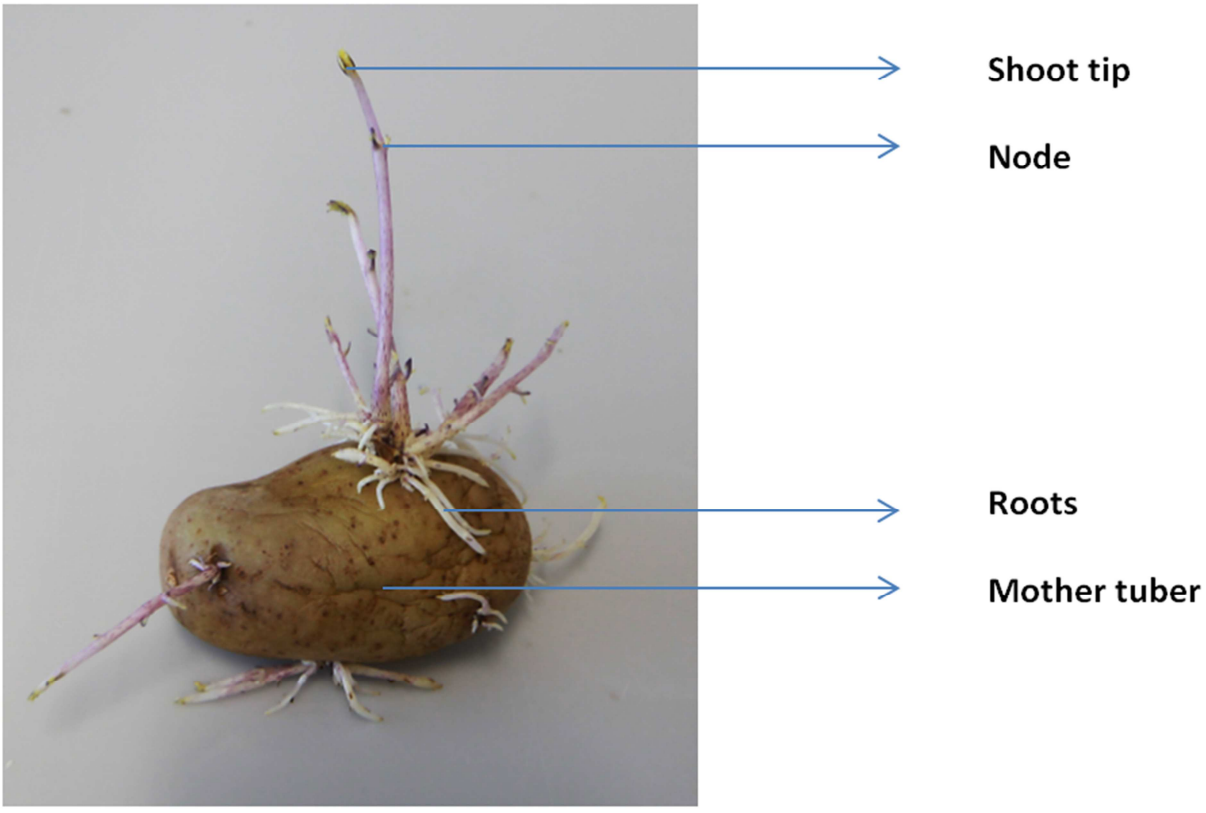


Photo 2.2: A young plant after sprouting/emergence

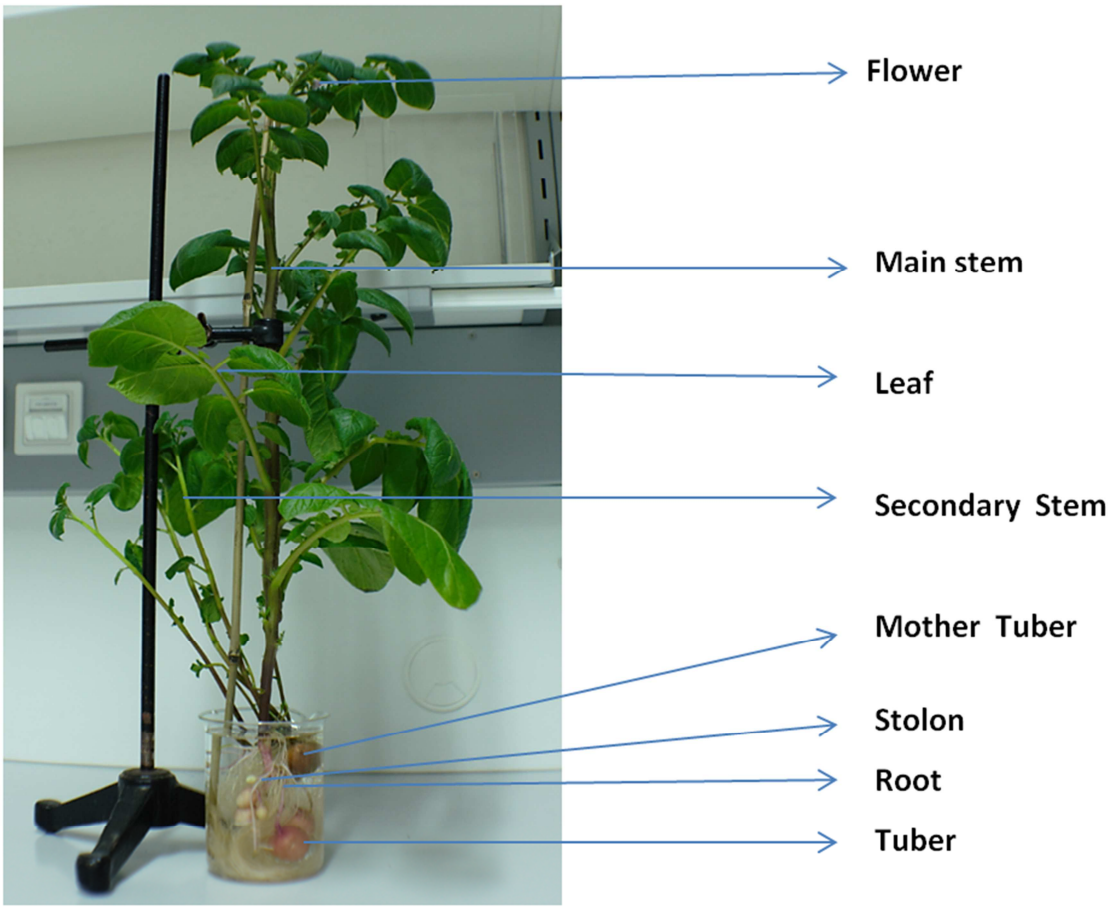


Photo 2.3: A grown up plant

2.2 Production

The recent FAO statistics shows that world's annual potato production in 2014 was 385 million tonnes where China, India, the Russian Federation, Ukraine, USA, Germany, Bangladesh, France, Poland and the Netherlands are the top 10 potato-producing countries (Figure 2.1). The potato production in the developed world has been stagnant or declining over the years while it got a high momentum in Asia (in 2014 more than 2 fold that of 1995) and Africa (in 2014 about 3 fold that of 1995). During the same time the European production went down by 17% (Figure 2.2). Today, as the world's third largest food crop, potato has a major role to play in feeding the world (Smith, 2011), and it contributes significantly to food security on a global scale (Jong, 2016). Potato is consumed almost daily by more than a billion people, and millions of people in the developing countries depend on potatoes for their survival. Potato cultivation is expanding strongly in the developing world as its ease of cultivation for resource poor conditions and nutritive content made the crop a

valuable support for food security and cash earning for millions of farmers (Woolfe, 1987; Lutaladio et al., 2010).

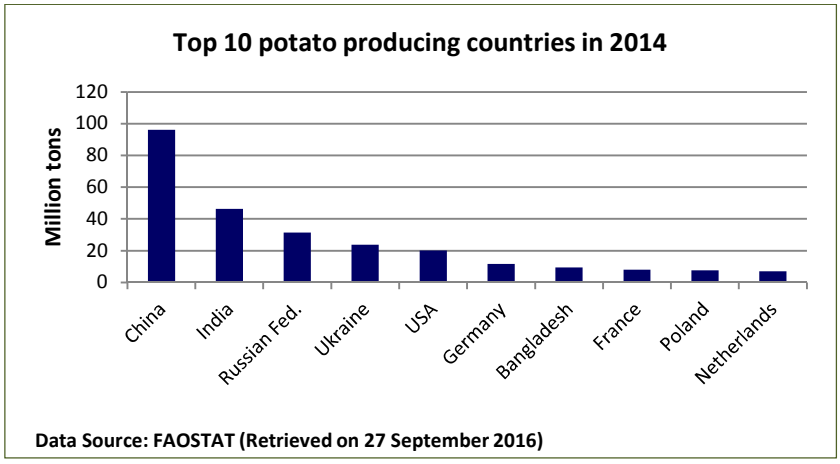


Figure 2.1: World champions in potato production

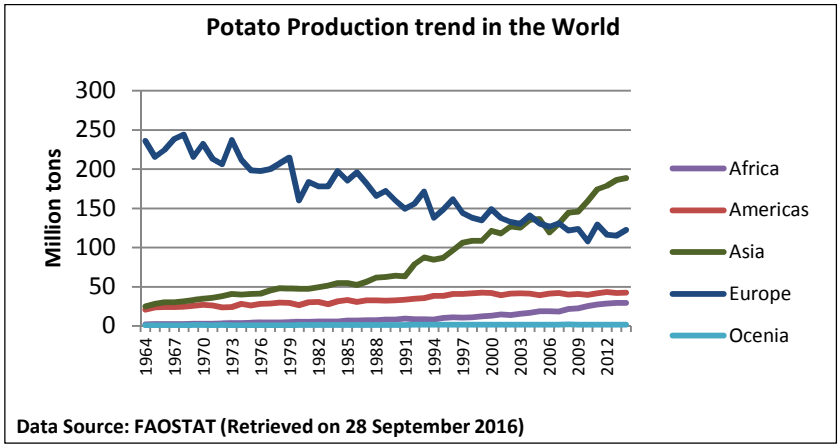


Figure 2.2: Global potato production trend

2.2.1 Importance and economic impact

Not only as an important food crop, potato is also cultivated as one of the main commercial crops in many countries (Ali and Haque, 2011, Kawar, 2016). Millions of farmers depend on potatoes for food as well as cash income, as the potato cropping systems help them to improve resilience, especially among smallholder farmers for nutritious food, increasing household incomes, and reducing shocks of food price volatility (Devaux et al., 2014). Haque et al. (2015) studied with the farmers and traders, and reported that the potato farmers in Bangladesh would be economically benefitted if they use modern inputs, adopt technologies and practices. International Potato Center (CIP) has set their strategic objectives focusing on potatoes as "E*nhancing food security in Asia through the intensification of local cereal-based*

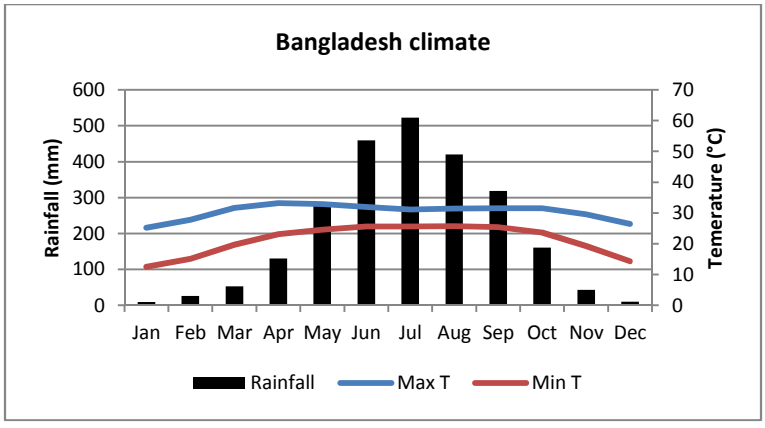
*systems with the early-maturing agile potato". The e*arly-maturing agile potato varieties (particularly varieties produced in 70 days for table and a 90-day for processing) in the lowlands and highlands of South China, North Vietnam, Bangladesh, India, and the plains of Nepal and Eastern Pakistan are considered as a profitable and nutritious complement to low-income cereals (Devaux et al., 2014). Being a short duration crop, it produces high quantity of dry matter, edible energy, and consumable protein in a shorter production cycle as compared to cereals like rice and wheat (Kawar, 2016). Potatoes help to alleviate hunger and malnutrition in developing countries (Guenthner, 2010; Thiele et al., 2010), and the crop is getting more importance at a faster rate in the Asian countries (Scott and Suarez, 2012). Attention for potato is growing by the potato breeders and industries with particular focus on Asia and Africa that brought the crop's rapid expansion decades ahead (Singh, 2008; Walker et al., 2011).

2.2.2 Potato production in Bangladesh

Bangladesh belongs to South Asia and lies between 20˚34´ to 26˚38´ N, and 88˚01´ to 92˚41´ E (Ahmed, 2006; BBS, 2015). The area of the country is 147,570 square km with more than 700 km long coastlines (Islam and Uddin, 2002). The country is bordered by India on the west, east, and north, and by the Bay of Bengal in the south (Ahmed, 2006). Geologically, it is a part of the Bengal Basin which has been filled by sediments washed down from the highlands on three adjacent sides, especially from the Himalayas, and a network of rivers originating in the Himalayas flow over the country (Photo 2.4). These sediments are the building blocks of the landmass of the delta (Ahmed, 2006). About 80% of the land is flat with a general slope of 1˚-2˚ from north to south, intersected by numerous rivers and their distributaries.

Photo 2.4: Bangladesh in the map

As Bangladesh is located at the edge of a tropical zone and lies on the Tropic of Cancer, it provides a tropical monsoon climate (Rahman, 2010). There are four prominent seasons, namely, winter (December to February), pre-Monsoon (March to May), Monsoon (June to early-October) and Post-monsoon (late-October to November). They are quite varying in temperature and precipitation gain (Ahmed, 2006; Nishat and Mukherji, 2013; Khatun, et al., 2016). The average temperature of the country ranges from 7.2^{0}C to 12.8^{0}C during winter and 23.9^{0}C to 31.1^{0}C during summer. January is the coldest month and May is the hottest (Figure 2.3) (Ahmed, 2006).



Data source: Bangladesh Meteorological Department
(http://bmd.gov.bd/?/p/=Normal-Monthly-Rainfall, downloaded on 27 Sept, 2016)

Figure 2.3: Average monthly maximum, minimum temperature and rainfall in Bangladesh

Bangladesh agriculture is traditionally subsistence in nature. Marginal and small farmers, together with landless households, constitute more than 70% of the farm families (Hossain, 2005). Agriculture is the backbone and is synonymous to the food security of the country (Faroque et al., 2013). Agricultural sectors play a vital role in the economy, which employ more than 45% of the total labour force and contribute 17% share to the Gross Domestic Product (GDP) (BBS, 2015). Land is the major source of wealth and livelihood in rural Bangladesh, but the arable land per person is one of the lowest in the world with a figure 0.05 ha per capita (Rahman and Mondal, 2015). The crop production statistics of Bangladesh for the year 2014 shows that the maximum area harvested was for Rice (76.11%) which was followed by other crops as shown in Figure 2.4 (FAOSTAT, 2016).

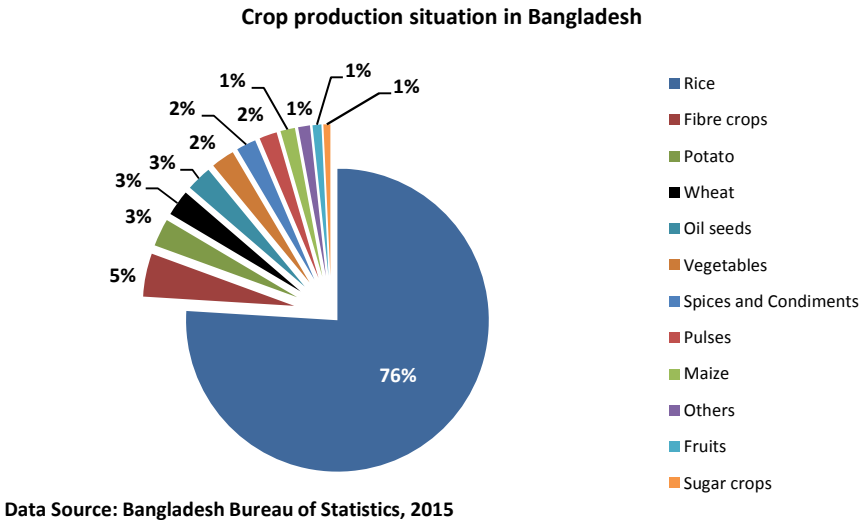


Figure 2.4: Crop production scenario in Bangladesh

In Bangladesh, potato is grown in 0.49 million hectares of land, and the country produced 9.4 million tons in 2014 with an average yield of 19.03 ton/ha (FAOSTAT, 2016). The average yield appears considerably low as around 19 ton/h (Hossain et al., 2008; Uddin et al., 2015) compared to developed countries, because the crop is produced in a short day cultivation cycle which hastens tuber and crop development (Haque et al., 2012). Under these conditions, potato takes only 90 to 115 days for maturity and the early varieties can be harvested 75 days after plantation (Uddin et al., 2015). Due to short duration and ease of cultivation, cultivated area, production and yield of potato have increased dramatically in last few decades (Siddique et al., 2015). The FAOSTAT data show that in 1961 the total potato production in Bangladesh was 0.34 million tons which slowly rose to 1.55 million in

1998 and after that an accelerated growth was going on and continued to a production quantity of 9.4 million tons at present (Figure 2.5). A list of local and developed varieties can be found in Appendix 1. Government efforts are more concentrated on potato production and to foster sustainable crop production systems in Bangladesh. A crop zoning map has been developed recently by the Bangladesh Agricultural Research Council (BARC) and the Department of Agricultural Extension (DAE), which identified potato growing zones for better production planning, management and secured production in the country (Photo 2.5).

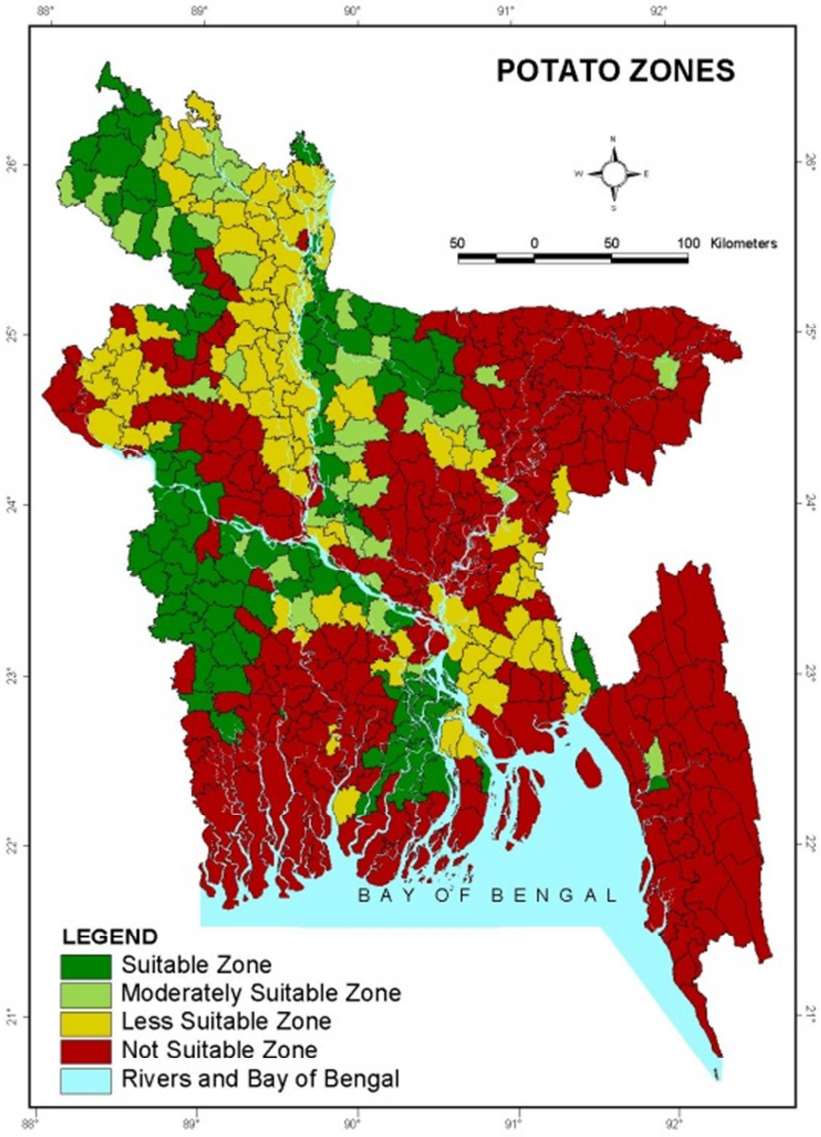


Figure 2.5: Potato growing zones in Bangladesh

Source: Bangladesh Agricultural Research Council
(http://maps.barcapps.gov.bd/images/crop_zoning/potatozone5.jpg, downloaded on 27 Sept, 2016)

2.3 Crop response to environment

2.3.1 Atmospheric CO_2

A number of scientific works show that elevated CO_2 increases plant biomass production and crop yield (Drake et al., 1997; Tubiello et al., 2007; Yang et al., 2007; Ainsworth and McGrath, 2010; Hasegawa et al., 2013). However, this increase has a limit and that in C_3 plants is approximately 650 ppm (Bunce, 1992). Up to that value any increase in atmospheric CO_2 results in an increase in the photosynthetic rate, but a long-term exposure to elevated CO_2 may result in acclimation, causing a decline in photosynthetic performance (Long and Drake, 1992). Unlike C_3 species (e.g. wheat, soybean, potatoes, sunflower), C_4 plants (e.g. maize, sorghum, millet) respond to elevated CO_2 at a different degree and less sensitive to variations in stomatal conductance than C_3 species do (Leakey et al., 2009; Lobell et al., 2013). Grain yields of C_3 crops may increase up to 20% while that increase in C_4 crops is presumably less than 13% (Ainsworth and McGrath, 2010; Lobell et al., 2013). Doubling of CO_2 concentrations increases photosynthesis by 30- 50% in C_3 species while that range is in C_4 species only 10–25% (Tubiello et al., 2007; Leaky et al., 2009). Under water-limited conditions, highest response to elevated CO_2 is observed (Kang et al., 2002) with increase in water use efficiency (WUE) (Leakey et al., 2009), but contrasted by reduction in nutrient availability and plant nutrient concentrations (Yang et al., 2007), increase in canopy temperature and reduction in stomatal conductance (Asseng et al., 2015). Potato (cv. Bintje) exposed for a long duration (50 days) to elevated CO_2, increased photosynthesis between 10% and 40% compared to ambient CO_2, and a subsequent shift from elevated to ambient CO_2 caused a 20–40% decline in photosynthetic rate (Katny et al., 2005). Tuber dry matter yields were increased 9 and 40%, respectively, in the medium (CO_2 partial pressure 53 Pa) and high (CO_2 partial pressure 70 Pa) level treatments as compared to the low level (CO_2 partial pressure 35 Pa) of CO_2 treatments. It was also evident that leaves of different age vary in their responses to changes in atmospheric CO_2 concentration (Sicher and Bunce, 1999).

2.3.2 Temperature

Temperature affects mostly plant and crop physiological processes underlying yield determination, hence the complexity appears at the final yield response (Asseng et al.,

2015). Usually optimum temperature for leaf growth and photosynthesis in C_4 crops is higher than in C_3 crops (Van Goudriaan and Laar, 1994). Higher temperature affects crop production negatively, indirectly through accelerated phenology (Wang et al. 2008; Lobell et al., 2012) that reduces time for biomass accumulation (Wang et al., 2013). A severe reduction occurs in the rate of photosynthesis at 36˚C, in C_3 crop potato (Ku et al., 1977). Crops with a high base temperature could benefit from increasing temperature for emergence while crops with low base temperature experience an advanced phenology (Angus et al., 1981) in relatively cooler periods. The expected increase in annual mean temperature increases agriculture production (Yang et al., 2007; Chen et al., 2013), reduces frost damage (Baethgen et al., 2003), and such benefits of temperature are expected for the crops growing in cooler seasons (Tian et al., 2012). Crop development, such as sprouting, emergence, and leaf area development in potato, depends on temperature, and dry matter distribution between the various organs is determined by temperature and photoperiod (Haverkort et al., 2004). The effect of temperature is particularly important for potato plants and high temperature drastically affects potato production (Gregory, 1965; Slater, 1968). At higher temperatures, daily growth is reduced due to increased respiration. Under this condition dry matter distribution mainly goes for foliage production and tuber dry matter becomes unacceptably low (Hoverkort et al., 2004). Soil temperatures higher than 18°C tend to reduce tuber yield, especially if ambient air temperature reaches as high as 30°C during the day and 23°C at night (Monneveux et al., 2014).

2.3.3 Rainfall

Climate change is likely to appear in changing precipitation both in amounts and patterns differently all over the world with an increase at the higher latitudes in equatorial zones and with a decrease at lower latitudes in the sub-tropics (Giorgi and Bi, 2005). As management options for crop production and seasonal water use include sowing time, nutrient management, plant density and cultivar choice (Passioura, 1977), they are largely dependent on rainfall amounts and events, and any change like increased drought frequency (Hennessy et al., 2008) can cause reduction in crop production and yields. Too much rainfall also can impair crop growth by waterlogging (Araki et al., 2012; Sadras et al., 2012) and nutrient leaching (Anderson et al., 1998). Changes in rainfall intensity and distribution are particularly critical to soil for infiltration, water balance, soil mineralization and water-use efficiency for

crops (Khan et al., 2009; Wang et al., 2009). Stress caused by drought is quite common in potato (Onder et al., 2005). Frequent rainfall deficit during the vegetation period causes drought stress and is one of the highest risks that threaten potato production (Miyashita et al., 2005). Potato plants are also sensitive to flooded soils where roots can be irreversibly damaged due to lack of oxygen. Excessive precipitation in Montenegro notably hampers the production of potatoes, and sometimes completely destroys it (Jovovic et al., 2016).

2.3.4 Solar radiation

Dry matter accumulation depends on the amount of solar radiation intercepted by the crop (Haverkort et al., 2004). A reduction in solar radiation and an increase in diffuse light fraction have been observed in the past (IPCC, 2013). A reduction in solar radiation is usually associated with an increase in the diffuse light fraction (Farquhar and Roderick, 2003; Liu et al., 2005). As plant production is primarily driven by sunlight where plants transform solar energy into sugars, a reduction in solar radiation will potentially reduce photosynthesis and growth (Asseng et al., 2015). Yet a decrease in photosynthesis with less radiation could be overridden by improved canopy light distribution through diffusion or dimming (Sinclair et al., 1992; Rodriguez and Sadras, 2007). Like other crops, potato yield improvements are also obtained by increasing the net daily photosynthetically active radiation (PAR) through higher solar irradiance or longer photoperiod (Stutte et al., 1996). In a standard clear day, gross carbohydrate production increases from 108 to 529 kg/ha/day at 50^{o}N with increasing day lengths, while it remains at about 420 kg/ha/day round the year near the equator (Haverkort, 1990). Usually photoperiod duration doubles from December to June at 50^{o}N, while PAR increases at higher rates from 2.11 to 17.01 MJ/m^{2}/day due to higher elevation of the sun above the horizon .The efficiency of the conversion of intercepted radiation into dry-matter remains constant in irrigated potato, which may be affected largely by soil moisture deficits greater than 47 mm (Jefferies and Mackerron, 1989). Furthermore, geographic position also influences potato production and growing potatoes in winter at 30-40^{o}N is convenient for escaping summer heat, however low solar irradiance will be a yield constraint (Haverkort, 1990).

2.4 Potato and drought response

2.4.1 Drought

Drought is a recurring extreme climate event over land characterized by below normal precipitation over a period of months to years (Dai, 2011; Siddique et al., 2016). It is a predominant cause of low yields worldwide, and plant water stress is considered as the key yield-limiting constraint in the plant-soil-atmosphere continuum (Bodner et al., 2015). In agricultural context, drought appears as the lack of moisture required for normal plant growth and development to complete the life cycle (Manivannan et al., 2008). Such deficiency of water has significant impact on agriculture of affected land (Siddique et al., 2016). A continuous shortfall in precipitation (meteorological drought) coupled with higher evapotranspiration demand leads to agricultural drought (Mishra et al., 2010). Drought severely affects plant growth and development with substantial reductions in crop growth rate and biomass accumulation, which consequently hampers the productivity of crops (Farooq et al., 2011).

Drought stress is one of the most vital, multidimensional abiotic stress factors that adversely affect plant growth, metabolism, and yield (Osakabe et al., 2014). The response of plants mostly depends on intensity, duration and severity of imposed drought (Pinheiro and Chaves, 2011). Drought along with high temperature and radiation drives plants towards stress and is one of the most important environmental constraints to growth, productivity, and plant survival (Miller et al., 2010; Arve et al., 2011). The main consequences of drought are reduced cell division and restricted cell expansion, reduced leaf size, hampered stem elongation and root proliferation (Farooq et al., 2009). Plants under drought conditions tend to have lower stomatal conductance, thus helping to conserve water, but at the same time reducing leaf internal CO_2 concentration and photosynthesis (Chaves et al., 2002).

2.4.2 Drought stress in plants

Drought stress is outlined by changes in water relations, physiological processes, alterations in the cell membrane structure, and ultra-structure of cell organelles (Yordanov et al., 2003). Plants experience drought stress because of two major reasons i.e. deficit water supply to the roots and high transpiration rates. These conditions mostly prevail under arid and semi-arid climates (Rahdari and Hoseini, 2012). To overcome the low water availability, plants adapt using stress avoidance and stress tolerance mechanisms (Lawlor, 2013). Plants also

undergo various changes to avoid water stress induced damages. Some changes are morphological like increased development of root hairs, deepening of roots, and rolling of leaves (Rao and Chaitanya, 2016).

Most of the changes related to water deficiency occur in the leaves, the energy production organ of plants. Under mild to moderate water stress, plants reduce their stomatal conductance and thus help to maintain the water balance (Drapal et al., 2017). Severe water stress affects cell turgor which is counteracted by osmotic adjustment through accumulating osmolytes like amino acids, sugars and polyols inside the cell (Evers et al., 2010; Zingaretti et al., 2013).

Drought stress is associated with changes in the content of phytohormones (Yang et al., 2002). Abscisic acid (ABA) is one of the most important hormones that play a major role in drought tolerance (Raghavendra et al., 2010). In general, water deficit condition accelerates ABA biosynthesis (Chaves, 1991; Jia and Zhang, 2008), which regulates stomatal closing (Lee, 2010) and decreases stomatal conductance to minimize transpiration losses (Yamaguchi-Shinozaki and Shinozaki, 2006). Under mild to moderate stress conditions, stomatal characteristics are affected that result in less biomass, while under severe conditions non-stomatal factors can become dominant (Liu et al., 2010) leading towards increased accumulation of reactive oxygen species (ROS) in plants. ROS are the most striking and injurious products appearing as a result of abiotic stress which occurs in different cellular and sub-cellular compartments (Vaahtera and Brosche, 2011). The overproduction of ROS disrupts normal plant metabolism through shifting regulatory responses during transcription and protein expression (Vasquez-Robinet et al., 2008). Biochemical and physiological metabolisms are also affected that constrain photochemical efficiency, and Rubisco activity may be impaired due to oxidative damage, protein degradation, DNA and RNA damage and membrane lipid peroxidation (Finkel and Holbrook, 2000; Vellosillo et al., 2010).

2.4.3 Drought tolerance and water relations

Passioura (1996) described drought tolerance as a nebulous term that distinguishes xerophytic from mesophytic vegetation. However, in agricultural context it is defined in terms of yield in relation to a limiting water supply for crop growth (Passioura, 2007). The most important aspect of drought tolerance is that the pattern of development of the crop must match the pattern of the water supply in relation to the evaporative demand. That

evaporative demand determines the effectiveness with which a crop can use a limited supply of water in producing harvestable yield (Passioura, 1996). This type of matching phenology to its environment is the most important determinant of a crop under drought (Passioura, 2007). Development of crop plants tolerant to drought stress might be a promising approach and a number of valuable contributions have been made by a number of scientists in this research area (Ingram and Bartels, 1996; Penna, 2003; Reddy et al., 2004; Agarwal et al., 2006).

Considering water supply for crops as a resource, Passioura (1996) hypothesized that the efficient use of this resource is determined by factors as (a) capturing as much as possible of it (b) using the captured water as effectively as possible when trading it, at the stomata, for carbon dioxide to photoassimilate; and (c) converting as much of this assimilate as possible into a harvestable form.

This are symbolically expressed as:

$Y = T \times WUE \times HI$

Where, Y is the yield, T is the amount of water transpired, WUE is the water use efficiency and HI is the harvest index.

Viets (1962) defined water use efficiency as the ratio of plant production to evapotranspiration (ET) measured on the same area. However, Tanner and Sinclair (1983) summarized some early studies and defined water use efficiency as the biomass accumulated per unit of water transpired and evaporated per unit crop area. Another definition of water use efficiency is in terms of transpired water only, where WUE is defined as the amount of economic yield (Y) produced per unit of water used by evapotranspiration (ET). Measuring the transpiration component is hard to do in practice, and is only possible on an experimental basis. However, that type of research compares differences among species using transpiration efficiency (TE), which is the ratio of biomass yield to transpiration (Tolk and Howell, 2009).

2.4.4 Drought adaptation

Adaptation of plants to drought can involve avoidance or tolerance, and thus stress adjustment scenarios can be divided into (i) avoidance of tissue water deficits/dehydration, (ii) tolerance of tissue water deficits, and (iii) efficiency mechanisms (Turner, 1986; Jones, 2013). Plant response to drought has several different morphological and physiological characteristics, which depend on phenological growth stages and genotype (Shi et al., 2015). The drought escape process involves rapid phenological development within short life span for utilizing maximum moisture content in soil (Maroco et al., 2000; Deguchi et al., 2015) as a strategy of escaping mainly terminal drought conditions. Drought avoiding is associated with enhanced water uptake by increased root depth or altered root characteristics (Jackson et al., 2000) or by reducing water loss by stomatal closure or modifying heat transfer in the leaf boundary layer (Ku et al., 1977; Jones, 2013; Deguchi et al., 2015). Drought tolerance is a mechanism by which plants maintain metabolism even at low leaf water potential (Deguchi et al., 2015) thus improving WUE and improving efficiency of assimilate conversion into harvestable yield (HI). Tolerance of plant tissue to water deficits most commonly involves maintaining turgor, either through osmotic adjustment (Morgan, 1984; Martinez et al. 2007) or by producing rigid cell walls or decreasing cell size (Wilson et al., 1980).

A plant may combine a range of drought tolerance mechanisms (Ludlow, 1989), however, an important trade off exists within the mechanisms as they may reduce potential yield (for example, stomatal closure conserves water but also reduces photosynthetic assimilation due to restricted CO_2 influx) (Chaves et al., 2002; Obidiegwu et al., 2015). To counteract ROS, plants produce various types of antioxidants. Production of these antioxidants and their activation are coupled with the degree of drought tolerance among different plant species (Sunkar et al., 2006). To avoid injuries under water deficit conditions, plant water status is in many cases tightly controlled by the plant via stomatal conductance, root and leaf expansion rates and leaf senescence, which tend to reduce transpiration or to increase water uptake (Tardieu, 1996). However, a decrease in stomatal conductance with a decrease in leaf water potential results in a reduced net photosynthetic rate, and the consequent decrease in assimilate production is resulting in a reduced growth and yield (Nikinmaa et al., 2013). Here stomata density and stomata size also play an important role in determining the

transpiration rate and leaf conductance in order to provide a rapid response to water deficits (Wolfe et al., 1983; Jones, 2013).

2.4.5 Drought response in potato

The response to drought of potato depends on the phenological timing, duration and severity of the stress (Jeffery, 1995). It is rather complicated as the differential yield responses of potato have not been consistently related to specific physiological or morphological traits (Stark et al. 2013). Drought reduces plant growth (Deblonde and Ledent, 2001), shortens the phenological development (Kumar et al., 2007) and decreases the number and size of tubers (Eiasu et al., 2007; Schafleitner et al., 2007). Water limited condition reduces leaf growth (Walworth and Carling, 2002; Lahlou et al., 2003), leaf size (Jefferies and MacKerron, 1987), LAI (Lahlou et al., 2003; Shahnazari et al., 2007), ground coverage (Ojala et al., 1990) and increases the rate of leaf senescence (Fleisher et al., 2008). Potato stem growth is sensitive to drought, stem height is affected at early stages (Deblonde and Ledent, 2001) and drought reduces total aerial biomass (Lahlou et al., 2003). Plants produce large root mass, and high leaf/stem ratio with low number of branches may contribute to high and stable yields in drought prone environments (Deguchi et al., 2010). Although high HI has been reported under severe drought (Jeffries and MacKerron, 1993; Deblonde et al., 1999; Deguchi et al., 2010), that trait was not influenced under moderate drought conditions (Deblonde and Ledent, 2000). Under drought, a reduction in radiation interception due to reduced canopy expansion (Jefferies and MacKerron, 1987) caused a reduced photosynthetic rate and eventually a reduction in tuber yield. Drought events not only reduce photosynthetic rate in plants but also reduce nitrate reductase activity, which consequently affects nitrogen uptake for optimal growth (Schafleitner et al., 2007).

Potatoes exhibit isohydric characteristics (Liu et al., 2005) with a tight stomatal control and a minimum threshold of water potential, which causes stomata to close (Limpus, 2009). Consequently, they also show decreasing stomatal conductance under drought stress (Liu et al., 2005). Under water deficit condition, closing stomata earlier in response to drought can save water for future growth (Spitters and Schapendonk, 1990), and estimates of stomatal conductance by Carbon Isotope Discrimination (CID) studies (Anithakumari et al., 2012) show that drought tolerant genotypes exhibited high WUE, stomatal control, and root

elongation in order to maintain photosynthesis and putative sucrose export to tubers (Turner, 1996; Condon et al., 2002; Tambussi et al., 2007).

2.4.6 Soil water, transpiration and water use efficiency in potato

About 80% of the world's cropped area is cultivated under rain-fed condition and in this condition, crop yield is highly affected, even the yield penalty can rise as high as 50% compared to fully irrigated crops (Rosegrant et al. (2002). Therefore, rain-fed agriculture predominantly produces lowest yield per unit land as compared to temperate regions. In dry regions 5 to 10 % of the precipitation is mostly used for crop physiology as compared to about 50% in temperate region (Rockström et al., 2007) and a generalised rain water balance sheet illustrated by them shows that only 15-30% water is consumed for transpiration, 30-50% is lost for non-productive evaporation, 10-25% goes for run off and 10-30% water is moved down by drainage. Stewart and Steiner (1990) also reported that only 23% of total annual precipitation water was used for transpiration by plants and the rest goes for storage and evaporation loss, however they ignored seepage and percolation loss.

Water deficit appears as the main yield-limiting factor particularly in the semiarid tropics and revolves around the critical need towards a good match for water supply and demand. Not only genetic aspects are involved with this demand and supply issue but also crop management has a noticeable role for better or more conservative uses of water (Vadez et al., 2013). Supply of a small amount of water during key crop stages can bring higher benefits. Manschadi et al. (2006) reported that 55 kg of grain could be contributed by each mm of water supply during grain filling stage of wheat. Similar yield increases have been found as 59 kg ha^{-1} mm^{-1} water in wheat (Kirkegaard et al., 2007), 37-45 kg ha^{-1} mm^{-1} in pearl millet (Vadez et al., 2013) and 40 kg ha^{-1} mm^{-1} in chickpea (Zaman-Allah et al., 2011). For potato, a continuous and adequate water supply is required and soil water content needs to be maintained within a relatively narrow range (Wright and Stark, 1990) from tuber initiation until near maturity. Cantor et al. (2014) confirmed that irrigation is required for early potato cultivation in southern Italy because rainfall cannot meet crop water needs and the irrigation regime supports 50% of crop water requirements for satisfactory yield. Dalla Costa et al. (1997) reported that continuous drought stress reduced photosynthesis and plant biomass, and tuber yield decreased almost proportionally to water consumption, and even a short

period of water shortage can result in reduction both of tuber production and of tuber quality (Miller and Martin 1987).

Water productivity (WUE) or in other words TE could be defined differently at different levels of application and different perspectives. As TE depends on both genetic and environmental components, TE ratio is quite complex as it is also affected by VPD and CO_2 concentration in the stomatal chamber (Sinclair, 2012). It shows an inverse relationship with VPD (Tanner and Sinclair, 1983; Sinclair et al., 1984; Sinclair, 1994) and can be partitioned into biological (crop) and physical (meteorological) components expressed as: WUE = k/VPD, where k is a crop species-specific coefficient of crop seasonal water use (VanToai and Specht, 2004). Large genetic variation in the capacity to restrict transpiration under high VPD has been identified in soybean, peanut, cowpea, chickpea, pearl millet, maize, sorghum, wheat etc. (Fletcher et al., 2007; Devi et al., 2010; Gholipoor et al., 2010; Kholova et al., 2010; Zaman-Allah et al., 2011; Belko et al., 2012; Schoppach and Sadok, 2012; Yang et al., 2012).

High stomatal resistance also can be observed when potato leaf temperature rises above 25^{o}C while VPD is relatively constant (Ku et al., 1977). Like stomatal closure, leaf temperature is strongly influenced by environmental factors, particularly by the radiation interception on the leaf, and the heat transfer coefficient to the air (Hsiao, 1973). Finally transpiration is known to be affected by a number of factors as leaf area, root to leaf ratio, leaf orientation, leaf shape, leaf surface characteristics, specific leaf area, distribution of stomata etc. (Obidiegwu et al., 2015).

2.4.7 Genotypic response to drought

Numerous studies have been made all over the world to evaluate responses of potato cultivars to drought. Soltys-Kalina et al. (2016) worked with 18 cultivars from Europe and US naming Calrose, Cayuga, Katahdin, Pontiac, Sebago, Seneca, Sequoia, Wauseon, Yampa, Ari, Urgenta, Humalda, Carpatin, Magura, Dalila, Ermak, Igor and Ulster Supreme. They found that yields of five cultivars Wauseon, Katahdin, Magura, Calrose, and Cayuga did not significantly decline under drought stress. More drought-tolerant cultivars like Gem Star Russet or Ranger Russet were examined with other cultivars Alturas, Russet Burbank, Russet Norkotah and Summit Russet, and it was found that cultivars within a similar maturity group

can be affected differently by water stress. Some genotypes can maintain relatively high yields of marketable tubers even under fairly severe stress (Stark et al., 2013).

Reports on genotypic response to drought using canopy temperatures from drought-stressed plots show that most drought-resistant genotypes usually have the lowest canopy temperatures during drought periods, apparently due to a greater ability to conserve or extract soil water and thus maintain transpiration (Stark and Pavek, 1987). In a previous study with 14 genotypes including Russet Burbank, Lemhi Russet, Frontier Russet, Monona, Kennebec, Red Pontiac and Nooksack for evaluating canopy temperatures under water stress, Stark et al. (1991) found that genotypes from warmer region were less susceptible to drought than those of cooler region. Nooksack performed best among other two genotypes Lemhi and Russet Burbank for producing more high quality tubers (US grade 1) at deficit irrigation levels (Martin and Miller, 1983). A study with four genotypes Alegria, Milva, Desiree and Saturn under long term drought stress proved that enhanced heat stress during drought can be caused by loss of transpiration that affects leaf cooling (Sprenger et al., 2016).

