Climate Resilience in Moroccan Dryland Wheat: a Modelling Study on Food Security

1: Introduction

1:1. Acknowledgements

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1:2. Partners

- ICARDA, International Center for Agricultural Research in the Dry Areas https://www.icarda.org/
- AquaCrop, Food and Agriculture Organisation of the United Nations http://www.fao.org/aquacrop/en/
- RICCAR, Regional Initiative for the Assessment of Climate Change Impacts on Water Resources and Socio-Economic Vulnerability in the Arab Region (RICCAR) https://www.riccar.org/

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1:4. Abstract

The International Centre for Agricultural Research in the Dry Areas (ICARDA) has carried agronomic research on drought resistant crops since the 1970s. Varieties derived from their research are now common throughout the world, especially in developing countries. Their field trials at Merchouch research station in Morocco have assessed the performance of several different genotypes of bread and durum wheat under different seasons, as well as the effect of different planting dates and water regimes. This study analyses the results of these trials and then uses the data to calibrate the AquaCrop model. AquaCrop is found to be able to simulate rainfed yields with a high degree of accuracy but to significantly overestimate yield gains from irrigation in dry years. The model is then run using down-scaled climate model data for the study area to project future yields. Under future climate scenarios yields are projected to increase by 6.5% by the period 2060-70 under RCP 4.5 with CO_2 enrichment considered, but to decline by 5.9% without it. Under RCP 8.5 they are projected to increase by 14.1% by this period with CO_2 enrichment but to decline by

6.6% without it. Irrigation is found to compensate for some of the yield losses in dry years, even when the overestimation of yield gains by AquaCrop are accounted for. The variabilities around CO_2 enrichment and the possible adaptation strategies to climate change are also discussed.

1:5. Key terms

- *Yield* – total mass of fruit or grain of a crop.
- Biomass - total *above-ground* matter produced by the crop, including yield.
- *Harvest index (HI)* – the proportion of total biomass which contains the yield. HI = yield / biomass (can be expressed as a percentage).
- *Water Productivity (WP)* – units of biomass produced by the crop per unit of water under non-limiting conditions. It is a constant characteristic of the crop.
- *Water Use Efficiency (WUE)* - The yield produced per unit of water as actually measured in the field. It is an efficiency or performance indicator of that particular crop variety in that season. It is usually calculated per unit of water *transpired* but may be calculated from water *applied,* or irrigation plus rainfall (Oweis and Hachum, 2006)
- *Field Capacity (FC)* - The amount of soil moisture that is held after excess water has drained away, which is usually two or three days after rain or irrigation (Israelson, and West, 1922).
- *Permanent Wilting Point (PWP)* – The lower limit of moisture below which plants begin to wilt.
- *Saturation (SAT)* - The point at which the soil holds as much water as it is physically capable of doing so and any further water added will immediately run off.
- *Representative Concentration Pathway (RCP)* – a projected future climate change scenario, based on a certain level of greenhouse gas emissions

2: Background Information

2:1. Food security and climate change

The Food and Agriculture Organisation (FAO) of the United Nations (UN) has defined Food Security as when everyone in the world reliably has enough to eat. The FAO report *How to Feed the World in 2050* found that cereal production may need to rise by 50% by 2050 to feed the world's growing population and that 80% of the necessary production increases would have to come from yield increases rather than expansion of arable land. However the rate of growth has fallen from 3.2% per year in 1960 to 1.5% in 2000. (FAO, 2009)

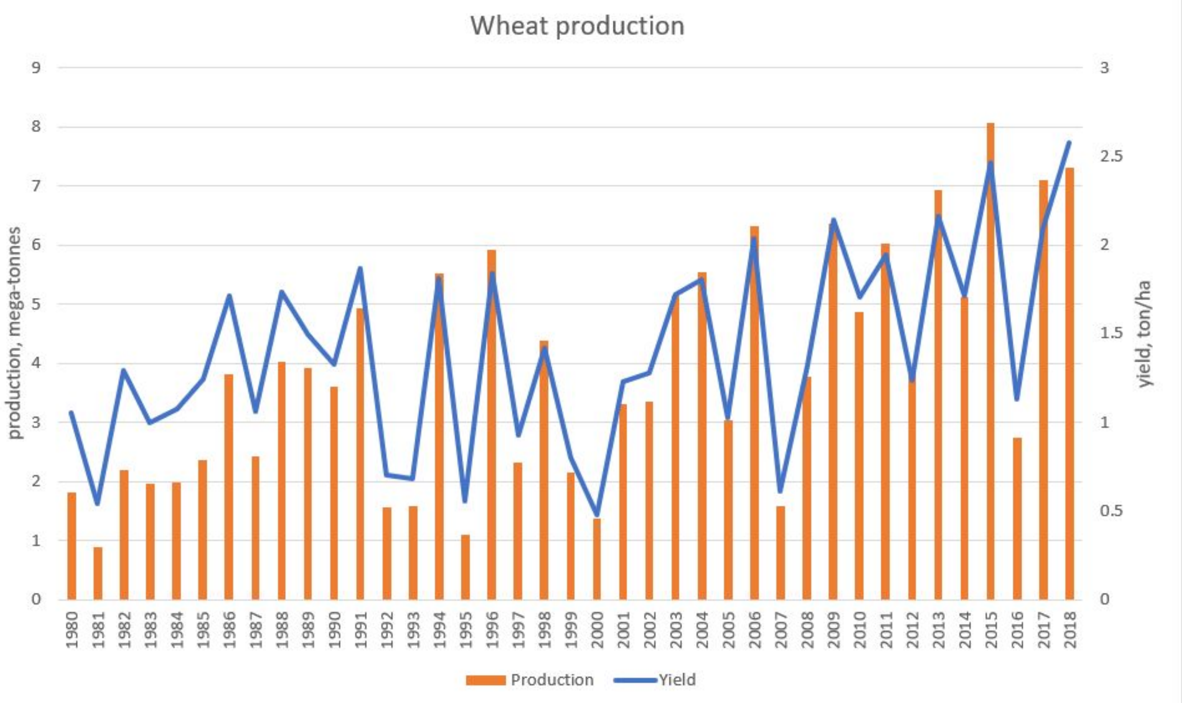
It is almost universally scientifically accepted that the climate has already warmed and will continue to do so, causing far-reaching global change, and that this due to human greenhouse gas emissions, mostly of carbon dioxide (IPCC, 2014). Most climate change scenarios project an increase in average global precipitation, but also increased variability by region and season. Many climate models project the Mediterranean and North-Africa to become more vulnerable to drought and heatwaves even if current emissions are drastically cut (IPCC, 2014; Giorgi 2006; Bouras et al, 2019).

2:2. Morocco country profile

Morocco can be broadly divided into two climatic regions: a Mediterranean north-west, with hot, dry summers and mild, wet winters and a hot, arid south-east with high temperatures and very low rainfall year-round. The Mediterranean has been identified as a 'climate hot spot,' meaning it is especially vulnerable to climate change, with the greatest factor being a large decrease in mean precipitation and an increase in variability (Giorgi 2006).

Wheat is one of the most widely grown crops, with 734 million tonnes produced in 2017 and it is the most drought resistant of all major crops. It is by far the most important crop in Morocco, with 7.3 million tonnes produced in 2018, compared to 2.8 million for barley and just 118 thousand for maize. Despite considerable year-to-year variation, both production and yields have increased over time, with the typical yield currently around 2 tonnes/ha. There has been considerable variation in production due to droughts, with 2016 seeing just 2.7 million tonnes, compared to 8 million the previous year, but total production has increased significantly over time. Wheat production from the year 1980 to the present is displayed in figure 1, FAOSTAT. Due to the long, hot, arid summers, cereal crops are planted following the winter rains and harvested in the spring, with early November being the typical seeding date (Oweis and Hachum, 2012).