Coleman (1986) worked with cultivars Shepody and Raritan in a greenhouse experiment observing leaf water retention, transpiration rate and stomatal resistance and he reported that under well-watered conditions, Raritan exhibited a higher transpiration rate than Shepody while under drought, Raritan consistently demonstrated superior performance over Shepody in leaf water retention, epicuticular wax levels, desiccation tolerance and root growth. In another study, Asterix showed less canopy temperature cooling under water stress condition while genotypes, CIP 393371.58 and CIP 396244.12 showed better performance with water stress (Al Mahmood et al., 2016). Souza et al. (2014) examined FTSW, transpiration and leaf growth of four potato genotypes during soil drying and reported that advanced clones SMINIA 02106-11 and SMINIA 00017-6 were more tolerant to soil water deficit than the cultivar Asterix. Greater reduction in transpiration rate was observed in genotype CIP 391004.18 and Asterix compared with three other CIP genotypes under drought condition, while under control, Asterix showed the highest transpiration rate (Al Mahmood et al., 2016). In Japan, Konyu varieties showed higher plant hydraulic conductance compared with Konafubuki and higher leaf water potential regardless of soil water conditions, resulting in a smaller reduction in transpiration rate per unit leaf area under drought condition (Deguchi et al., 2015).

Basu et al. (1998) reported that net rate of photosynthesis with an irradiance of >500 µmol m^2 s^{-1} (PAR) significantly decreased under water stressed condition in a cultivar Kufri Sinduri. Such reduction in photosynthetic capacity was also found in genotype Bintje, which declined immediately with decreased water potential during drought tests (Vos and Oyarjun, 1987). Supplemental irrigation increased the average fresh tuber weight and the number of tubers per plant in Shepody and Russet Burbank (Belanger et al., 2002). Under non-limiting field environments cultivars Bondi, Fraser and Russet Burbank produced highest tuber yield and produced heavier but fewer tubers than others (Oliviera et al., 2016). Sprenger et al. (2015) studied 34 European potato cultivars and found that Desiree and Saturna were more drought-tolerant cultivars while Milva and Alegria were very sensitive. The contribution of above ground characteristics and root mass on yield, HI and LAI were examined in three Konyu cultivars and Konafubuki in Japan. The experiment showed that in addition to large root mass, high HI was coupled with high leaf/stem ratio, and low number of branches may contribute to achieve high and stable yields in drought prone environments (Deguchi et al., 2010).

3 Material and methods

Three glasshouse experiments and three field experiments were conducted to monitor genotypic response to the environment, with special focus on water stress condition. Glasshouse experiments helped in screening out genotypes responding to water stress. Field experiments in Tulln and Bangladesh were carried out to evaluate performances of the genotypes under field conditions.

3.1 Glasshouse experiments

Glasshouse experiments were conducted at the BOKU University and Research Centre Tulln (UFT), Austria. The glasshouse environment was controlled automatically by a software. Three experiments were conducted in three different seasons; however, similar environmental conditions were set during the experiments.

3.1.1 Location

The UFT is located in lower Austria at 48°18' N and 16°4' E. All three experiments were conducted in the glasshouse under direct supervision and supports of the Division of Agronomy, the University of Natural Resources and Life Sciences (BOKU).

3.1.2 Climatic conditions

Table 3.1: Climatic conditions and parameters in the glasshouse

Parameters	Day time	Night time
Temperature	20^{o}C (Exp 1 = 21.3 ± 0.6, Exp 2 = 22.4 ± 1.4, Exp 3 = 28.0 ± 4.5 ; variations indicated by SD)	12^{o}C (Exp 1 = 11.9 ± 0.5, Exp 2 = 12.5 ± 0.5, Exp 3 = 14.4 ± 1.4 ; variations indicated by SD)
Duration	13 hours	11 hours
Lamp settings for light	at <20 Klux day light intensity, grow lamps turned on and > 80 Klux lamps turned off (not to suffer plants from low light intensity).	
Humidity	Not regulated	

3.1.3 Genotypes

Genotypes used in the experiments were collected from various sources in different countries. Table 3.2 shows the sources and characteristics of tubers.

Table 3.2: Potato genotypes and their uses in the experiments

Name	Seed tubers		Genotype characteristics					Data source
	Source	Used in	Shape	Flesh colour	Skin colour	Skin texture	Resistance to drought	
Desiree	HZPC, Netherlands	Exp 1, Exp 2, Exp 3	Oval	Light yellow	Red	Rough	High to very high	NIVAP, Netherlands
Caesar	HZPC, Netherlands	Exp 2, Exp 3	Oval to long	Light yellow	White to yellow	Smooth to intermediate	n.a	NIVAP, Netherlands
Spunta	HZPC, Netherlands	Exp 2, Exp 3	Long to oval	Light yellow	White to yellow	Smooth to intermediate	High to very high	NIVAP, Netherlands
Farida	HZPC, Netherlands	Exp 2, Exp 3	Oval to long oval	Light yellow	Yellow	n.a	High	HZPC, Netherlands
Diamant	BRAC, Bangladesh	Exp 1, Exp 2	Oval to long	Light yellow	White yellow	Smooth to intermediate	High to very high	Arche Noah, Austria; IPK, Germany
Cardinal	BRAC, Bangladesh	Exp 1, Exp 2	Oval	Light Yellow	Red	Smooth	High to very high	SASA, UK
Granola	SaKa GmbH, Germany	Exp 1	Oval to round	Yellow	White to yellow	Intermediate to rough	High	IPK, Germany; NEIKER, Spain
Agria	NÖS, Austria	Exp 1	Oval/ Long to oval	Yellow/ deep yellow	White to yellow	Intermediate to rough	Medium to high	IPK, Germany; NEIKER, Spain
Tosca	NÖS, Austria	Exp 1	Oval to round	Yellow	White to yellow	Smooth	High	IPK, Germany; SASA, UK
Diego	NÖS, Austria	Exp 1	Oval to long	Yellow	Light yellow to cream	n.a	n.a	NÖS, Austria

3.1.4 Pots

Plastic pots of 7 litre size were used in the experiments having a height of 33 cm, diameter at top of 24 cm and at the bottom of 18 cm. Pots had 4 holes at the bottom to drain out excessive water properly. Six kilogram of substrate was filled in each pot, which left about 4-

5 cm empty area from the top. A porous mat was placed at the bottom of the pots and a thin layer of small granules of stones (about 100 g of < 5mm size) were used for better water and air permeability.

3.1.5 Soil substrate

Substrate for the pots was made out of a mixture of field soil, sand and compost. Soil for the mixture was collected from an adjacent arable field, dried, ground and passed through a 2 mm sieve. Washed sand (0.6-0.9 mm size), compost (for garden use without turf grass material) and a 15-6-12 grade (N-P_2O_5-K_2O) mixed commercial fertilizer were collected from a garden shop. Required amounts of fertilizer principally based on nitrogen (N), phosphorus (P) and potassium (K) (Table 3.3) were used in the substrate in order to supply sufficient nutrition to the plants. These four materials were mixed thoroughly by a concrete mixturer machine for 3 minutes, and soil, sand and compost were used at a ratio of = 1.0 : 1.0 : 0.8 by volume. All the pots were filled with 6 kg substrate one day before planting.

Table 3.3: Mineral composition and fertilizer used

Nutrient	Minimum required dose in average soil (kg/ha)	Required amount per pot (g/ 6 kg substrate)	Nutrients supplied from fertilizer (g/pot)
N	130	0.34	0.34
P_2O_5	45	0.12	0.13
K_2O	105	0.27	0.27

3.1.6 Planting of tubers

As the genotypes were collected from different sources, they differ in sprout initiation and tubers showing no initiation were brought to normal temperature earlier than the sprout initiated tubers. Depending on the sprouting condition, tubers apparently similar in size in each genotype were brought to room temperature 7-15 days ahead of planting. On the day of planting, 25 healthy and almost evenly sprouted tubers from each genotype were selected and individually weighed. Tubers were planted by hand about 2.5 cm deep in the substrate, and after planting about 1600 ml of water near to the field capacity was added slowly to the pots until it reached to the bottom tray. Planting dates and genotypes used are given in the Table 3.4.

Table 3.4: Planting dates and genotypes in different experiments

Genotype	Planting date		
	Exp 1	Exp 2	Exp 3
Granola	15.12.2014		
Agria			
Tosca			
Diego			
Cardinal		14.02.2015	
Diamant			
Desiree			14.04.2016
Caesar			
Spunta			
Farida			
Mondial			

3.1.7 Experimental design and treatments

All three experiments were conducted with two water treatments, well-watered (WW) and water stress (WS). Well-watered plants received sufficient amount of water and soil moisture level was maintained always near (about 4% less) to the field capacity. In WS treatment, water stress was imposed after desired period by withdrawing water supply and plants were allowed to use available soil moisture in the pots eventually go through progressive soil drying. The number of genotypes and replications in each treatment (Table 3.5) were as follows;

Table 3.5: Factors used in different experiments

Factors	Experiments			Remarks
	Exp 1	Exp 2	Exp 3	
Water	2	2	2	WW, WS
Genotype	7	7	4	
Replication	4	5	5	

The experiment was conducted following randomized complete block design (RCBD) considering water and genotypes as the fixed factors arranged randomly in blocks (block are the replications). Before applying dry down condition, all the pots were placed randomly in four trays in the cabin. At the onset of the dry down treatment, area of the four trays was marked for the blocks and pots of each dry down treatment for each genotype were randomly placed within a block.

3.1.8 Initial biomass harvest and preparation for dry-down treatment

All pots were maintained in a well-watered condition for normal crop growth before the dry down cycle started (Sinclair and Ludlow, 1986; Ray and Sinclair, 1998; Devi et al., 2009; Souza et al., 2014). When most of the plants had reached the growth stage of 9-12 leaves, plants with homogeneous phenotype were selected and pots were filled with water up to saturation (Souza et al., 2014). They were kept overnight to reach field capacity. Next morning, all additional stems were cut except one healthy and vigorous in each pot. Then the selected homogenous single-stem plants from each genotype were randomly divided into 3 groups. One group for WW treatment, one group for WS treatment and the third group for initial biomass harvest. Five plants for each genotype were harvested for the initial biomass that was accumulated until this growth stage. For the initial biomass, plants were cut at the base and the shoot was taken in a paper bag for drying at 65˚C in the oven (Memmert Universalschrank UFE 600, Linder Labortechnik, Overath, Germany) for 48 hours. Harvest dates for initial biomass can be found in the Table 3.6.

Table 3.6: Plant growth stage at and growth period until initial biomass harvest and pot sealing in different experiments

	Plant growth condition and age		
	Exp 1	Exp 2	Exp 3
Growth stage (BBCH scale)	15-19 (Leaf development stage)	17-19 (Leaf development stage)	19 (Leaf development stage) to 51 (Inflorescence emergence stage)
Date	25 (DAP)	23 (DAP)	33 (DAP) Extended days were allowed in the Exp 3 due to slow growth of Desiree to reach all genotypes at least at 9 leaf stage.

3.1.9 Pot sealing and setting up dry-down conditions

The soil drying experiment was established following the protocol initially described by Sinclair and Ludlow (1986). The method was used in other experiments for maize (Muchow and Sinclair, 1991; Ray and Sinclair, 1997); peanut (Devi et al., 2009); soybean (Ray and Sinclair, 1997); sorghum (Gholipoor et al., 2012); potato (Souza et al., 2014). One day before the onset of the dry-down condition, all pots were saturated with water as other scientists did (Sinclair and Ludlow, 1986; Ray and Sinclair, 1997; Souza et al., 2014) and left overnight to reach at the field capacity (Souza et al., 2014).

Next day, all the pots were sealed with 2 layers of polyethylene bag (60 cm x 40 cm) just above the base of the stem (Photo 3.1a, Photo 3.1d). It was successfully done with the help of a piece of soft sponge not to restrict stem growth and avoid gaseous flow at the joint. To make the piece of sponge impermeable to gases, it was wrapped by thin layers of kitchen cling film (Photo 3.1b). A slender bamboo stick for plant support and a slender plastic tube for adding irrigation water were carefully wrapped by the sponge to make the whole pot air tight (Photo 3.1c). A stopper was used at the top of the irrigation tube to avoid water vapour loss through it .

Photo 3.1a: Pots sealed with bags

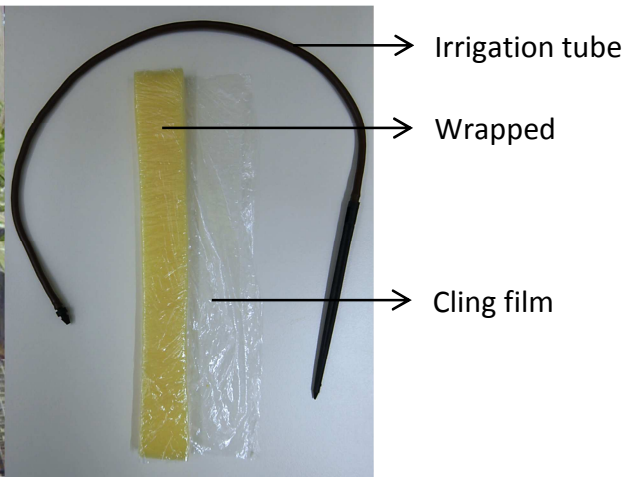


Photo 3.1b: Materials used for pot sealing

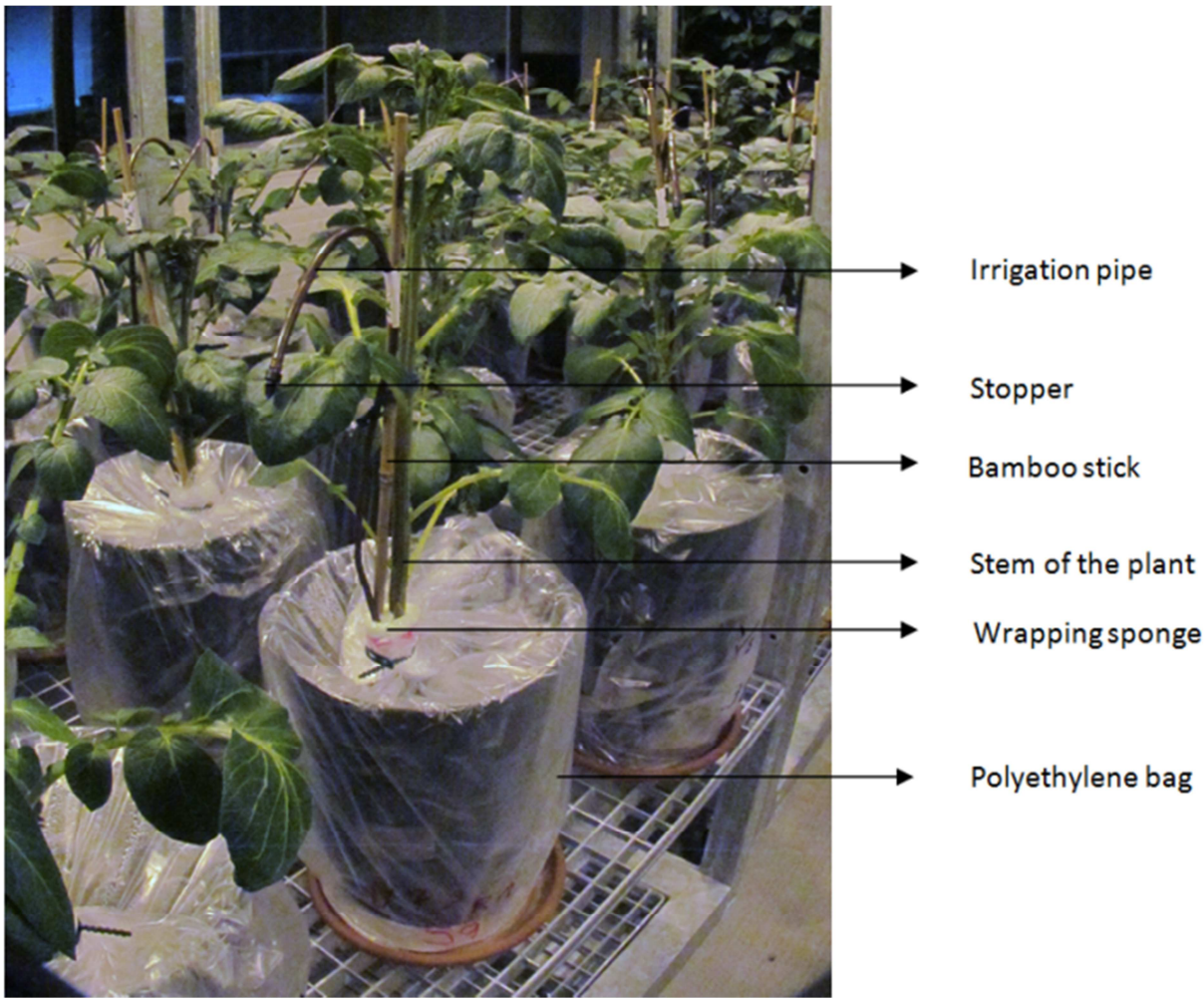


Photo 3.1c: Method of pot sealing

Photo 3.1d: A sealed pot

3.1.10 Transpiration measurement and plant watering

Daily transpiration (T) measurement was started from the day after pot sealing. This whole plant level T measurement was done gravimetrically (Cirelli et al., 2012) by weighing pots every day with a laboratory platform balance (Sartorius CPA 16001S, Sartorius AG, Germany) at a precision of 0.1 g. The weights of the pots were taken every day at 9:00 am before active photosynthesis and transpiration start. T was determined by measuring the difference between the weight of the pot on a specific day and the initial weight at pot sealing (Sinclair and Ludlow, 1986; Muchow and Sinclair, 1991; Souza et al., 2014). In other words, it was calculated as follows;

Transpiration loss of water in a day (24 hours) = pot weight of the day - pot weight of the previous day. The daily pot weight was recorded in a spreadsheet (Photo 3.2) where daily transpiration and water requirement for each plant was calculated as follows:

$T_{i} = Wat_{i}$

$Wat_{i} = W_{i-1} - W_{i}$

Where,

Wat_{i} = Daily water requirement

i = number of the day (i = 1,2,3,……..n) when measurement was taken

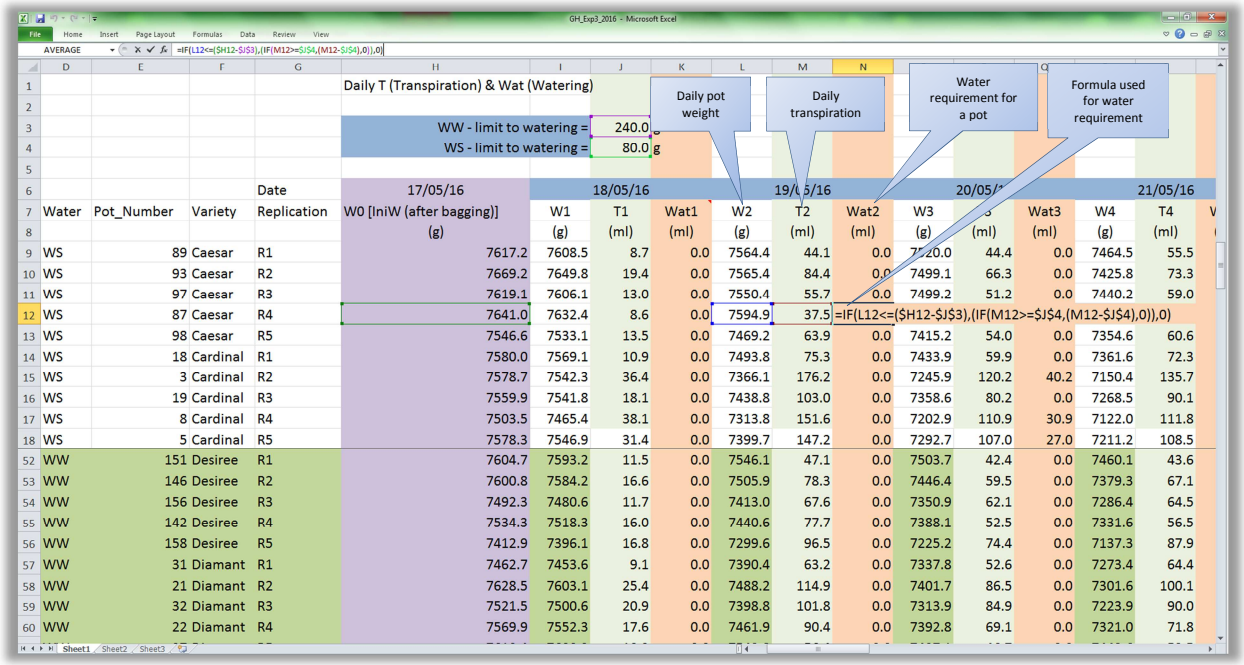
T_{i} = Daily transpiration

W_{i} = Daily pot weight

For WW pots, potential growth condition was maintained by replenishing water loss daily. Devi et al. (2009) watered their peanut plants by 80% of the field capacity (approximately 100 g below the saturated weight that corresponds to 5% of the total pot weight). In our case, we used 6 kg of substrate instead of 2 kg for peanuts that Devi et al. (2009) used. Due to more substrate and more available water than peanut experiment, we considered a threshold of 240 g (about 4% pot weight) water less than the field capacity at pot sealing to avoid anaerobic condition in the pots.

Water lost more than 240 g from the initial day was replenished to all WW pots. For WS pots, in general no water was given back for daily transpiration loss, unless the daily transpiration exceeded more than one third (80 g) of the threshold we considered. If a plant transpired more than 80 g of water in a day, that excess amount was replenished to avoid

rapid wilting. Water was added to the pots through the narrow tube (Photo 3.1b) with the help of a syringe.



Daily T (Transpiration) & Wat (Watering)

WW - limit to watering = 240.0 g
WS - limit to watering = 80.0 g

					17/05/16	18/05/16										
	Water	Pot_Number	Variety	Replication	W0 [IniW (after bagging)] (g)	W1 (g)	T1 (ml)	Wat1 (ml)	W2 (g)	T2 (ml)	Wat2 (ml)	W3 (g)	T3 (ml)	Wat3 (ml)	W4 (g)	T4 (ml)
9	WS	89	Caesar	R1	7617.2	7608.5	8.7	0.0	7564.4	44.1	0.0	7520.0	44.4	0.0	7464.5	55.5
10	WS	93	Caesar	R2	7669.2	7649.8	19.4	0.0	7565.4	84.4	0.0	7499.1	66.3	0.0	7425.8	73.3
11	WS	97	Caesar	R3	7619.1	7606.1	13.0	0.0	7550.4	55.7	0.0	7499.2	51.2	0.0	7440.2	59.0
12	WS	87	Caesar	R4	7641.0	7632.4	8.6	0.0	7594.9	37.5	=IF(L12<=($H12-$J$3),(IF(M12>=$J$4,(M12-$J$4),0)),0)					
13	WS	98	Caesar	R5	7546.6	7533.1	13.5	0.0	7469.2	63.9	0.0	7415.2	54.0	0.0	7354.6	60.6
14	WS	18	Cardinal	R1	7580.0	7569.1	10.9	0.0	7493.8	75.3	0.0	7433.9	59.9	0.0	7361.6	72.3
15	WS	3	Cardinal	R2	7578.7	7542.3	36.4	0.0	7366.1	176.2	0.0	7245.9	120.2	40.2	7150.4	135.7
16	WS	19	Cardinal	R3	7559.9	7541.8	18.1	0.0	7438.8	103.0	0.0	7358.6	80.2	0.0	7268.5	90.1
17	WS	8	Cardinal	R4	7503.5	7465.4	38.1	0.0	7313.8	151.6	0.0	7202.9	110.9	30.9	7122.0	111.8
18	WS	5	Cardinal	R5	7578.3	7546.9	31.4	0.0	7399.7	147.2	0.0	7292.7	107.0	27.0	7211.2	108.5
52	WW	151	Desiree	R1	7604.7	7593.2	11.5	0.0	7546.1	47.1	0.0	7503.7	42.4	0.0	7460.1	43.6
53	WW	146	Desiree	R2	7600.8	7584.2	16.6	0.0	7505.9	78.3	0.0	7446.4	59.5	0.0	7379.3	67.1
54	WW	156	Desiree	R3	7492.3	7480.6	11.7	0.0	7413.0	67.6	0.0	7350.9	62.1	0.0	7286.4	64.5
55	WW	142	Desiree	R4	7534.3	7518.3	16.0	0.0	7440.6	77.7	0.0	7388.1	52.5	0.0	7331.6	56.5
56	WW	158	Desiree	R5	7412.9	7396.1	16.8	0.0	7299.6	96.5	0.0	7225.2	74.4	0.0	7137.3	87.9
57	WW	31	Diamant	R1	7462.7	7453.6	9.1	0.0	7390.4	63.2	0.0	7337.8	52.6	0.0	7273.4	64.4
58	WW	21	Diamant	R2	7628.5	7603.1	25.4	0.0	7488.2	114.9	0.0	7401.7	86.5	0.0	7301.6	100.1
59	WW	32	Diamant	R3	7521.5	7500.6	20.9	0.0	7398.8	101.8	0.0	7313.9	84.9	0.0	7223.9	90.0
60	WW	22	Diamant	R4	7569.9	7552.3	17.6	0.0	7461.9	90.4	0.0	7392.8	69.1	0.0	7321.0	71.8

Photo 3.2: A screenshot of spread sheet for determining water requirement and data recording

In the spreadsheet we entered pot weights (W_i) daily which generate other two records as daily transpiration (T_i) and water requirement (Wat_i) to be added to the pots. The formula used as an example in the spreadsheet was as follows:

$T_2 = W_2 - W_1$

Water requirements for WW plants:

$Wat_2 = [(W_0-240)-W_2]$, if $W_2 <= W_0-240$; otherwise $Wat_2 = 0$

Water requirements for WS plants:

$Wat_2 = T_2-80$, if $W_2 <= W_0-240$ and if $T_2 >= 80$; otherwise $Wat_2 = 0$

3.1.11 Normalizing transpiration

Ray and Sinclair (1998) calculated the ratio of the daily water loss from the water stressed plant to the mean daily loss from the well-watered plants. The term was defined as daily transpiration ratio (TR) that is achieved by dividing daily transpiration of each individual plant in the water deficit regime by the daily mean transpiration of the well-watered plants of the same genotype. It was expressed by them was as follows:

$$TR = \frac{Transpiration\ of\ stressed\ plants}{Average\ transpiration\ of well-watered\ plants}$$

The value of TR usually varies among the plants and to minimize the differences a second time normalization is required that gives normalized transpiration of each water stressed plants to a value around 1.0 during first few days of soil drying period when the soil water content remains comparatively high. To obtain a normalized transpiration ratio (NTR), Ray and Sinclair (1998) averaged the TR values of 2nd day to 5th day and divided daily TR of each water stressed plants by that averaged TR of 4 days.

In our experiments, daily transpiration rate of the drought stressed plants were normalized by two steps in order to minimize variations in weather conditions (Ray et al., 2002) and among the plants (Ray and Sinclair, 1998) as well. To facilitate comparison for day to day variations and to minimize it, individual transpiration (T) value in a WS pot was divided by the average of the transpiration of the WW pots of the same genotype (Devi, et al, 2009, Souza et al., 2014). Further normalization for NTR was done by dividing TR value by the average of the TR values obtained in the early four days (2nd to 5th day excluding the first day) of water withdrawal. While Ray et al. (2002) used the data of first three days, Ray and Sinclair (1998) used days 2-5 TR values. In our case, we used four days data for better consistency as Ray and Sinclair (1998) used. The reason for the exclusion of the first day transpiration was that as it was still affected by the recent pot saturation (Zamanallah et al., 2011) and time difference for individual pots during the experiment setup. The two-step normalization was calculated on a spreadsheet (Photo 3.3, 3.4) and was made as follows;

First step normalization (Photo 3.3):

$TR = \frac{T}{\frac{Tw\ of (Rep1+Rep2+Rep3+Rep4+Rep5)}{5}}$, where T = daily transpiration of WS plants; Tw = daily transpiration of WW plants

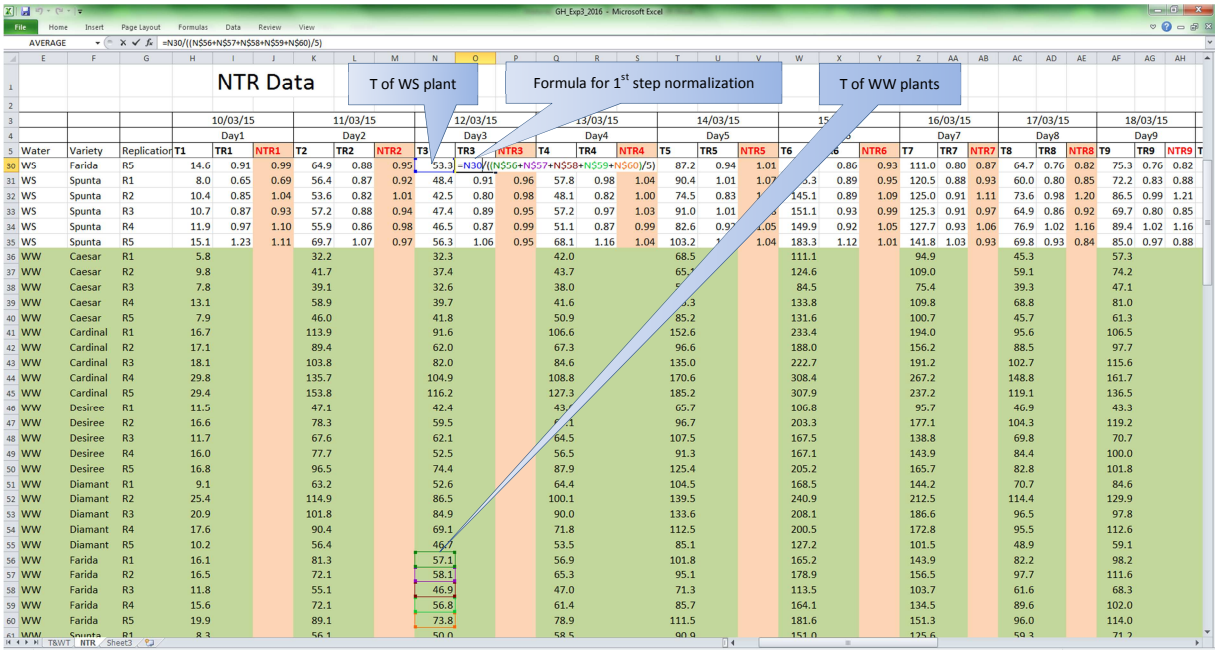


Photo 3.3: A screenshot of 1st step normalization (TR)

Second step normalization (Photo 3.4):

$$NTR1 = \frac{TR1/(TR2+TR3+TR4+TR5)}{TRw2+TRw3+TRw4+TRw5}$$

$$NTR2 = \frac{TR2/(TR2+TR3+TR4+TR5)}{TRw2+TRw3+TRw4+TRw5}$$

…

$$NTRn = \frac{TRn/(TR2+TR3+TR4+TR5)}{TRw2+TRw3+TRw4+TRw5}$$

Where;

$NTR_{1...n}$ = Normalized transpiration rates of WS plants on day n

$TR_{1...n}$ = Transpiration rate of WS plants on day n

$TRw_{1...n}$ = Transpiration rate of WW plants on day n

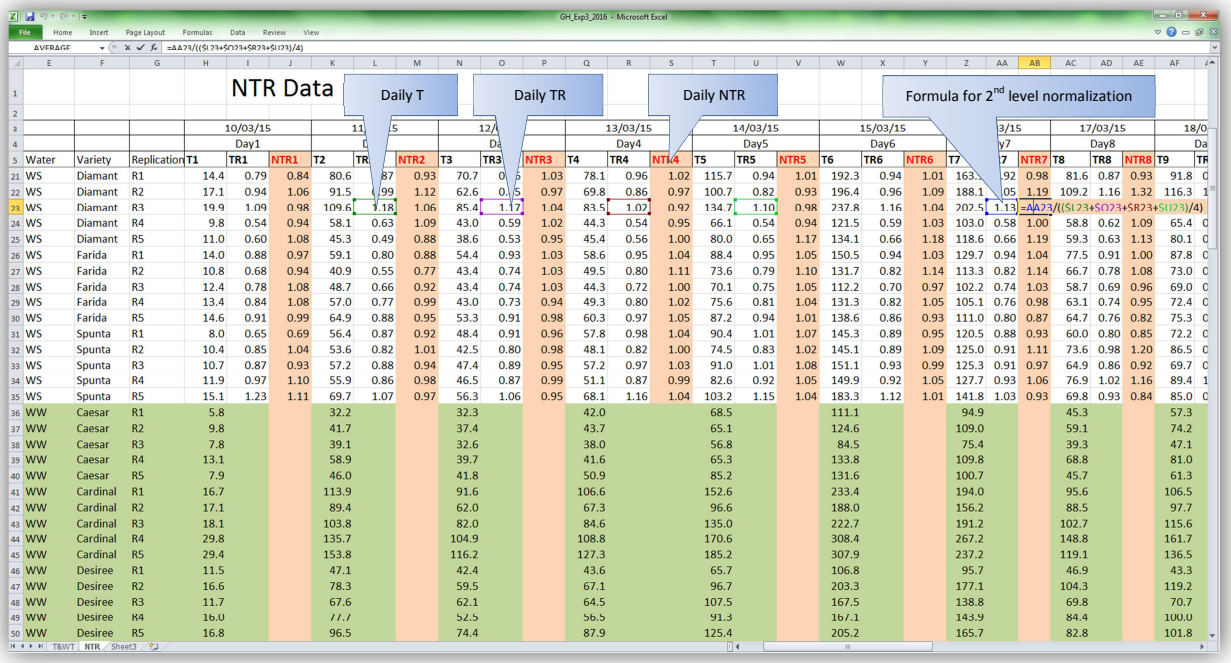


Photo 3.4: A screenshot of 2nd step normalization (NTR)

3.1.12 Transpiration efficiency

Sinclair and Ludlow (1986) described the response of the plants to soil drying at three distinct stages. In stage I, TR remained constant and equal to that of WW plants (TR ≈ 1.0). Stage II began when the rate of soil water supply to the plant became lower than potential transpiration and stomata get closed for maintenance of plant water balance (TR < 1.0 - ≥ 0.1). Stage III appeared with a very low TR (TR < 0.1) when stomata had a minimum conductance (Sinclair and Ludlow, 1986) and mostly epidermal transpiration occurs. We conducted our experiment until the WS pots reached to a NTR less than 0.1 (10% of the normal transpiration) (Sinclair and Ludlow, 1986; Zamanallah et al., 2011; Souza et al., 2014). The biomass accumulated during this period was the function of water transpired (Passioura, 1996). The amount of water transpired had been measured daily but the final biomass was obtained after harvest and Transpiration efficiency (TE) was calculated as below:

$TE = \frac{M}{T}$; where M = accumulated biomass and T = water transpired.

3.1.13 Transpiration in response to VPD

The transpiration rate of plant is physically controlled by the magnitude of the VPD and stomatal conductance (Zhao and Ji, 2016). The limited-transpiration trait which restricts water loss by the plants under high VPD conditions is found very useful for conserving soil water (Sinclair et al., 2016; Zhao and Ji, 2016). It is evident that plant growth under high VPD conditions results in a decrease in stomatal conductance and conserves soil water (Devi et al., 2010). Individual genotypes exhibit limited TR at atmospheric VPD greater than about 2 kPa (Turner et al., 1984; Isoda and Wang, 2002; Devi et al., 2010). Very specific VPD experiments were conducted in maize (Ray et al., 2002), soybean (Sinclair and Ludlow, 1986), peanut (Devi et al., 2010) etc. In those cases they maintained VPD levels very carefully controlled. In our experiments, VPD was not controlled in such a way and it appeared as a combined effect of temperature and humidity in the glasshouse cabin. The temperature and humidity data were recorded in the glasshouse every 12 minutes intervals. We took daily averages of the weather data and VPD was calculated following the methods of Howel and Dusek (1995).

$$VPD = e^*(T) \times \left(1 - \frac{RH}{100}\right)$$

Where, $e^*(T)$ = saturated vapour pressure in kPa (kilo pascal) at a given temperature T in °C and RH = relative humidity in %. They calculated saturated vapour pressure according to the formula given below:

$$e^*(T) = 0.611 \times \exp\left(\frac{17.27T}{T+237.3}\right)$$

Zhao and Ji (2016) calculated VPD in the same way with a little difference in expression as:

$VPD = \left(1 - \frac{RH}{100}\right) SVP$, where SVP is the saturated vapor pressure and $SVP = 0.6108 \exp\left(\frac{17.27T}{T+237.3}\right)$

We found that both expressions had the similar VPD results and we used Howel and Dusek's method in our calculations.

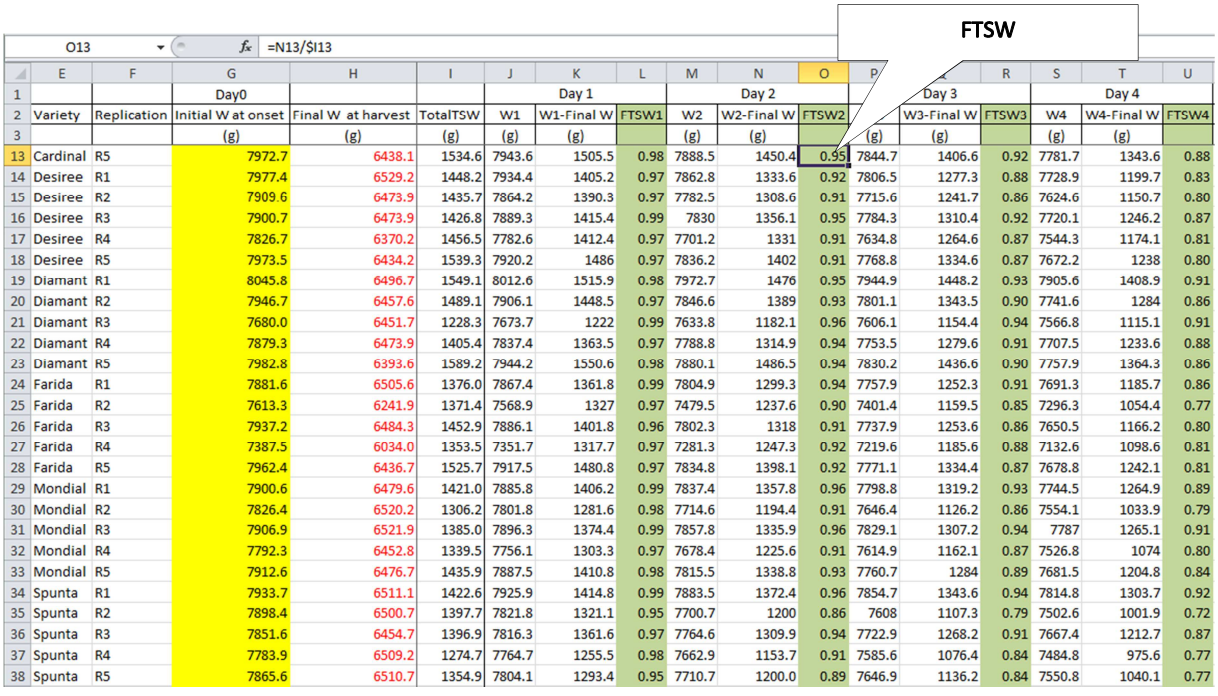
3.1.14 Determining FTSW

The total transpirable soil water available to the plant in each pot was calculated as the difference between the initial and final pot weight for the entire period of soil drying (Sinclair and Ludlow, 1986; Devi and Sinclair, 2011). We recorded pot weights daily and determined T and water requirements while FTSW was calculated at the end of the experiment. We took the final pot weight when all transpirable soil water had been used up and calculated FTSW according to Devi and Sinclair (2011) as described earlier by Sinclair and Ludlow (1986).

$$\text{FTSW} = \frac{\text{Daily weight} - \text{final weight}}{\text{Initial weight} - \text{final weight}}$$

We used a spreadsheet (Photo 3.5) to get the calculations done automatically after entering the final pot weight at the end.

In the spreadsheet, $W_{1.....n}$ indicates the pot weight on day n, initial W is the pot weight at sealing (onset of dry down) and Final W is the pot weight at harvest.



	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
1			Day0				Day 1			Day 2			Day 3			Day 4	
2	Variety	Replication	Initial W at onset	Final W at harvest	TotalTSW	W1	W1-Final W	FTSW1	W2	W2-Final W	FTSW2		W3-Final W	FTSW3	W4	W4-Final W	FTSW4
3			(g)	(g)	(g)	(g)	(g)		(g)	(g)		(g)	(g)		(g)	(g)	
13	Cardinal	R5	7972.7	6438.1	1534.6	7943.6	1505.5	0.98	7888.5	1450.4	0.95	7844.7	1406.6	0.92	7781.7	1343.6	0.88
14	Desiree	R1	7977.4	6529.2	1448.2	7934.4	1405.2	0.97	7862.8	1333.6	0.92	7806.5	1277.3	0.88	7728.9	1199.7	0.83
15	Desiree	R2	7909.6	6473.9	1435.7	7864.2	1390.3	0.97	7782.5	1308.6	0.91	7715.6	1241.7	0.86	7624.6	1150.7	0.80
16	Desiree	R3	7900.7	6473.9	1426.8	7889.3	1415.4	0.99	7830	1356.1	0.95	7784.3	1310.4	0.92	7720.1	1246.2	0.87
17	Desiree	R4	7826.7	6370.2	1456.5	7782.6	1412.4	0.97	7701.2	1331	0.91	7634.8	1264.6	0.87	7544.3	1174.1	0.81
18	Desiree	R5	7973.5	6434.2	1539.3	7920.2	1486	0.97	7836.2	1402	0.91	7768.8	1334.6	0.87	7672.2	1238	0.80
19	Diamant	R1	8045.8	6496.7	1549.1	8012.6	1515.9	0.98	7972.7	1476	0.95	7944.9	1448.2	0.93	7905.6	1408.9	0.91
20	Diamant	R2	7946.7	6457.6	1489.1	7906.1	1448.5	0.97	7846.6	1389	0.93	7801.1	1343.5	0.90	7741.6	1284	0.86
21	Diamant	R3	7680.0	6451.7	1228.3	7673.7	1222	0.99	7633.8	1182.1	0.96	7606.1	1154.4	0.94	7566.8	1115.1	0.91
22	Diamant	R4	7879.3	6473.9	1405.4	7837.4	1363.5	0.97	7788.8	1314.9	0.94	7753.5	1279.6	0.91	7707.5	1233.6	0.88
23	Diamant	R5	7982.8	6393.6	1589.2	7944.2	1550.6	0.98	7880.1	1486.5	0.94	7830.2	1436.6	0.90	7757.9	1364.3	0.86
24	Farida	R1	7881.6	6505.6	1376.0	7867.4	1361.8	0.99	7804.9	1299.3	0.94	7757.9	1252.3	0.91	7691.3	1185.7	0.86
25	Farida	R2	7613.3	6241.9	1371.4	7568.9	1327	0.97	7479.5	1237.6	0.90	7401.4	1159.5	0.85	7296.3	1054.4	0.77
26	Farida	R3	7937.2	6484.3	1452.9	7886.1	1401.8	0.96	7802.3	1318	0.91	7737.9	1253.6	0.86	7650.5	1166.2	0.80
27	Farida	R4	7387.5	6034.0	1353.5	7351.7	1317.7	0.97	7281.3	1247.3	0.92	7219.6	1185.6	0.88	7132.6	1098.6	0.81
28	Farida	R5	7962.4	6436.7	1525.7	7917.5	1480.8	0.97	7834.8	1398.1	0.92	7771.1	1334.4	0.87	7678.8	1242.1	0.81
29	Mondial	R1	7900.6	6479.6	1421.0	7885.8	1406.2	0.99	7837.4	1357.8	0.96	7798.8	1319.2	0.93	7744.5	1264.9	0.89
30	Mondial	R2	7826.4	6520.2	1306.2	7801.8	1281.6	0.98	7714.6	1194.4	0.91	7646.4	1126.2	0.86	7554.1	1033.9	0.79
31	Mondial	R3	7906.9	6521.9	1385.0	7896.3	1374.4	0.99	7857.8	1335.9	0.96	7829.1	1307.2	0.94	7787	1265.1	0.91
32	Mondial	R4	7792.3	6452.8	1339.5	7756.1	1303.3	0.97	7678.4	1225.6	0.91	7614.9	1162.1	0.87	7526.8	1074	0.80
33	Mondial	R5	7912.6	6476.7	1435.9	7887.5	1410.8	0.98	7815.5	1338.8	0.93	7760.7	1284	0.89	7681.5	1204.8	0.84
34	Spunta	R1	7933.7	6511.1	1422.6	7925.9	1414.8	0.99	7883.5	1372.4	0.96	7854.7	1343.6	0.94	7814.8	1303.7	0.92
35	Spunta	R2	7898.4	6500.7	1397.7	7821.8	1321.1	0.95	7700.7	1200	0.86	7608	1107.3	0.79	7502.6	1001.9	0.72
36	Spunta	R3	7851.6	6454.7	1396.9	7816.3	1361.6	0.97	7764.6	1309.9	0.94	7722.9	1268.2	0.91	7667.4	1212.7	0.87
37	Spunta	R4	7783.9	6509.2	1274.7	7764.7	1255.5	0.98	7662.9	1153.7	0.91	7585.6	1076.4	0.84	7484.8	975.6	0.77
38	Spunta	R5	7865.6	6510.7	1354.9	7804.1	1293.4	0.95	7710.7	1200.0	0.89	7646.9	1136.2	0.84	7550.8	1040.1	0.77

Photo 3.5: A screenshot of spread sheet for calculating FTSW

3.1.15 FTSW threshold

When plants go through a drying cycle or drought, Sinclair and Ludlow (1986) described three distinct stages (as mentioned in section 3.1.12) of hydration of plants. Stage I is

extended as long as water is freely available from the soil and both stomatal conductance and water vapour loss are maximal. The rate of water loss from the plants is largely determined by environmental conditions. This stage we regarded as phase I in terms of water consumption. According to Sinclair and Ludlow (1986), stage II begins when the water uptake from the soil cannot match the potential transpiration demand. Under this condition, the rate of soil water loss declines as a consequence of declining soil hydraulic conductivity due to a decrease in the volumetric water content. We regarded this stage as Phase II in terms of water consumption. The existence of these two stages was confirmed already by Ritchie (1981) and Ray and Sinclair (1998), who observed that transpiration decline began at FTSW 0.31 in maize and at 0.35 in soybean. This transition appears as a breakthrough of the transpiration rate and we regarded it as the threshold of FTSW.

Sinclair and Ludlow (1986) worked with 4 different crop species (soybean, black gram, pigeon pea and cowpea). They determined the transition of Phase I to Phase II using a sigmoidal equation as;

$$y = \frac{2}{[1-\exp(-14x)]^{-1}}$$

where y = Transpiration ratio and x = FTSW

Further Devi et al. (2010) used GraphPad Prism 2.01 (GraphPad Software Inc., San Diego, USA) for successful regression analysis to find out the breakpoint between the two linear segments in their peanut experiments.

In our experiments, we used a two segment linear regression function and determined breakpoint of TR (transition of phase I and II or FTSW threshold) with the help of software Sigmaplot 12.5 (Systat Software GmbH, Germany, see Figure 3.1) following the equations as:

$$\text{Region 1 (t)} = \frac{y1(T1-t)+y2(t-T1)}{T1-t1}, \quad t1 \le t \le T1$$

$$\text{Region 2 (t)} = \frac{y2(t2-t)+y3(t-T1)}{t2-T1}, \quad T1 \le t \le t2$$

Where,

Region 1 = Regression line starting from the maximum FTSW to the breakpoint

Region 2 = Regression line starting from the break point to minimum FTSW

T1 = transition or the breakpoint

t1 = min(t), the minimum FTSW = 0

t2 = max(t), the maximum FTSW = 1.0

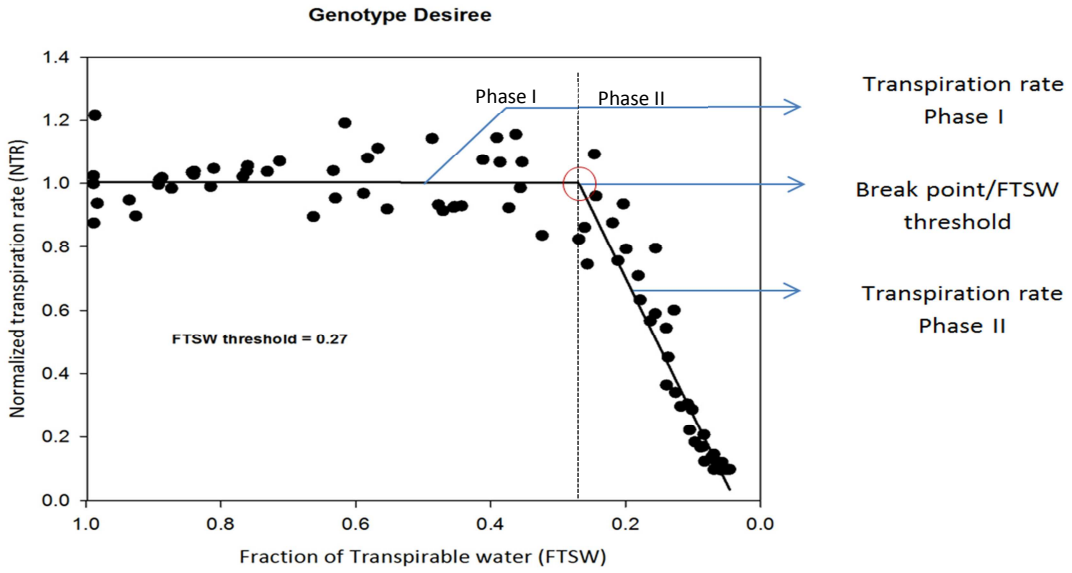


Figure 3.1: A two segment linear regression curve showing breakpoint of TR and indicating FTSW threshold

3.1.16 Biomass harvesting

As it has been mentioned before that our experiments were designed to run until the water stressed plants reached to their lowest limit of transpirable water (FTSW = 0). At this stage, plants were no more capable of transpiring and NTR value was < 0.10, we regarded this stage as physiologically dead. At this stage, we opened all the pots out of the sealed polyethylene bags. We separated leaves from each plant and their fresh weight was recorded. Then the stem was cut at the base, chopped them into small pieces and weighed. Soon after leaf and stem harvest, we collected under-ground shoot parts (only in experiment 1) attached to and tubers developed from the harvested stem. We washed them well and immediately after air drying, their fresh weight was taken. During biomass harvest, we excluded roots and mother tuber. All harvested plant parts were put in separate paper bags and fresh weight data was recorded. Harvest dates and age of the plants Table (3.7) were as follows;

Table 3.7: Harvest dates and dry down days among the experiments

Experiment	Harvest date	Plant age (DAP)	Dry down days
Experiment 1	12.02.2015	59	34
Experiment 2	10.04.2015	55	32
Experiment 3	14.06.2016	61	28

3.1.17 Dry matter determination

After recording fresh weight of the leaves, stem and tubers by a fine balance (MXX-612, Denver Instrument, USA), they were placed in the oven (UNE-600, Memmert GmbH, Germany) at a temperature of 60^{o}C. For better drying of tubers, they were sliced into thin pieces and air-dried before placing into the oven. When all of the samples were dried to crispiness, they were brought out from the oven and weighed out. Dry matter yield was calculated as a total of leaf, stem and tubers (plus underground stolons for the Exp 1).

3.2 Field experiment in Tulln

3.2.1 Location and field conditions

A field experiment was conducted in the research field in Tulln, adjacent to the UFT (Photo 3.6). The soil of that field was developed from depositing soil from other areas. It had a mild slope from north to south and no potatoes had been grown in previous years.

Source: Google map

Photo 3.6: Experiment field in Tulln

3.2.2 Weather conditions

Long term weather data shows that Tulln has a warm and temperate climate (Figure 3.2). This area receives a significant rainfall, even in the driest month there is a sufficient amount of rain. The average maximum temperature in July is 9.7 °C and minimum temperature goes down to -3.9°C in January. Yearly rainfall averages here 625 mm.

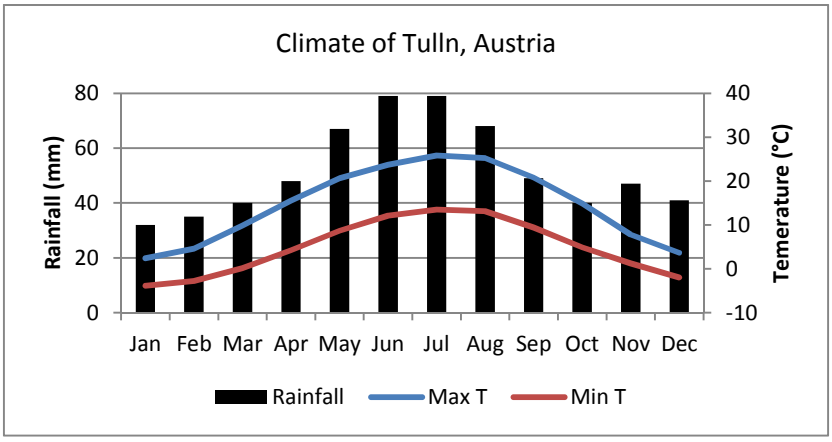


Figure 3.2: Climate of Tulln

3.2.3 Genotypes

Four genotypes were selected from the previous glasshouse experiments. They were Desiree, Caesar, Farida and Cardinal. Well sprouted seed tubers were supplied from different source breeders/companies. Descriptions of the genotypes could be found are in Table 3.1.

3.2.4 Soil properties

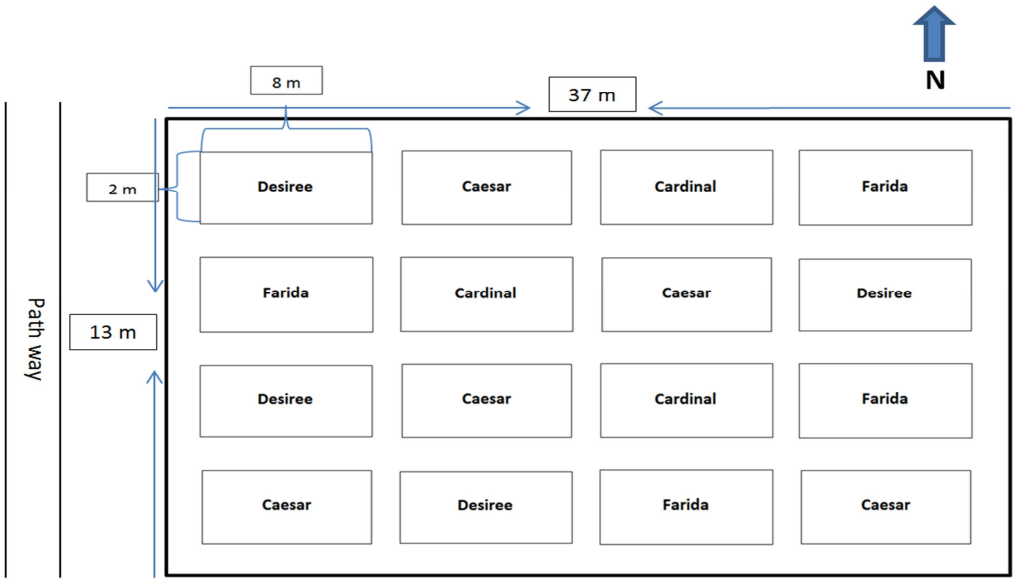
As the experimental field was filled by soils of different sources, a high number of gravels were found in it and no clear structure was observed in the soil profile. Chemical analyses were done for the top soils and nutrient contents were as follows (Table 3.8):

Table 3.8: Nutrient contents in the field soil (0-30 cm)

C (%)	N (%)	P (mg/kg)	K (mg/kg)
2.94	0.11	50.9	70.2

3.2.5 Experimental design and layout

A piece of land (137 x 13 m) was taken from the field for the RCBD experiment. Four varieties were assigned randomly in each of the four blocks. Each plot and block were isolated by one meter bare area and blocks were placed north to south (Figure 3.3)



Plot size: 8 m x 2 m
Plant spacing: 50 cm x 40 cm
Tubers/plot: 80

Figure 3.3: Layout of the field experiment in Tulln

3.2.6 Land preparation

The field was ploughed with tractor and tilled by power tiller. Weeds and roots from previously grown lupine were removed from the plot area and fertilizer was broadcasted evenly during final land preparation. Fertilizer was mixed well with soil with a power tiller and the plots with 8 m x 2 m size were laid out (Figure 3.3).

3.2.7 Planting tubers

Tubers were planted manually on 20 May 2015. Before planting, a 5-8 cm deep furrow was made 25 cm away from the border in each plot and further furrows were made at 50 cm interval from the a row. There were 4 rows in 2 m wide plots. First tuber was planted 20 cm away from the border and further tubers were planted at a spacing of 40 cm. The planted tubers were then buried with soil and a 10-15 cm high ridge was made over the tubers by hand.

3.2.8 Crop management

Three weeks after planting, plots were hand weeded. Further weeding was done whenever it was required (at 33 DAP, 49 DAP and 62 DAP). No irrigation was made during the whole experiment period and rain water (22 mm) was only source of plant water supply. Soon after planting tubers, some activities of field moles were seen but with the course of time they disappeared and no severe damage was noticed.

3.2.9 Soil sampling and soil moisture determination

Soil samples were taken 4 times during first harvest to the final harvest (H1-H4). Another initial sampling for soil was made once outside the plots at the time of planting. During soil sampling, the inner blocks were used (Figure 3.4). Five samples were taken with the help of an auger at layers of 20 cm depth each from top (0 cm) to 100 cm down. Gravels and stones were separated and wet samples were weighed. Then they were put into the oven at 105˚C for 72 hours. After drying soils were weighed again. Soil moisture was determined gravimetrically (Blake, 1965) on oven dry basis (w/w) as follows;

$$\text{Soil moisture (\%)} = \frac{Wet\ soil\ (g) - Oven\ dry\ soil\ (g)}{Oven\ dry\ soil\ (g)} \times 100$$

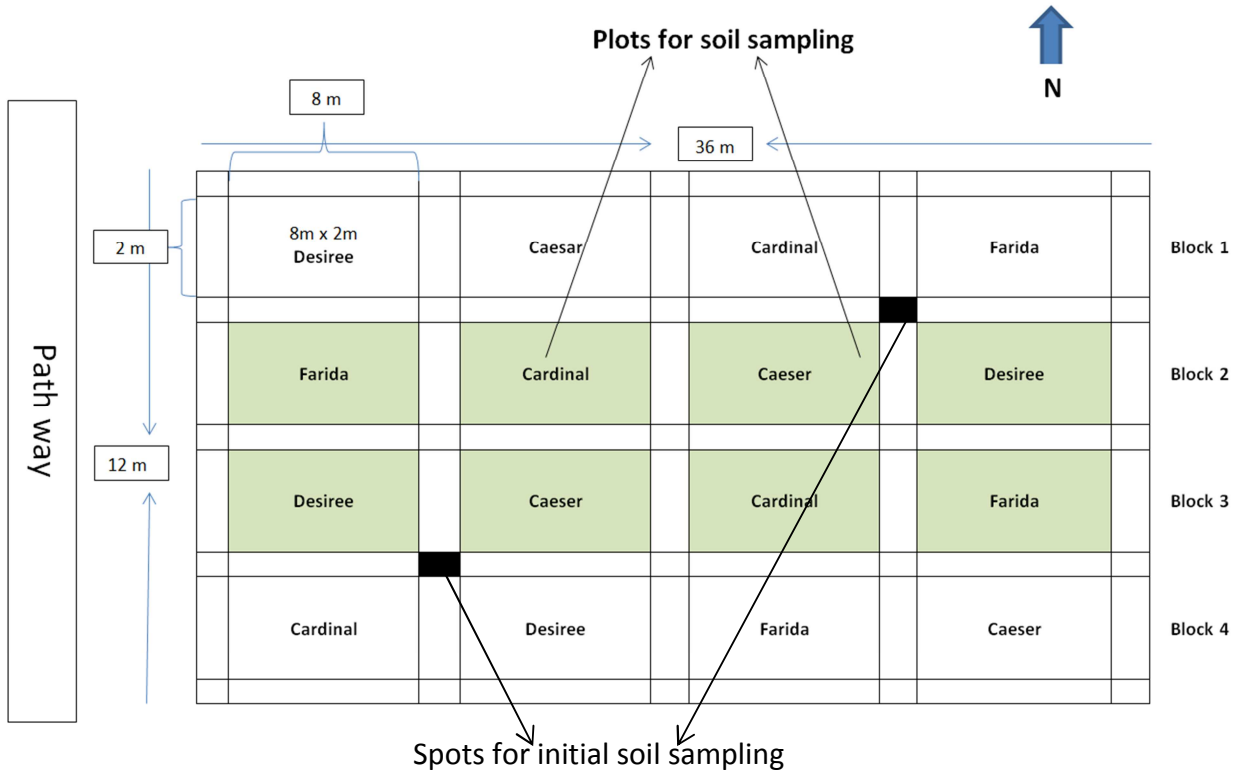


Figure 3.4: Soil sampling in the field experiment in Tulln

3.2.10 Plant sampling and biomass harvest

Plant samples were taken at different growth stages for biomass yield and growth properties. Four plants in sequence from two rows in the middle of each plot were selected and harvested at the bases from the ground. Underground parts were left for tuber harvest and harvested plants were brought immediately into the laboratory. Leaves were separated, weighed and they were passed through a leaf area meter. Stems were cut into small pieces and their fresh weight was recorded. Only tubers were collected afterwards and underground stems, roots and mother tubers were excluded. Collected tubers were then washed, air dried and their fresh weight was recorded as well. All fresh samples were then placed into the oven for drying at 65^{o}C and dried up to crispiness as we did in the glasshouse experiments. At H1, all harvested plant parts were sent for drying. However, at other harvests a portion of fresh materials were sub-sampled and placed for drying. Biomass harvest dates are given in the Table 3.9.

Table 3.9: Plant sampling and biomass harvest dates

Harvest time	Days after planting (DAP)	Development stage
H1	29	Leaf development to inflorescence initiation (BBCH scale 19-51)
H2	50	Flowering (BBCH scale 61-65)
H3	78	End of flowering/fruiting (BBCH scale 69 to 70)
H4	99	Senescence (BBCH scale 71-75)

3.2.11 Leaf area determination

Immediately after harvesting plants in each harvest period, fresh leaves were separated and passed through an area meter (LI-3100, LI-COR Environmental, USA). The area meter scanned leaves and provided data for total area in square centimetre. We calculated specific leaf area and leaf area index (LAI) from that data as follows;

Leaf area/plant: Area meter data/no. of plants harvested (i.e. four)

LAI = (Leaf area/plant) / plant spacing (area in square cm)

= Leaf area per plant /2000 (as plant spacing 50 cm x 40 cm)

3.2.12 Dry matter yield

Dry plant samples were weighed out by an analytical balance with readability of 0.01 g (MXX-612, Denver Instrument, USA). Total dry matter yield was calculated as follows:

TDM = Stem_DM + Leaf_DM + Tuber_DM

Where,

TDM = Total dry mass

Stem_DM = Dry mass of stems

Leaf_DM = Dry mass of leaves

Tuber_DM = Dry mass of tubers (without mother tuber)

3.3 Field experiments in Bangladesh

3.3.1 Location and field conditions

Two field experiments were conducted in two locations under different agro-ecological conditions. One location was about 60 km away in the west (Manikganj, 23°52' N, 90°02' E) and the other was about 250 km away in the north-west (Rajshahi, 24°23' N, 88°37' E) from Dhaka. The Manikganj experiment was conducted on the research field of Bangladesh Jute Research Institute (BJRI) while the Rajshahi experiment was set up in a farmer's field (Photo 3.7a, 3.7b).

Photo 3.7a: Experiment field in Manikganj

Photo 3.7b: Experiment field in Rajshahi
(Image source: Google maps)

3.3.2 Climatic conditions

Climatic conditions were a bit different in two locations. Weather in Manikganj (Figure 3.5a) was moderate and monthly average temperatures reached a maximum of 36 °C and a minimum to 12.7 °C with the annual rainfall total being 4067 mm. The weather in Rajshahi had lower rainfall with an annual total of 2442 mm. Heavy rainfall starts later than in Manikganj and lasts only for 4 months (Figure 3.5b).

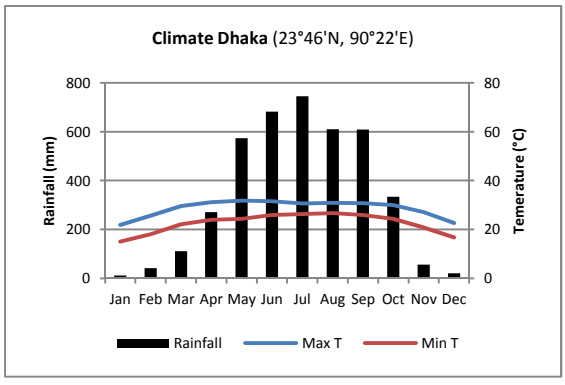
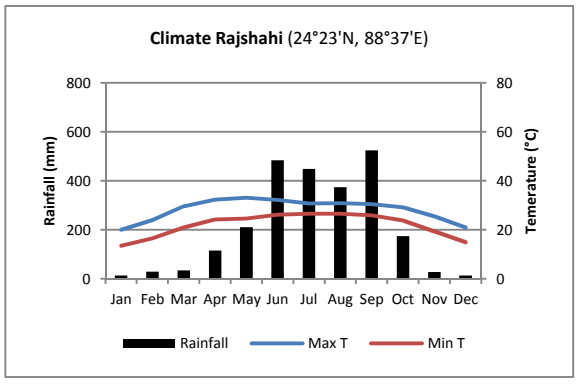


Figure 3.5a: Climate chart for Dhaka



Data Source: Bangladesh Meteorological Department

Figure 3.5b: Climate chart for Rajshahi

3.3.3 Genotypes

Four genotypes were used in both of the experiments (Table 3.10). Seed tubers of two popular local varieties were collected from the farmers in Bogra (popular potato growing district) and other two were collected from a reputed seed company. Collected seed tubers were well sprouted and were ready for planting.

Table 3.10: Potato genotypes used in the field experiment in Bangladesh

Name	Cultivar type	Genotype properties
Cardinal	Imported variety	Genotype descriptions are available in Appendix-1
Diamant	Imported variety	
Lalpakri	Local	
Shilbilati	Local	

3.3.4 Soil properties

Soils of both locations were characterized by flood plain soils. In Manikganj, it was formed by the deposits of rivers flown from the Brahmaputra river system and Rajshahi was blessed with the river Ganges. Soil properties of the two locations (Table 3.11) were as follows;

Table 3.11: Soil properties of the experimental fields

Location	Soil layer	C (%)	pH	N (%)	Olsen P (µg/g)	K (meq/100g)
Manikganj	0 - 30 cm	2.0	6.5	0.10	12.0	0.14
Rajshahi	0 - 30 cm	0.9	7.5	0.09	18.0	0.11

3.3.5 Experimental design and layout

Both experiments were conducted with four genotypes (Table 3.10) and exposed to two different water conditions (WW and WS) in a 2-factorial RCBD design. Treatment plot size was 8 m x 2 m and isolated by one meter from each plot in the Manikganj site. We followed a similar layout as we did in the field experiment in Tulln. All WW and WS plots were

randomly assigned in each block. However, 4 m x 2m plots were allocated for the Rajshahi experiment (due to scarce supply of seed tubers).

3.3.6 Land preparation

The Manikganj field was tilled 3 times upto 40 cm with a tractor. Weeds and roots from previous crop jute were removed from the plot area and fertilizer was broadcasted evenly in the area during final land preparation. During final land preparation, a rotary cultivator down to 30 cm was used for preparing good tilth. In the farmer's field in Rajshahi, plots were tilled 5 times with a power tiller up to 30 cm depth and residues from the previous crops were mixed well. At final land preparation, fertilizer was mixed well with soil with the power tiller and layout of plots was made for tuber planting.

3.3.7 Fertilizer dose

To supply sufficient nutrients for the crop, recommended dose of fertilizers (Table 3.12) as prescribed by Bangladesh Agricultural Research Council (BARC, 2012) was used for both locations.

Table 3.12: Fertilizer doses for the experimental fields

Location	N (Kg/ha)	P (Kg/ha)	K (Kg/ha)	S (Kg/ha)	Mg (Kg/ha)	Zn (Kg/ha)	Bo (Kg/ha)
Both (Manikganj and Rajshahi)	135	30	90	15	5	2	1

3.3.8 Planting tubers

Tubers were planted manually on 28 November, 2015 in Rajshahi and on 30 November, in Manikganj. We made furrows in the similar way (5-8cm deep) keeping same spacing as we did in our field experiment in Tulln (plant spacing 50cm x 40cm). Similar to field experiment in Tulln, we had 4 rows in our 2 m wide plots and in each row first tuber was planted 20 cm away from the border and further were done at a spacing of 40 cm. The planted tubers were buried with soils from the space between the rows and about 30 cm ridges were made with the help of spades. After digging soils in between the rows, they were used as irrigation canal in the WW treatments.

3.3.9 Crop management and irrigation in WW treatment

Weeding was made in both the experiments by hand pulling. Three irrigations were provided in Rajshahi experiment, while in Manikganj, it required only two. Irrigation requirement in WW plots was determined by analysing soil moisture in the soil before irrigation. About 10 mm water was applied in the plots (Table 3.13) each time in both the experiments. In Rajshahi experiment, incidence of late blight attack was evident in the adjacent potato fields and one spray with Mancozeb (a recommended copper fungicide) was applied against *Phytophthora infestans*. In Manikganj, no *Phytopthora* blight was noticed, however some activity of black cutworm (*Agrotis ipsilon*) was found and the grubs were collected and destroyed manually.

Table 3.13: Weeding and irrigation schedule in field experiments in Bangladesh

Location	Hand weeding (DAP)				Irrigation		
	1st	2nd	3rd	4th	1st	2nd	3rd
Rajshahi	10 DAP	41 DAP	80 DAP	-	11 DAP	42 DAP	81 DAP
Manikganj	18 DAP	40 DAP	51 DAP	58 DAP	8 DAP	41 DAP	

3.3.10 Soil sampling and soil moisture determination

Soil samples for moisture analyses were made 4 times during the harvests and once before planting in both of the experiments. A 110 cm long stainless steel probe was used for soil sampling and and samples were taken layer wise from each 20 cm depth starting from top soil to 100 cm down. Soil samples were dried at 105^{o}C in the laboratory of Institute of Biological Sciences (IBS), Rajshahi University, for the Rajshahi experiment and in the laboratory of the Department of Soil Science, Sher-E-Bangla Agricultural University, Dhaka, for the Manikganj experiment. Soil moisture was determined following the same way we did in the field experiment in Tulln.

3.3.11 Plant sampling and biomass harvest

Plant samples were taken at 4 different growth stages for biomass yield in both of the experiments. Four subsequent plants from each plot were selected randomly and harvested. We followed the same method for biomass harvest as at Tulln and took the fresh weight before bringing to the laboratory. Biomass samples were dried at 65^{o}C in the laboratory of

Institute of Biological Sciences (IBS), Rajshahi University, for the Rajshahi experiment and in the laboratory of the Department of Soil Science, Sher-E-Bangla Agricultural University, Dhaka, for the Manikganj experiment. Harvest dates were as given in the Table 3.14.

Table 3.14: Plant sampling and biomass harvest

Harvest time	Days after planting (DAP)		Plant growth condition
	Rajshahi	Manikganj	
H1	31	31	Leaf development (BBCH scale 15-17)
H2	39	39	Leaf development (BBCH scale 17-19)
H3	59	59	Leaf development (BBCH scale 19) (no inflorescence)
H4	84	84	Senescence (BBCH scale 75-79)

3.3.12 Dry matter yield

Dry plant samples of stem, leaf and tuber were weighed with a precision balance (readability 0.01 g). Like field experiment in Tulln, we did not collect underground stem, roots and mother tuber. Total dry matter yield was calculated as follows;

TDM = Stem_DM + Leaf_DM + Tuber_DM

Where,

TDM = Total dry mass

Stem_DM = Dry mass of stems

Leaf_DM = Dry mass of leaves

Tuber_DM = Dry mass of tubers (without mother tuber)

3.4 Statistical analyses and preparing graphs

Data from all experiments were recorded in spreadsheets. They were analysed for ANOVA, comparison of means, regression coefficient of determination etc. using statistical software SAS (Version 9.4, SAS Institute Inc. USA). Simple line and pie graphs were prepared with MS excel but linear regression curves, two-segment regression curves, bar graphs were made with the help of Sigma Plot (Version 12.5, Systat Software GmbH, Germany).

4 Results

4.1 Glasshouse experiments in Tulln

Three experiments were conducted in different seasons. Experiment 1 (Exp 1) was conducted in winter 2014-15, experiment 2 (Exp 2) started in winter and ended in spring 2015. The experiment 3 (Exp 3) was set up in the next year from spring to summer 2016 having different environmental conditions towards more extreme temperatures.

4.1.1 Environmental and plant growth conditions in the glasshouse

Figure 4.1 shows the temperature recorded in the glasshouse experiments. Temperature limit was set to 12˚C for night and 22˚C for day time and Exp 1 had maintained that properly. Exp 2 had slight deviations from the 2nd week of March and with a sudden rise in the 2nd week of April 2015. A substantially increasing temperature was observed at the beginning of Exp 3 which fluctuated widely with maximum of more than 35˚C during day and minimum of about 18˚C from the last week of May 2016.

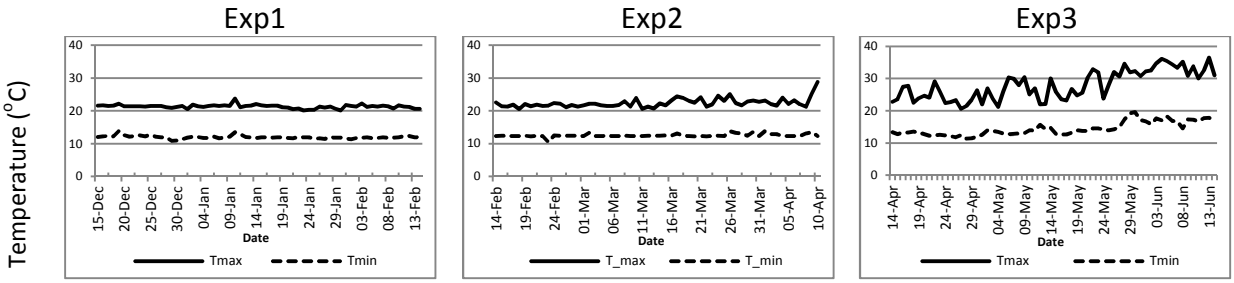


Figure 4.1: Temperature ranges observed in the glasshouse experiments

Humidity in the glasshouse cabins was maintained almost similarly with maxima around 60% and minima around 30% in both Exp 1 and Exp 2 (Figure 4.2). High fluctuations were observed in Exp 3, where daily maximum humidity reached some times more than 80% and dropped to as low as 15%. Dryness in the cabin was evident in 2nd and 3rd week of April and in the 1st and 2nd week of June, 2016.

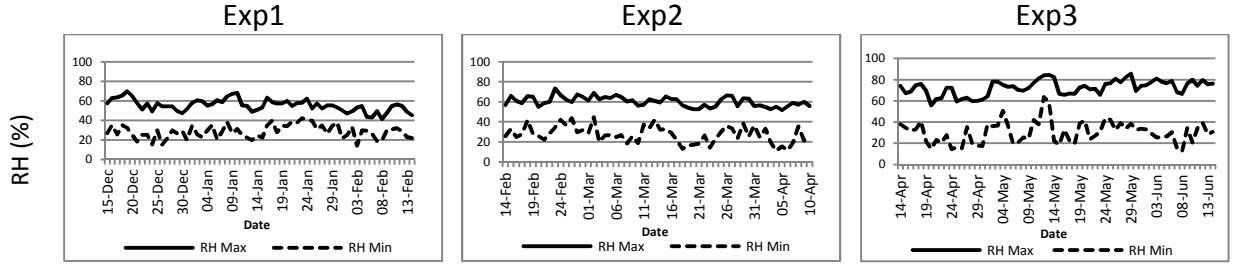


Figure 4.2: Humidity ranges observed in the glasshouse experiments

Also changes in VPD were varying considerably among the experiments (Figure 4.3). In the winter period of December 2014 to January 2015 (Exp 1), daily maximum VPD was less than 2.0 kPa (Figure 4.4). It was maintained around 2.0 kPa during the Exp 2 (2nd week of February 2015 to 1st week of April 2015) and then suddenly peaked to 3.0 kPa during the last days of the Exp 2. In the Exp 3 in 2016, daily maximum VPD fluctuated extremely and reached around 4.0 kPa in the 2nd week of June. The daily minimum VPD varied considerably (Figure 4.3) but maintained below 1.0 kPa in all experiments.

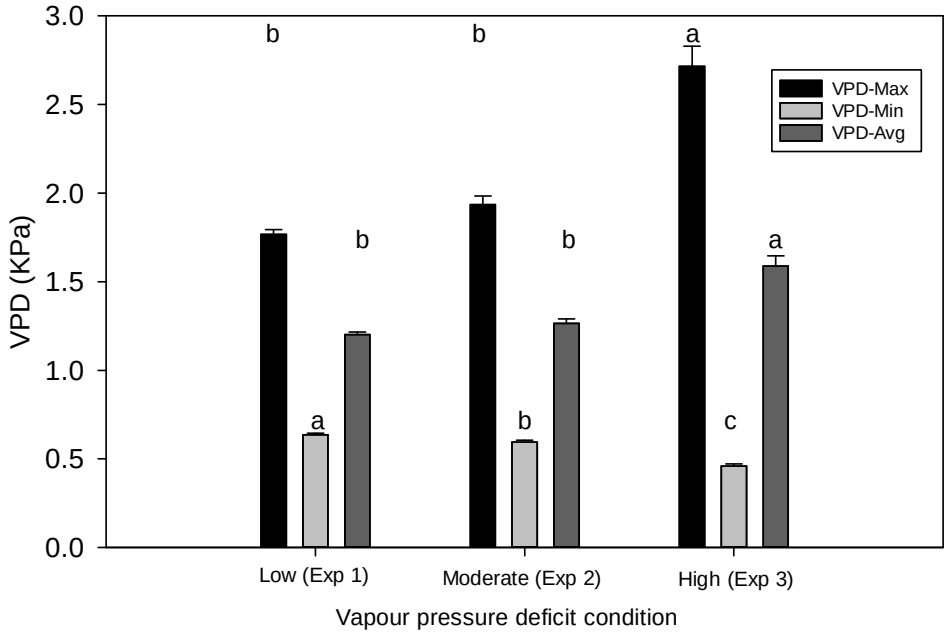


Figure 4.3: Magnitude of VPD changes in glasshouse experiments (error bars indicate SEM and different letters indicate differences in means)

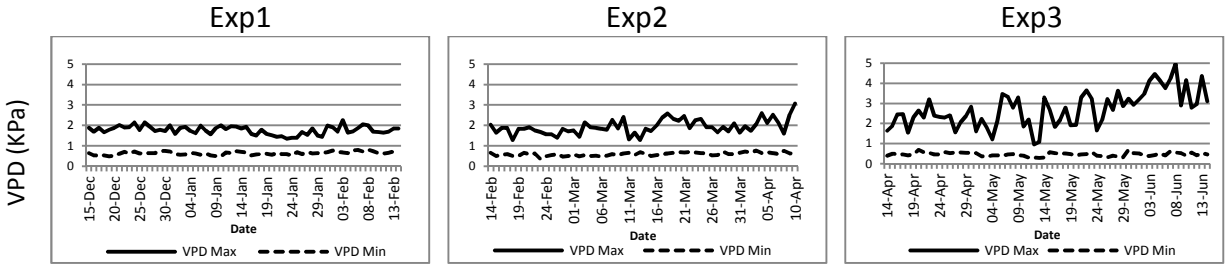


Figure 4.4: VPD ranges observed in the glasshouse experiments

Table 4.1 shows that average daily temperature remained below 20˚C in all three experiments. In the winter period (Exp 1), it was a bit low (16.9˚C), however other two

experiments had a favourable temperature around 20˚C (Krystyna, 2013) for good growth. Average relative humidity during the dry down cycle ranged from 37.4% in the Exp 3 to 49.9% in the Exp 2. Comparatively high average VPD was recorded in the Exp 3 (1.6 KPa) in the summer weather, while it was below 1.2 KPa in the Exp 1 under winter conditions. Lower growing degree days (GDD) were calculated in the winter period (around 250 in the Exp 1 and Exp 2) until onset of dry down while that was much higher (above 400) during the summer period in the Exp 3. Smaller plants with 1.64 g/plant shoot (Figure 4.5) were used in the 2nd experiment at the age of 23 DAP while larger plants were used in the Exp 1 (2.19 g/plant) and Exp 3 (2.93 g/plant) at the age of 25 and 33 days, respectively.

Table 4.1 Growth conditions of plants during the experiments from onset of drought stress to final harvest

	Avg. Temp (^{o}C)		Avg. RH (%)		Avg. VPD (KPa)		Thermal time (GDD)		Age of the plants (days)	
	Onset of drought stress	End	Onset of drought stress	End	Onset of drought stress	End	Onset of drought stress	End	Onset of drought stress	End
Exp 1	16.9	16.8	42.0	42.2	1.19	1.16	253.4	597.6	25	61
Exp 2	18.4	17.5	49.9	43.8	1.35	1.30	251.7	585.6	23	55
Exp 3	18.1	20.4	37.4	51.3	1.52	1.59	406.4	878.1	33	61

In the Exp 3, comparatively large plants (2.93 g/plant at age of 33 DAP) were used with high values of GDD and longer growing period (Table 4.1). Figure 4.5 also gives details about the genotypic variations in growth of the initial plants. Influence of both genotype and growing period varied significantly. In the Exp 1, Granola had the lowest (1.86 g/plant) biomass while the highest was observed with Desiree (2.83 g/plant). In Exp 2, initial plant biomass ranged from 1.48 g/plant to 2.43 g/plant and Spunta had significantly higher biomass than others. Larger plants in the Exp 3 also differed significantly and plants of Farida and Diamant were about 1.5 folds larger than those of Caesar and Desiree.

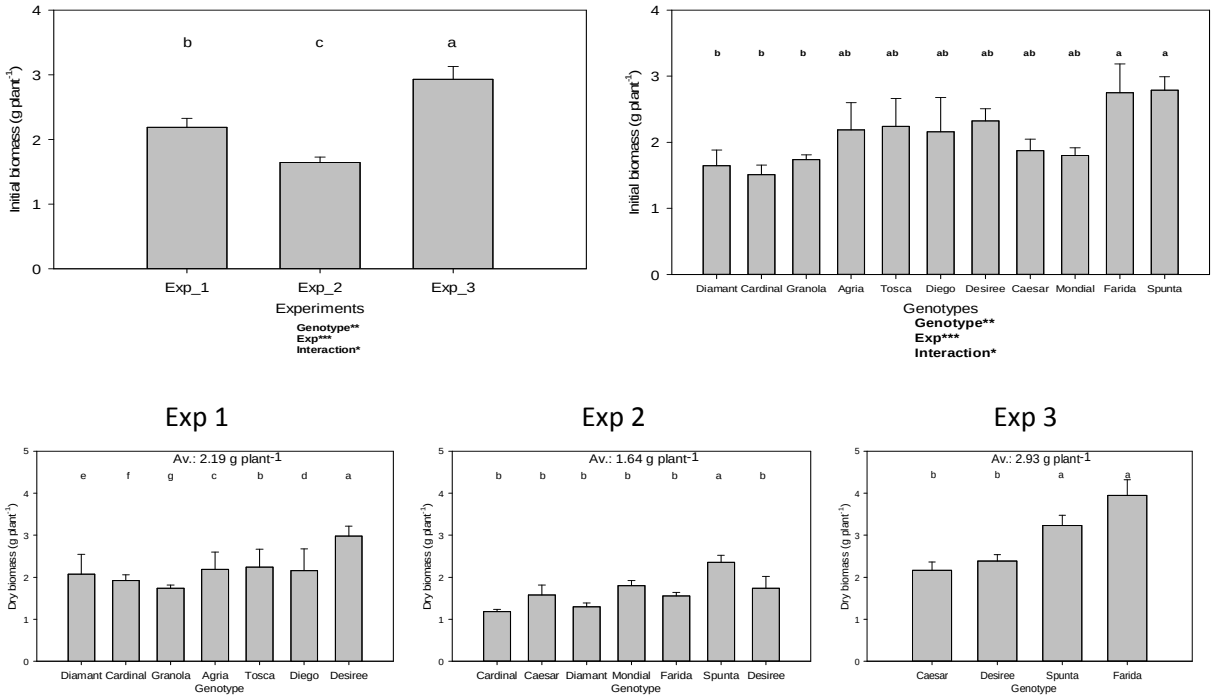


Figure 4.5 Initial plant weight in the experiments at the start of drought stress treatment (error bars indicate SEM and different letters indicate differences in means)

4.1.2 Plant response in transpiration

4.1.2.1 Transpiration under different VPD conditions

Device settings for the glasshouse cabins were kept the same in all three experiments (Table 3.1) in order to maintain identical environment, however ambient environment (temperature, humidity and solar radiation) outside the glasshouse influenced significantly on VPD (Figure 4.3) and resulted in varying environment conditions.

a. Transpiration under low VPD condition (Exp 1)

Figure 4.6 shows that total amount of water transpired by the plants was significantly different among the water treatments. The WS plants used less than half the amount (1606.0 ml) than the WW plants (3955.4 ml) during the dry down period. The VPD was comparatively low (Figure 4.3, 4.4) during the winter season. Genotypes transpired significantly different amount of water in the WW treatments, however no variations were observed among WS plants (Figure 4.7). The influence of genotypes and water treatments were interacted also and showed their important relationship in transpiration.