1. *Historical wheat production in Morocco, taken from FAOSTAT, Food and Agriculture Organisation of the United Nations*



2. *Map of Morocco showing average rainfall (Pala et al., 2011)*

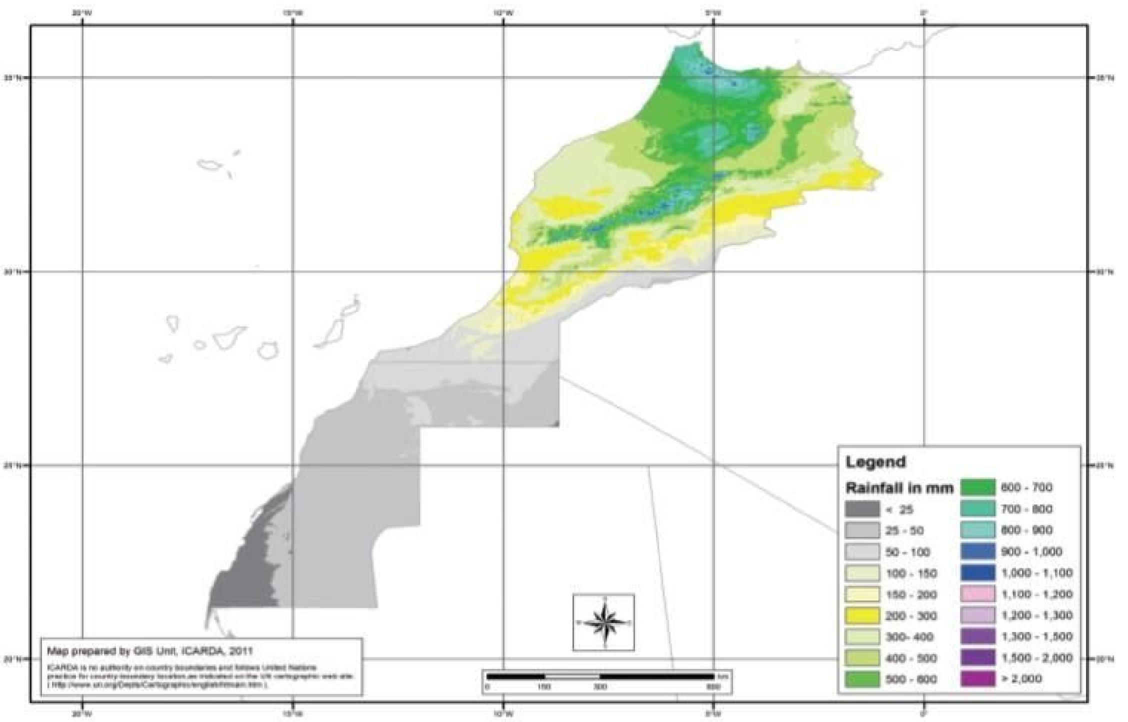


Figure 3. Rainfall zones of Morocco.

Much agricultural land in Morocco may be defined as dryland agriculture, defined as having growing period between 1 and 179 days. This includes some 40% of the world's surface but excludes true deserts, where no agriculture is possible. (FAO, 2008). Wheat in Morocco is mostly rainfed and grown on marginal land with soil quality and rainfall only just sufficient to support agriculture (FAO, Morocco country guide). While only 20 to 25% of cropland is irrigated in Morocco, it contributes 65% of the monetary value of crops, due to the poor productivity of rainfed agriculture (Taheripour et al., 2020). According to information from the World Bank (2020) agriculture makes up around 12% of Morocco's GDP, making both food production and the economy highly vulnerable to water shortages.

A review of case studies by ICARDA found a significant gap between potential and actual yields in Morocco, with mean potential yield being between 61 and 153% greater than typical yields, as shown in figure 3. (Pala et al., 2011). Merchouch was among the more productive areas, with typical wheat yields of 3.1 ton/ha (above the national average). However the potential yields were estimated at 5.23 ton/ha, 68% higher than actual yields.

3. *Gap between actual and potential wheat yields in Morocco, by regions (Pala et al. 2011)*

Region	Rainfall (mm)	Potential yield (kg/ha)	Farmers' yield (kg/ha)	Yield gap (kg/ha)
Loukos	> 600	8560	4700	3860
Douyet	450–600	5400	3350	2050
Marchouch	350–450	5230	3100	2130
Settat	250–350	4550	1800	2750
Tessaout	< 250*	6270	3500	2770

Source: Miloudi Nachit, durum wheat breeder, ICARDA.
*Irrigated

2:3. CO_2 enrichment

While increased heat and moisture stress are expected to negatively affect crop yields in Mediterranean and semi-arid climates, the increased concentration of atmospheric carbon dioxide (CO_2) is expected to increase yields by making more carbon available for photosynthesis. This is known as the CO_2 fertilisation or enrichment effect, and many studies project it to have the potential to mitigate some of the damage caused by increased heat and drought stress (Liu et al., 2018; Rosenzweig et al. 2014). It has been studied in Free-Air Carbon Dioxide Enrichment (FACE) trials, which expose the plant to elevated CO_2 concentrations in open-air field trials, so giving the most natural response possible. However there is considerable uncertainty as to the extent of this effect, which will be assessed and studied in detail over the course of this study.

2:4. Supplemental Irrigation

Supplemental irrigation (SI) involves only irrigating the crop when rainfall is insufficient to allow plant growth. SI is applied to crops which could normally produce a yield without SI, and it is timed for the most crucial stages in development such as grain-filling and anthesis (Oweis and Hachum, 2012). It should achieve the optimum moisture level between field capacity and permanent wilting point. The addition of small amounts of SI has been shown to dramatically increase yields of rainfed crops in rainfed wheat in dryland agriculture (Oweis, 1997). Wheat is most sensitive to water stress during anthesis; field trials carried out by Boutfirass (1990, 1997) found that irrigation was effective when applied during the early stages of development, again during anthesis and finally during the early grain filling period. Crucially SI has been demonstrated to dramatically increase the WUE efficiency of crops (Oweis and Hachum, 2006). In Morocco and much of the surrounding area water is the key limiting factor in agriculture, so the attractions of irrigation techniques which can boost productivity with relatively little water are obvious.

3: ICARDA field trial

3:1. Merchouch station

ICARDA has carried out on-going field trials on wheat at Merchouch since 2015, with the aim of evaluating the performance of various different genotypes. The trials assessed in this study examined ten genotypes of Durum Wheat (DW) and ten of Bread Wheat (BW).
The crops were mechanically planted with a spacing of spacing of 0.2m and a seeding rate of 150kg/ha. No mulches or any agronomic practices affecting surface run-off were applied. The ground-water table at the site is 150 meters below the surface and did not affect the trial. No weeds or pests were present, the irrigation water had low salinity and adequate fertiliser was applied, so for the purposes of the trial weeds, salinity and fertility may be considered non-limiting.

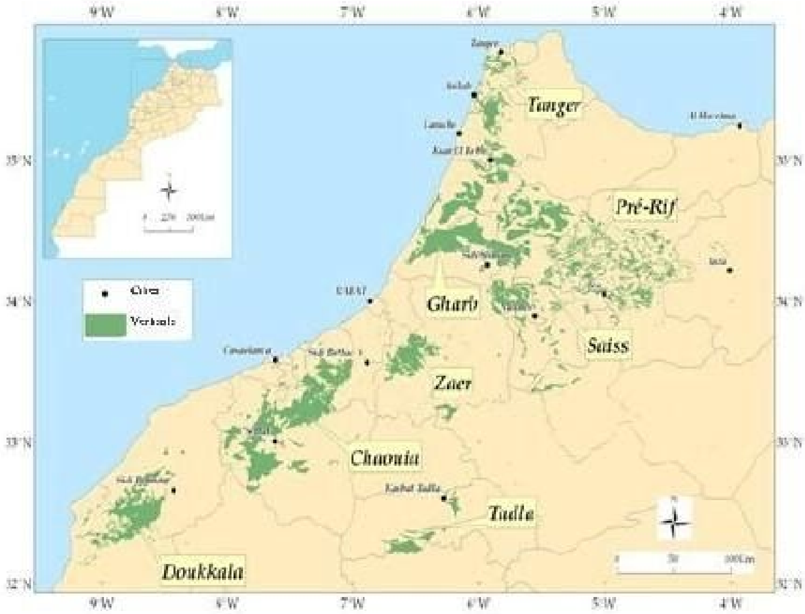
For DW two different seeding dates were examined, one in mid-November (SD1) and another in late December (SD2). Two different water regimes were applied, rainfed (conventional) cropping, and supplemental irrigation (SI), in which enough water was applied to bring soil moisture content to 100% of field capacity (FC). All irrigation was supplied through drip irrigation. For bread wheat only one seeding date was used, but four different water regimes were applied: rainfed, irrigation to 100% FC, to 66% FC and to 33% FC. All trials were replicated three times and mean and standard deviation for yield and total biomass were calculated.

Merchouch station is situated 70 km south-east of Rabat (33°36’57.1’’N 6°43’02.1’’W) at an elevation of 390 meters (ICARDA / Barisani, 2019). As with most of Morocco’s agricultural areas, Merchouch has a Mediterranean climate. The average annual temperature for the site is 18°C, the average annual rainfall is 405mm, almost all of which falls from late Autumn to early Spring, and the average reference evapotranspiration (ETo) is 2.88 mm per day (Barisani / ICARDA, 2019). Daily weather data is recorded at the site, and for the two seasons examined, this has been grouped by growing season (from November to June).

3:2. Soil at Merchouch

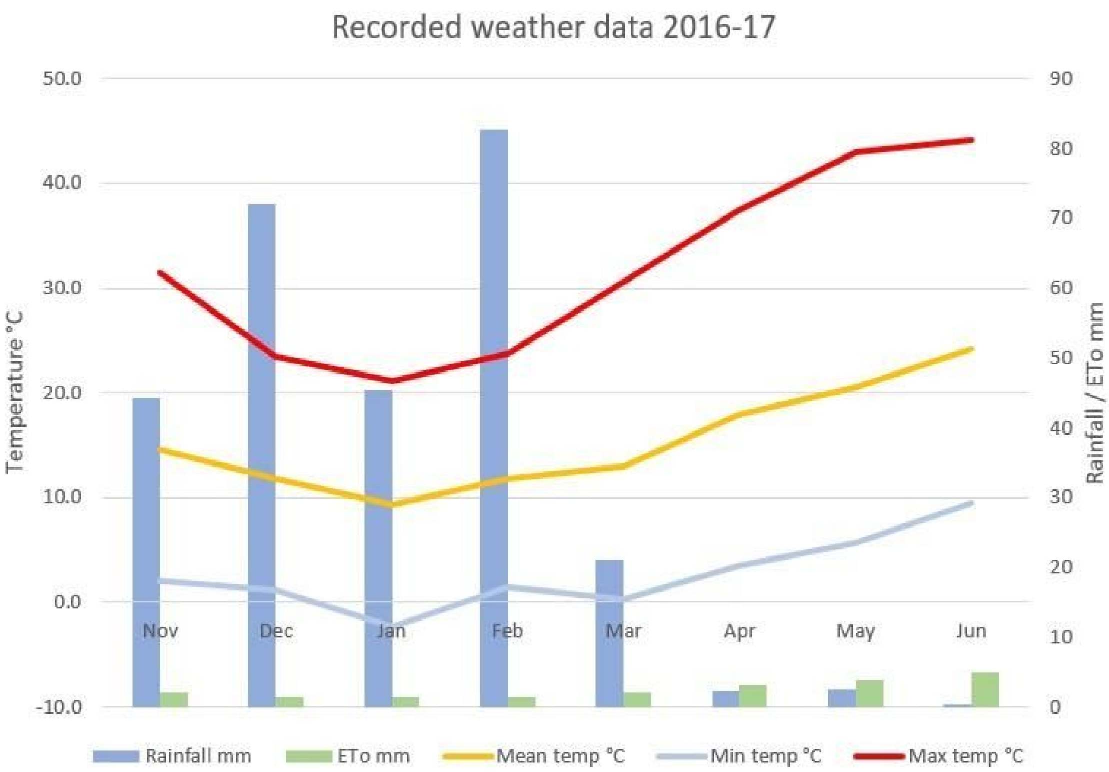
The site has a shallow clay soil, with a typical depth of 0.6 meters over three horizons. It is a Vertisol, of which there are 1 million hectares in Morocco, the distribution of which are shown in figure 4. World-wide there are thought to be around 308 million hectares of Vertisols, located in 76 countries. The majority of these were in Australia, (70 million ha.), India (60 million ha.) and Sudan (50 million ha.) (USA-SCS, 1994). They are found in many climatic zones but are most abundant in tropical and semi-arid regions, and Africa accounts for 35% of currently known Vertisols (Ahamd and Mermut, 1996). Vertisols, also known as Tirs in Morocco, are characterised by a high content of expansive clay, which tends to crack during drier years. Physically they appear as dark or black clays.