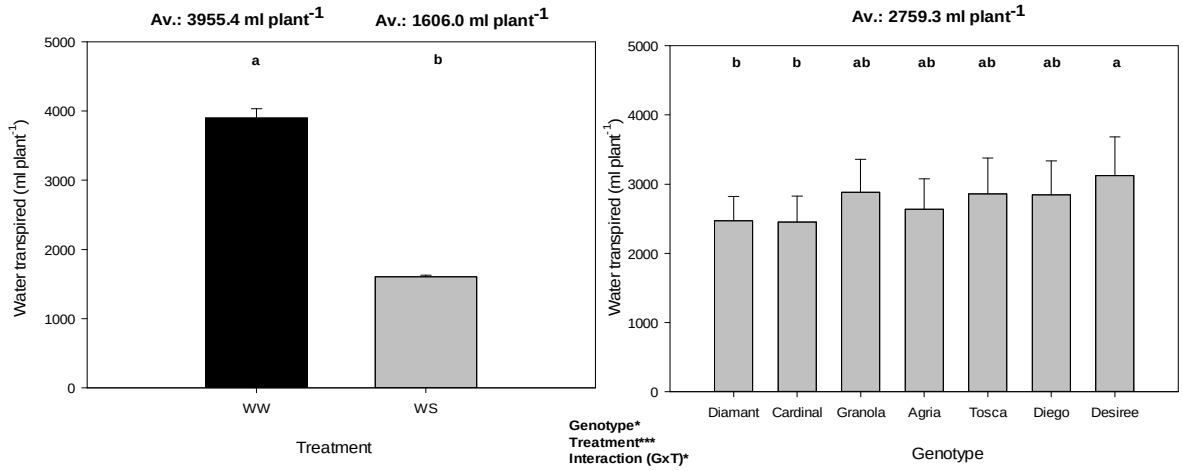


Figure 4.6: Total transpiration among the water treatments and genotypes in Exp 1 (error bars indicate SEM)

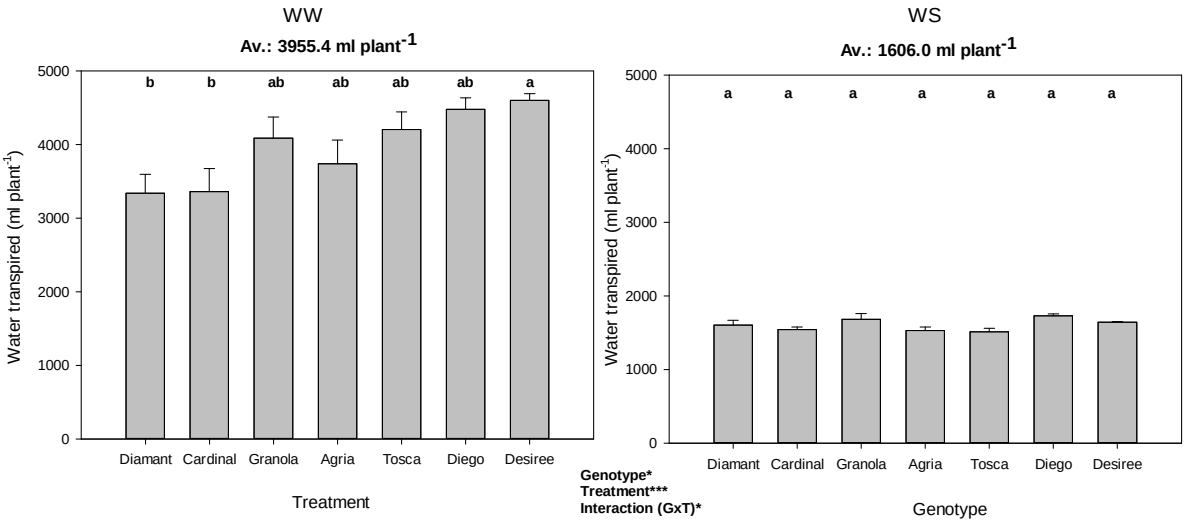


Figure 4.7: Total amount of water transpired by different genotypes in Exp 1 (error bars indicate SEM and different letters indicate differences in means)

b. Transpiration under moderate VPD condition (Exp 2)

The dry down cycle in the Exp 2 was run from 2nd week of March to mid-April. During this period VPD was at moderate level (Figure 4.3, 4.4). Total T was influenced significantly by the water treatments and genotypes (Figure 4.8). Average Total T was 3262.1 ml/plant in WW pots, which was a bit lower than that of Exp 1. Under well-watered conditions, Caesar consumed the lowest amount of water (2292.0 ml) in comparison to others (Figure 4.9) and the highest was found in Spunta (3995.3 ml). An average T of 1597.3 ml/plant was recorded in WS plants, which was very close to the value of Exp 1. Like in Exp 1, no significant difference among the genotypes was recorded in the WS treatments (Figure 4.9), but

interaction between the effects of genotypes and water treatments were visible under this environment condition.

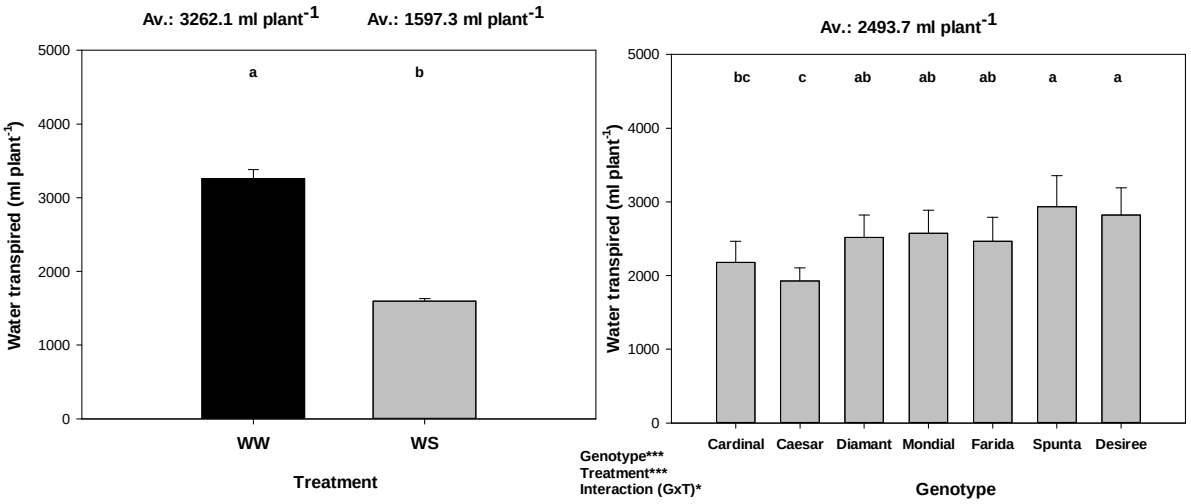


Figure 4.8: Total transpiration in different treatments and genotypes in Exp 2 (error bars indicate SEM and different letters indicate differences in means)

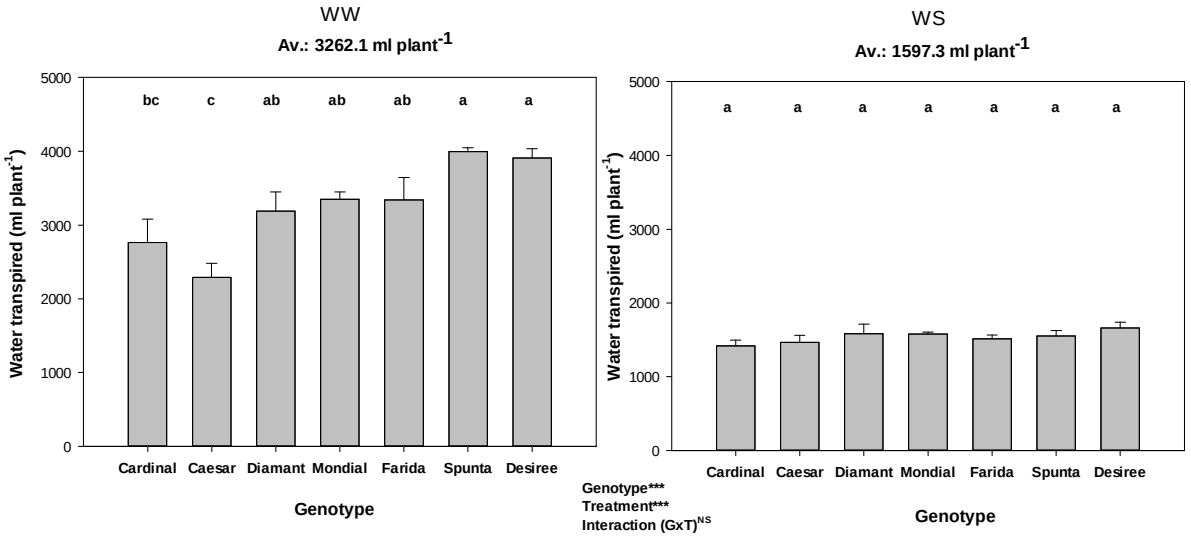


Figure 4.9: Total amount of water transpired by different genotypes in Exp 2 (error bars indicate SEM and different letters indicate differences in means)

c. Transpiration under high VPD condition (Exp 3)

Under high VPD condition (Figure 4.3, 4.4) similar pattern of transpiration like in the Exp 2 was also observed in the Exp 3 (Figure 4.10). Average T was 3162.3 ml/plant and 1565.3

ml/plant in the WW and WS pots, respectively. Caesar also consumed significantly less (2267.0 ml/plant) water than Farida (3791.9 ml/plant) in WW treatment and ranked similarly (Figure 4.11) as found in the Exp 2. The Total T in the WS treatments showed no significant variations among genotypes as observed in other two experiments. A strong interaction between the influence of water treatment and genotypes existed in this experiment under high VPD conditions.

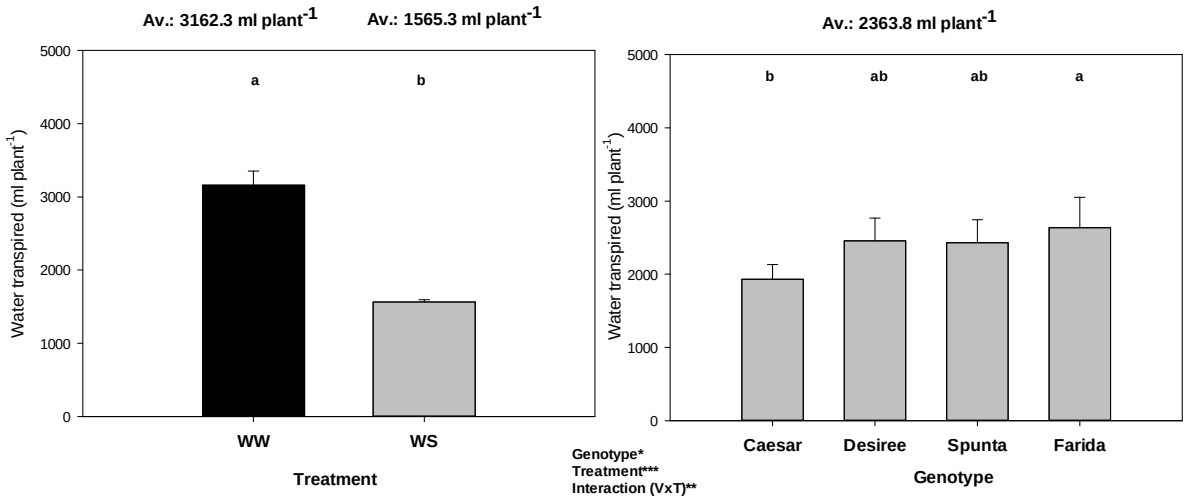


Figure 4.10: Total transpiration in different treatments in the Exp 3 (error bars indicate SEM and different letters indicate differences in means)

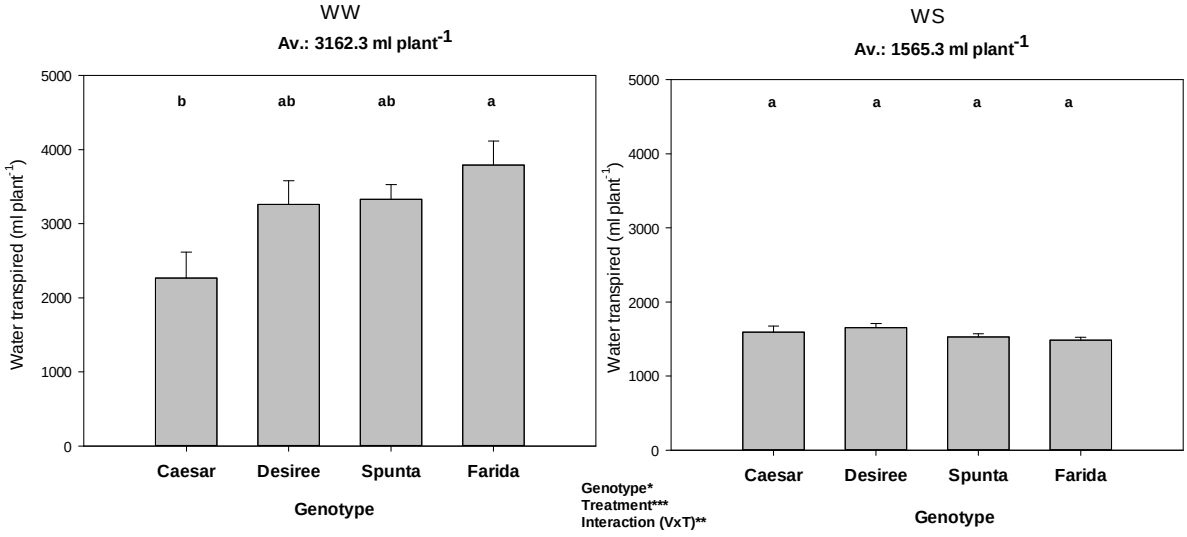


Figure 4.11: Total amount of water transpired by different genotypes in Exp 3 (error bars indicate SEM and different letters indicate differences in means)

4.1.2.2 Progressive soil drying and soil moisture consumption

In three glasshouse experiments, all the pots were sealed and water loss occurred only through transpiration. We assume that soil water status at the death of the plants (when plants reached to less than 10% of the normal transpiration) was the lower limit (0%) and the field capacity at the onset of dry down was the upper limit (100%) and available soil moisture for plant consumption was the difference between these two limits, which corresponds to the total T in glasshouse experiments. Different plants responded differently in growth, so all plants were grown until they reached the lower limit of soil water status. Practically plants in different experiments did not reach to death at the same date (Figure 4.12) and the water transpired until death day varied a little among experiments (Figure 4.13). Death day among the experiments varied significantly and that in the Exp 3 was earlier than in the other two experiments (Figure 4.12). Genotypes showed significantly different death dates and Diego and Agria survived longer than others. Similar influence of both genotype and VPD was observed in daily transpiration but no such difference existed in total T or consumption of available soil water (Figure 4.13)

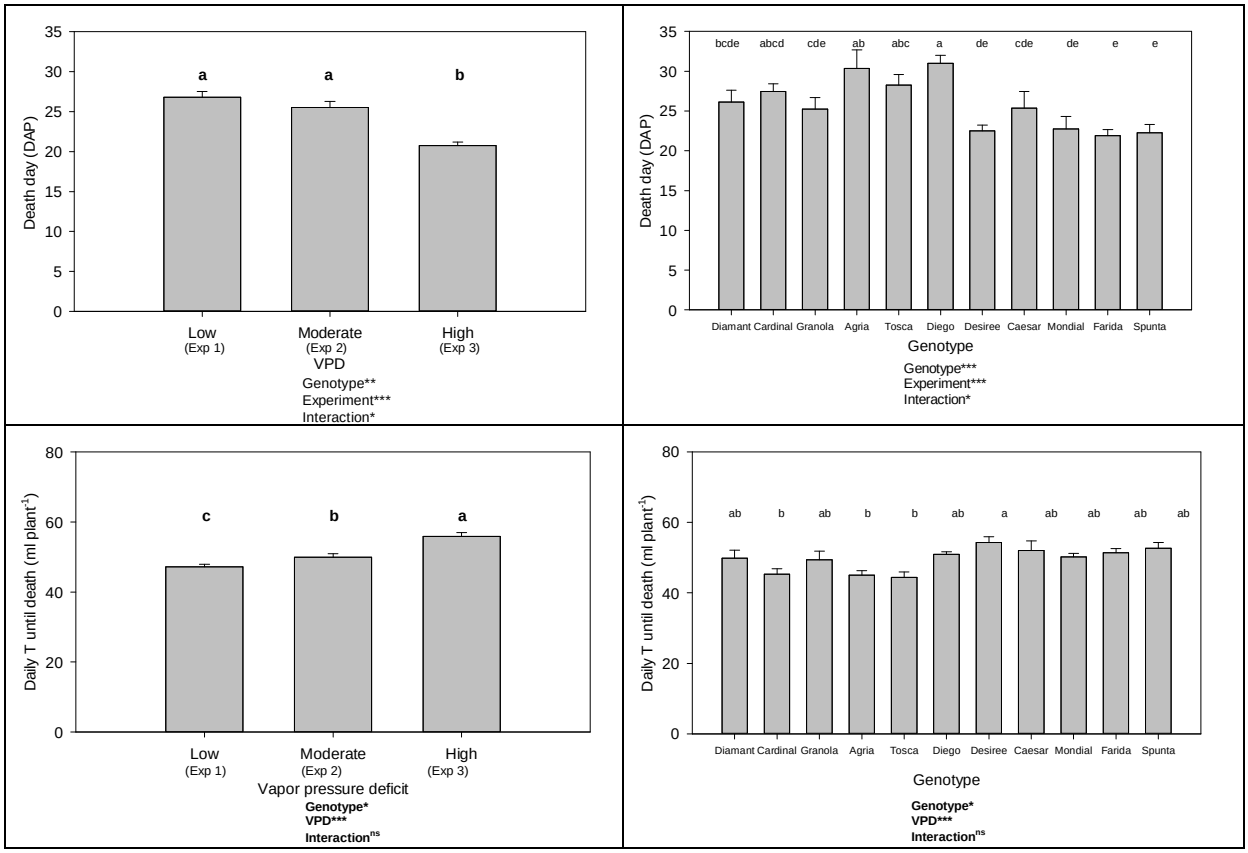


Figure 4.12: Death dates and daily transpiration among the genotypes during dry down cycle (error bars indicate SEM and different letters indicate differences in means)

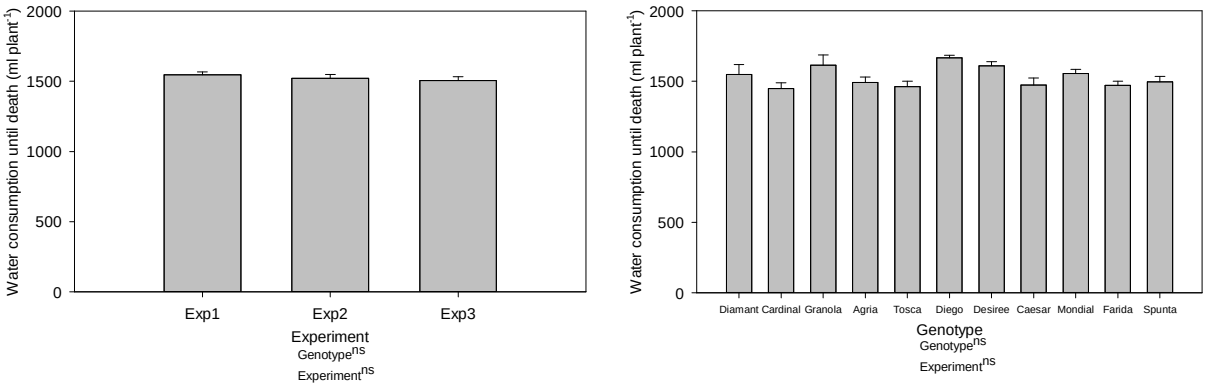
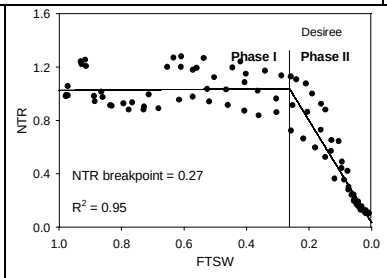
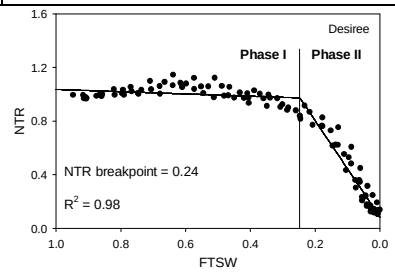
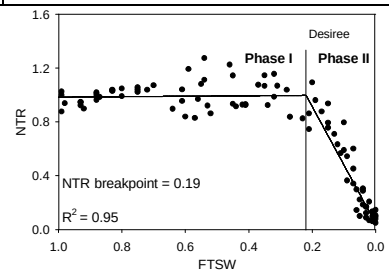
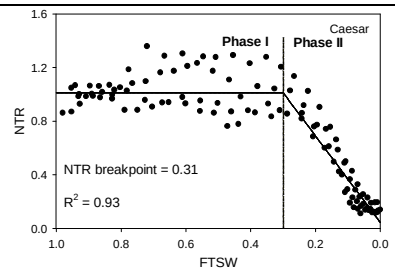
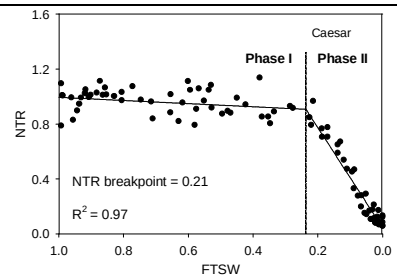
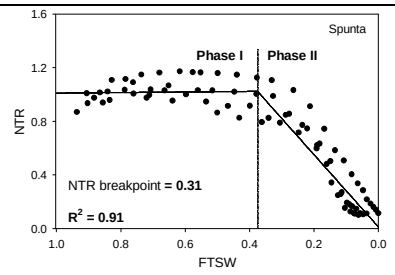
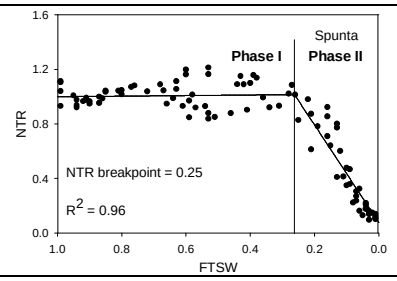
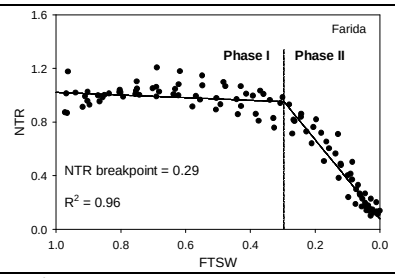
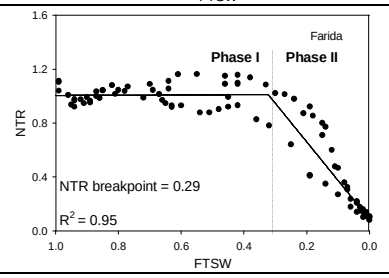
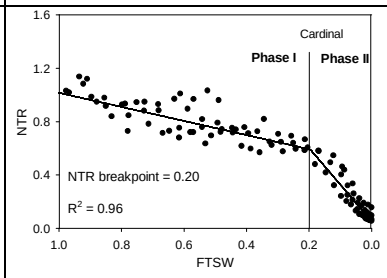
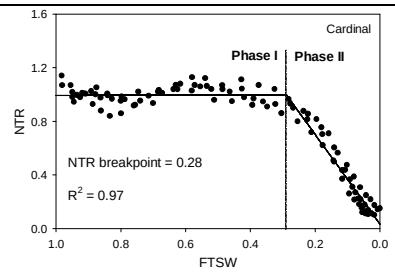
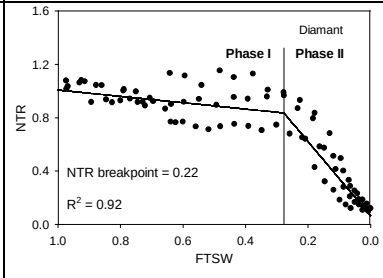
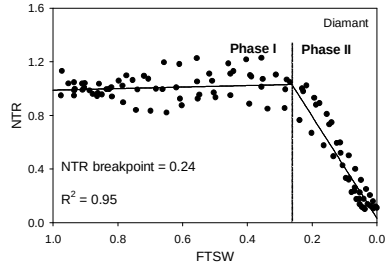


Figure 4.13: Soil water consumption until death date (error bars indicate SEM and different letters indicate differences in means)

4.1.2.3 Transpiration under water stress conditions

a. Genotypic response to progressive soil drying and soil moisture threshold

Figure 4.14 shows genotypic responses of transpiration to progressive soil drying. In this figure, two segment linear regression lines were estimated in order to determine the break point of transpiration ratio (TR). At the early stages of soil drying, starting from 100%, plants had quite high levels of available soil moisture and transpired almost constantly until the break point appeared. Then transpiration declined sharply and plant available soil moisture became 0% on the death day. This break point also corresponds to the critical available soil moisture level and has been regarded as threshold for individual genotypes. In the Exp 1, normalized transpiration (NTR) break point or FTSW threshold ranged from 0.19 in Granola to 0.36 in Tosca and Diego. In this experiment under low VPD condition Tosca and Diego had a significantly higher threshold than others (Figure 4.15). Desiree had a mid-range threshold (0.27), which was similar to the value in the Exp 2 (0.24) and these values were significantly higher than in the Exp 3 (0.19). All genotypes showed a similar FTSW threshold in the Exp 2. In the Exp 3, Farida appeared with a significantly higher threshold (0.29) than Caesar and Desiree. In most cases a reduced threshold value was obtained under high VPD conditions with an exception for Cardinal in the Exp 1 (0.20) which was considerably less than the value found in the Exp 2 (0.28). Figure 4.15 confirmed that both genotype and VPD influenced significantly on FTSW threshold, but their interaction effect was also significant. High VPD condition significantly reduced threshold level as compared to lower VPD conditions.

	Exp 1 (Low VPD)	Exp 2 (Moderate VPD)	Exp 3 (High VPD)
Desiree			
Caesar			
Spunta			
Farida			
Cardinal			
Diamant			

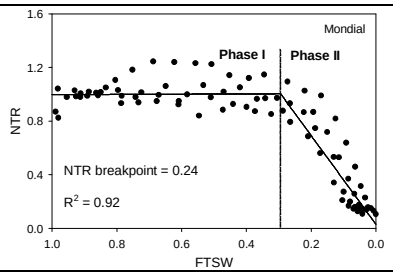
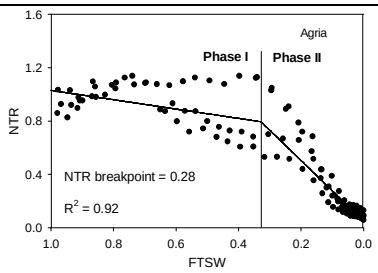
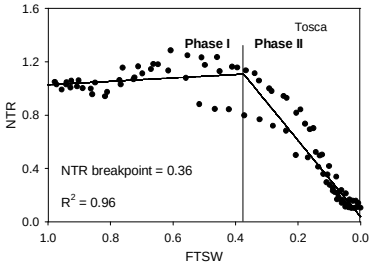
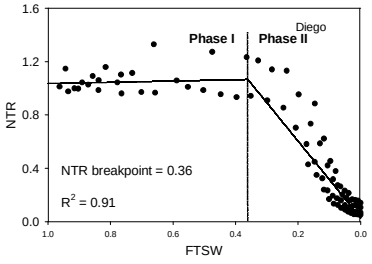
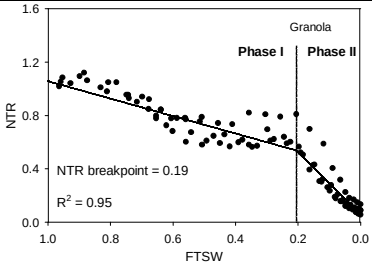
	Exp 1 (Low VPD)	Exp 2 (Moderate VPD)	Exp 3 (High VPD)
Mondial			
Agria			
Tosca			
Diego			
Granola			

Figure 4.14: Genotypic response of NTR to changing FTSW during soil drying phases

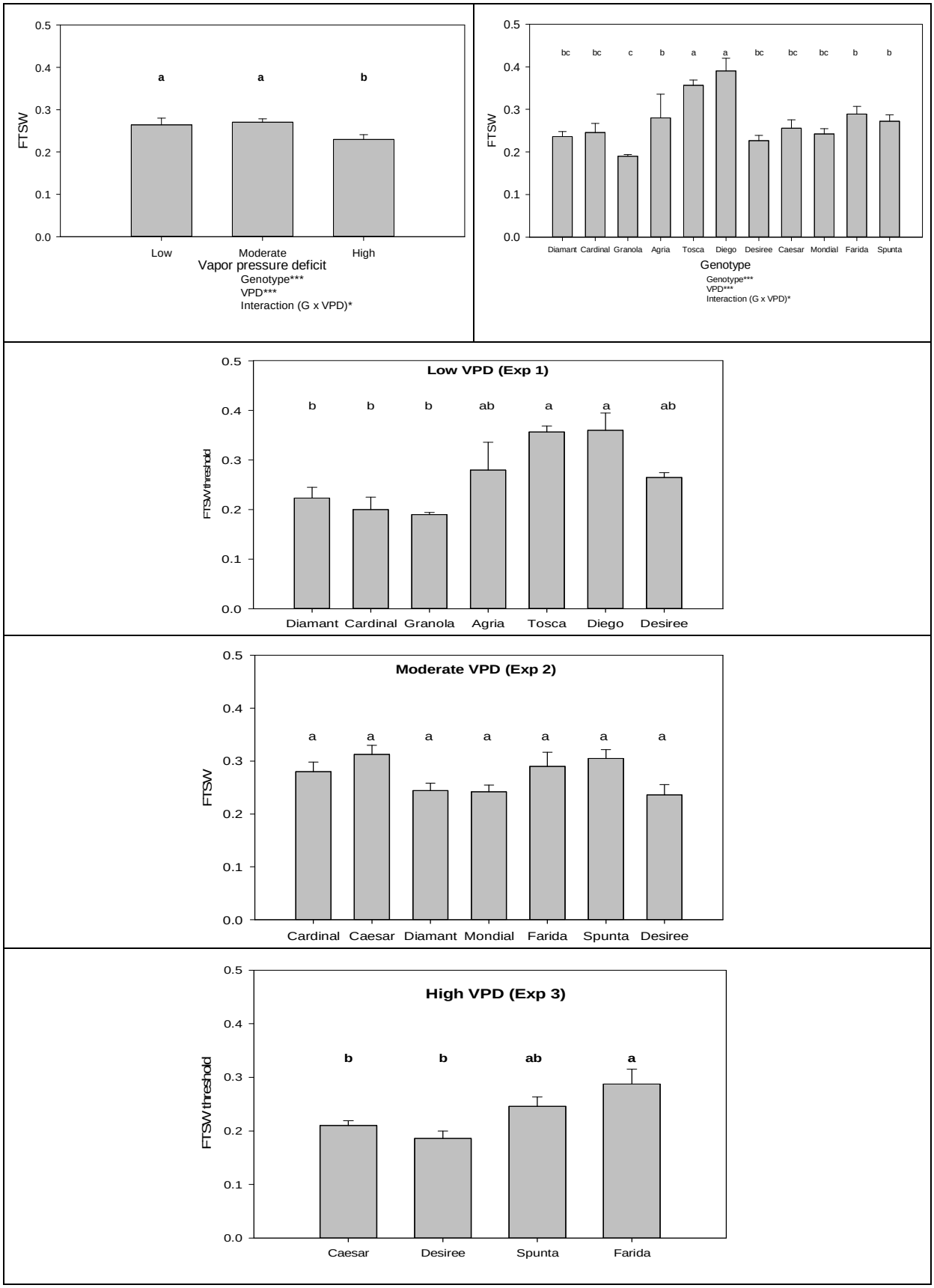


Figure 4.15: Soil moisture threshold in different genotypes under different VPD conditions (error bars indicate SEM and different letters indicate differences in means)

b. Dry down phases and transpiration

The FTSW threshold (Figure 4.14) divided the dry down period into two phases. Phase I had almost similar rate of T both in WW and WS treatments until the FTSW threshold was reached. Phase II showed a steep decline in T towards the death day. Significantly different phase I was exhibited among the genotypes and considerably long duration was found in Agria (18 days) in the Exp 1, while Phase II was identical that ranged from 8 to 15 days (Figure 4.16). Caesar along with Cardinal and Diamant passed through a longer Phase I than other genotypes in the experiment 2. Caesar here exhibited longest Phase II (15 days). No genotypic variations in phase durations were seen in the Exp 3 under high VPD conditions. The significant influence of genotype and VPD was coupled with each other in prolonging phase I however they acted independently in phase II.

Average daily T varied significantly among the experiments and genotypes in Phase I that was about 2 folds more than in Phase II in all experiments and no such variations were observed in Phase II. Lowest T rate was found in Agria, Caesar and Farida in the Exp 1, Exp 2 and Exp 3 respectively (Figure 4.17). Desiree consistently showed higher T while Farida appeared with a reduction under high VPD conditions in the Exp 3. The influence of genotype and VPD showed similar pattern and interacted similarly as observed in duration of phase I and phase II.

c. Soil moisture consumption and water savings during dry down cycle

Genotypes consumed different amounts of water through transpiration in different experiment (Table 4.2). Although FTSW threshold was different among the genotypes in the Exp 1 and Exp 3 (Figure 4.15) but not in the Exp 2, however water consumed by them was significantly different. Highest water was transpired by Granola (1378.4 ml), Diamant (928.4 ml) and Desiree (1298.0 ml) in the Exp 1, Exp 2 and Exp 3 respectively. The lowest consuming genotype Tosca consumed about 40% less than Granola and saved a total of 385.3 ml water in the Exp 1. Similarly, Spunta consumed 43.7% and Farida consumed 29.6% less than the maximum consumption and saved 282.4 ml and 296.4 ml water in the Exp 2 and Exp 3 respectively.

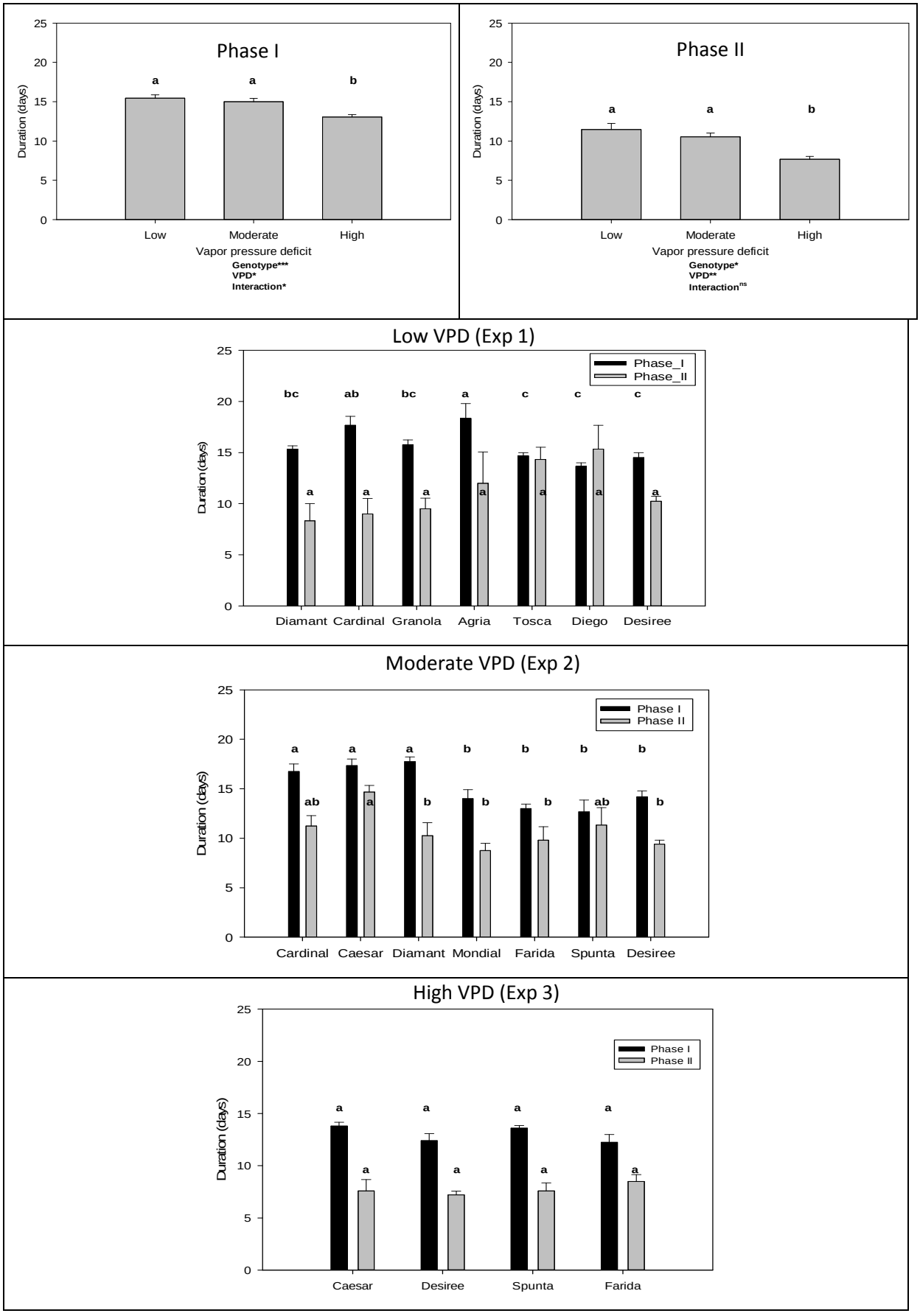


Figure 4.16: Duration of dry down phases (error bars indicate SEM and different letters indicate differences in means)

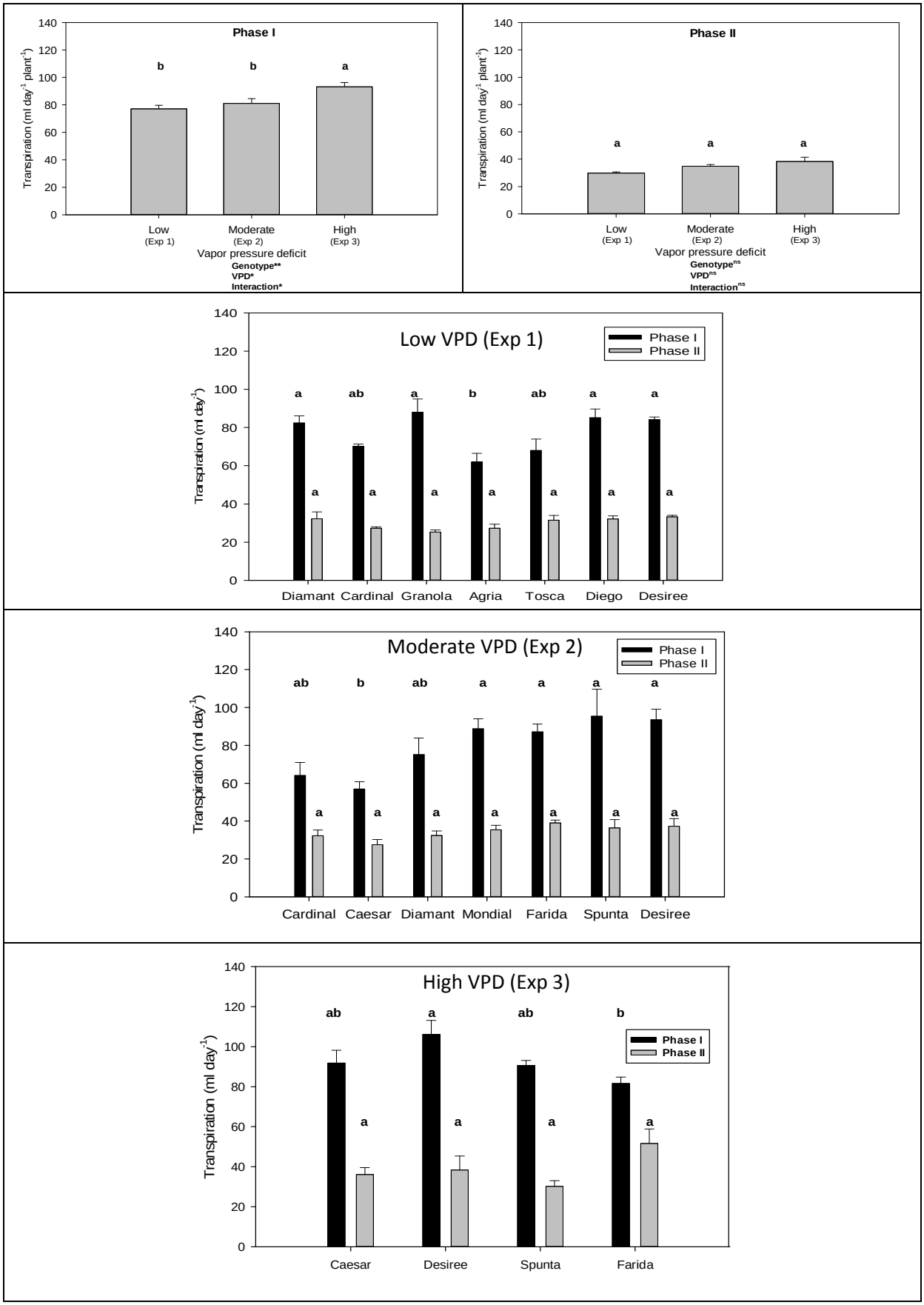


Figure 4.17: Daily average transpiration at different dry down phases (error bars indicate SEM and different letters indicate differences in means)

Table 4.2: Soil moisture consumption through transpiration and water saved at FTSW threshold (different letters indicate differences in means)

Experimental condition	Genotype	Soil water consumed until FTSW threshold (ml)	Less water consumption compared to highest consuming genotype (%)	Water saved as compared to highest consuming genotype (ml)
Low VPD (Exp 1)	Granola	1378.4[a]	0.0	0.0
	Diamant	1262.5[ab]	9.2	115.9
	Cardinal	1241.8[ab]	11.0	136.6
	Desiree	1217.6[ab]	13.2	160.8
	Agria	1129.9[ab]	22.0	248.5
	Diego	1097.0[ab]	25.7	281.4
	Tosca	993.1[b]	38.8	385.3
Average		1188.6	17.1	189.8
Moderate VPD (Exp 2)	Diamant	928.4[a]	0.0	0.0
	Desiree	766.8[b]	21.1	161.6
	Cardinal	755.1[b]	22.9	173.2
	Caesar	749.7[b]	23.8	178.7
	Mondial	702.9[b]	32.1	225.5
	Farida	650.0[b]	42.8	278.4
	Spunta	645.9[b]	43.7	282.4
Average		742.7	26.6	185.7
High VPD (Exp 3)	Desiree	1298.0[a]	0.0	0.0
	Caesar	1290.5[a]	0.6	7.6
	Spunta	1234.9[a]	5.1	63.2
	Farida	1001.6[b]	29.6	296.4
Average		1206.3	8.8	91.8

4.1.3 Biomass production during dry down cycle

4.1.3.1 Accumulated dry biomass

Accumulated dry biomass of leaf, stem and tuber was on average 21.9, 18.3 and 7.4 g/plant in the Exp 1, Exp 2 and Exp 3, respectively (Figure 4.18a, 4.18b, 4.18c). The ANOVA from three experiments show that influence of both genotypes (except Exp 3) and water treatments played a significant role on biomass production and no interaction existed between them. A portion of the biomass in the Exp 1 was also contributed by underground stems and stolons, which were not included in other experiments. So, the slightly elevated

biomass in Exp 1 is quite similar to that from the Exp 2. WS treatments produced almost half of the dry mass as compared to WW.