4. *Map of Morocco showing distribution of Vertisols (Moussadek, 2014)*

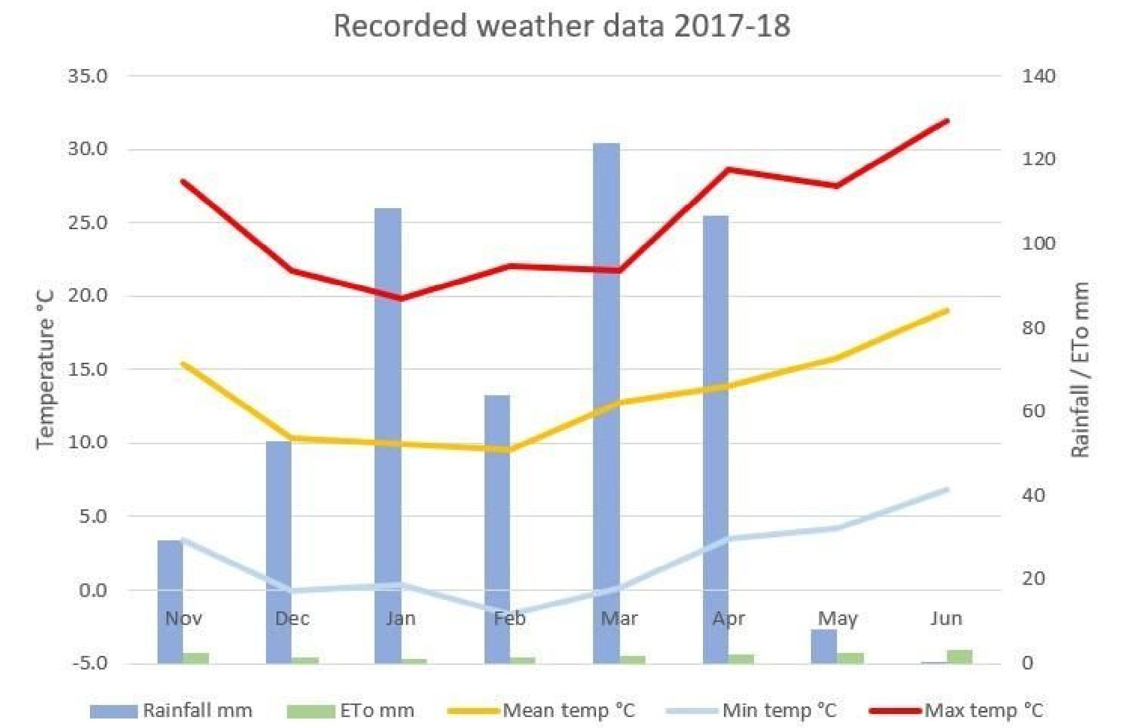


3:3. Weather data comparison

5. *Recorded weather data at Merchouch station for 2016-17 season*



6. *Recorded weather data at Merchouch station for 2017-18 season*



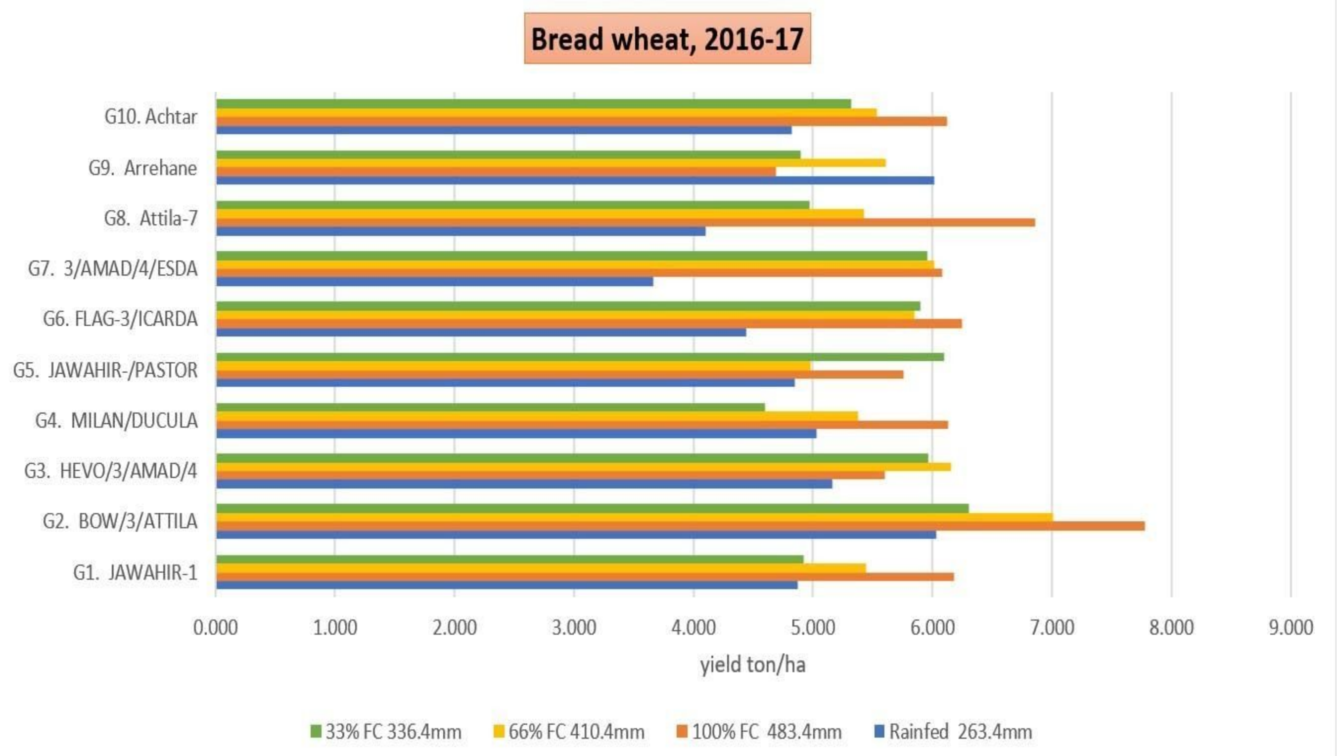
It can be seen in figures 5 and 6 that for all the crucial climate parameters relevant to yield, 2016-17 (season 1) experienced much greater stress than 2017-18 (season 2). Crucially, over the course of the growing season (November to June) season 1 received 263.4 mm, while season 2 received 493.4 mm, with the typical annual average being 400mm.

Similarly ETo was much higher in season 1, with an average of 5.02 mm compared to 3.05 mm, 66% higher. Season 1 had one day in June when ETo exceed 8mm, and thirty-nine between late April and June when it exceeded 4mm, while season 2 had just one day when it exceeded 4. The maximum temperature in season 1 was 44.1°C compared to just 32°C in season 2. Season 1 had seven days in which the maximum temperature was over 40°C, and thirty-two where it exceeded 30°C, while season 2 had just four days when the temperature exceeded 30°C. For both seasons minimum temperature only dropped below freezing on a very few nights in winter, so the effect of cold stress on yield may be considered negligible. It is therefore clear that much greater heat and water stress was experienced by the crops in season 1, as reflected in the universally lower yields and total biomasses.

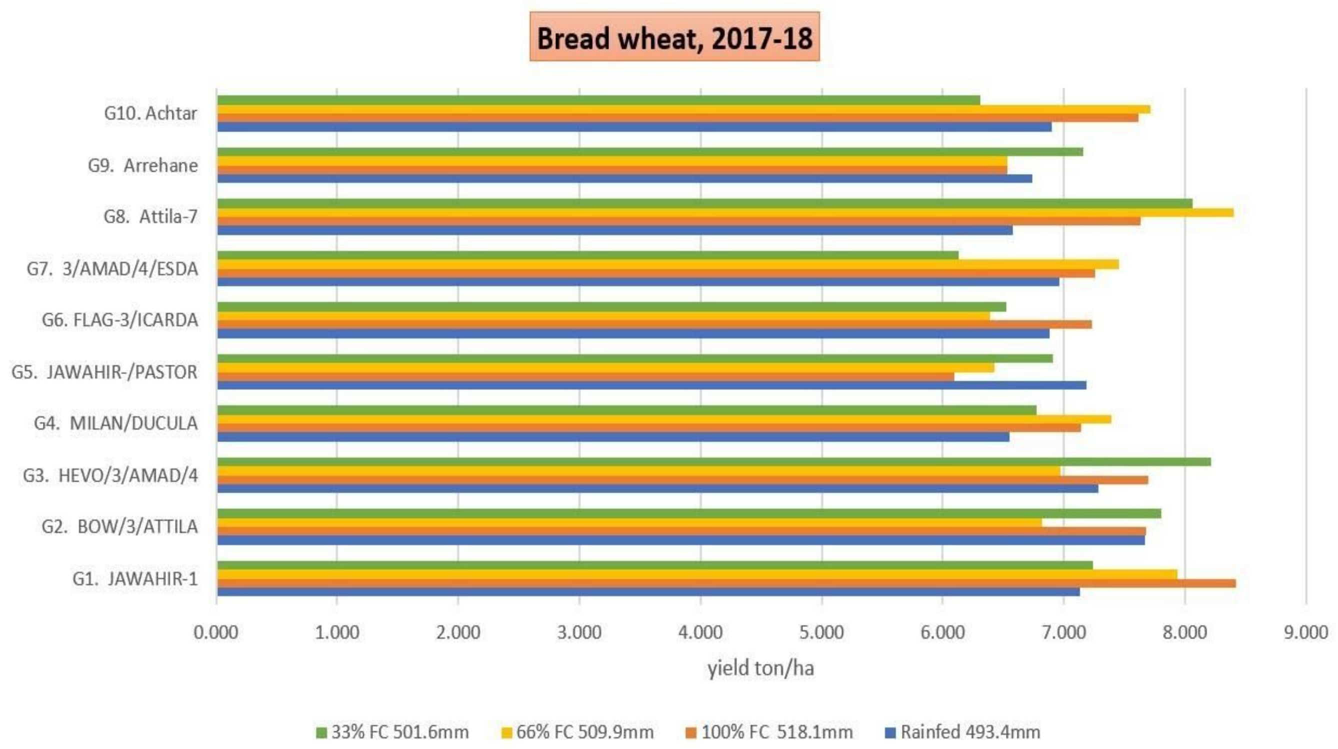
For both seasons, there was a difference of two degrees in mean temperature for the SD1 period (mid-November to end of May) and SD2 (mid-December to end of June). For 2016-17 these figures were 14 and 16°C respectively, and for 2017-18 they were 12.3 and 13.5°C.