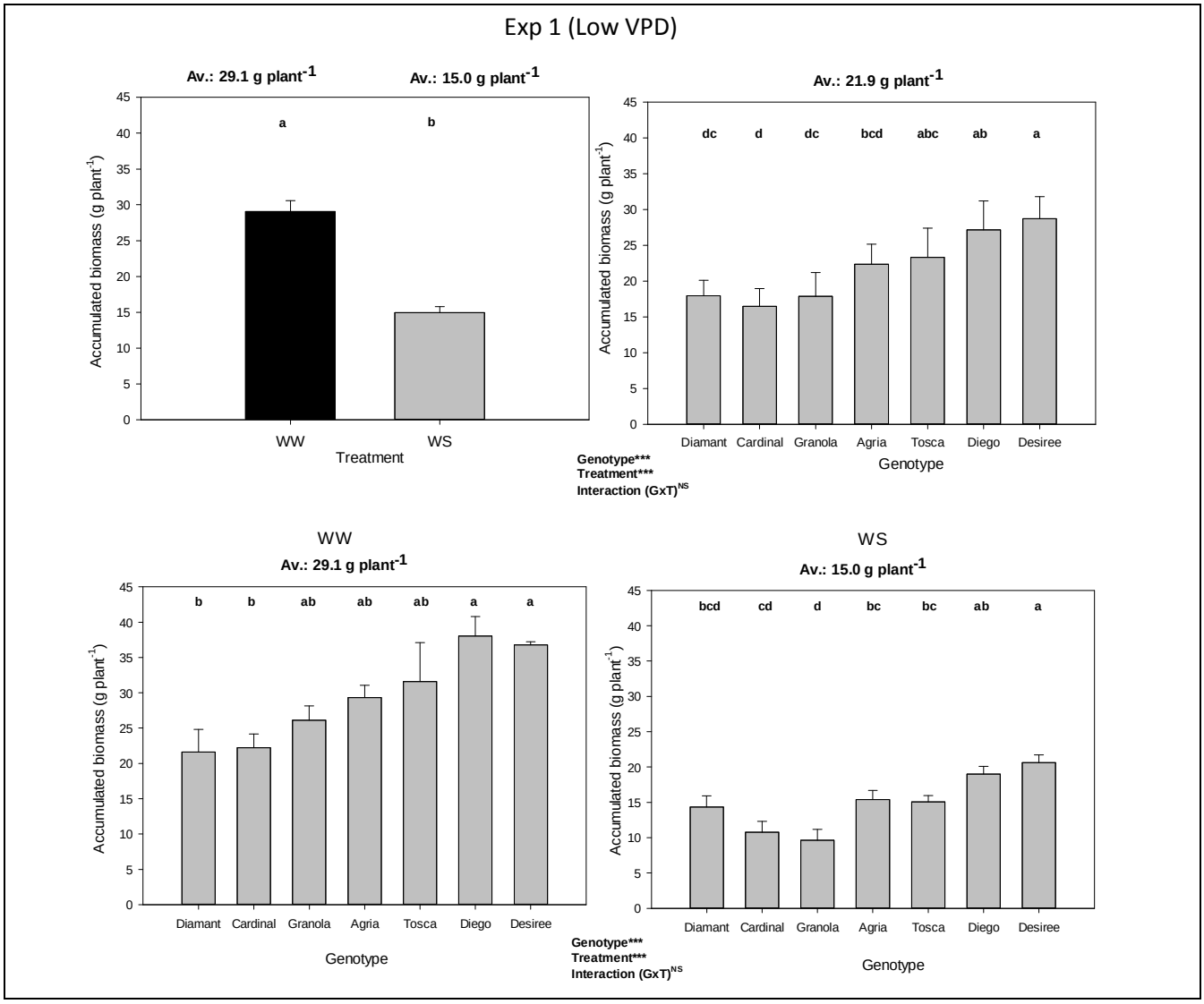


Figure 4.18a: Accumulated dry biomass production in Exp 1 (error bars indicate SEM and different letters indicate differences in means)

Biomass production was affected maximum in Granola (36.9% of WW) under low VPD condition in the Exp 1. Desiree had that (50.2% of WW) in the Exp 2 and Farida (28.1% of WW) under high VPD conditions in the Exp 3 (Table 4.3). Caesar was comparatively less affected (79.5% and 91.0% of WW in Exp 2 and Exp 3, respectively) shows its better adaptability to water stress regardless to VPD changes.

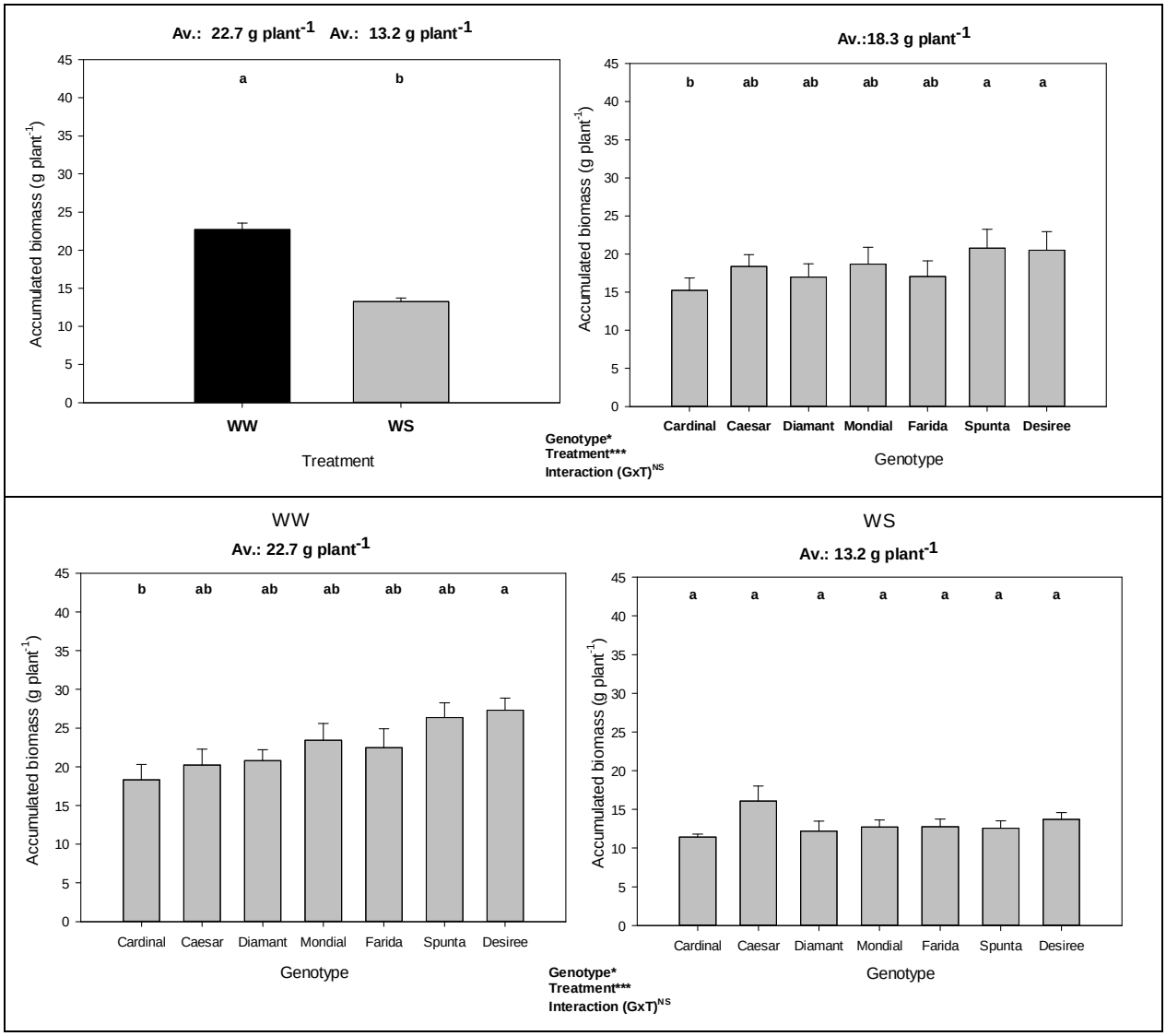


Figure 4.18b: Accumulated dry biomass production in Exp 2 (error bars indicate SEM and different letters indicate differences in means)

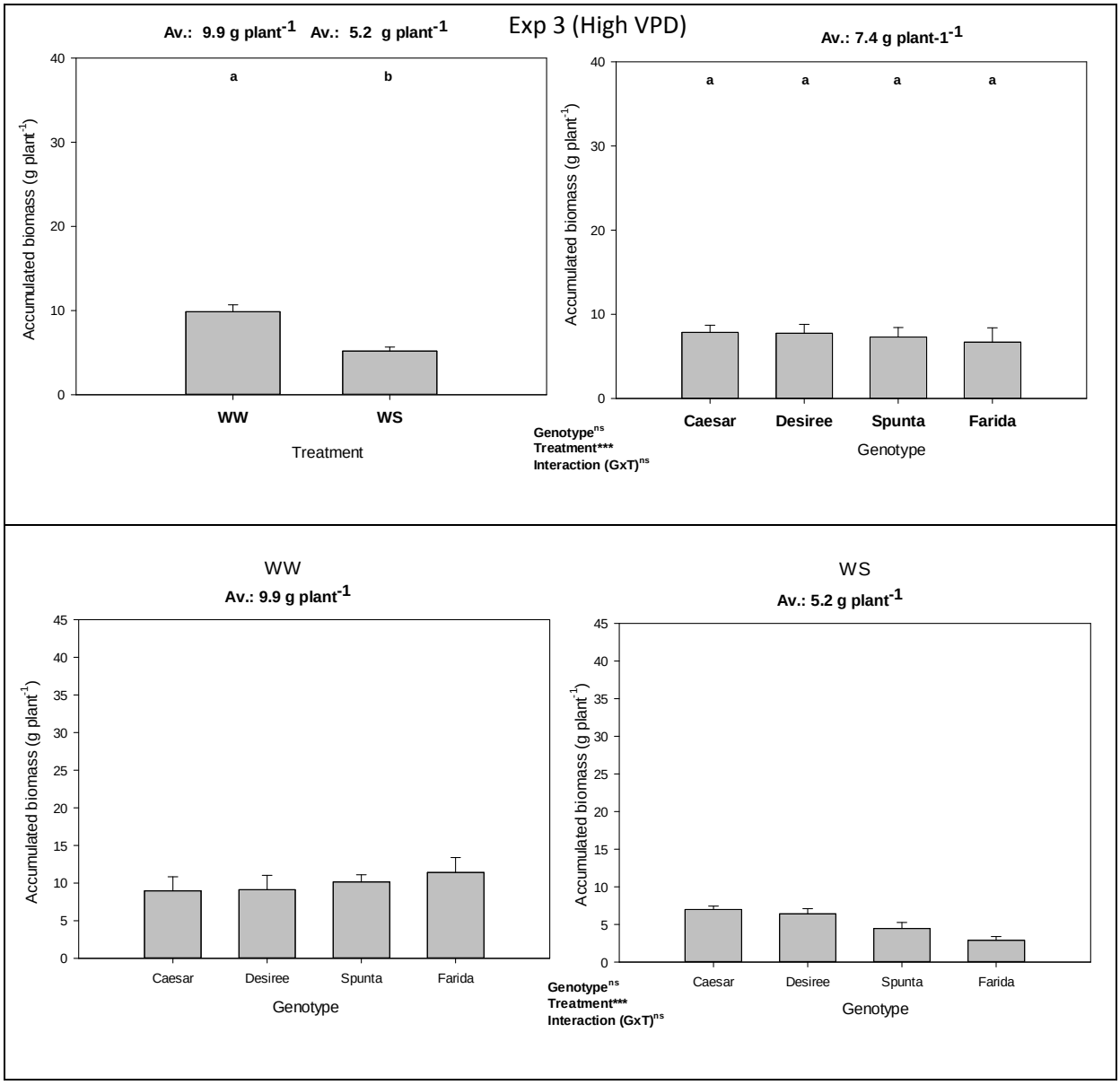


Figure 4.18c: Accumulated dry biomass production in Exp 3 (error bars indicate SEM and different letters indicate differences in means)

Table 4.3: Relative performance of biomass production by genotypes under water stress treatments (different letters indicate differences in means)

Genotype	Relative performance of WS plants relative to WW (%)		
	Exp 1	**Exp 2**	**Exp 3**
Desiree	56.1^{ab}	50.2^{b}	70.3^{b}
Caesar		79.5^{a}	91.0^{a}
Farida		52.7^{b}	28.1^{c}
Spunta		52.3^{b}	43.9^{c}
Mondial		54.4^{b}	
Diamant	66.2^{a}	58.6^{ab}	
Cardinal	48.3^{ab}	62.4^{ab}	
Granola	36.9^{b}		
Agria	52.5^{ab}		
Tosca	47.7^{ab}		
Diego	58.1^{ab}		

4.1.3.2 Stem dry mass

Average stem dry mass in both water treatments did not vary widely among the experiments (Figure 4.19), it was on average 3.6 g, 4.0 g and 4.0 g per plant, in the Exp 1, Exp 2, and Exp 3, respectively. Effect of water stress on stem production was significant in each experiment. Significantly highest stem weight was produced by Tosca in the Exp 1 which was followed by Desiree and Diego. In the Exp 2, Mondial had the highest stem biomass and Desiree again followed. No significant main effect of genotypes was observed in the Exp 3, where stem biomass production was similar to that of Exp 2. Water treatments showed a significant role on stem production which also influenced considerably on the activity of genotypes.

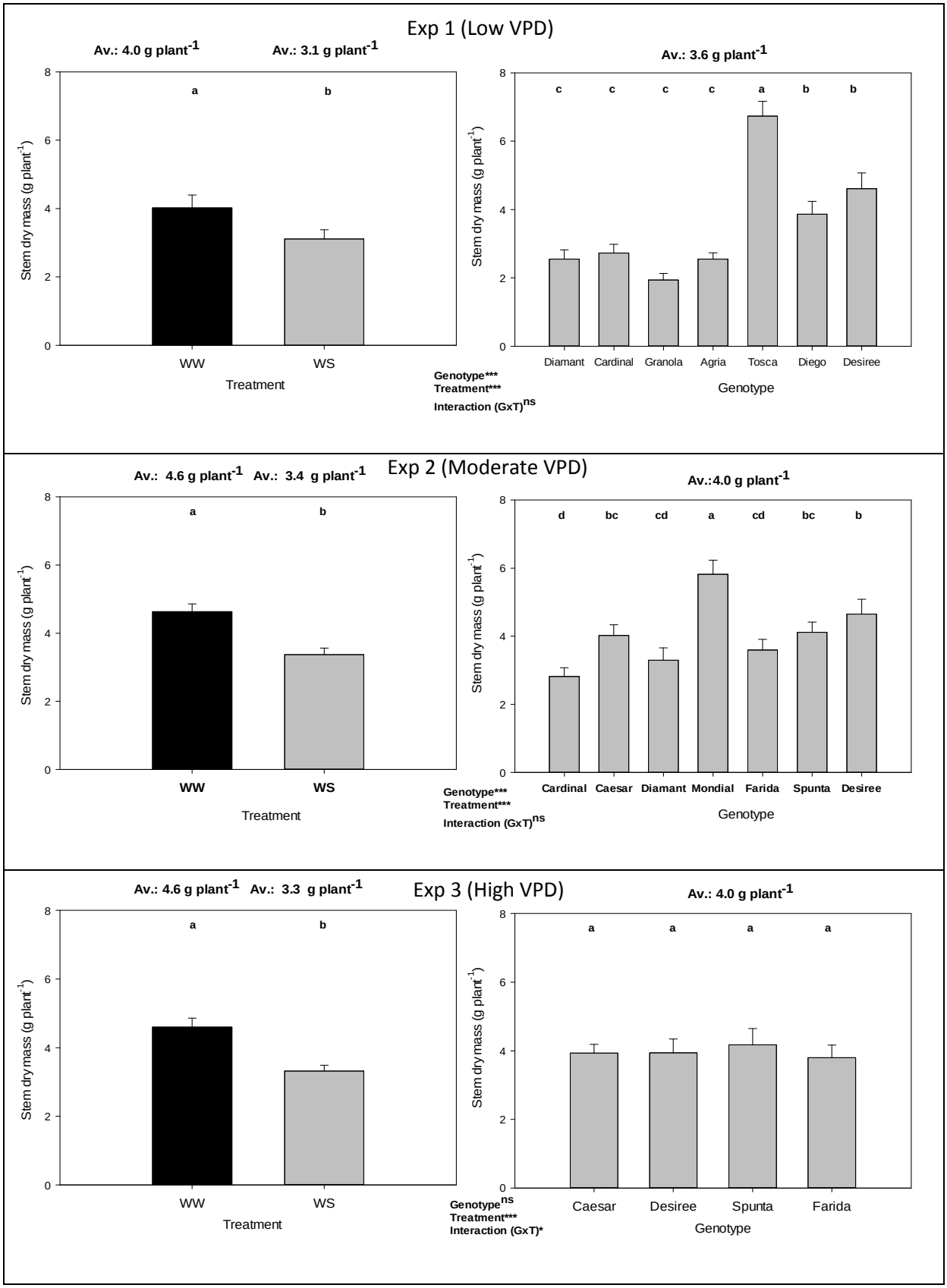


Figure 4.19: Stem dry mass in different treatments (error bars indicate SEM and different letters indicate differences in means)

4.1.3.3 Leaf dry mass

Foliage production varied to some extent among the experiments. An average of 6.1 g/plant was recorded in the Exp 1, which was followed by 5.5 g/plant in the Exp 2 and 3.9 g/plant in the Exp 3 (Figure 4.20). Like for stem production, water stress effect was also significant on leaf growth. Highest leaf dry matter was produced by Desiree (8.24 g/plant) in the Exp 1, while in the Exp 2, that production was observed in Farida, Desiree and Mondial with considerably less dry mass than Exp 1. Farida consistently produced highest leaf dry matter in the Exp 3. Although average leaf production was reduced under high VPD condition in the Exp 3, still Farida produced significantly more leaves than Caesar as found in the Exp 2. The influence of genotype and water treatments was significant in all experiments. Water supply also inturrpted the genotypic activity for leaf production in the Exp 3 as found in stem production.

4.1.3.4 Tuber dry mass

Figure 4.21 shows that tuber production varied widely among the experiments. Extremely low tuber dry mass was produced in the Exp 3 (2.3 g/plant) under high VPD conditions.

Under this condition, neither influence of water stress nor genotypic variations were observed on the production of tuber dry mass. Exp 1 and Exp 2 had an average production of 14.4 g/plant and 10.2 g/plant, respectively. Considering that underground stems and stolons were not separated in the Exp 1, we can assume that tuber mass in the Exp 1 was quite similar to that of Exp 2. Desiree had the highest tuber production in the Exp 1, while Spunta had that in the Exp 2. Significant effect of water stress was exhibited in both Exp 1 and Exp 2 and no interaction existed between genotype and water stress influences.

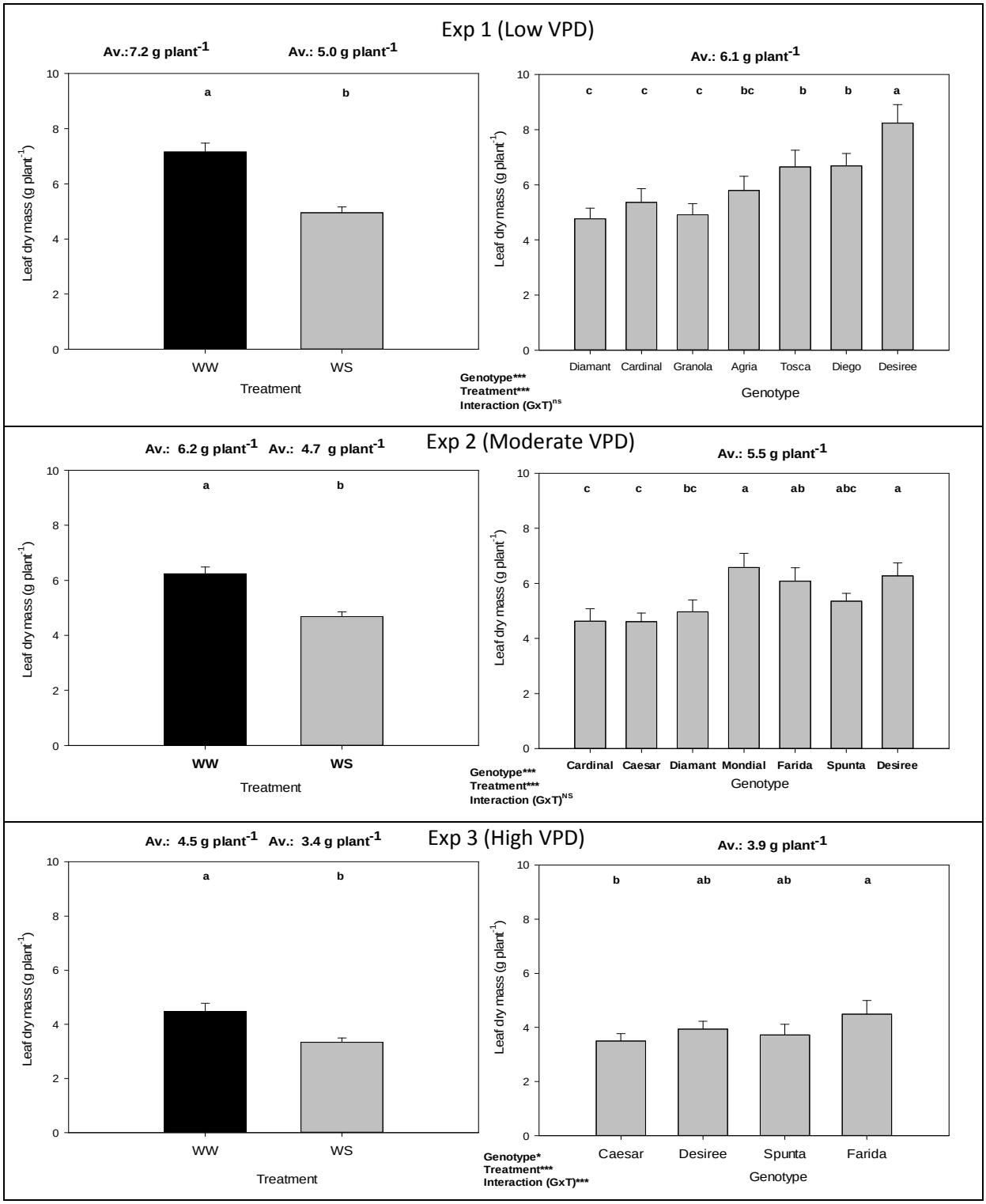


Figure 4.20: Leaf dry mass in different treatments (error bars indicate SEM and different letters indicate differences in means)

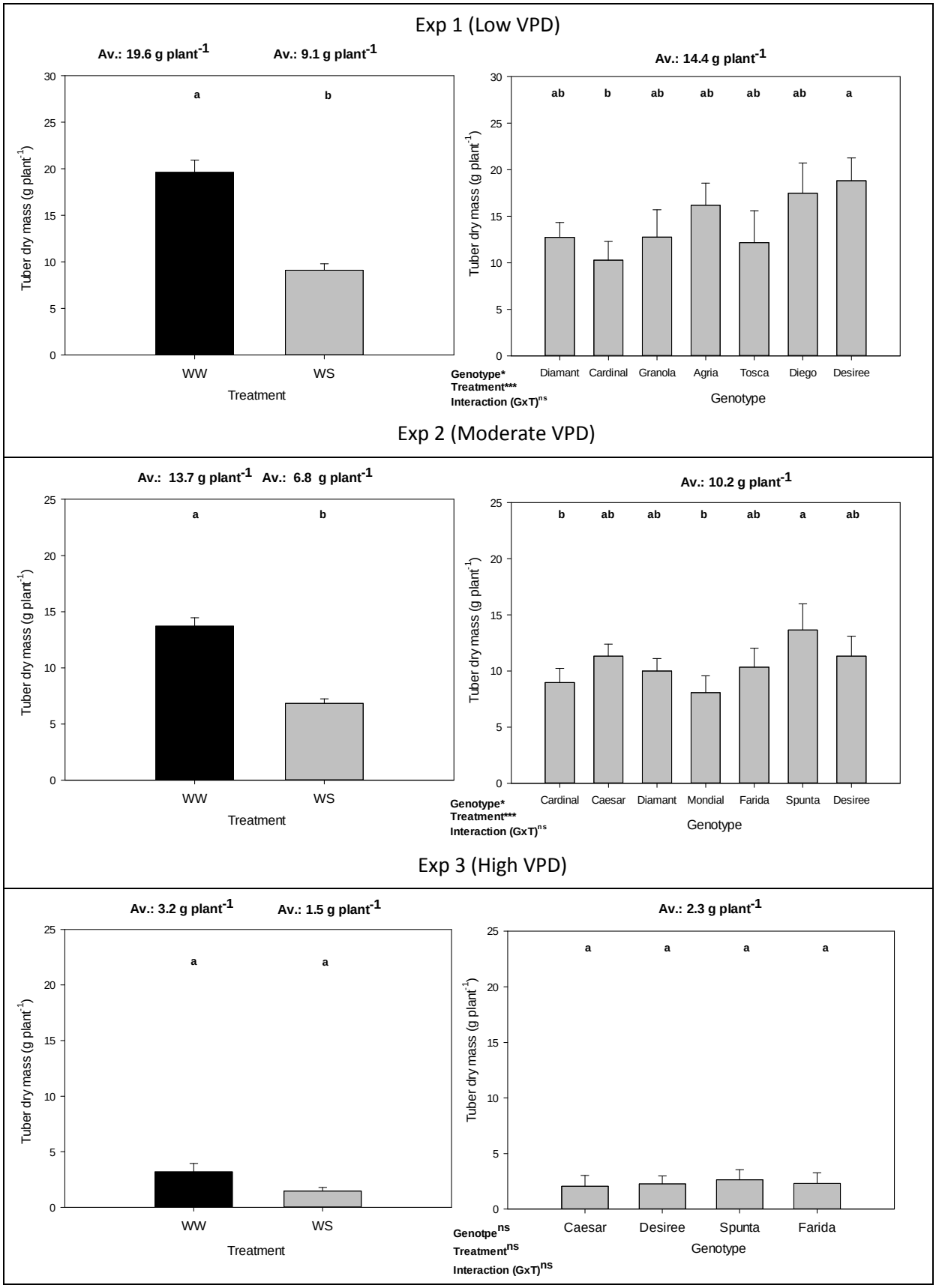


Figure 4.21: Tuber dry mass in different treatments (error bars indicate SEM and different letters indicate differences in means)

4.1.4 Transpiration efficiency

Plant biomass and yield are a result of water consumed by the plants and their efficiency is determined by their production per unit of water use. They varied to some extent due to variations in the environmental conditions. Genotypic variations under different environment were determined and are presented in the following sub-sections.

4.1.4.1 TE based on accumulated biomass

Accumulated biomass per litre of water transpired was higher in the WS plants as compared to WW treatments (Figure 4.22a). This advantage of water stress condition was significant only in the Exp 1 and Exp 2. Comparatively high VPD prevailed in the Exp 3 extremely reduced tuber production (Figure 4.21) and ultimately yielded substantially less biomass.

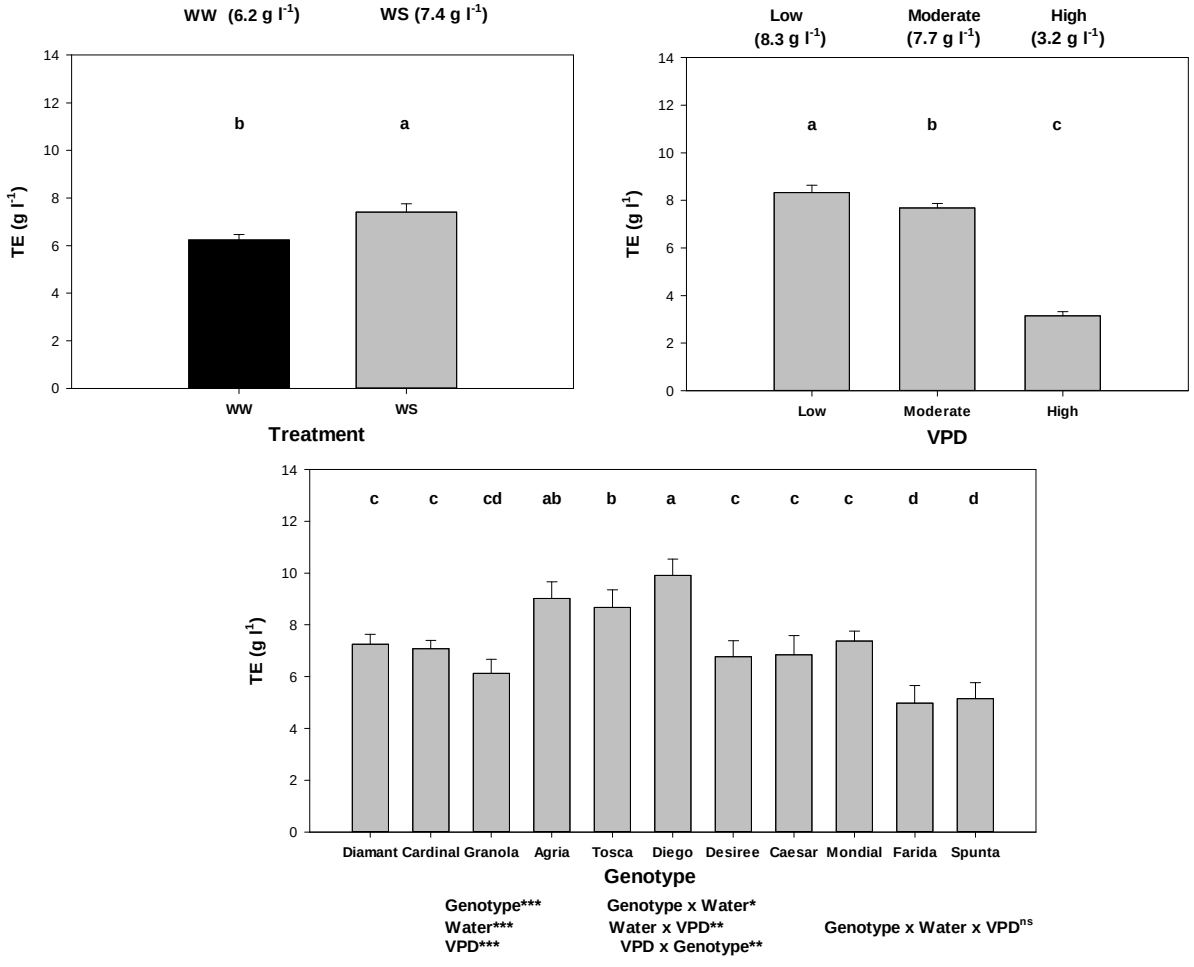


Figure 4.22a: TE in all experiments (error bars indicate SEM and different letters indicate differences in means)

Genotypes showed significant variations and TE also varied significantly in different VPD conditions. Water stress and VPD also affected significantly on genotypic performance and a good interaction between them showed their dependency to each other. In the Exp 1, Desiree had a high TE (12.6 g l^{-1}) which was followed by Diego and Agria (Figure 4.22b) under water stress condition. Caesar was the best in TE as compared to others with TE values of 10.9 g l^{-1} and 4.4 g l^{-1} in the Exp 2 and Exp 3 respectively (Figure 4.22c, 4.22d). Influence of genotypic variations was very clear in all three experiments under different VPD conditions, but that of water stress was only visible under lower VPD conditions (Exp 1 and Exp 2).

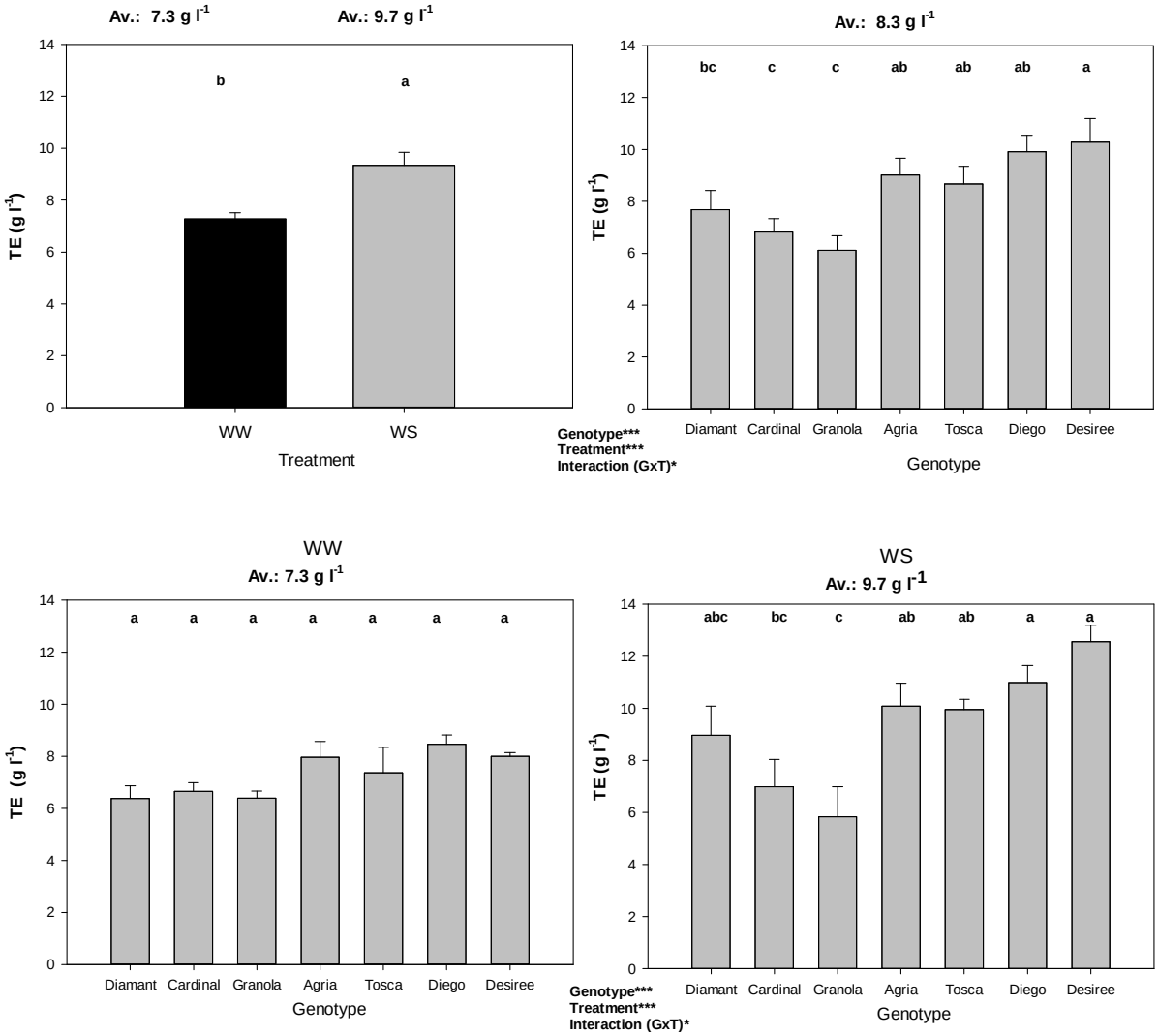


Figure 4.22b: TE at low VPD condition in the Exp 1 (error bars indicate SEM and different letters indicate differences in means)

Although contribution of water treatment and genotype was found to act independently in the Exp 2 however interaction between these two factors existed in the Exp 1 and Exp 3 demonstrated their relationship and influenced each other for TE.

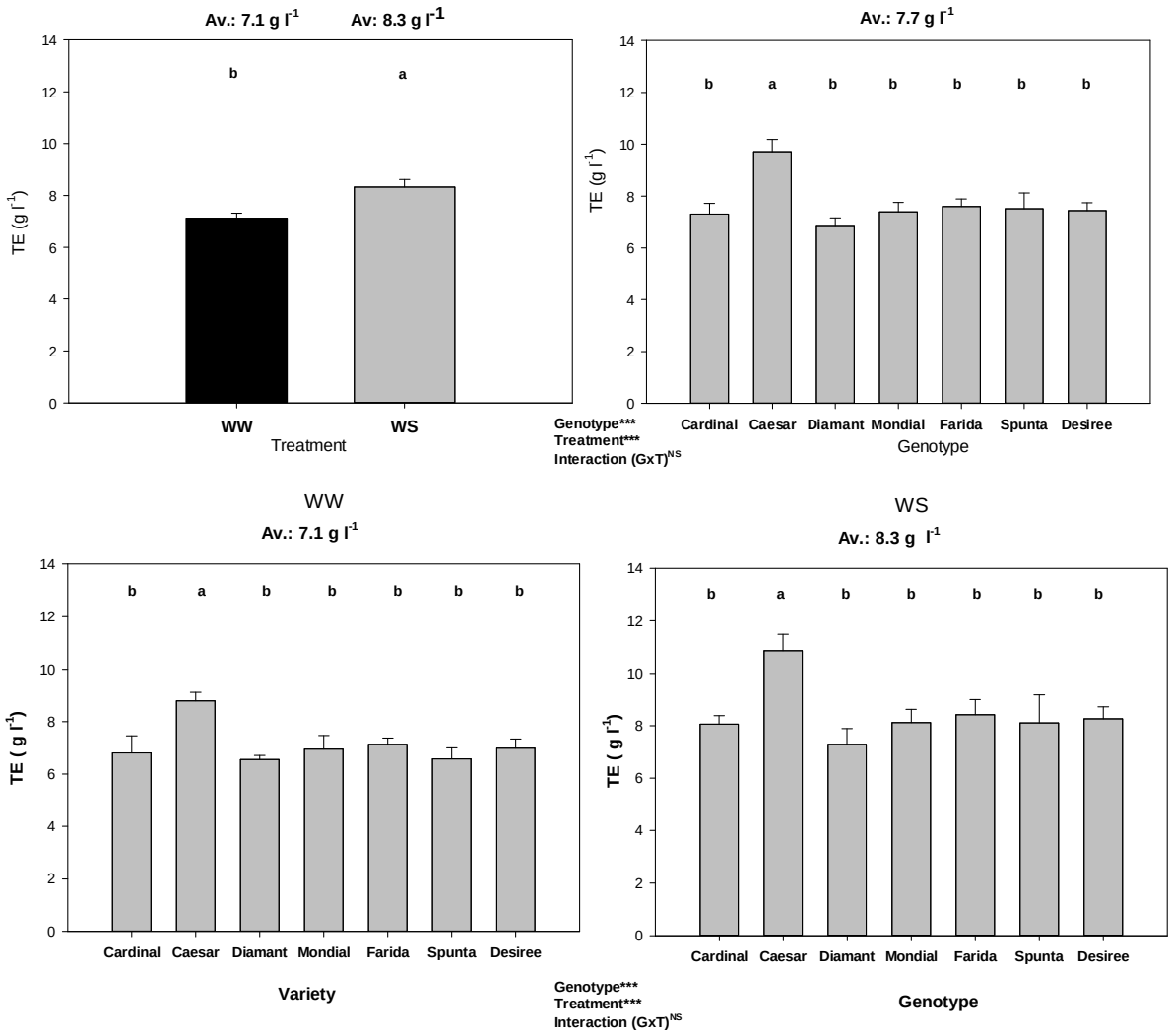


Figure 4.22c: TE at moderate VPD condition in the Exp 2 (error bars indicate SEM and different letters indicate differences in means)

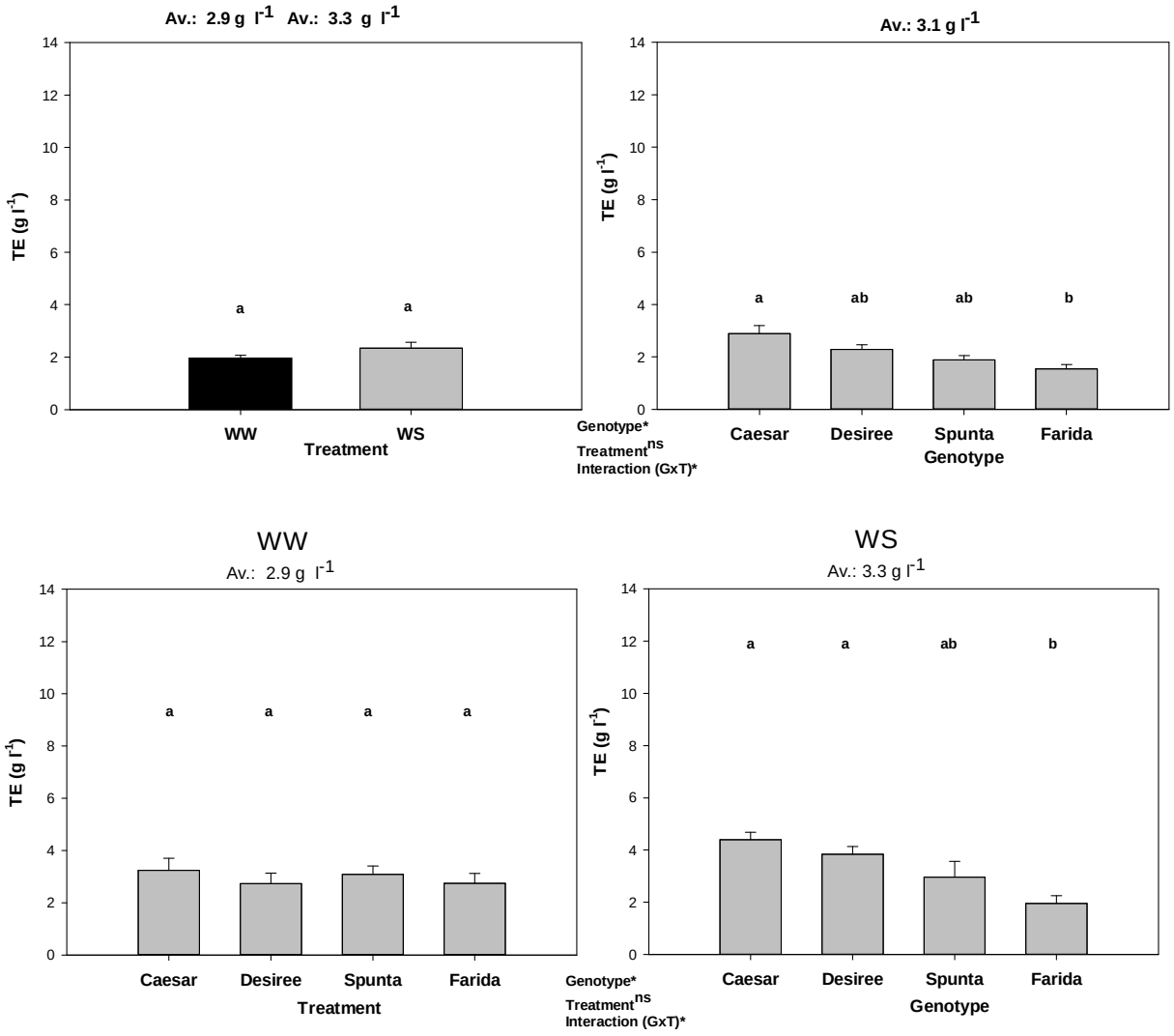


Figure 4.22d: TE at high VPD condition in the Exp 3 (error bars indicate SEM and different letters indicate differences in means)

4.1.4.2 TE based on shoot biomass

Water stress significantly influenced TE based on shoot biomass production in all three experiments. Comparatively high TE value (3.4 g l^{-1} $plant^{-1}$) was found in the Exp 2 at moderate VPD condition which was followed by Exp 1 (3.0 g l^{-1} $plant^{-1}$) and Exp 3 (2.2 g l^{-1} $plant^{-1}$). Tosca had the highest shoot TE in the Exp 1 (Figure 4.23) which was followed by Desiree. Mondial performed best in the Exp 2 and was followed by Caesar and Desiree. In the Exp 3, Caesar was the best over Desiree and Farida. The influence of both genotypes and water stress was very clear in all experiments and significant interaction existed in the Exp 2

and Exp 3 show that their contribution was not independent and both were influenced by each other.