3:4. Bread wheat overview

7. Yields for bread wheat from field trial 2016-17



8. Yields for bread wheat from fields trial 2017-18



The yields from the bread wheat trials are displayed in figures 7 and 8. A strong positive correlation between average yields and water applied was observed, with a correlation co-efficient of 0.940 and a co-efficient of determination (R^2) of 0.883. The average yield in the 2016-17 season was 4.901 ton/ha, with a standard deviation of 0.707 across the genotypes. The average yield in 2017-18 was much higher, at 6.988 ton/ha, with a lower standard deviation of 0.324, with every individual genotype also having a higher average yield than in 2016-17. The much greater rainfall in 2017-18 season seemed to result not just in higher yields but also a more stable performance across the genotypes.

In 2016-17 the 100% FC irrigation was considerable, as nearly as much water was used in irrigation (220mm) as there was rainfall. The average yield for 100% FC irrigation was 6.146, 12% below the yield in rainier season, while the standard deviation was 0.758, suggesting that SI in a dry year still cannot bring yields above the level of a wet season and that the various genotypes respond to irrigation differently. The much greater heat stress experienced may also account for the much lower yields in 2016-17, and why yields could not match those of 2017-18 even when the irrigation water nearly matched that which fell as rain in the following season.

In season 1 a close correlation between yield and total water applied is observed, with the highest yields being for those which received the most water, although with several exceptions. A similar correlation was observed for both biomass and harvest index; the more water applied, the greater the total biomass and harvest index.
Due to the much higher rainfall in 2017-18, the levels of irrigation were much lower relative to the rainfall, with only 24.7 mm of water applied during the maximum irrigation. SI resulted in increased yields, with the yield for 100% FC being 7.329 tonnes, compared to 6.988 for rainfed. Considerable variation among the genotypes was still observed for their yield response to SI.

9. *Bread wheat genotypes, ranked by yield*

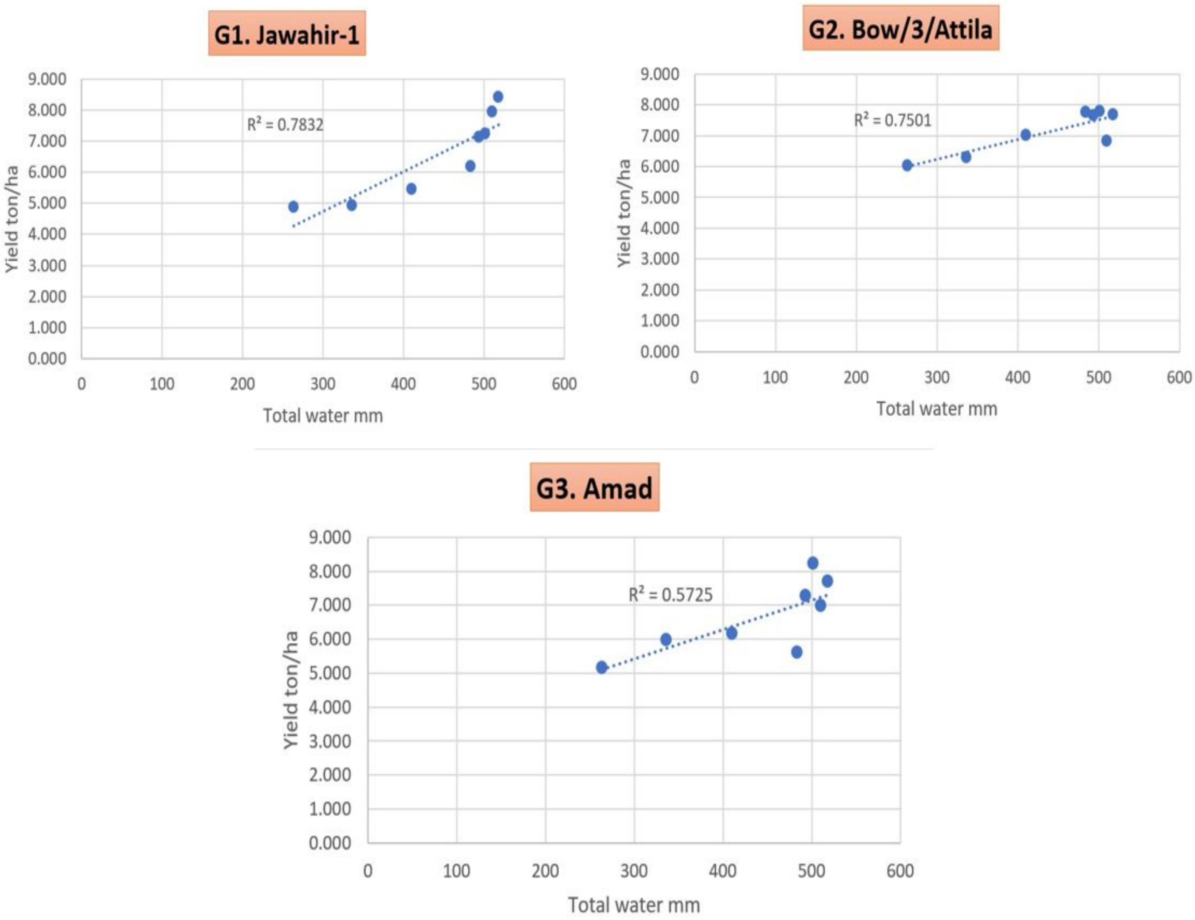
Ranked by yield, averaged across all water regimes for both seasons	
Genotype	**Yield ton/ha**
G2. BOW/3/ATTILA	7.135
G3. SERI.1B//KAUZ/HEVO/3/AMAD/4	6.632
G1. JAWAHIR-1	6.520
G8. Attila-7	6.504
G10. Achtar	6.293
G7. 3/AMAD/4/ESDA	6.192
G6 FLAG-3/ICARDA-SRRL-5	6.184
G4. MILAN/DUCULA//AL-ZEHRAA-1	6.125
G5. JAWAHIR-1/3/PASTOR/SERI//PFAU	6.037
G9. Arrehane	6.023

10. *Yields of best performing bread genotypes, showing standard deviations*

2016-17 Total water (inc. rain) →	Rainfed 263.4 mm		100% FC 483.4 mm		66% FC 410.4 mm		33% FC336.4 mm	
Genotype ↓	Yield t/ha	Std dev	Yield t/ha	Std dev	Yield t/ha	Std dev	Yield t/ha	Std dev
G1. JAWAHIR-1	4.875	0.147	6.183	0.637	5.442	0.349	4.925	0.289
G2. BOW/3/ATTILA	6.033	1.208	7.775	1.542	7.008	0.633	6.308	1.424
G3. AMAD	5.167	0.370	5.600	1.263	6.158	0.479	5.967	0.617
2017-18 Total water (inc. rain) →	Rainfed 493.4 mm		100% FC 518.1 mm		66% FC 509.9 mm		33% FC 501.6 mm	
Genotype ↓	Yield t/ha	Std dev	Yield t/ha	Std dev	Yield t/ha	Std dev	Yield t/ha	Std dev
G1. JAWAHIR-1	7.133	1.115	8.417	0.174	7.942	1.161	7.242	0.587
G2. BOW/3/ATTILA	7.667	0.838	7.675	0.814	6.817	1.215	7.800	0.391
G3. AMAD	7.283	1.123	7.692	0.698	6.975	1.220	8.217	0.190

In figure 9 the yields of the genotypes average over both seasons and all water regimes are displayed. The three highest yielding were Jawahir-1, Bow/3/Attila (shortened to Attila) and Seri/1B//kauz/hevo/3/amad/4 (shortened to Amad), and these were selected for modelling in AquaCrop over the second part of the study. The relationship between water and yield for these genotypes is sown in figure 11.