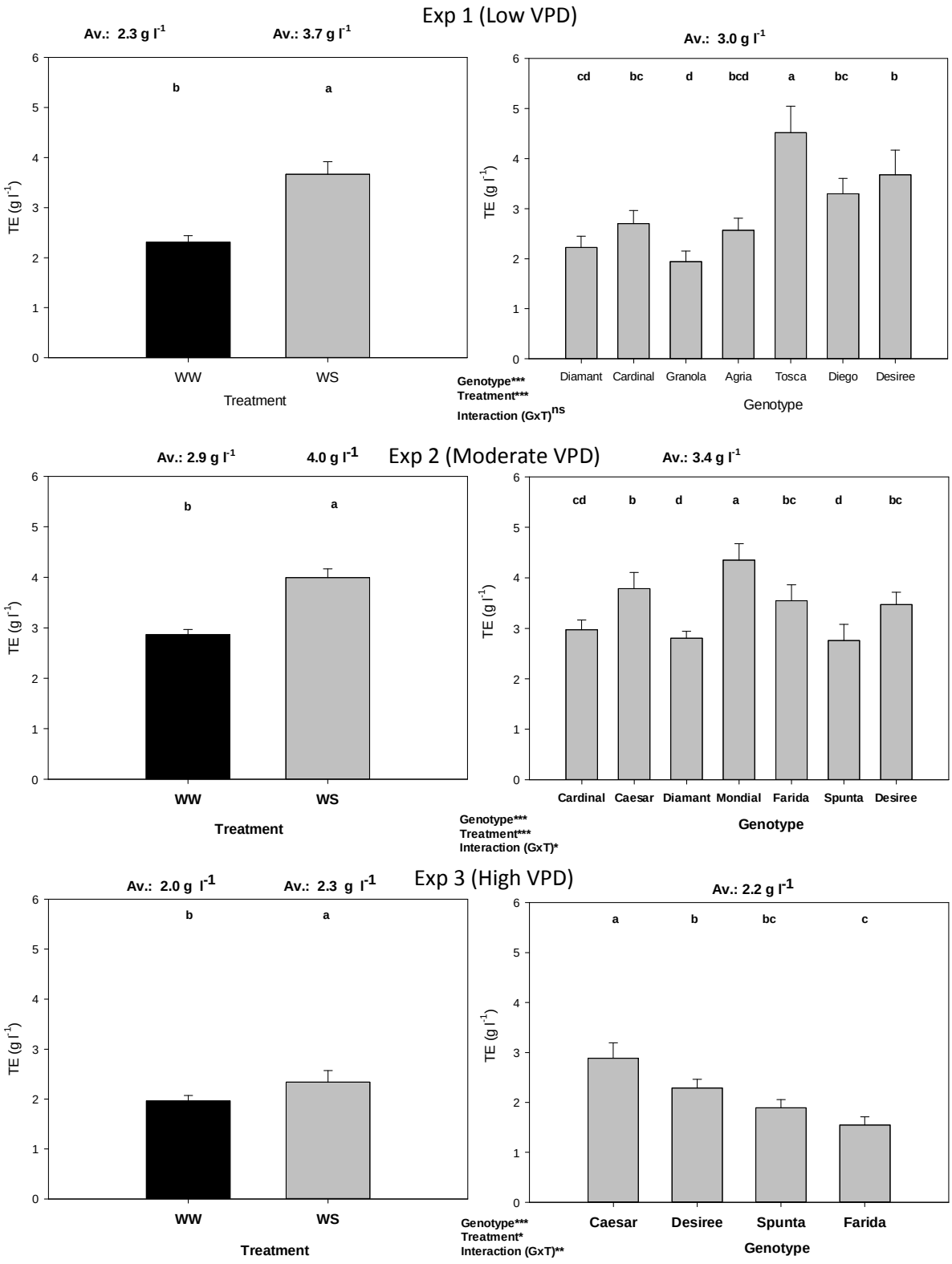


Figure 4.23: TE based on shoot biomass production (error bars indicate SEM and different letters indicate differences in means)

4.1.4.3 TE based on tuber biomass

Water stress did not play a considerable role on TE based on tuber dry mass in the Exp 1 and Exp 2, but the importance of genotypes was evident (Figure 4.24). None of these effects contributed significantly in the Exp 3 under high VPD conditions and no interactions between

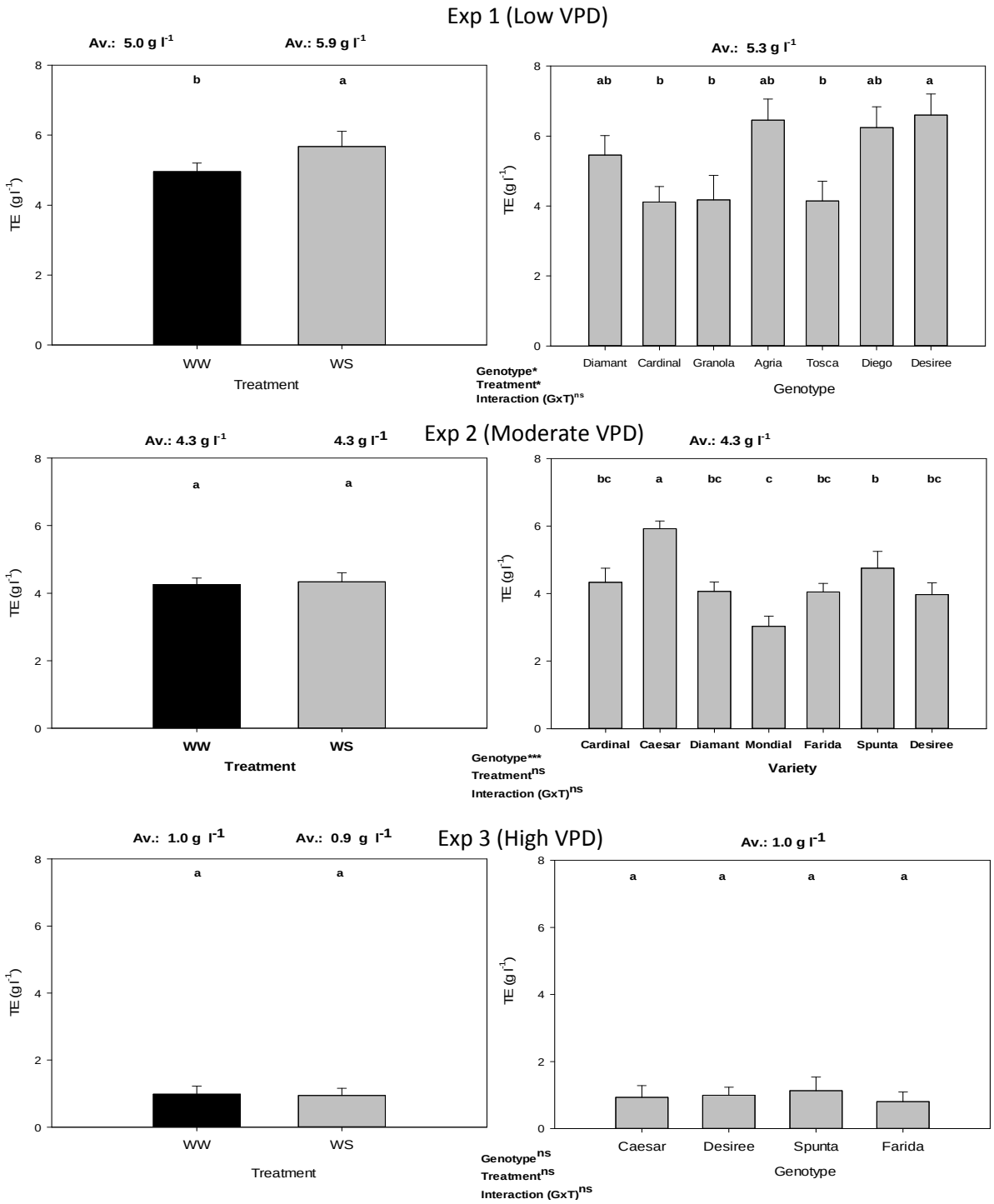


Figure 4.24: TE based on tuber biomass production (error bars indicate SEM and different letters indicate differences in means)

them existed in all experiments. Maximum average TE was obtained in the Exp 1 (5.3 g tuber l^{-1}) under low VPD conditions which declined with increasing VPD conditions in the Exp 2 (4.3 g tuber l^{-1}) and Exp 3 (1.0 g tuber l^{-1}). Desiree had the highest TE and was followed by Agria and Diego in the Exp 1. Caesar was the best as compared to others in the Exp 2 and no significant variations was observed among the genotypes in the Exp 3 under high VPD conditions.

4.1.5 Relationships between TE and water saving properties

During dry down cycle genotypes respond differently to stomatal closure that resulted in different FTSW threshold. FTSW threshold showed a good relationship (R^2 = 0.461) with total water transpired during phase I (Figure 4.25). Water savings during this phase was associated with FTSW values (R^2 = 0.533, FTSW vs. water savings) (Figure 4.26). A very weak correlation (R^2 = 0.125) between FTSW and TE shows their independence on contribution to water saving traits (Figure 4.27). Almost no influence of TE was observed on water savings or on total T during phase I (Figure 4.28, 4.29).

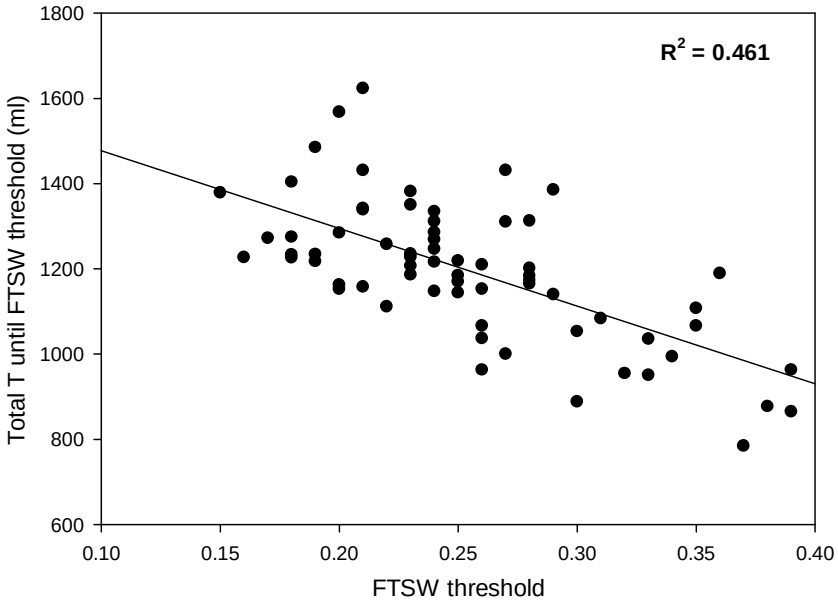


Figure 4.25: Relationship between total transpiration and FTSW threshold in phase I during dry down cycle

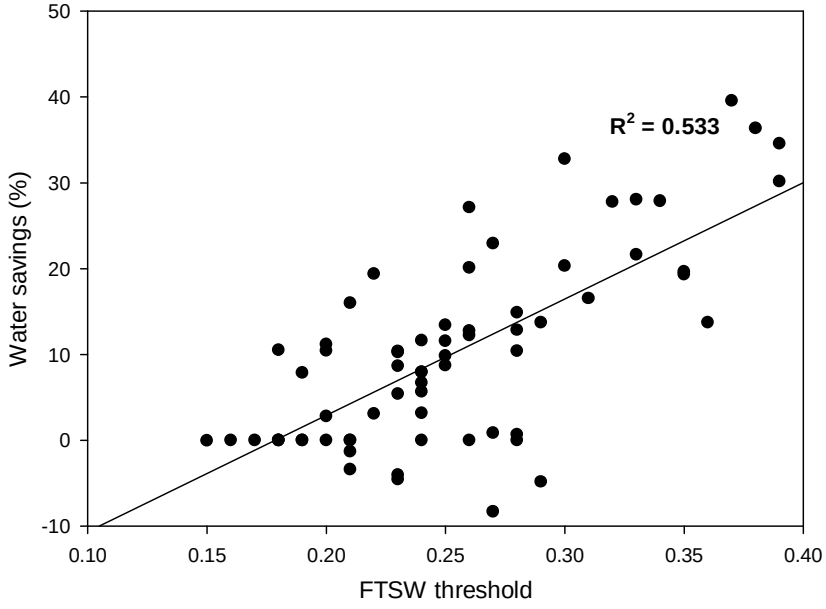


Figure 4.26: Relationship between water savings and FTSW threshold during dry down cycle

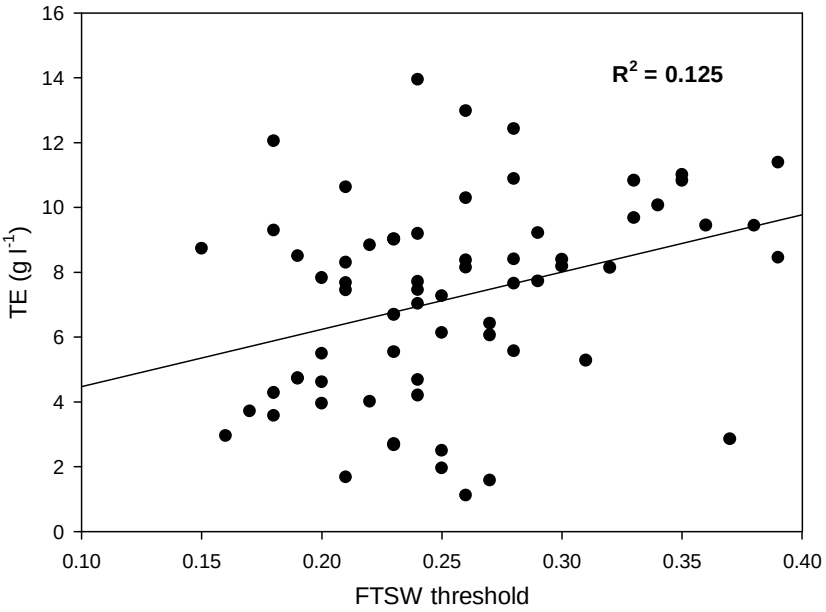


Figure 4.27: Relationship between water TE and FTSW threshold in WS plants

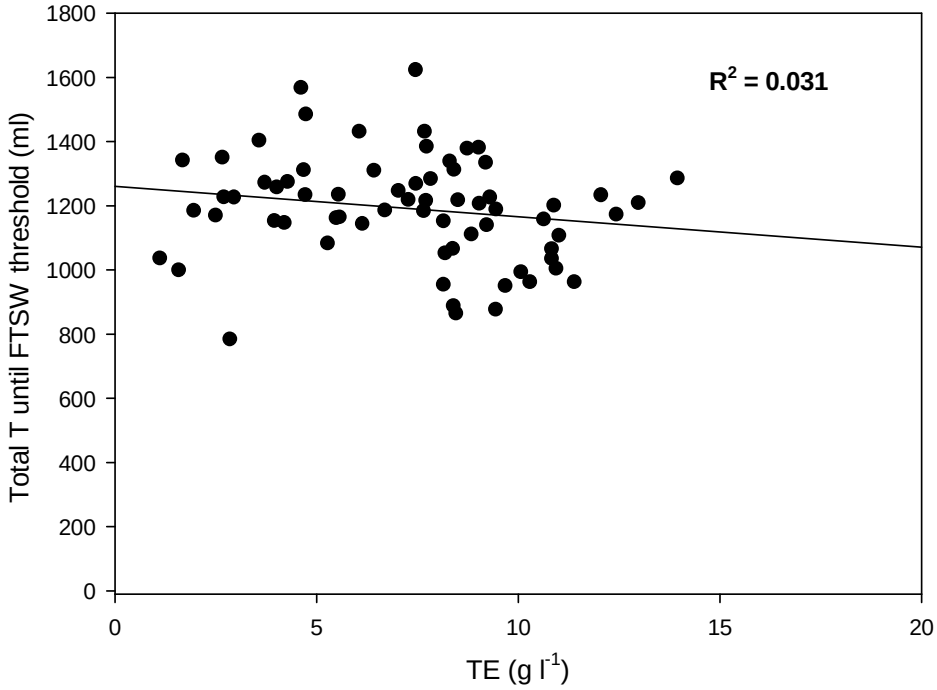


Figure 4.28: Relationship between total transpiration and TE during dry down cycle

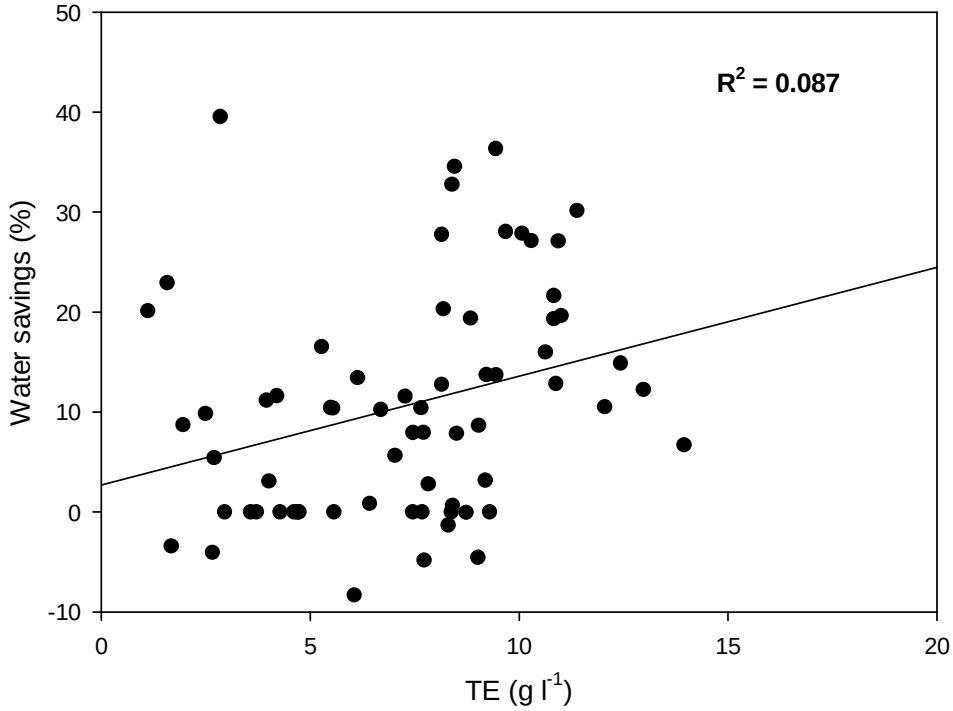


Figure 4.29: Relationship between water savings and TE in WS plants

4.1.6 Harvest index and yield determination

Harvest index (HI) was affected significantly by water stress and VPD conditions (Figure 4.30). WW treatments had higher HI at 0.51 compared to 0.40 in WS plants. Lower VPD conditions had higher HI values while less than half was found under high VPD conditions. Genotypes showed also significant variations and all these three factors worked independently as no interactions between them were visible so far on harvest index.

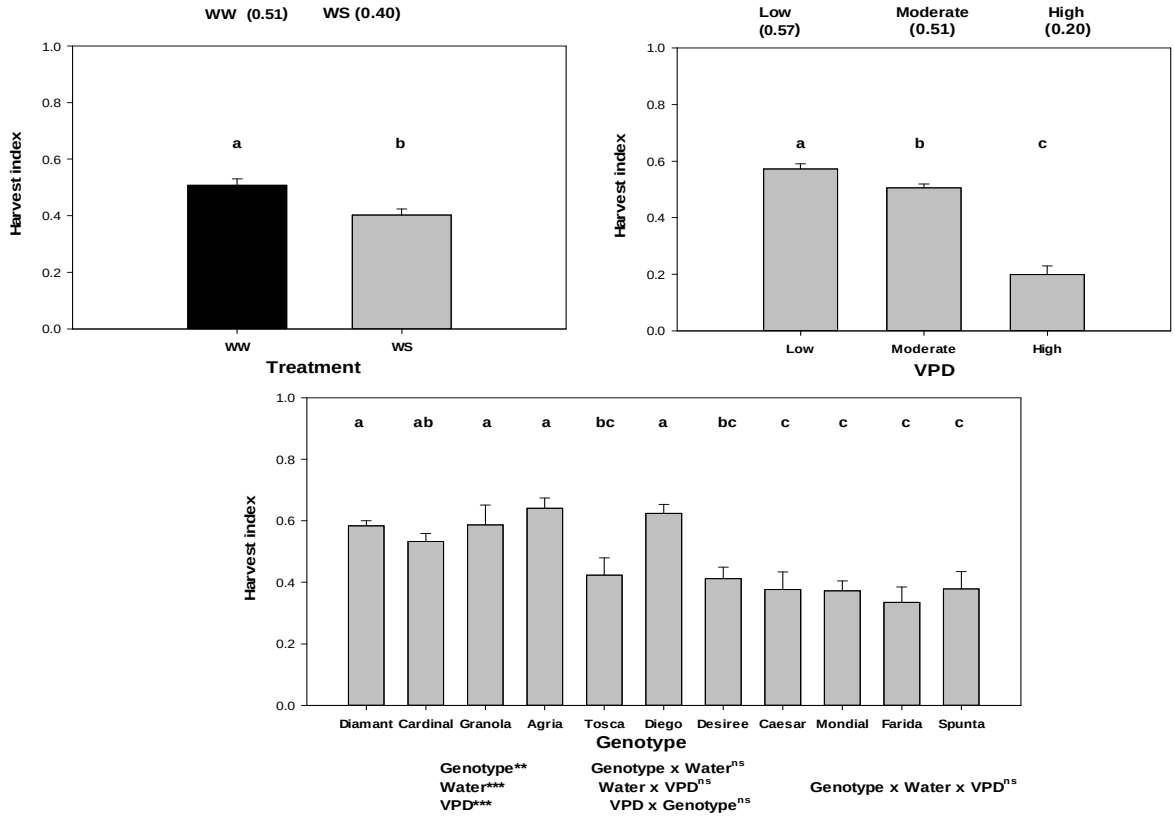


Figure 4.30: Harvest index in different experiments (error bars indicate SEM and different letters indicate differences in means)

Passioura's mechanistic relationship between T, TE and HI was tested for yield formation. The equation calculated yield (Y) as a function of these three factors and was expressed as Y = T x TE x HI. The regression analysis found a very good relationship between the calculated yield and the observed yield in all three experiments with R^2 values 0.999, 0.999 and 0.987 in the Exp 1, Exp 2 and Exp 3, respectively (Figure 4.31). Three components in the equation worked almost independently and linear regression showed R^2 values as 0.03, 0.08 and 0.45 for TE vs. T, T vs. HI and TE vs. HI respectively (Figure 4.32, 4.33, 4.34). TE also showed a very strong correlation with total biomass production in WS plants (R^2= 0.95, Figure 4.35) as compared to WW (R^2 = 0.66, Figure 4.36).

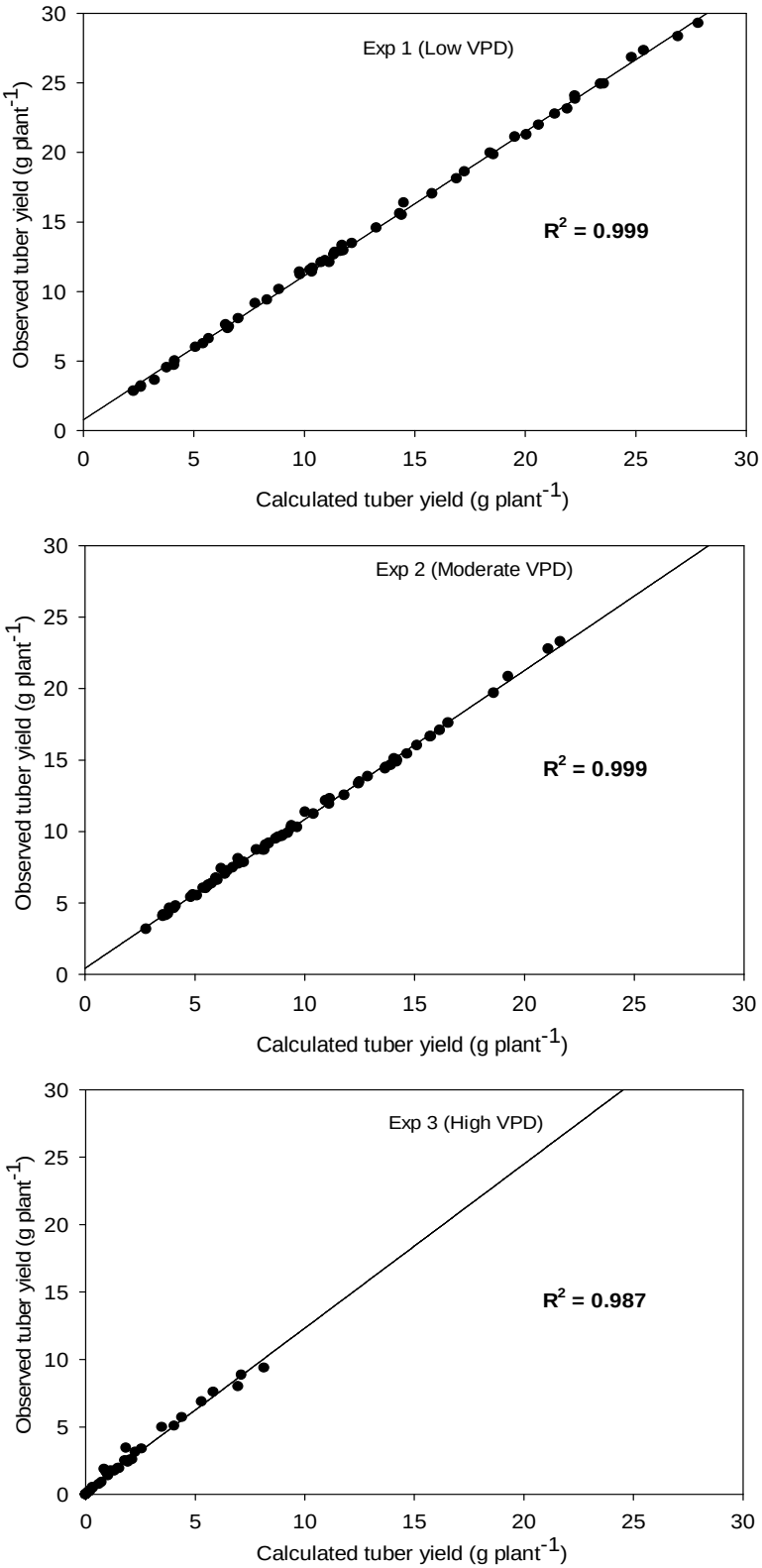


Figure 4.31: Fitness of Passioura's equation for estimation of tuber dry mass yield in different experiments

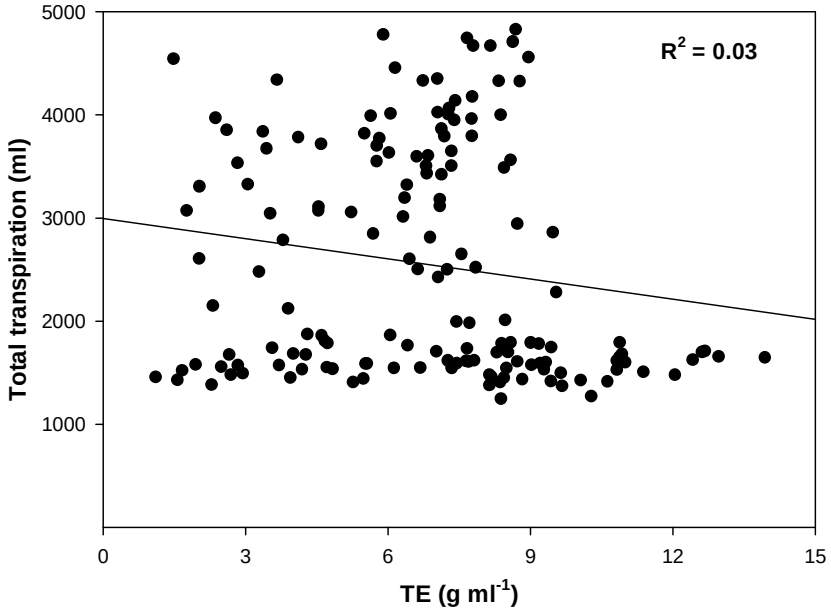


Figure 4.32: Relationship between TE and total transpiration

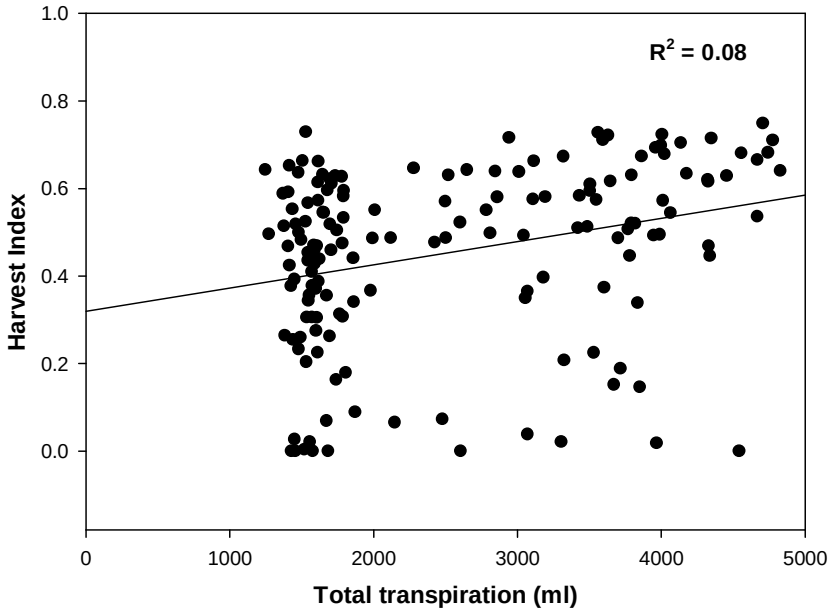


Figure 4.33: Relationship between total transpiration and HI

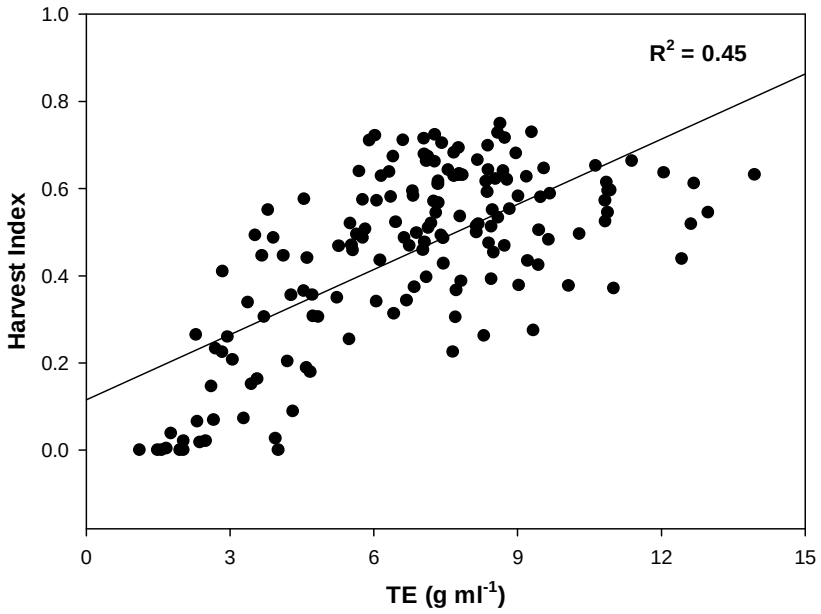


Figure 4.34: Relationship between TE and HI

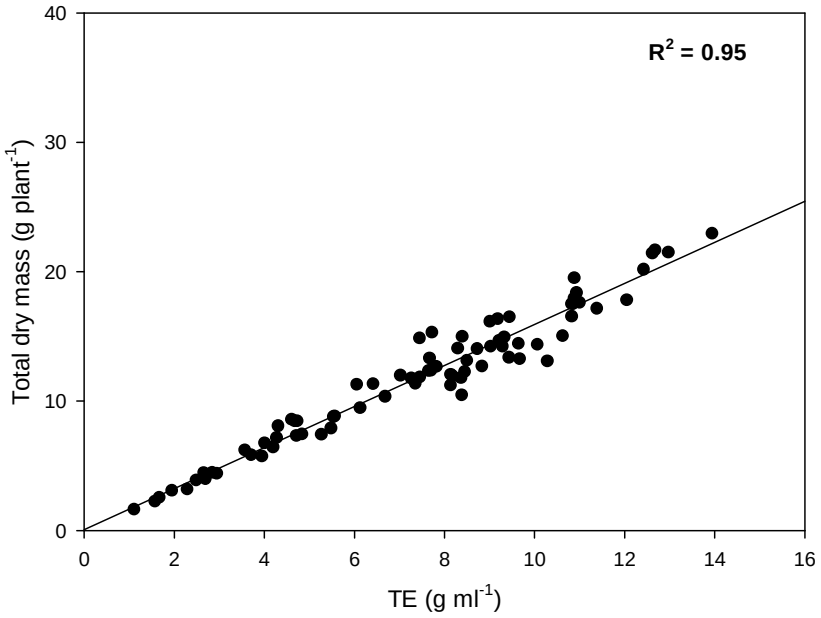


Figure 4.35: Relationship between TE and total dry mass production in WS plants

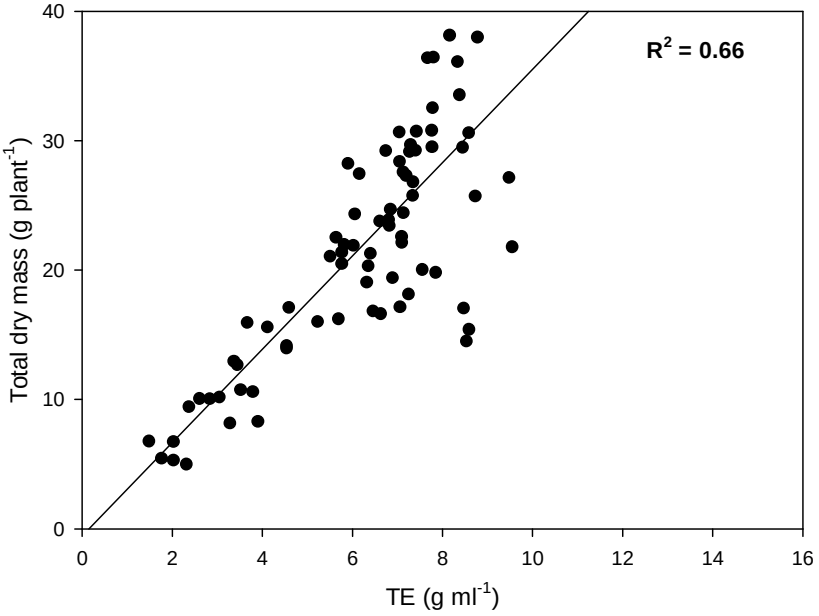


Figure 4.36: Relationship between TE and total dry mass production in WW plants

4.2 Field experiment in Tulln

4.2.1 Weather and plant growth conditions

Figure 4.37 shows the weather conditions during the field experiment in Tulln. Obviously, the experiment went through 4 spells of high temperature. The first episode started at the end of May and lasted for 2 weeks with daily maximum more than 30˚C. The second spell started at the end of June with temperatures to above 36˚C for a week. Another heat wave happened for about 10 days starting in the middle of July with maximum temperature above 37˚C. Finally, a prolonged dry period (more than 2 weeks) occurred at the beginning of August with no rain and daily maximum was again as high as 37˚C. In between these dry spells, the experiment received a good amount of rainfall. A total of 140.5 mm rain was recorded during the experimental period.

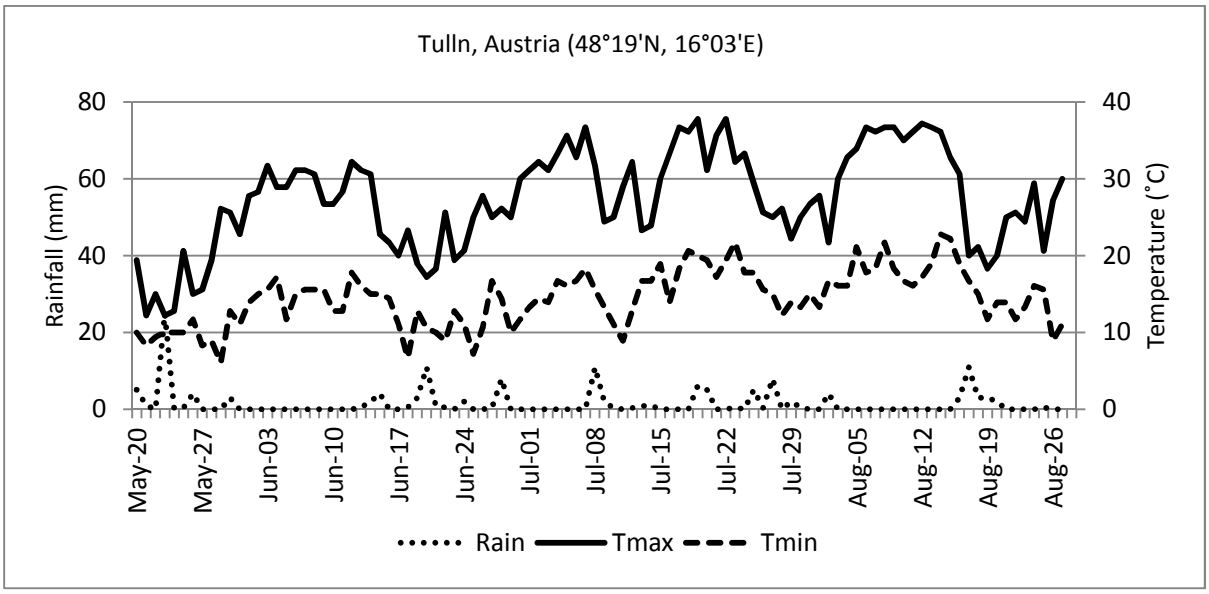


Figure 4.37: Weather conditions during the field experiment in Tulln

Vapour pressure deficit fluctuated considerably during the dry periods. Maximum VPD during day spiked to above 3.0 KPa during the 3rd and 4th dry spell (Figure 4.38). Minimum VPD remained more than 2.0 KPa in most of the days of the 4th dry period. During rest of the experiment, daily maximum and minimum VPD remained below 2.0 and 1.0, respectively.

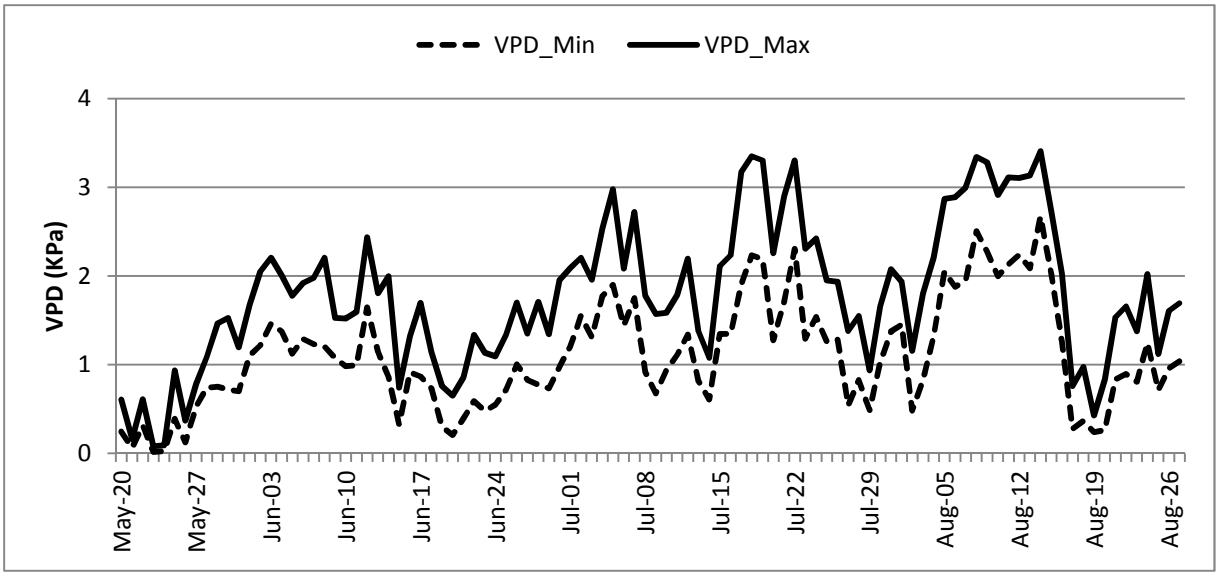


Figure 4.38: VPD observed during the field experiment in Tulln

4.2.2 Soil moisture

Figure 4.39 shows the soil moisture conditions in the experiment field in Tulln which significantly varied in different harvest times and at different soil depths as well. Initially soil moisture was 16.3% (w/w) which did not show much difference at the first harvest. Soil moisture content declined significantly with the progress of harvest dates and a high depletion was observed at harvest 3 (10.4%). Lowest moisture status was found in the top layer and significantly high moisture was retained at deeper layers. Both the harvest time and depth of soil contributed significantly to soil moisture and their interactions also played a significant role. A gradual decrease of soil moisture from the initial status progressed from top layer towards deeper layers with the advancement of crop development. Soil water was heavily depleted from all layers at harvest 3.

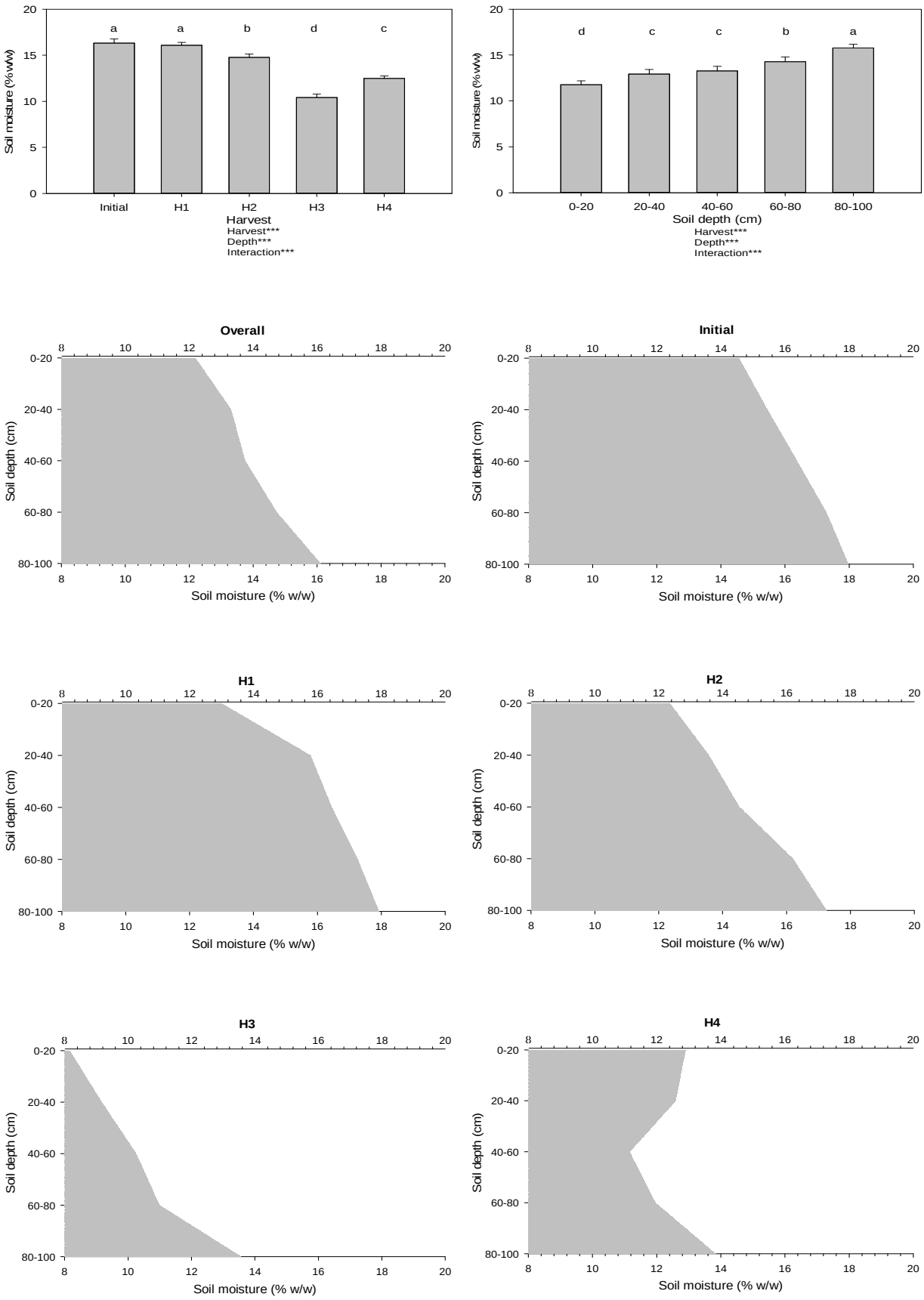


Figure 4.39: Soil moisture status in the field experiment in Tulln (error bars indicate SEM and different letters indicate differences in means)

4.2.3 Biomass production and plant growth properties

4.2.3.1 Total biomass

Table 4.4 shows that genotypes affected significantly total biomass production and obviously harvest time had a significant role. The total biomass of leaf, stem and tuber production varied significantly among the genotypes in most of the harvests. After 29 days of planting in Harvest 1, highest dry biomass (55.6 g/m^2) was produced by Farida and the lowest (19.6 g/m^2) by Caesar. At 2nd harvest (50 DAP) during active growth stage, all four genotypes produced identical biomass and Caesar had recovered its growth. At harvest 3 (78 DAP), significantly highest biomass was produced by Farida (694.6 g/m^2) which was followed by Cardinal (528.3 g/m^2). Farida secured its best performance at the final harvest (99 DAP) yielding 742.4 g/m^2 dry biomass.

Table 4.4: Total dry mass production (leaf, stem, tuber) by genotypes at different harvest dates (different letters indicate differences in means)

	H1 (29 DAP, inflorescence initiation stage)	**H2** (50 DAP, flowering stage)	**H3** (78 DAP, late flowering/ fruiting stage)	**H4** (99 DAP, senescence stage)
Cardinal	28.7^{b}	243.2^{a}	528.3^{ab}	535.7^{b}
Desiree	27.5^{b}	252.9^{a}	370.3^{b}	562.2^{b}
Caeser	19.6^{b}	216.4^{a}	370.0^{b}	576.3^{b}
Farida	55.6^{a}	304.4^{a}	694.6^{a}	742.4^{a}
	Genotype*** Harvest*** Interaction (G x H)*			

4.2.3.2 Stem dry mass

Genotypes showed significant variations in stem production at each harvest date (Table 4.5). Harvest time influenced remarkably on the genotype performance but their influence was not appeared independently. A good interaction between them showed that relationship on stem production. Genotype Farida had a better stem growth than any other at all harvest dates. The growth in Farida steadily increased until harvest 3 and then slowed down. Caesar

and Desiree kept their growth continued until the final harvest. Stem production in Cardinal slowed down from the 3rd harvest. At the final harvest, Farida had produced most stem tissue (183.3 g/m^2), Cardinal was lowest (87.7 g/m^2) with the other two genotypes in between.

Table 4.5: Stem dry mass production by genotypes at different harvest dates (different letters indicate differences in means)

	H1 (29 DAP) (g/ m^2)	**H2 (50 DAP) (g/ m^2)**	**H3 (78 DAP) (g/ m^2)**	**H4 (99 DAP) (g/ m^2)**
Cardinal	7.2^{ab}	50.7^{b}	85.3^{b}	87.7^{c}
Desiree	7.3^{ab}	52.0^{b}	66.7^{b}	121.7^{b}
Caeser	5.6^{b}	61.8^{ab}	96.6^{b}	134.0^{b}
Farida	14.0^{a}	81.7^{a}	152.9^{a}	183.3^{a}
	Genotype*** Harvest*** Interaction (G x H)***			

4.2.3.3 Leaf dry mass

In case of leaf growth, similar trends were observed as in stem production. Leaf production started to slow down from the 2nd harvest among all the genotypes. Desiree almost stopped leaf production in between 2nd and 3rd harvest and again started until harvest 4. Like in stem production, main effect of genotype was highly significant (Table 4.6). Harvest time had also significant influence and their interaction was also significant for leaf production.

Table 4.6: Leaf dry mass production by genotypes at different harvest dates (different letters indicate differences in means)

	H1 (29 DAP) (g/ m^2)	**H2 (50 DAP) (g/ m^2)**	**H3 (78 DAP) (g/ m^2)**	**H4 (99 DAP) (g/ m^2)**
Cardinal	21.6^{b}	115.0^{a}	157.8^{b}	168.1^{b}
Desiree	20.2^{b}	121.6^{a}	126.4^{b}	190.4^{b}
Caeser	14.0^{b}	114.8^{a}	171.8^{b}	194.4^{b}
Farida	41.6^{a}	152.6^{a}	223.8^{a}	263.1^{a}
	Genotype*** Harvest*** Interaction (G x H)*			

4.2.3.4 LAI

Together with leaf growth Farida had the highest LAI among all genotypes. It reached to maximum (more than 3) at harvest 3 and then declined. Similar pattern was also evident in Caesar while other two varieties peaked already at 2nd harvest. A little increase in LAI after 3rd harvest was observed in Desiree after its decline from the 2nd harvest, however these changes were not significant (Table 4.7).

Table 4.7: LAI in genotypes at different harvest dates

	H1 (29 DAP)	**H2 (50 DAP)**	**H3 (78 DAP)**	**H4 (99 DAP)**
Cardinal	$0.4^{b\ (b)}$	$2.1^{a\ (a)}$	$1.9^{b\ (a)}$	$1.1^{b\ (ab)}$
Desiree	$0.3^{b\ (b)}$	$2.2^{a\ (a)}$	$1.7^{b\ (a)}$	$1.9^{ab\ (a)}$
Caeser	$0.2^{b\ (c)}$	$2.0^{a\ (b)}$	$2.6^{ab\ (a)}$	$1.6^{ab\ (b)}$
Farida	$0.8^{a\ (b)}$	$2.8^{a\ (a)}$	$3.3^{a\ (a)}$	$2.6^{a\ (a)}$
	Genotype*** Harvest*** Interaction (G x H)^{ns} • Letters show significant differences among genotypes within harvest date • Letters in parenthesis show significant differences at different harvest dates within a genotype			

4.2.3.5 Fresh tuber yield

Highest and lowest fresh tuber yield at final harvest was recorded in Farida (1949.3 g/m^2) and in Cardinal (1323.9 g/m^2), respectively, but they were not significantly different (Table 4.8). Significant variations were observed only in harvest 3, where Farida had also the highest yield. Influence of harvest time was significant and the interaction with genotypes was also evident on fresh tuber yield. An accelerated tuber growth was observed during 2nd and 3rd harvest for Farida and Cardinal while that growth behaviour appeared later in Desiree and Caesar. Most of the genotypes had a continued growth until final harvest except Cardinal.

Table 4.8: Fresh tuber yield by genotypes at different harvest dates (different letters indicate differences in means)

	H1 (29 DAP) (g/m^2)	**H2 (50 DAP) (g/m^2)**	**H3 (78 DAP) (g/m^2)**	**H4 (99 DAP) (g/m^2)**
Cardinal	0	498.0^{a}	1284.2^{ab}	1323.9^{a}
Desiree	0	583.1^{a}	982.5^{bc}	1612.4^{a}
Caeser	0	328.9^{a}	583.3^{c}	1568.4^{a}
Farida	0	500.6^{a}	1704.6^{a}	1949.3^{a}
	Genotype*** Harvest** Interaction (G x H)**			

4.2.3.6 Tuber dry matter concentration

Dry matter content in tubers varied significantly among the genotypes in different harvest times. Harvest time played a significant role on dry matter concentration which interacted considerably with genotypic effects (Table 4.9). All genotypes achieved significantly highest dry matter at harvest 3 which ranged from 17.4 (%) in Caesar to 22.0 (%) in Cardinal. They had almost equal dry matter content at final harvest with a subsequent decrease from harvest 3 except Cardinal.

Table 4.9: Tuber dry matter concentrations at different harvest dates

	H1 (29 DAP) (%)	**H2 (50 DAP)** (%)	**H3 (78 DAP)** (%)	**H4 (99 DAP)** (%)
Cardinal	NA	$15.6^{a\,(b)}$	$22.0^{a\,(a)}$	$21.2^{a\,(a)}$
Desiree	NA	$13.5^{ab\,(b)}$	$18.2^{b\,(a)}$	$15.6^{b\,(b)}$
Caesar	NA	$12.3^{b\,(c)}$	$17.4^{b\,(a)}$	$15.8^{b\,(b)}$
Farida	NA	$13.6^{ab\,(b)}$	$18.6^{b\,(a)}$	$15.3^{b\,(b)}$
	Genotype*** Harvest*** Interaction (G x H)* • Letters show significant differences among genotypes within harvest date • Letters in parenthesis show significant differences at different harvest dates within a genotype			

4.2.3.7 Tuber dry mass

Table 4.10 shows that tuber dry mass varied significantly among the genotypes only at harvest 3 as already found with fresh tuber production. Influence of harvest time and its interaction with genotype was also found similar to fresh tuber yield. Farida was the best tuber dry mass producer at harvest 3. A significant difference between Farida and Caesar in the 3rd harvest disappeared towards the final harvest. Farida and Cardinal attained the maximum tuber dry mass at harvest 3 and a slight decrease was observed afterwards. Desiree and Caesar showed a steady mass accumulation until harvest 4.

Table 4.10: Tuber dry mass at different harvest dates (different letters indicate differences in means)

	H1 (29 DAP) (g/m^2)	**H2 (50 DAP) (g/m^2)**	**H3 (78 DAP) (g/m^2)**	**H4 (99 DAP) (g/m^2)**
Cardinal	0	77.5^{a}	285.3^{b}	279.9^{a}
Desiree	0	79.4^{a}	177.2^{ab}	250.1^{a}
Caeser	0	40.6^{a}	101.7^{b}	247.5^{a}
Farida	0	70.0^{a}	318.0^{a}	296.1^{a}
	Genotype** Harvest*** Interaction (G x H)**			

4.2.3.8 Tuber numbers

Tuber numbers did not vary significantly earlier at harvest 2, but they differ significantly in later harvests (Table 4.11). A high number (more than 100/m^2) of tubers was recorded in Cardinal at the final harvest and more tubers as compared to other genotypes were also recorded in other harvests. Caesar and Farida produced only almost half the number of tubers of Cardinal without much variation after harvest date 2. Number of tubers in Desiree was in between and tuber formation increased between 3rd and final harvest.

Table 4.11: Tuber umbers produced by genotypes at different harvest dates

	H1 (29 DAP)	**H2 (50 DAP)**	**H3 (78 DAP)**	**H4 (99 DAP)**
Cardinal	0	$77.8^{a\,(a)}$	$97.2^{a\,(a)}$	$103.9^{a\,(a)}$
Desiree	0	$52.5^{a\,(a)}$	$54.1^{b\,(a)}$	$76.6^{b\,(a)}$
Caeser	0	$39.4^{a\,(a)}$	$29.2^{b\,(a)}$	$45.5^{c\,(a)}$
Farida	0	$38.4^{a\,(a)}$	$47.8^{b\,(a)}$	$55.8^{c\,(a)}$
	Genotype*** Harvest*** Interaction (G x H)** • Letters show significant differences among genotypes within harvest date • Letters in parenthesis show significant differences at different harvest dates within a genotype			

4.3 Field experiments in Bangladesh

4.3.1 Weather and plant growth conditions

Figure 4.40a and 4.40b show that there was a very little variation in temperature and rainfall records at two experimental sites in Bangladesh. Temperature in Rajshahi was a bit lower than in Manikganj, daily minimum mostly remained around 10˚C and went below 10˚C for last two weeks in January. Manikganj temperature never dropped below 10˚C. Daily maximum fluctuated mostly between 20˚C to 30˚C in both locations, but daily maximum temperature in Rajshahi fell to around 18˚C in the 3rd week of January. In both sites, from the last week of January temperature rose rapidly and reached to more than 33˚C before harvest. The experiment at Rajshahi received a comparatively good amount of rain (21 mm) in the 3rd week of January, while rainfall at Manikganj was negligible (3 mm).

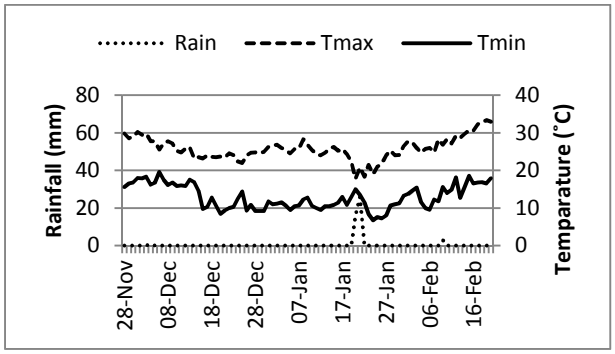


Figure 4.40a: Weather in Rajshahi site

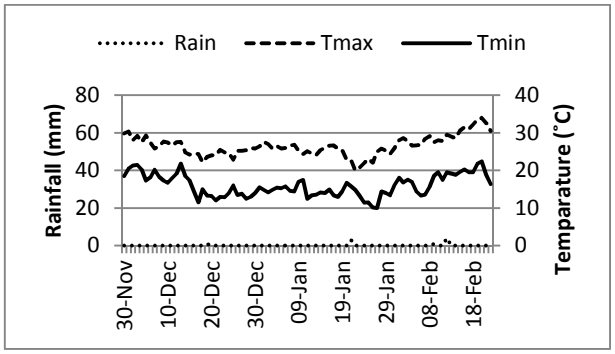


Figure 4.40b: Weather in Manikganj site

VPD did not vary remarkably in both the sites (Figure 4.41a, 4.41b). Daily minimum VPD was almost stable in Rajshahi near to 0.1 KPa. Manikganj had some fluctuations but remained around 0.2 KPa. Daily maximum VPD in Rajshahi site was fluctuating around 1.0 KPa and never went above 2.0 KPa. In Manikganj, it remained around 1.5 KPa and reached above 2.5 KPa before harvest.

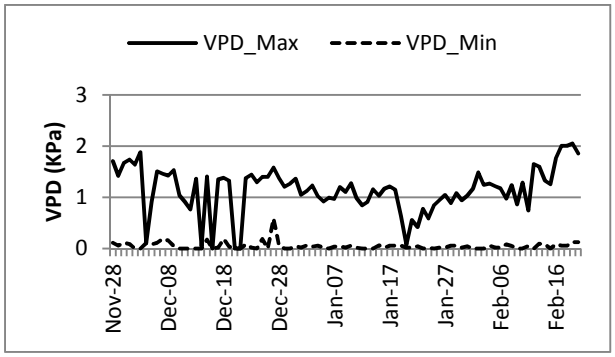


Figure 4.41a: VPD in Rajshahi site

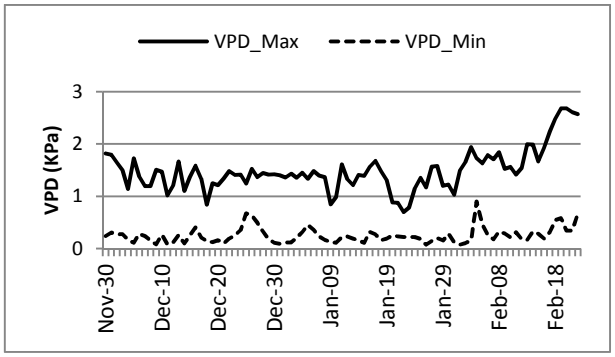


Figure 4.41b: VPD in Manikganj site

4.3.2 Soil moisture

Figure 4.42 shows the soil moisture conditions observed during the experiment period in both locations. In Rajshahi, effect of water treatment was significant but in Manikganj it was not. Harvest time and soil depth with their interactions also had an influence on soil moisture contents. Other interaction effects did not have a significant role in both experiment sites.

Moisture retained in soil at the beginning of the experiments was varying significantly at different depths in both locations. Soil moisture retained as 20.7% (w/w) at 0-20 cm depth to 27.6% (w/w) at 80-100 cm depth in Rajshahi. That initial soil moisture in Manikganj was higher (26.8%) in upper layer at 0-20 cm and lower in deep layers as 15.0% at 80-100 cm soil depth. A gradual depletion of soil moisture appeared in upper layers and movement of water in deep layers was also found in both locations.

Soil moisture in top layer was found to be depleted significantly at early harvest dates, then recovered a bit and again decreased. This trend was found in Rajshahi and such depletion proceeded with the advancement of crop development up to 60 cm depth. Deeper layers did not show any depletion rather a significant increase during 1st and 2nd harvest at 80-100 cm depth. In Manikganj, a significant depletion of soil moisture with harvest time was also evident up to 60 cm depth and a significant increase in soil moisture occurred in the deeper layers.

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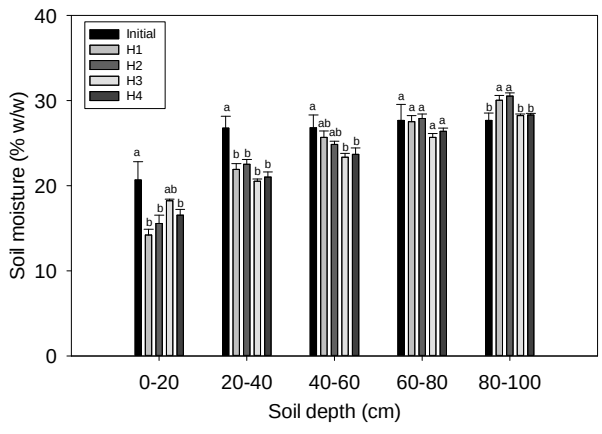
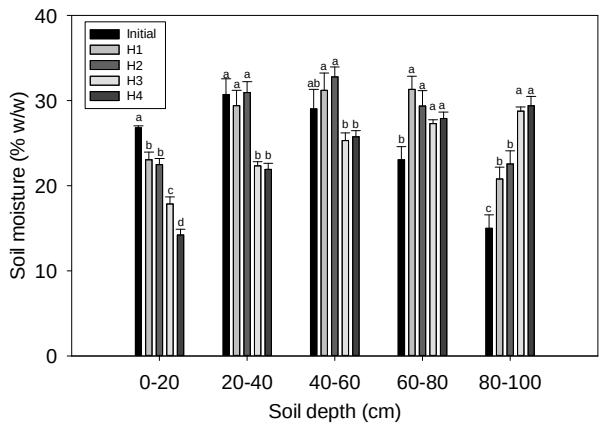
<tr><td colspan="2"> 
</td><td colspan="2"> 
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<tr><td>Water*
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Soil depth***
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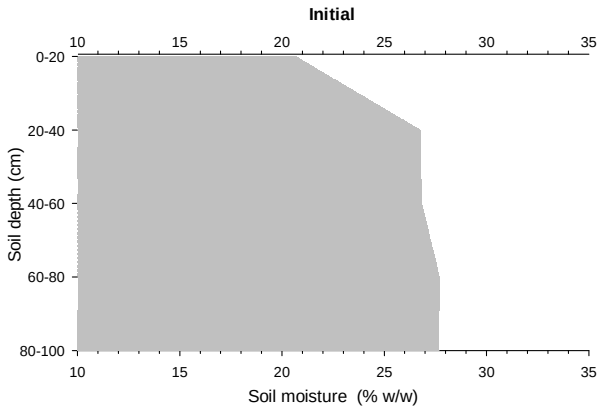
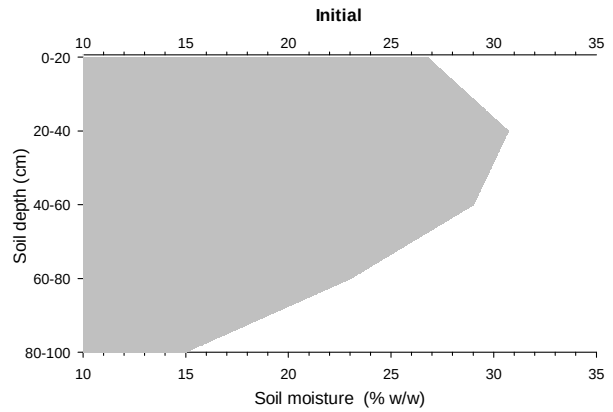
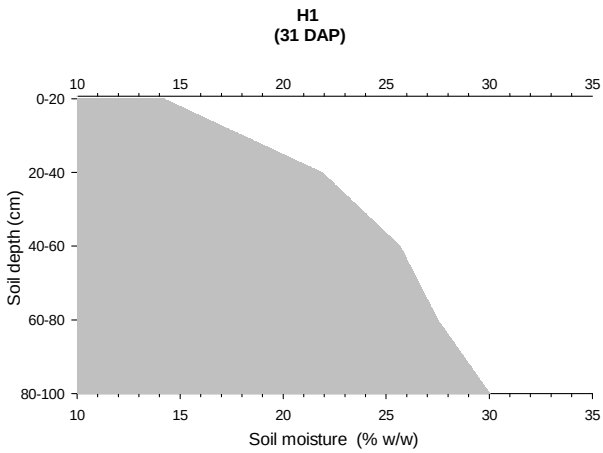
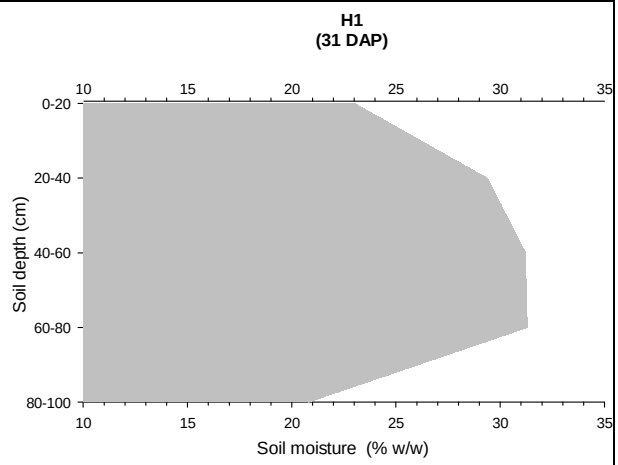
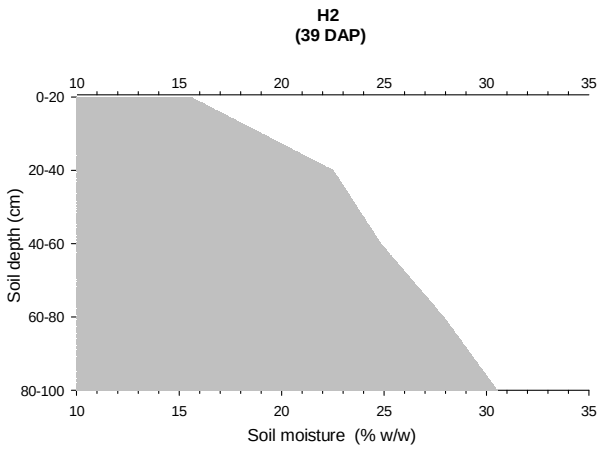
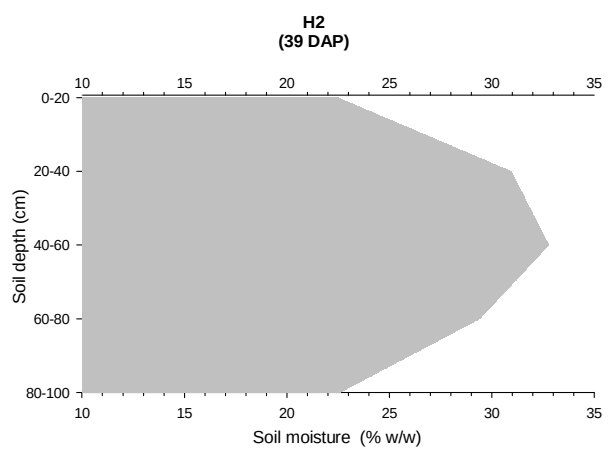
</table>

Experiment site: Rajshahi	Experiment site: Manikganj
	
	
	

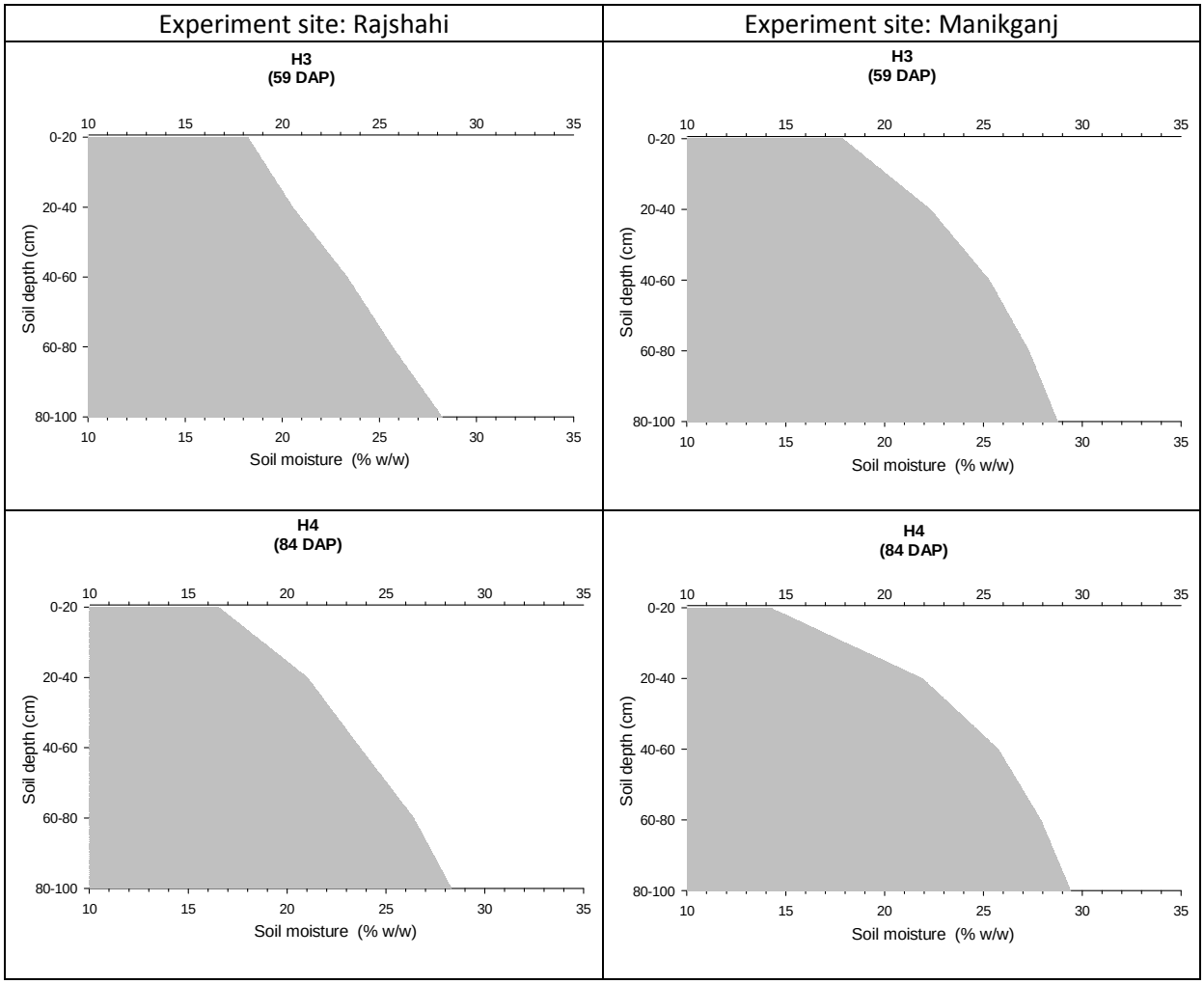


Figure 4.42: Soil moisture conditions in Bangladesh experiments (error bars indicate SEM and different letters indicate differences in means)

4.3.3 Biomass production and plant growth properties

4.3.3.1 Total biomass

Total dry mass (stem, leaf and tuber) production among the genotypes in both experiments shows that initially plants grew faster in Manikganj than in Rajshahi site (Figure 4.43). Influence of genotypes was very clear on biomass production in both locations. Water treatment did not play any significant role except one instance at the first harvest in Manikganj. No interaction between genotypes and water existed in both locations in any harvest. Total biomass averaged 4.8 g/m^2 at the 1st harvest in Rajshahi and that was 14.5 g/m^2 and 12.5 g/m^2 in Manikganj under WW and WS conditions, respectively. In harvest 2, at Rajshahi plants produced about half of biomass (10.1 g/m^2) as compared to Manikganj (20.9 g/m^2) and in both locations Lalpakri and Diamant performed better than others.

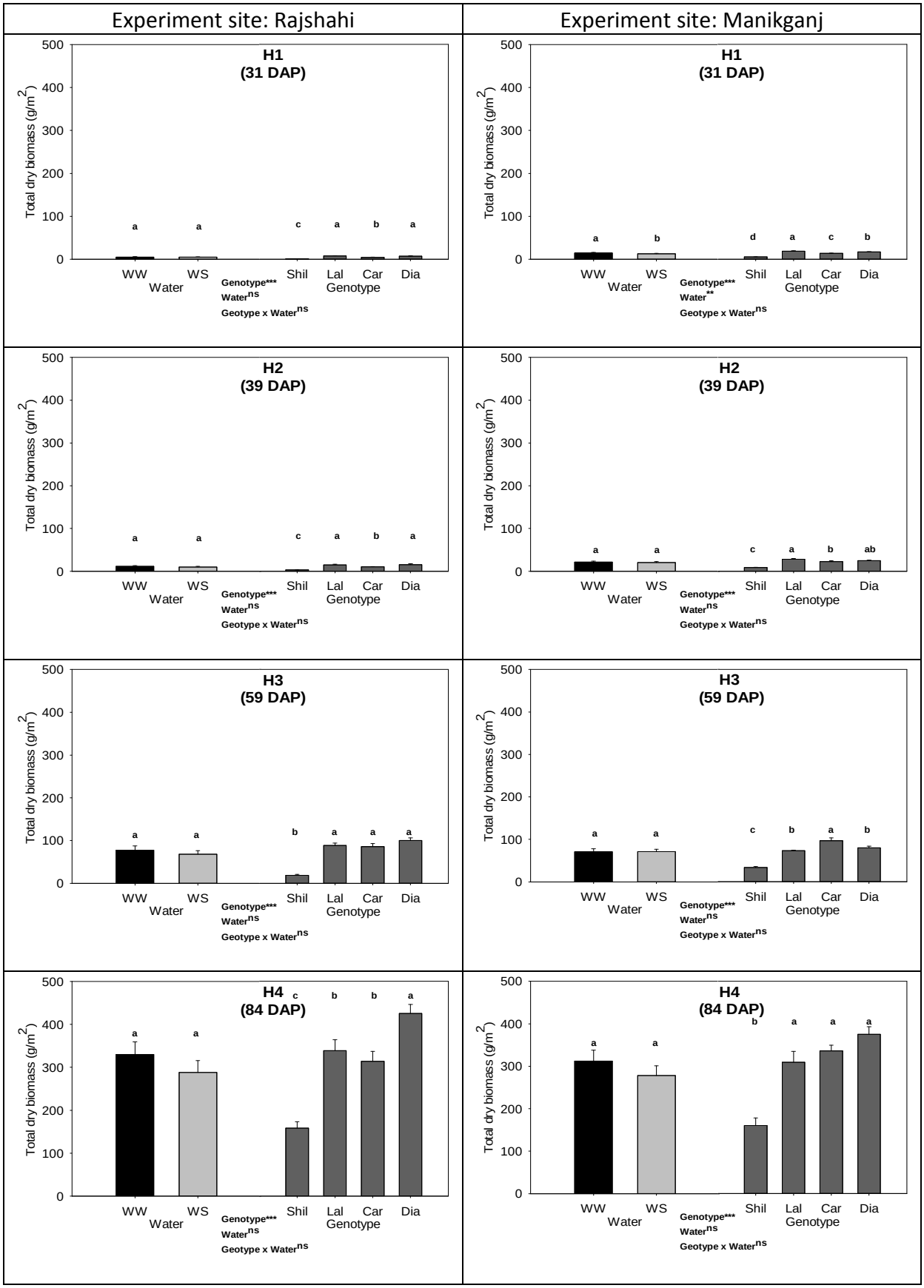


Figure 4.43: Total dry biomass productions in Bangladesh experiments (error bars indicate SEM and different letters indicate differences in means)

In the 3rd harvest, Cardinal recovered its growth similar to Lalpakri and Diamant in both locations, and even produced significantly more biomass than others in Manikganj. At final harvest, almost similar biomass was produced in both sites (average 308.8 g/m^2 in Rajshahi and 295.1 g/m^2 in Manikganj). Shilbilati performed consistently very poor as found in other harvests in both locations. At final harvest, Diamant, Cardinal and Lalpakri produced identical biomass in Manikganj, while Diamant appeared as the best in Rajshahi.

4.3.3.2. Stem dry mass

Figure 4.44 shows that stem production did not respond to water treatments at all in Manikganj experiment and that influence was visible only during advanced stages (harvest 3 and harvest 4) in Rajshahi. Genotypes responded significantly at early growth stages in Manikganj which was found extended up to harvest 3 in Rajshahi location. Mostly stem biomass produced in Rajshahi was less than at Manikganj, and due to influence of water stress at harvest 3 and harvest 4, WS plants produced significantly less amount of stem than WW plants. Shilbilati was very poor in stem growth at early development stages which recovered well and became identical to others at harvest 3 in Manikganj and at final harvest in Rajshahi.

4.3.3.3 Leaf dry mass

Water stress did not affect leaf development in Manikganj exept for an interaction with genotypes at harvest 3 (Figure 4.45). At Rajshahi there was a main effect of water treatments at harvest 3. Genotypes influenced significantly on leaf production and Shilbilati always produced lowest leaf dry mass regardless to harvest time or locations. Cardinal had a slow leaf growth at early stages of plant growth, however with the progress of time it became identical to Lalpakri and Diamant.

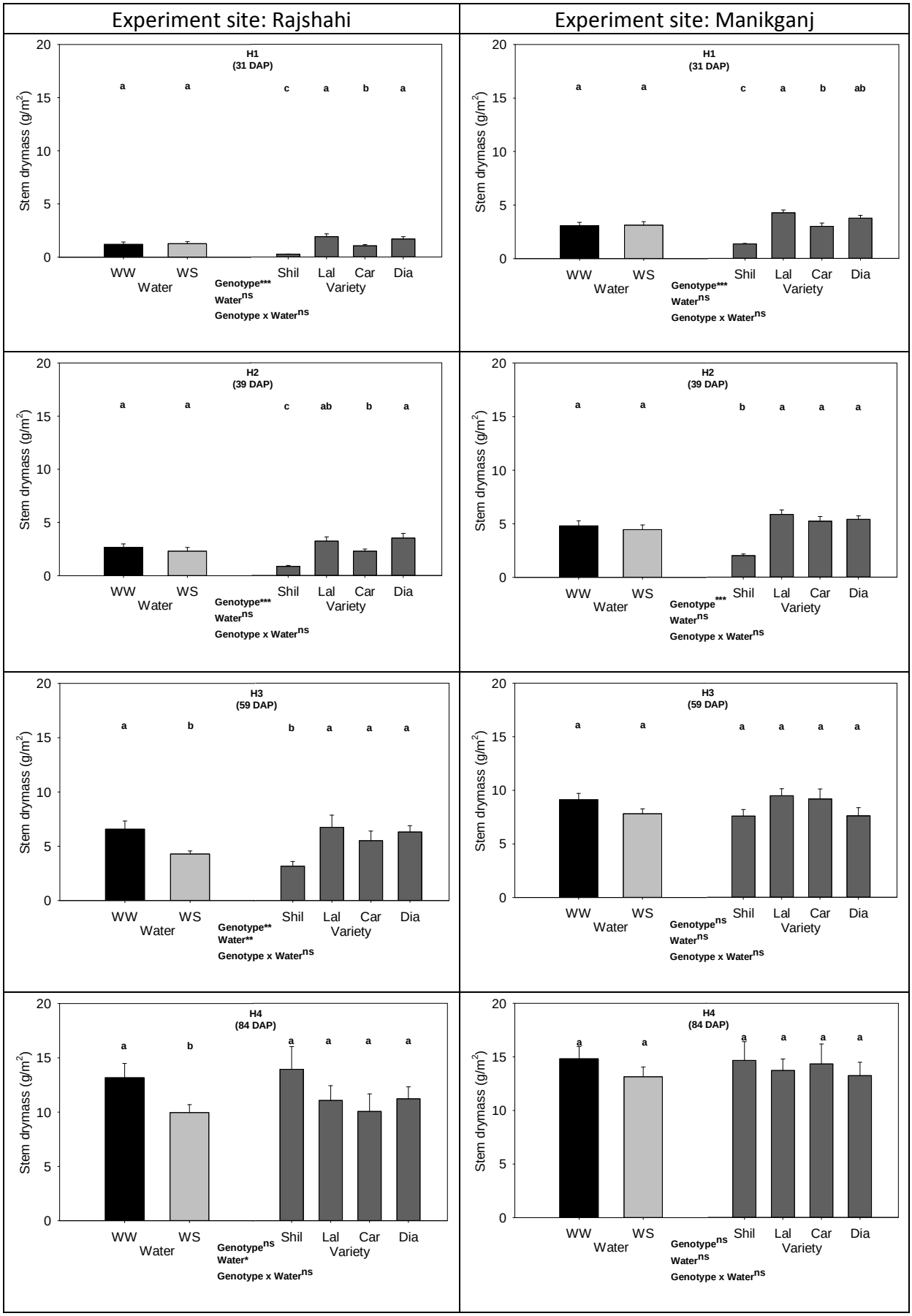


Figure 4.44: Stem dry mass productions in Bangladesh experiments (error bars indicate SEM and different letters indicate differences in means)

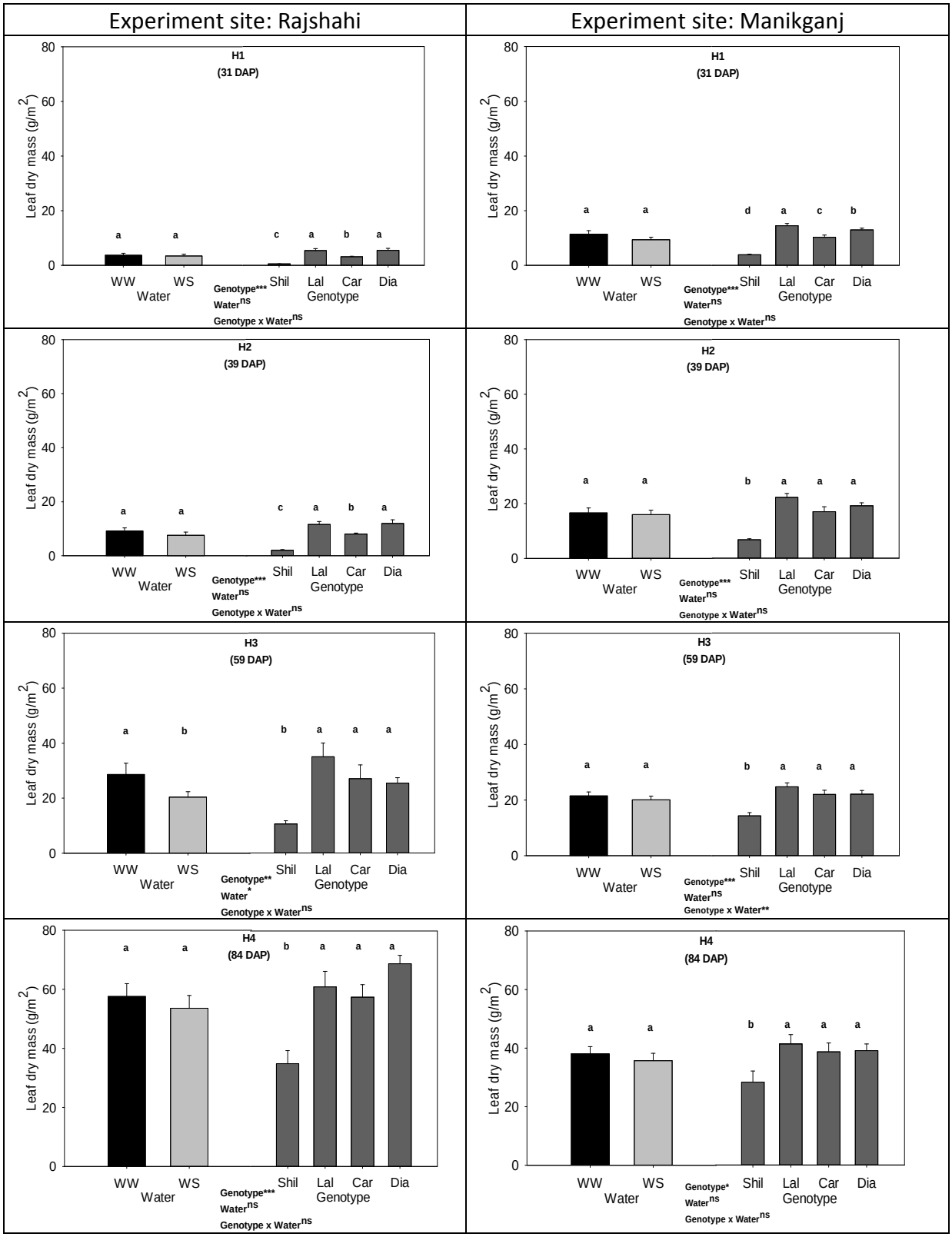


Figure 4.45: Leaf dry mass productions in Bangladesh experiments (error bars indicate SEM and different letters indicate differences in means)

4.3.3.4 Fresh tuber yield

No tubers were formed until the 2nd harvest in both experiment sites. Water treatment did not play any significant role on fresh tuber yield in both experiments except at the final harvest in Manikganj (Figure 4.46). Genotypes had strong effects on tuber formation however no interactions existed between water and genotypes. Diamant produced consistently high tuber weight in Rajshahi while Cardinal did that in Manikganj. Shilbilati yielded lowest amount of tubers in both locations.