11. *Regression analysis of water / yield correlation of the three highest yielding genotypes*



3:5. Jawahir-1

Jawahir-1 showed an increase in yield under 100% FC irrigation in season 1, with the difference between rainfed and 100% FC being nearly twice the standard deviation of 100% FC, suggesting the increase is not simply due to measurement error. It also seemed to respond more favourably to SI in season 2 than any other genotype, with its average yield of 8.417 under 100% FC, the highest of all the BW trials. All three replications had high yields under 100% FC irrigation in this season with a standard deviation of just 0.174. However standard deviations for other water regimes, including rainfed, were around 15%, with some replications matching the average yield of 100% FC. Therefore it is uncertain that the benefits of SI in a wet season are statistically significant, and further trials will be necessary to understand it. A regression analysis of the relationship between yield and water found Jawahir to have a strong correlation, with correlation co-efficient of 0.884 and an R^2 of 0.783.

3:6. Attila

Attila had the highest average yields by a considerable margin, particularly in the dry season 2016-17, suggesting that it may be among the most drought resistant of all the genotypes. It also responded favourably to irrigation under water stress; when irrigated to 100% FC in the dryer season 1 its yield of 7.775 was by far the highest for this season, and actually exceeded its rainfed yield in season 2. However for this irrigation one replication had a much lower yield than the others, meaning its typical yield under 100% FC might be even higher and further study will be necessary to understand its response to irrigation. When subject to SI in the wetter season 2 it showed little increase in yield. It had strong correlation between water and yield, with a correlation co-efficient of 0.866 and an R^2 of 0.750.

3:7. Amad

When Amad was irrigated to 100% FC during the dry season 1 it seemed to show very little response. However a single failed replication brought the average yield down and the average between the other two replications was 6.4. Further trials will be necessary to understand its response to rainfall and irrigation, and why one replication failed. Amad increased its yield when subject to SI in season 2, although not as much as Jawahir-1, and Amad had the lowest standard deviations under 100 and 33% FC. Amad also consistently displayed among the highest harvest index of all genotypes over all the trials (see appendices 1A and 1B). It displayed moderate correlation between water and yield, with a correlation co-efficient of 0.756 and an R^2 of 0.572.
These three genotypes did display some instability, with higher standard deviations among the replications when compared to some of other, lower-yielding genotypes, particularly in rainfed trials. However, even in their lowest yielding replications these genotypes still often had yields above the overall average for all genotypes. Further field trials with more

replications will be necessary to fully understand their response to levels of rainfall and irrigation, and other environmental stressors.

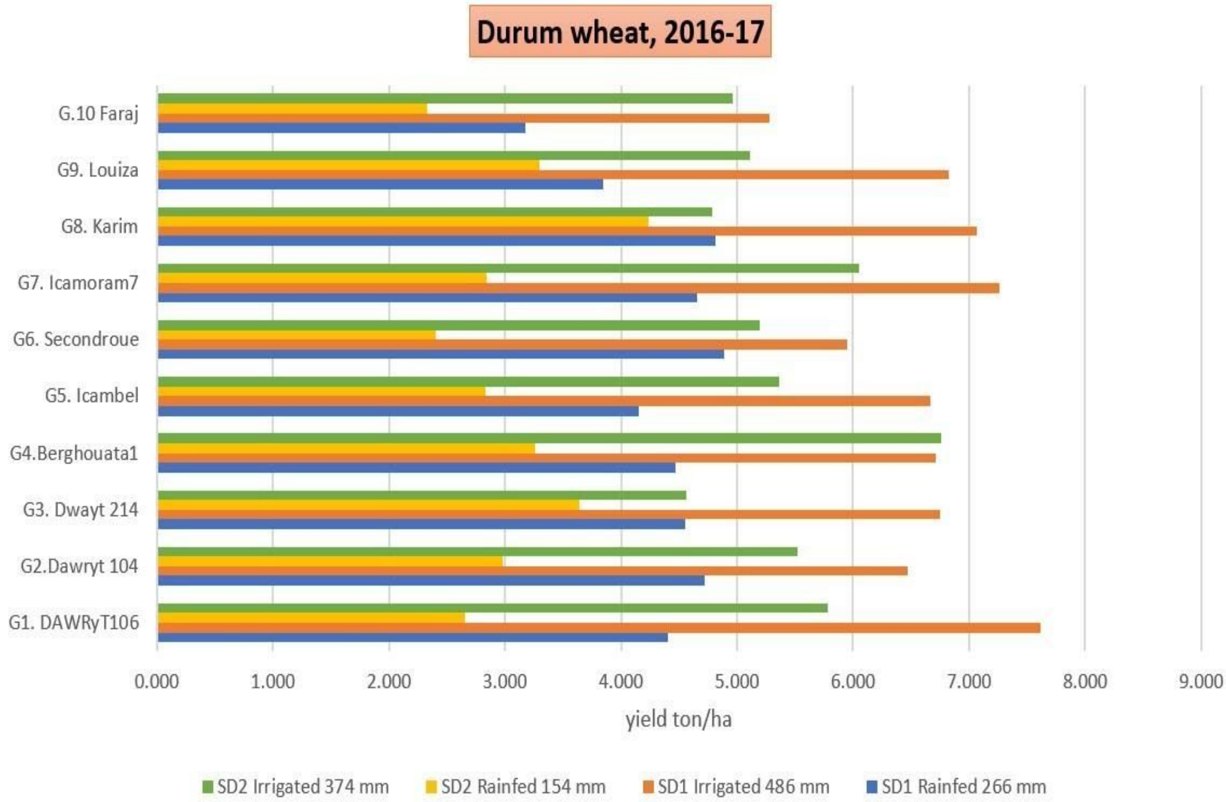
3:8. Durum wheat overview

The yields for the durum wheat genotypes are shown in figures 12 and 13. For durum wheat, as with bread wheat, a positive correlation was observed between yield and water, although weaker than for bread wheat with a correlation co-efficient of 0.825 and an R^2 of 0.680. In the dry season 1, average rainfed yields for the first seeding date, which received 266mm of water were 4.368 ton/ha, while the second seeding date which only received 154mm had yields of 3.048 ton/ha. The irrigated crops in the first seeding date received 486mm of water (82% more than rainfed) and yielded 6.66 ton/ha, an increase of 52%. The irrigated crops in the second seeding date received 374mm of water (an increase of 142%) and yielded 5.4 ton/ha, an increase of 77.5% over rainfed.

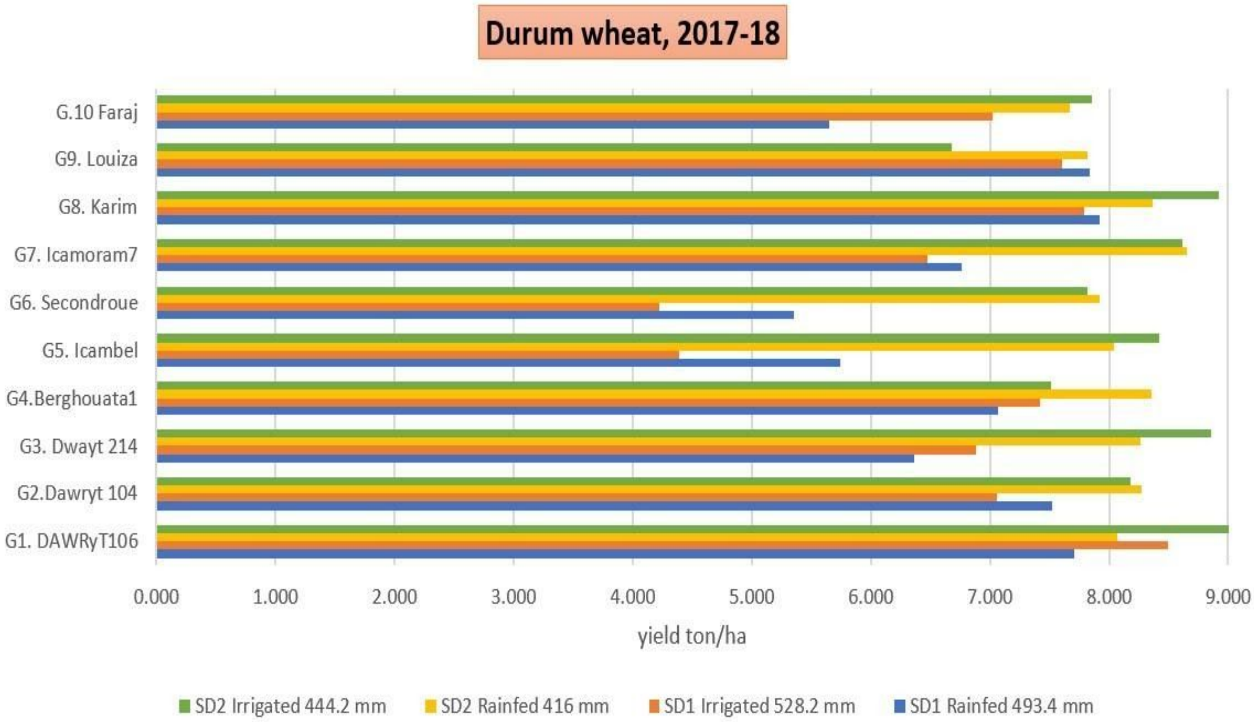
It therefore clear that in a dry season the optimal planting date is the typical one of mid-November, and that a mid-December planting date would result in drastically decreased yields, even when heavily irrigated. However it is difficult to forecast with certainty the rainfall over an entire growing season, making it difficult to determine the optimal sowing date in advance.

For the wet season 2017-18, 493.4mm of water fell as rain during the period of SD1, while irrigated crops in SD1 received a total of 528.2mm. The average yield for rainfed crops was 6.793 ton/ha, while for irrigated it was 6.737, a negligible improvement. Due to the cool, wet conditions in the 2017-18 season, the second seeding date was not subject to greater heat stress than the first, so of the measured variables, difference in water probably accounts for most of the difference in yield.

12. Yields for durum wheat from field trial 2016-17



13. *Yields for durum wheat from field trial 2017-18*



For SD2 416mm fell as rain, while irrigated crops received a total of 444.2mm, an increase of 6.7%. The yield for rainfed crops in SD2 was 8.143 ton/ha while for irrigated it was 8.248 ton/ha, again a negligible difference but a considerable improvement for both of 22% over the earlier seeding date. From the results of season 2, it seems that for these genotypes the optimum amount of water is between 416 and 444.2 mm, while water in excess of this can cause yields to decline. It is possible that the heavy rains would have resulted in soil saturation, causing aeration stress and consequent reductions in yields.

Several durum genotypes, notably DAWRyT106, experienced significant yield improvements under SI in season 2, but Icambel and Secondroue actually declined in yield significantly when irrigated. Both of these genotypes had much higher yields for SD2, and Icambel also increased its yield when irrigated for this sowing date. The values for total biomass and harvest index also had a seemingly inconsistent relationship with water. In particular DAWRyT106 decreased its HI (but increased biomass and hence yield) when irrigated in SD1 2017-18, but increased its HI while maintaining the same biomass when irrigated for SD2 (appendices 2A and 2B). This is difficult to explain and it is possible that factors not recorded in the field trial data caused these seemingly inconsistent responses to irrigation and sowing date; for example freak weather events such as hailstorms can destroy crop canopy, thus distorting the measurements of biomass and HI. One replication for the rainfed SD1 trial of DAWRyT106 had much lower biomass and yield than the others; hence the increase in biomass and yield for the irrigated trial may be exaggerated by this failure.

The highest yielding genotypes across all seeding dates, water regimes and seasons were the ICARDA derived DAWRyT106 and the locally popular Karim variety. The other local variety, Faraj, had consistently among the lower yields.

3:9. DAWRyT106

DAWRyT106 was observed to respond favourably to irrigation, with yields increasing for irrigated trials for both seeding dates. SD2, in spite of receiving less rainfall than SD1, had the highest yields, with the highest yield of any genotype in all of the trial of 9.671 ton/ha being achieved for the irrigated trial for the second seeding date, which received 444.2mm of water. All three replications had high yields in this case, with a standard deviation of just 0.082, and in all cases there was less variation among replications which the crops in were irrigated. The second highest yield for this genotype was 8.492 ton/ha, for the irrigated trial for SD1 in 2017-18, which also received the most water, 528.2mm.

During the much drier 2016-17 season, the second seeding date resulted in lower yields, even with irrigation, while the best yield of 7.617 tonnes was achieved by the irrigated trial for the first seeding date. HI remained below that reported in the wetter 2017-18 season for all trials in 2016-17 (appendices 2A and 2B). In a linear regression analysis of yield and water applied, it had an R^2 of 0.824 and a correlation co-efficient of 0.907.

3:10. Karim

Karim was observed to have among the highest yields for all trials. In general, across both seasons yield and biomass increased as more water was added, however the maximum yields were achieved by the second seeding date of 2017-18, suggesting an optimal water amount of around 450mm. During 2017-18 the yield of Karim responded negligibly to irrigation during both seeding dates. However irrigation during SD1 in 2016-17 resulted in significantly increased yields, from 4.658 to 7.067 ton/ha. Irrigation after the second seeding date brought about only a small improvement in yield, from 4.238 to 4.783 ton/ha. In a linear regression analysis of yield and water applied, it had an R^2 of 0.643 and a correlation co-efficient of 0.801.

Attempts to calibrate AquaCrop for Karim and DAWRyT106 proved unsuccessful, and the model was unable to simulate their yields as recorded in the field trials, in particular their increased yields under the later seeding date in 2017-18. Therefore the three highest yielding bread genotypes were focused on.

3:11. Final comments

WUE is typically measured as yield per unit of water transpired, but unfortunately in the ICARDA trial only data on how much water was applied and not transpired was available, and WUE was calculated from total water applied. There can be considerable difference between water applied and transpiration and so the calculated WUE from the ICARDA trials should be taken with caution and is not directly comparable to many others in the literature.

For both durum and bread wheat, yields far exceeded those typical in Morocco, even in the lowest yielding average trial. These trials were carried out under controlled conditions with perfect fertility and without the presence of pests of diseases. Therefore they are unlikely to represent the yields of these genotypes under current Moroccan agronomic practices. However, they provide a useful indication of theoretical maximum yields, and so highlight how much yields may be improved in the future.

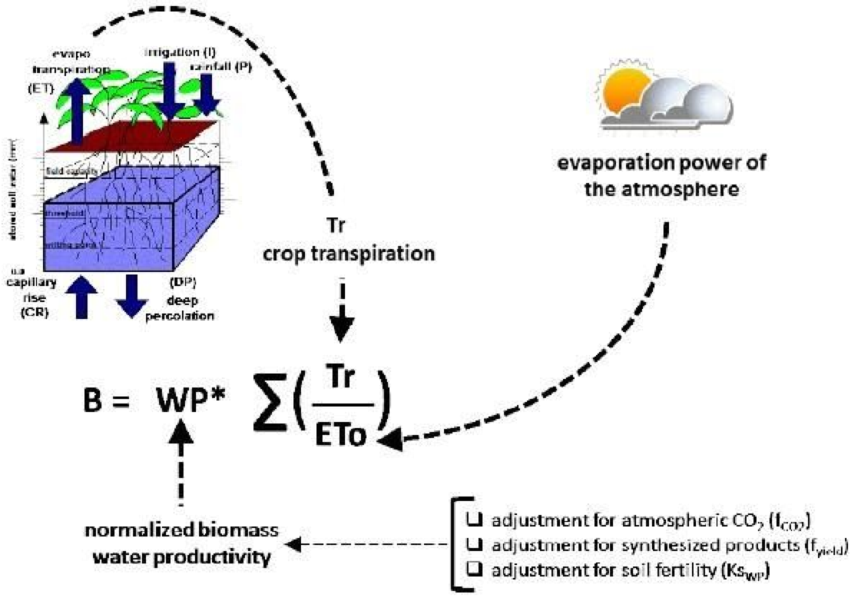
4: AquaCrop

4:1. calculation of yield

AquaCrop was designed by the FAO as a simple, practical and user-friendly model aimed at farmers and irrigation managers, economists and water engineers. It requires a relatively small number of input parameters which are easily obtainable for many different crops and sites around the world, unlike previous crop models, making it applicable to a wide variety of different situations (Steduto et al., 2009).