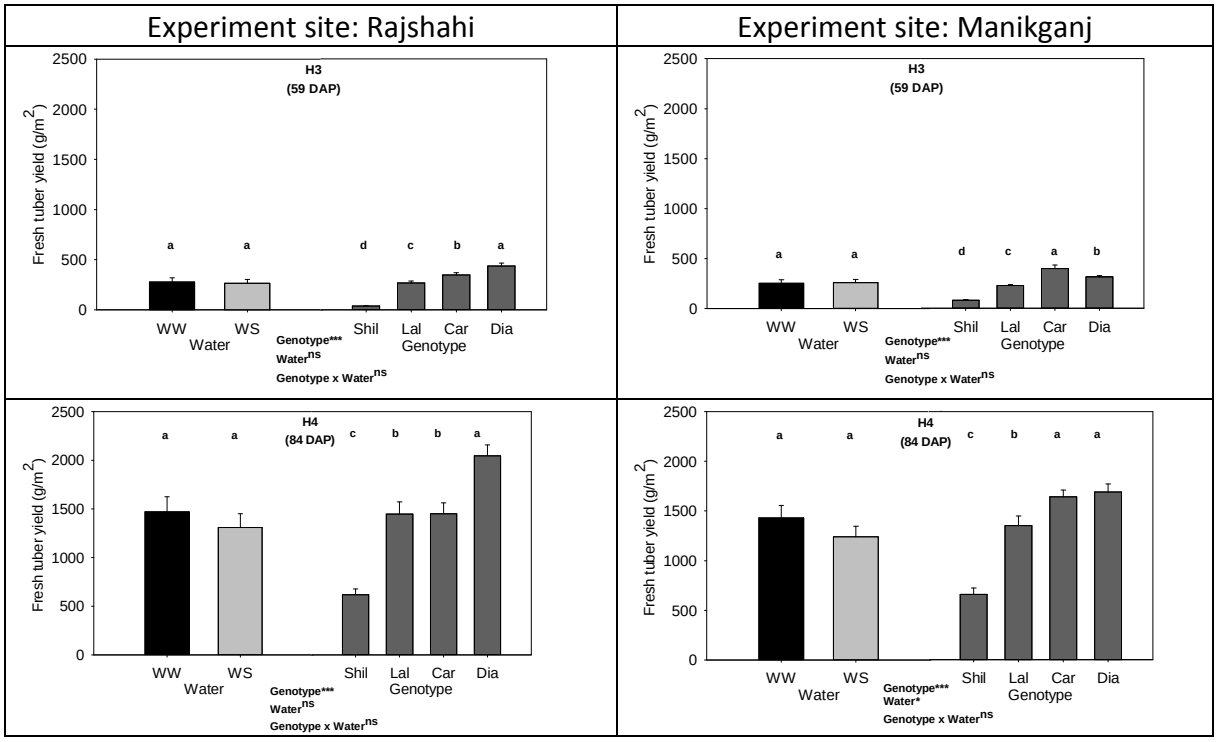


Figure 4.46: Fresh tuber yields in Bangladesh experiments (error bars indicate SEM and different letters indicate differences in means)

4.3.3.5 Tuber dry matter concentration

Water treatment did not play any significant role on tuber dry matter concentration in both locations regardless to harvest time (Figure 4.47). Significant variations existed among the genotypes at early tuber growth stage in both locations and Shilbilati had the lowest dry matter concentration. At final harvest, tuber dry matter concentration was identical for all genotypes.

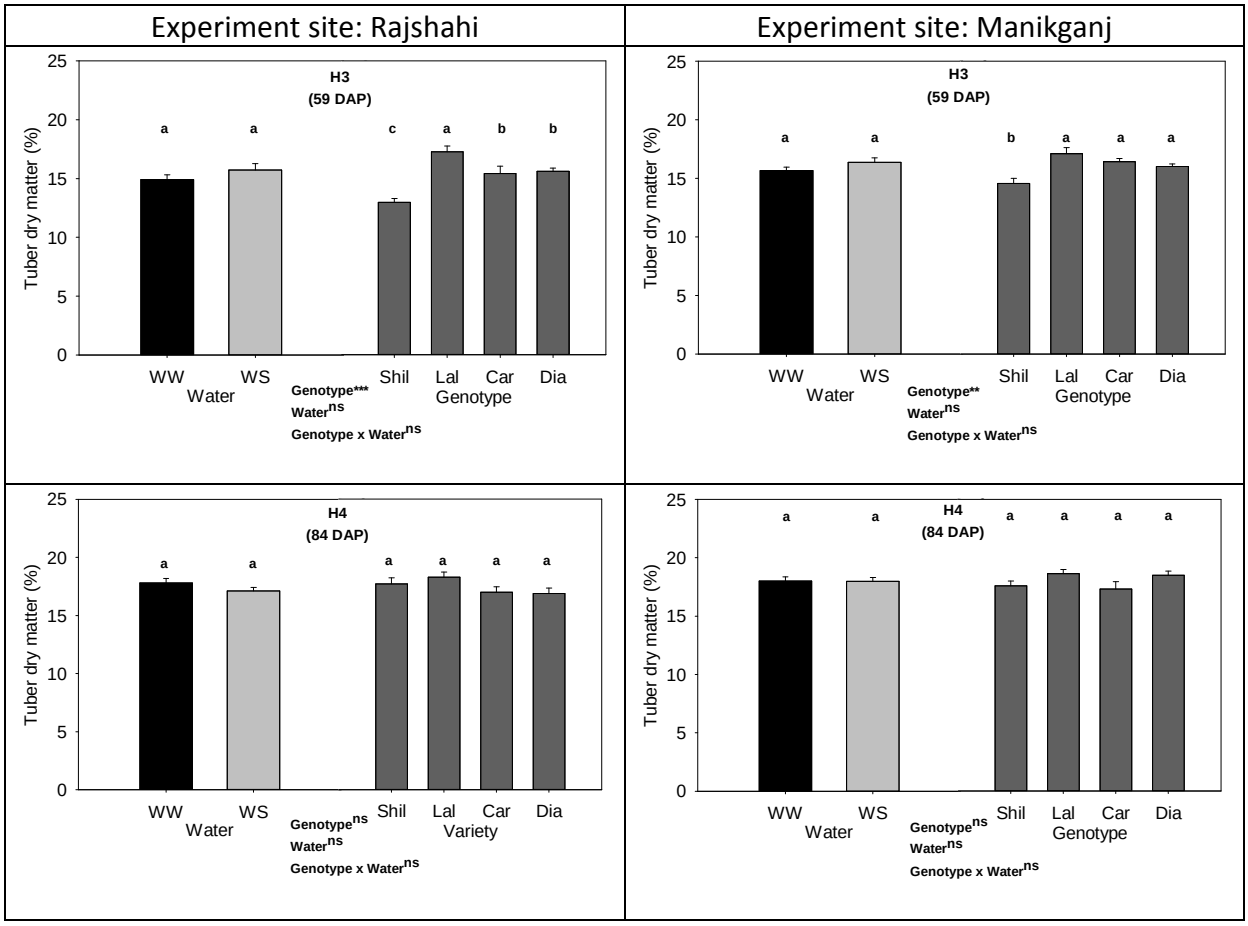


Figure 4.47: Tuber dry matter contents in Bangladesh experiments (error bars indicate SEM and different letters indicate differences in means)

4.3.3.6 Tuber dry mass

Figure 4.48 shows that tuber dry mass did not respond to water treatments significantly in all harvests in both locations. Genotypes had a significant role for variations in tuber dry mass at both harvests in both locations. At early stage in harvest 3, Diamant performed better in Rajshahi while Cardinal did that in Manikganj. At final harvest, Diamant produced highest tuber dry mass in both locations and Shilbilati had the lowest performance as compared to others.

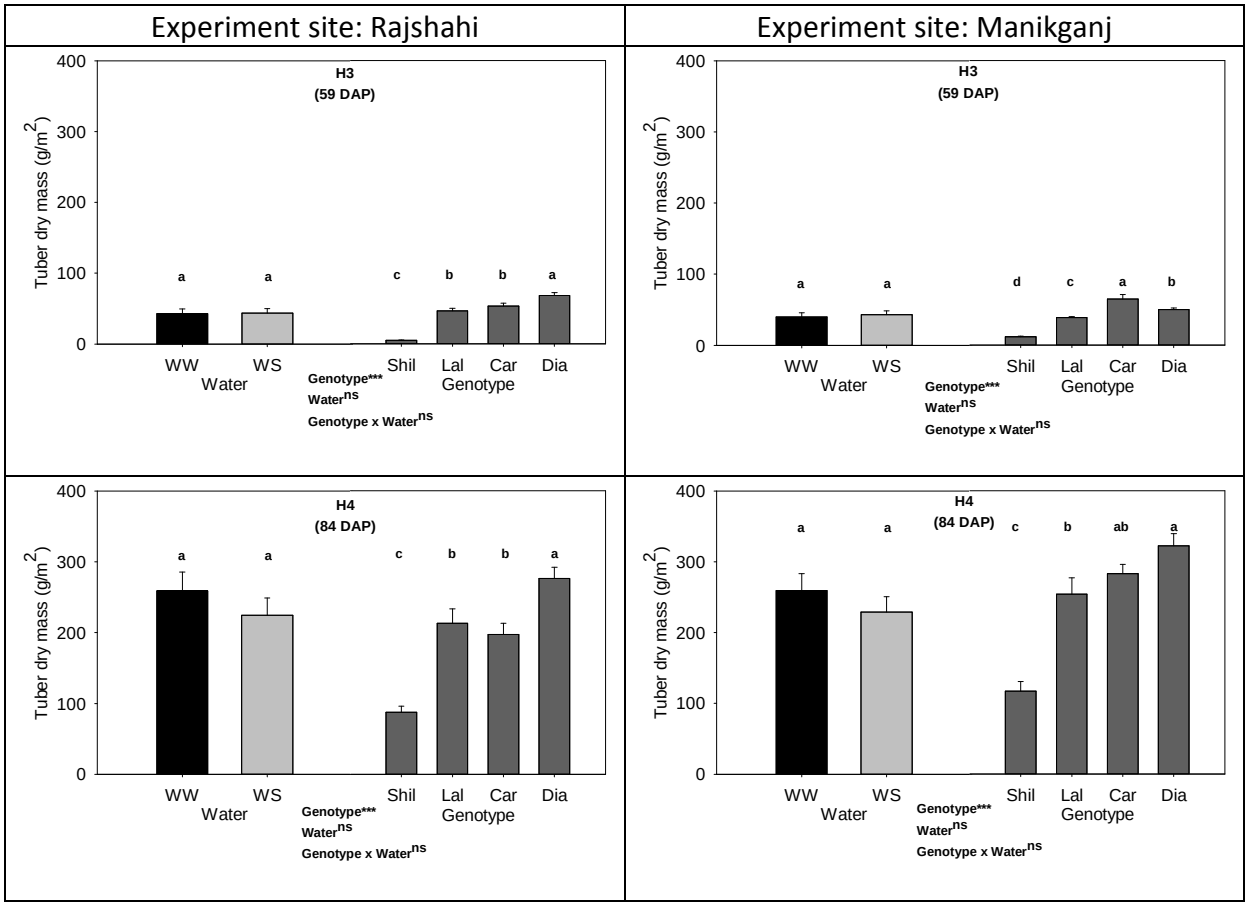


Figure 4.48: Tuber dry mass in Bangladesh experiments (error bars indicate SEM and different letters indicate differences in means)

4.3.3.7 Tuber numbers

Like tuber dry mass production, both experiments did not show any influence of water supply on tuber setting. Genotypic variations were very clear showing two groups of genotypes in both locations. Lalpakri and Shilbilati with large number of tubers and, in contrast, Diamant and Cardinal had less tubers (Figure 4.49). The genotypes had a similar pattern of tuber setting at both harvest stages and both experimental sites.

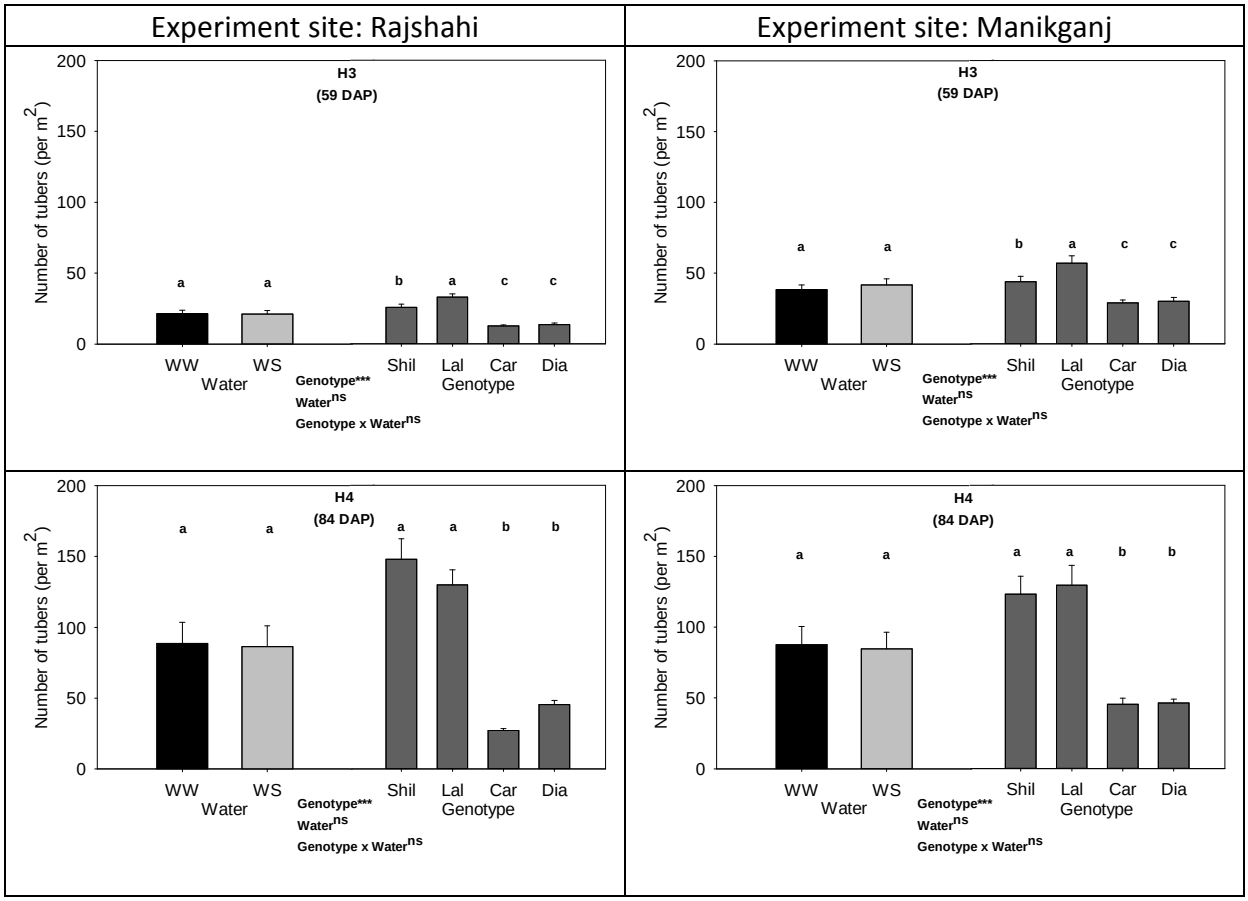


Figure 4.49: Number of tubers produced in Bangladesh experiments (error bars indicate SEM and different letters indicate differences in means)

5 Discussion

Genotype, environment and management interaction (G x E x M) in potato is likely different from other crops due to its pronounced biomass partitioning towards vegetative storage organs rather than seeds. The harvest index appears as high as 0.8 (Mazurczyk, et al., 2009) compared to 0.4 to 0.6 in most of the grains (Hay, 1995). Together with this physiological aspect, our approaches for evaluating transpiration and water saving traits of potato were exposed to some limitations. Although greenhouse experiments were planned to have identical environment (Table 3.1), ambient environment outside the glasshouse influenced considerably and resulted in varying environment conditions (Figure 4.1, 4.2, 4.3 and 4.4). Genotypes used in the glasshouse and field experiments were not always the same across the experiments. Due to discontinued supply of seed tubers from the breeder company, genotypes with similar performance in TE (Diego, Tosca, Agria used in the Exp 1) could not be included further and only Desiree (the most T-efficient genotype in the Exp 1) was common in all three glasshouse experiments (Table 3.4). In the field experiment in Tulln, we selected contrasting genotypes from the Exp 1 (Desiree and Cardinal) and Exp 2 (Caesar and Farida). Initially we planned to test these genotypes also in Bangladesh conditions. However, seed shipment from the breeder in the Netherlands was again interrupted and only Cardinal was common in Bangladesh experiments with Tulln. Soils of two locations in Bangladesh were also different in water holding properties particularly in deeper layers. In Rajshahi location, a hard plough pan was found in between 30-40 cm depth and percolation towards ground water was restricted. In Manikganj, a sand layer existed at 60 cm depth that allowed easy water movement in deeper layers (Figure 4.39).

As highest daily crop growth is achieved between 15˚C and 23˚C (Haverkort, 1990) and dry matter partitioning to tubers is favoured between 15˚C to 20˚C (Sale, 1979; Manrique and Bartholomew, 1991), we took into account that in our experiments. Although glasshouse cabins in Tulln were programmed for 12˚C at night and 22˚C during day, Exp 3 could not maintain that properly as others did. Due to temperature fluctuations in the ambient environment (summer weather in the Exp 3), deviations in temperature and relative humidity brought considerable changes in the VPD (Figure 4.3, 4.4). We took these environmental changes as an inducing factor and interpret the results of transpiration behaviour and plant biomass yield under different VPD conditions (section 4.1.2.1, 4.1.3.1).

For measuring daily T, we allowed all plants to grow at least until 9-leaf stage for easy handling of pot sealing and observing plants at active growth stage. At the onset of dry down cycle, random variations (Table 4.1) and genotype properties could not provide all plants with a similar growth (Figure 4.5) as plants responded with some degree of variations. We allowed all physiologically dead plants to continue until the last one reached to that point for the homogeneity of the environment and harvest time (Table 4.1). So, TE in our experiments was determined on the basis of total amount of water transpired during the complete dry down cycle not based on physiological death dates.

Total transpiration during the experiment period varied significantly among the genotypes in all experiments under well-watered condition (Figure 4.7, 4.9, 4.11), which substantially supports the hypothesis "Genetic variation exists in transpiration response of potato genotypes to continuous soil drying". Distinct variability in daily transpiration (Figure 4.12) among the genotypes (Tekalign and Hammes, 2005) as well as water treatments (Wilcox and Ashley, 1982) and VPD conditions (Fletcher et al., 2007; Gholipoor et al., 2010) proved their significant effect on this trait. Plants do not alter their transpiration behaviour until and unless it is challenged by a drought stress or water supply is stopped. Affected stomatal closure under mild to moderate drought conditions (Liu et al., 2010) go with the results in our experiments. Less than half of total transpiration by the WS plants during the dry down period as compared to WW plants (Figure 4.6, 4.8, 4.10) provides evidence that WS condition had restricted transpiration. When significant differences in transpiration among genotypes in well-watered condition disappeared under stress, it confirms a strong influence of water supply over the genotypic response (Figure 4.7, 4.9 and 4.11).

Not only the water supply and genotypes influenced on transpiration, a significant effect of experiment condition, especially the VPD, was observed. A number of studies has been made on the effect of VPD on transpiration in different crops (Fletcher et al., 2007; Devi et al., 2010; Gholipoor et al. 2010; Kholova et al. 2010; Choudhary et al., 2013), however very limited works have been done on potato. Stark et al. (1991) evaluated 14 genotypes for the sensitivity to VPD and found that genotypes at higher than average temperatures were less sensitive to changes in VPD than at lower temperatures. Higher temperatures increase stomatal resistance that limits transpiration (Ku et al., 1977) but more daily average T in the

3rd experiment under high VPD condition (Figure 4.17) proved that VPD played a significant role in accelerating transpiration.

As long as the key role players above are stopped influencing, the daily transpiration of WS plants in each genotype progressed almost linearly with the corresponding WW plants. This trend of relative transpiration or transpiration ratio (TR) continued with a normalized value near to 1.0 (NTR ≈ 1.0) until available soil moisture reached to a critical level (Figure 4.14). This critical level of soil water indicates the timing of stomatal closure (Ray and Sinclair, 1997; Sinclair and Ludlow, 1986). Below this threshold level, water stress appears and plants started to decline T rapidly because under mild to moderate stress conditions, stomatal characteristics are affected (Liu et al., 2010). Beyond that impaired photochemical efficiency, rubisco activity etc. appear as dominating (Xu et al., 2010) that ultimately bring plants towards a rapid death. Genotypes that transpire more as compared to others before the critical FTSW threshold deplete more water from the soil and advance rapidly towards stress. Devi et al. (2010) separated 17 peanut genotypes into groups with different rates of transpiration at low VPD of which 9 responded to limit T at 2.2 KPa, while others continued to increase T with increasing VPD. In our potato genotypes, most cases with higher FTSW at lower VPD conditions showed lower FTSW values under high VPD conditions. These genotypes did not restrict transpiration earlier as they did under lower VPD conditions (Figure 4.14, 4.15) which suggest similar transpiration properties as Devi's 2nd group. A wide range in FTSW threshold (0.19 to 0.36) under low VPD condition was also narrowed down to 0.19 to 0.29 depending on the genotypes under high VPD conditions. Our values remained within the range reported by Weisz et al. (1994) and almost passed with the different values found by Souza et al. (2014) in two different experimental conditions and these results of different FTSW threshold among the genotypes (Figure 4.15) supports the hypothesis "Potato genotypes are capable of restricting transpiration rate in response to soil drying".

Significant differences among the genotypes in FTSW threshold confirm the genotypic response to critical soil moisture during progressive soil drying, and genotypes that respond to water limiting condition and decline their T earlier than others retained more water in the pot for further consumption. These different genotypic responses to FTSW threshold (Tosca and Diego as compared to Granola in the Exp 1 and Farida as compared to Desiree and Caesar in the Exp 3) saved different amount of water at the same time. About 40% water

saved by Tosca as compared to Granola and about 30% by Farida compared to Desiree (Table 4.2) prove that not all but some genotypes save water. This also complies with the results documented by Devi et al. (2010) in peanut and partially supports hypothesis "Transpiration-efficient genotypes conserve soil water, which would be available later in the season for tuber production".

As dry down cycle proceeded, transpiration rate in WS plants progressed almost linearly with WW plants during the phase I until the FTSW appeared and further progress continued through phase II as described by Ludlow and Sinclair (1986). The duration of the phase I in glasshouse experiments was significantly influenced by the genotype and environment (VPD) as well (Figure 4.16). Longer phase I of Agria in the Exp 1 and that of Caesar, Cardinal and Diamant in the Exp 2 proves their genetic advantage under low VPD conditions. Daily transpiration during phase I in all experimental conditions showed significant variations among the genotypes (Figure 4.17). These variations confirm the results of delayed wilting properties of genotypes reported by Fletcher et al. (2007) and Sinclair et al. (2008). Prolonged phase I in Caesar as compared to Farida, Spunta and Desiree under moderate VPD in the Exp 2 which became identical to others under high VPD condition in the Exp 3 proves that favourable genotypic performance had a limitation with more stressful environment.

VPD also influenced average transpiration during phase I which did not show up during phase II (Figure 4.17). No variations in transpiration among the genotypes observed in phase II regardless the VPD conditions confirm that transpiration behaviour is mainly affected during phase I (Liu et al., 2010), but other metabolic activities were concerned in phase II (Xu et al., 2010; Drapal et al., 2016). Significant differences in transpiration among the genotypes in phase I brought substantial variations in water consumption until FTSW threshold had been reached. Lowest consumption by Tosca in the Exp 1, by Spunta in the Exp 2 and by Farida in the Exp 3 (Table 4.2) strongly supports both of the hypothesis "Genetic variation exists in transpiration response of potato genotypes to continuous soil drying" and "Transpiration-efficient genotypes conserve soil water, which would be available later in the season for tuber production".

Significant influence of water treatment, genotype and VPD along with their interactions existed on transpiration efficiency (TE) trait (Figure 4.22a). Genotypic variations for TE in

many legumes and grain crops have been well documented by a number of studies (Rao and Wright, 1994; Krishnamurthy et al., 2007; Devi et al. 2009, Gholipoor et al., 2010) and they found variations among the genotypes. No comparable study has been made so far on potato in terms of TE. In our experiments, WW plants did not show any significant differences except for Caesar in the Exp 2 (under moderate VPD condition) in TE in different environmental conditions. On the other hand, significant variations among the genotypes in WS conditions cast a light on the influence of drought stress on genotypes (Figure 4.22b, 4.22c, 4.22d). In most cases, such variations among genotypes were observed in the shoot TE (Figure 4.23) and tuber TE (Figure 4.24). The best performance of Desiree and Diego in the Exp 1 and Caesar in the both Exp 2 and Exp 3 proves that genotypes have variations in TE. Along with the genetic effects, a strong influence of VPD with its interaction with both water stress and genetic potential highlights the role of VPD on TE. TE based on total biomass at lower VPD was less than half at high VPD conditions. High TE at lower VPD in the Exp 1 that decreased with increased VPD (Figure 4.22a) confirms that TE in potato genotypes also depends on the environment. This dependency supports the relationship between TE and the attributes of plants that make them restrict water losses under high VPD (Vadez et al., 2014).

Not only the VPD and genetic traits were active on TE, but water supply or drought had an influential role (Figure 4.22a). A significantly higher TE (7.4 g l^{-1}) in WS treatments as compared to WW treatments (6.2 g l^{-1}) clearly showed the impact of water stress. Similar effect was also evident on stem TE (Figure 4.23), however influence of water was only visible under low VPD condition in the case of tuber TE (Figure 4.24). Although effect of water stress interacted with genotype and VPD (Figure 4.22a), it still had significant impact on TE.

If we consider the performances of individual genotypes for water saving properties and TE together, the best candidates for water saving Tosca in the Exp 1, Spunta and Farida in the Exp 2 and Farida in the Exp 3 did not appeared as the best for TE. Desiree in the Exp 1 and Caesar in the Exp 2 and Exp 3 had highest TE instead. Even the best water saving Farida and Spunta had significantly lower TE than Caesar. There was also no good match between high TE and high FTSW threshold (Figure 4.15, 4.22b, 4.22c, 4.22d). A very week relation between TE and FTSW (R^2= 0.125) and almost no influence of TE on water savings (R^2= 0.031) proves that water saving attribute and TE are not always associated as previously reported by

Sinclair et al. (2005), Sinclair et al. (2016), Devi and Sinclair (2011), Vadez et al. (2014), Souza et al. (2014). As TE was not found much involved in water saving therefore, water saving attribute may have contributed by root characteristics or it could be identified as a different trait, which may have triggered with transpiration properties but respond differently by the individual genotype under different environmental conditions.

Naturally WW treatments produced higher total biomass where water was non-limiting in the pot experiments. WS plants produced almost half biomass that confirms the importance of water supply on biomass production (Figure 4.18a, 4.18b, 4.18c). Similar effects of water were evident in stem production (Figure 4.19) and leaf production (Figure 4.20). Effect of water treatment was less clear under high VPD condition, where genotypes could not show their potential due to strong influence of VPD in the glasshouse. In terms of biomass production, Diamant and Cardinal remained at the bottom line in the Exp 1 and Exp 2. On the other hand, Desiree and Diego were the best in the Exp1 and Desiree and Spunta were in the Exp 2 (Figure 4.18a, 4.18b). Under high VPD condition in the Exp 3, all four genotypes had identical biomass and better performance of Desiree and Spunta as compared to Caesar and Farida disappeared (Figure 4.18c). The contrasting genotypes in the glasshouse experiments did not performed in the same way under field conditions, in Tulln. Desiree could not show its high potential compared to Cardinal, and Farida showed its excellence at all harvest dates when the field experiment passed through a number of dry spells (Figure 4.37), elevated VPD (Figure 4.38) and depleted soil moisture (Figure 4.39). None of the best genotypes in TE screened out in the glasshouse experiments as Desiree (Exp 1) and Caesar (Exp 2 and Exp 3) could produce highest yield under field conditions, which rejects our hypothesis “Higher TE produces higher potato tuber yield”.

This genotypic merit of Farida was not only found in biomass production but also observed in stem production (Table 4.5), leaf production (Table 4.6), LAI (Table 4.7), and fresh tuber yield (Table 4.8). Cardinal showed its distinct properties in tuber dry matter concentration and tuber numbers (Table 4.9, 4.11). Effect of drought stress was reflected remarkably when higher dry matter production in Farida, Caesar and Desiree at harvest 3 reduced significantly towards the final harvest (Table 4.9) after passing a dry period (Figure 4.37). This type of subsequent reduction in dry matter production under stress has been documented in

previous studies as reported by Ewing and Struik (1992) which can be explained by secondary tuber formation and those tubers could be resorbed later for further growth.

The contrasting performance of Shilbilati with Diamant and Cardinal in Bangladesh conditions had the matching scenario as shown by Cardinal with others in the field experiment in Tulln for total biomass, stem, leaf and tuber production. High number of tubers in Diamant and Cardinal in Tulln (Table 4.11) and that of Shilbilati and Lalpakri in Bangladesh experiments (Figure 4.49) confirm the presence of genetic variations. Genotypes in the field experiments in Bangladesh in one hand did not show water stress for fresh tuber yield as well as total biomass production due to more soil water retained in most of the layers. Response to water stress was observed on stem and leaf production at harvest 3 in the Rajshahi location when soil moisture was comparatively more depleted in the top to middle layers (Figure 4.39). On the other hand, the environmental condition (Figure 4.40a, 4.40b), especially low VPD throughout the experiment period (Figure 4.41a, 4.41b), helped more consistently to express genetic variability in biomass production as we had observed in the Exp 1 under low VPD conditions (4.18a, 4.18b).

Variations exhibited among the genotypes for TE, FTSW and water saving trait in all glasshouse experiments make it clear that they were mostly controlled by the genetic makeup as influenced by water availability and VPD. Water supply and environment influenced critically on transpiration behaviour, plant growth and yield properties. This scenario was more obvious when genotypes in the field experiment could not appear with similar pattern of response as found in the glasshouse experiments. That happened because genotypes could not show up their specific potential at high VPD conditions and depleted moisture level.

Furthermore, in response to drought stress during progressive soil drying, reduced biomass production coupled with reduced amount of transpiration occurred in WS plants (Figure 4.7, 4.9, 4.11) showed significantly enhanced TE compared to WW plants. Harvest index (HI) showed the similar effect and was affected strongly by VPD (Figure 4.30). Tuber yield (dry mass) under different VPD conditions showed a very good relationship with the components of Passioura's equation Y = T x TE x HI (Passioura, 1997). This equation fits very well in our glasshouse experiments, and R^2 values for calculated tuber dry matter (Y) and observed

tuber dry matter was 0.999, 0.999 and 0.987 in the Exp1, Exp2 and Exp3, respectively (Figure 4.31).

Although these three components often interact (Passioura, 2007), we found them showing their influences not much dependent with each other (linear R^2 = 0.03 for T vs. TE, R^2 = 0.08 for T vs. HI and R^2 = 0.45 for HI vs. TE) (Figure 4.32, 4.33, 4.34). TE was influenced by genetic potential, water supply and VPD conditions in both WW and WS plants (Figure 4.22a) and showed a very good relationship with total biomass production (R^2 = 0.95 or 0.66 for Total biomass vs. TE in WS or WW plants, respectively)(Figure 4.35, 4.36). Therefore, among three components of Passioura's equation, the role of TE was so important for determining yield. Although TE is not independently contributing to the yield but from the proven hypotheses above, expression of TE in a genotype is influenced by water supply and environment and it appears as a function of management which is mostly remained ignored. The micro environment in the potato field is always influenced by plant population, canopy structure, irrigation frequency, root elongation, radiation interception etc. that influence on VPD and genotypic response in TE, soil moisture threshold and water saving attributes. Although Drapal et al. (2016) highlighted that the role of genetics can predominate over the environmental conditions in potato, in practice, at least in our glasshouse experiments (under changing VPD conditions), TE could be modified not only by breeding but also by changing management (Tolk and Howell, 2009). Furthermore, future studies demand more focus on water saving attributes of genotypes under drought conditions which is still remained confined into TE traits. Perhaps TE will be more concerned with yield determination rather than water saving in near future and potato production will be befitted with the noble application of these traits.

6 Conclusion

The study conducted in the glasshouse and field experiments aimed at screening out and evaluating drought-adaptive traits in potato for better understanding of the contribution of TE trait on yield and crop performance under water limited management. It was focused on transpiration properties in response to drought condition, water saving and crop performance after imposing progressive soil drying. The attempt for identifying genetic variations in transpiration and dry matter production under continuous soil drying made with 11 genotypes from different countries in three glasshouse experiments showed significant differences among the genotypes.

Plants under water stress consumed almost half of well-watered condition. WS plants transpired almost in parallel with WW to the FTSW threshold and then transpiration declined rapidly due to stomatal closure in response to progressive soil drying. FTSW threshold varied significantly among the genotypes and a wide range in FTSW threshold (0.19 to 0.36) under low VPD condition was narrowed down to 0.19 to 0.29 under high VPD conditions. Genotypes with different FTSW had different timing of stomatal closure and consumed consequently different amount of water from the pots. At the same time some genotypes saved considerable amounts of water compared to the maximum water consuming genotype. About 40% soil water saved by Tosca as compared to Granola and about 30% by Farida compared to Desiree proved that some genotypes are capable of saving soil water and addressed well the hypothesis “Potato genotypes are capable of restricting transpiration rate in response to soil drying”.

Significant variations existed among the genotypes in TE in WS treatments (7.4 g l^{-1}) compared to WW (6.2 g l^{-1}) clearly showing the impact of water stress. Genotypes Desiree, Diego and Caesar had the highest TE but they were not the best in water saving. The weak relationship between TE and FTSW (R^2= 0.125) and almost no influence of TE on water savings (R^2= 0.031) proved that from our supported hypothesis “Transpiration-efficient genotypes conserve soil water, which would be available later in the season for tuber production”, TE and water saving ability were not always closely associated as previously reported from many studies.

Clearly reflected influence of water stress on WS plants which produced almost half the biomass as compared to WW plant was less clear under high VPD condition and genotypes could not show their potential due to strong influence of VPD. The suppression of the genetic potential was more evident when contrasting genotypes in the glasshouse experiments did not perform in the same way under field conditions. Desiree could not show its high potential compared to Cardinal, and Farida showed its excellence at all harvest dates when the field experiment passed through a number of dry spells, elevated VPD and depleted soil moisture in Tulln. Such results of the best genotypes in TE screened out in the glasshouse experiments rejected the hypothesis “Higher TE produces higher potato tuber yield”.

Contribution of TE fitted well with the Passioura’s mechanistic equation Y = T x TE x HI. The role of TE for yield estimation was not independent and was influenced by water supply, environment and management (water) as well. It leads us to think that TE could be modified not only by genetic improvement but also by changing management. The results on water saving properties which were not associated with TE and the contribution of TE to tuber yield by changing environment or management opens a new window of research for their application in potato production under drought conditions.

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8 Appendix

Appendix-1: Cultivated potato varieties in Bangladesh

Variety Name	Development Year	Characteristics	Duration (Days)	Yield (ton/h)	Data Source
Shilbilati	Local	Tubers elongated and humped, smooth and shiny skin, skin reddish white	90-100	n.a.	Kawochar et al., 2014
Lal shil	Local	Oval round, medium smooth skin, skin red	100-115	n.a.	
Dohazari Sada	Local	Oval round smooth and shiny skin, skin pinkish with creamy patches	n.a.	n.a.	
Lal Pakri	Local	Round, rough skin, skin red with white patches	100-110	n.a.	
Indurkani	Local	n.a.	n.a.	n.a.	Uddin et al., 2010
Pakri	Local	n.a.	n.a.	n.a.	
Surjamokhi	Local	Round irregular, smooth skin, skin pinkish white	95-105	n.a.	Kawochar et al., 2014
Jhaubilati	Local	n.a.	n.a.	n.a.	Banglapedia, 2016
Ausha	Local	Round, rough skin, pinkish skin with creamy patches	100-110	n.a.	Kawochar et al., 2014
Challisha	Local	Round, medium smooth skin, skin creamy white	100-110	n.a.	
Festa shill	Local	Oval, smooth skin, skin light reddish with whitish patches	110-115	n.a.	
Hagrai	Local	Round and irregular, smooth and shiny skin, skin pinkish white	110-115	n.a.	
Patnai	Local	Oval, smooth skin, shiny red with yellow patches surrounding the eyes	100-115	n.a.	
Sadaguti	Local	Round irregular, smooth skin, skin creamy white	100-115	n.a.	
BARI Alu- 71	2016	n.a.	n.a.	n.a.	BARI, 2014
BARI Alu- 70	2016	n.a.	n.a.	n.a.	
BARI Alu- 69	2016	n.a.	n.a.	n.a.	
BARI Alu- 68 (Atlantic)	2015	Round, yellow skin, white flesh	90-95	19-45	
BARI Alu- 65 (Rosagold)	2015	Oval, red skin, yellow flesh	90-95	26-42	
BARI Alu- 66 (Pamela)	2015	Oval to long oval, red skin, light yellow flesh	90-95	25-46	
BARI Alu- 67 (Gorgina)	2015	Short oval, yellow skin, yellow flesh	90-95	29-47	
BARI Alu- 64 (Folva)	2015	Short oval, yellow skin, light yellow flesh	90-95	31-48	
BARI Alu- 63	2015	Round to short oval, red skin, yellow flesh	90-95	32-51	
BARI Alu- 62	2015	Oval to long oval, yellow skin, light yellow flesh	90-95	35-56	
BARI Potato -61	2014	Short oval to long oval, yellow skin, light yellow flesh	90-95	36-43	
BARI Potato -60	2014	Long to very long, yellow skin, cream flesh	90-95	35-48	
BARI Potato -59	2014	Oval, yellow skin, cream flesh	90-95	39-48	
BARI Potato -58	2014	Oval to long oval, yellow skin, cream flesh	90-95	42-46	
BARI Potato -57	2014	Oval to long oval, yellow skin, white flesh	90-95	29-45	

Variety Name	Development Year	Characteristics	Duration (Days)	Yield (ton/h)	Data Source
BARI Potato -56	2014	Round to short oval, red purple	90-95	29-45	BARI, 2014
BARI Potato -55	2014	Oval to long oval, skin red	90-95	30-33	
BARI Potato -54	2014	Oval to long oval, skin yellow	90-95	25-57	
BARI Potato -53	2014	Round to short oval, skin red	90-95	32-34	
BARI Potato -52	2014	Short oval to oval, skin yellow	90-95	30-53	
BARI Potato -51	2014	Short oval to oval, skin red	90-95	36-47	
BARI Potato -50	2014	Round to short oval, skin red	90-95	34-62	
BARI Potato -49	2014	Round to short oval, skin yellow	90-95	25-66	
BARI Potato -48	2014	Short oval to oval, skin yellow	90-95	26-62	
BARI Potato -47	2014	Short oval to oval, skin yellow	90-95	62-63	
BARI Alu-46	2013	Round to oval, skin yellow	90-95	30-40	
BARI Alu -41	2012	Round to short oval, skin deep red	90-95	38-44	
BARI Alu-45 (Steffi)	2012	Short oval to oval, skin yellow	90-95	25-50	
BARI Alu-44 (Elgar)	2012	Short oval to oval, skin yellow	90-95	25-50	
BARI Alu-43 (Atlas)	2012	Oval to long oval, skin yellow	90-95	25-35	
BARI Alu-42 (Agila)	2012	Long oval, skin yellow	90-95	25-40	
BARI Alu-40	2012	Short oval, light skin yellow	90-95	35-55	
BARI Alu-39 (Bellini)	2012	Oval to long oval, skin yellow	90-95	31-37	
BARI Alu-38	2012	Oval to long oval, skin yellow	90-95	32-36	
BARI Alu-37	2012	Oval to long oval, skin yellow	90-95	38-44	
BARI Alu-36	2012	Long oval, skin red	90-95	34-42	
BARI Alu-35	2012	Oval, skin yellow	90-95	38-44	
BARI Alu-34 (Laura)	2012	Long oval, skin red	90-95	30-35	
BARI Alu-32 (Quincy)	2010	Oval to long oval, skin white	90-95	30-35	
BARI Alu-33 (Almera)	2010	Long oval, skin white	90-95	30-36	
BARI Alu-31 (Sagitta)	2010	Oval, skin white	90-95	25-30	
BARI Alu-30 (Meridian)	2009	Oval, skin white	90	30-32	
BARI Alu-29 (Courage)	2008	Round to oval, skin red	90	25-30	
BARI Alu-28 (Lady Rosetta)	2008	Round, skin red	90	25-30	
BARI Alu-27 (Esprit)	2008	Oval to round, skin white and flesh yellow	90	25-30	
BARI Alu-26 (Felsina)	2006	Oval to oblong, whitish smooth skin	90	25-30	
BARI Alu-25 (Asterix)	2005	Oval to oblong, skin red	90	25-30	
BARI Alu-24 (Dura)	2005	Long oval, red skin	90	25-30	
BARI Alu-23	2005	Oval to oblong, whitish skin	90	25-30	

Variety Name	Development Year	Characteristics	Duration (Days)	Yield (ton/h)	Data Source
(Ultra)					
BARI Alu-22 (Saikat)	2004	Round to oval, red skin	90	25-30	
BARI Alu-21 (Provento)	2004	Oval, whitish skin	90	25-30	
BARI Alu-19 (Bintje)	2003	Oval, yellowish skin, light yellow flesh	90-95	20-25	
BARI Alu-20 (Jaerla)	2003	Long oval , pale yellow skin	90	25	
BARI Alu-18 (Baraka)	2003	Oval to oblong, whitish skin	90	20-30	
BARI Alu-17 (Raja)	2000	Long oval, attractive red skin and yellow flesh	90	20-25	
BARI Alu-16 (Arinda)	2000	Oval, light yellow skin, yellowish flesh	90-95	25-35	
BARI Alu-15 (Binela)	1994	Round medium, light yellow skin, yellow flesh	90-95	30-35	
BARI Alu-14 (Cleopatra)	1994	Oval to round, red skin, flesh light yellow	n.a.	23-24	
BARI Alu-13 (Granola)	1994	Rount, whitish skin	90	25-30	BARI, 2014
BARI Alu-12 (Dheera)	1993	Round, medium light yellow skin, whitish flesh	90-95	25-30	
BARI Alu-11 (Chamak)	1993	Medium round, light yellow in skin colour	80-85	20-35	
BARI Alu-10 (kupri sindur)	1993	Medium round, red skin	n.a.	23-24	
BARI Alu-9 (Mondinal)	1993	Oval to long, yellowish skin, light yellow to cream flesh	n.a.	24-26	
BARI Alu-8 (Cardinal)	1993	Oval, light red, smooth skin	90	25-30	
BARI Alu-7 (Diamant)	1993	Oval, medium to large, yellowish white skin	90	25-30	
BARI Alu-6 (Multa)	1993	Oval, white flesh and skin	90	25-30	
BARI Alu-5 (Patrones)	1993	Long oval, white flesh and skin	90	25-30	
BARI Alu-4 (Ailsa)	1993	Oval, yellowish flesh and skin	n.a.	25-30	
BARI Alu-3 (Origo)	1990	Oval to long, yellowish skin, , light yellow flesh	n.a.	25-26	
BARI Alu-2 (Morene)	1990	Oval, yellowish skin, flesh cream	n.a.	24-26	
BARI Alu-1 (Heera)	1990	Flat round, light cream skin	90	30-40	
Elvira	1983	Oval, yellowish skin, yellow flesh	n.a.	24-25	
Ukama	1980	Oval to long, yellow skin, light yellow flesh	n.a.	25-26	
Kronia	1977	Oval, yellowish skin, light yellow flesh	n.a.	23-26	
Mirka	1977	Oval to long, yellowish skin, light yellow flesh	n.a.	23-24	
Donata	1970	n.a.	n.a.	23-24	
Arka	1970	Oval to long, red skin, flesh cream	n.a.	25-26	
Desiree	1970	Oval to round, red skin, yellow to light yellow	n.a.	23-25	

Variety Name	Development Year	Characteristics	Duration (Days)	Yield (ton/h)	Data Source
		flesh			
Humalda	1969	Oval, white to yellow skin, light yellow flesh	n.a.	24-25	
Ultimus	1960	Oval to long, Red skin, yellow to light yellow flesh	n.a.	22-24	