It requires data on soil, weather and crop variables to calculate productivity, as well as any management practices such as fertilisation or irrigation. It proceeds in several steps. Firstly percentage canopy cover (CC%) is calculated, based on crop parameters as well climate and soil factors which influence water available for growth. Crop transpiration is calculated by multiplying CC% by the crop's transpiration co-efficient (Kctr). From transpiration biomass is calculated, in accordance with the crop's water productivity (WP), as displayed below.

14. *Calculation of biomass in AquaCrop, where B is biomass, WP is normalised water productivity and* Σ *TR is cumulative transpiration*



The equation in figure 14 is central to AquaCrop and expresses how biomass is calculated. Normalised water productivity (WP*) is unit of biomass per unit of cumulative transpiration, usually expressed as grams per square meters per millimetre of water transpired. Studies have shown that the relationship between biomass produced and water consumed is strongly linear and approximately constant for a given species, once normalised for CO_2 concentration and climatic conditions (Steduto et al., 2007). Normalised WP values for each crop are based on available measurements of biomass and transpiration in the literature. A distinction should be made between normalised WP, which is a constant characteristic of a crop, and WUE, or unit of yield per unit of water as transpired, which is a performance or efficiency indicator.

AquaCrop uses five climate parameters, CO_2 concentration, maximum temperature, minimum temperature, rainfall and reference evapotranspiration (ETo) to calculate crop growth. ETo is an important factor in determining crop transpiration in the above biomass equation. It is the estimation of evapotranspiration from a ‘reference surface’ under the particular climatic conditions of the day. The reference surface is a hypothetical grass crop with an assumed height of 0.12 meters, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23. ETo is calculated using an equation derived originally from Penman and Monteith and used by the FAO in the form shown below.

15. *The form of the Penman Monteith equation used by the FAO (Allen et al., 1998)*

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

ET_o reference evapotranspiration [mm day^{-1}],
R_n net radiation at the crop surface [MJ m^{-2} day^{-1}],

G soil heat flux density [MJ m^{-2} day^{-1}],
T mean daily air temperature at 2 m height [°C],
u_2 wind speed at 2 m height [m s^{-1}],
e_s saturation vapour pressure [kPa],
e_a actual vapour pressure [kPa],
e_s - e_a saturation vapour pressure deficit [kPa],
D slope vapour pressure curve [kPa °C^{-1}],
g psychrometric constant [kPa °C^{-1}].

In AquaCrop climate files ETo data may either be directly inputted, or if this is not available, it may be calculated from windspeed, solar radiation, relative humidity and other factors affecting evapotranspiration, in accordance with the above equation. The ETo value for each day determines how much evapotranspiration may be expected over the course of the day and AquaCrop uses it to calculate how much biomass will be produced on that day. In the final step yield is calculated as a percentage of biomass, based on the crop's reference harvest index after adjustment for water stress. Therefore *Yield = Biomass x Harvest Index*

4:2. Crop parameters

AquaCrop has pre-loaded crop files for most crops, including wheat, which contain most of the parameters required to run them in the programme, based on typical values reported in the literature. These values are known as *conservative* parameters as they vary little between varieties, locations and climates. They include values such as reference water productivity and these values should not be altered without reliable experimental data to justify the changes. Non-conservative parameters vary depending on management practices and varieties, and are mostly concerned with phenological development, such as time from seeding to emergence. Harvest index is also treated as a non-conservative parameter when there is experimental data to support this change.

4:3. Thermal time and stress parameters

An important concept within AquaCrop is thermal time. Growing degree days are units of time based on the temperature of the calendar days based on periods when the crop will grow. Among the conservative parameters of a crop are its maximum and minimum growth temperatures, above and below which it does not grow; these are 26°C and 0°C for wheat, respectively. When the growing degree day for wheat is calculated, it will not grow below 0°C, it will increase its growth with warmer temperatures but show no further increase above 26°C (FAO, irrigation and drainage paper 66). By converting to thermal time, the crop will only proceed in its phenological stages, *growing degree days* when the temperature is within these thresholds.

Crops respond to water stress through reduction of canopy growth, stomatal closure, accelerated canopy senescence and changes in HI. These are described as percentages of soil water which may be depleted before a stress response is induced, and are conservative parameters. HI may be negatively affected by severe water stress, but positively affected by moderate stress resulting from inhibited leaf expansion and more biomass being partitioned to grain or fruit.

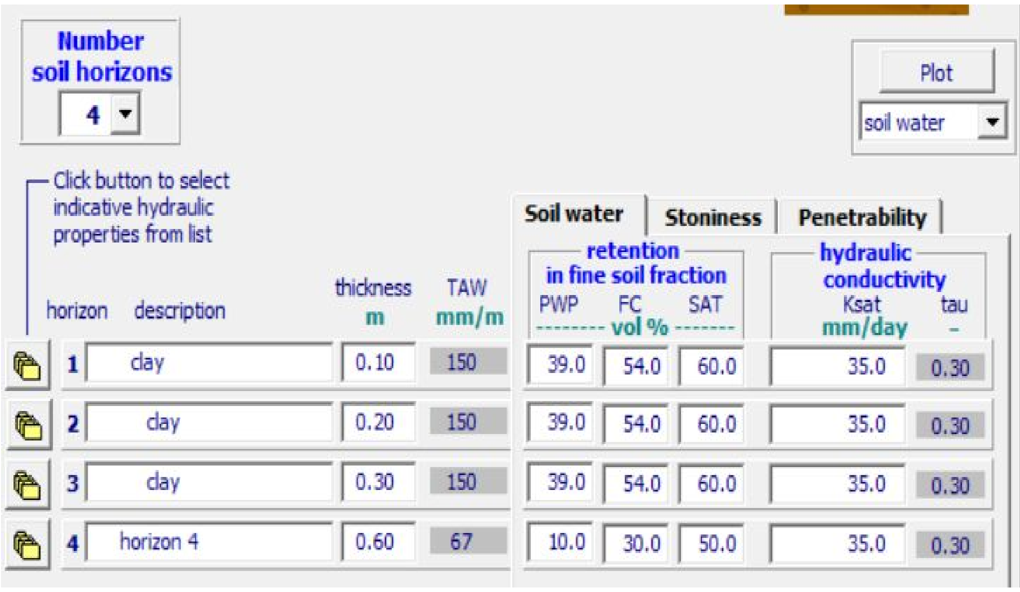
4:4. Calibration in AquaCrop

AquaCrop was calibrated and validated with the observed data from the field trial results. As precise measurements on canopy development were not available, the default parameters for wheat were used, and these were altered on a trial and error basis until a close match with both seasons was achieved. Only non-conservative parameters related to management and life-cycle were altered, and those used for all three genotypes are compared to the default wheat values in figure 16. The soil at Merchouch is known to be 60% clay and there have been tests to determine soil moisture content at field capacity, permanent wilting point and saturation. However these tests were not conclusive, with two different labs giving very different results. Due to the uncertainty, the indicative values in AquaCrop for a clay soil of 0.6 meters depth were used, subject to minor adjustments, as shown in figure 17.

16. *Non-conservative crop parameters used for calibration of AquaCrop. The values for the ICARDA genotypes are shown compared to default values for wheat*

		ICARDA bread wheat genotypes		
Parameters	**Default wheat**	**G1. JAWAHIR-1**	**G2. BOW/3/ATTILA**	**G3. AMAD**
plants per ha	4500000	2250000	2250000	2250000
initial canopy cover	6.75%	3.38%	3.38%	3.38%
max canopy cover	96%	97%	93%	97%
canopy growth coefficient	4.9	6.2	5.9	6.2
canopy decline coefficient	7.2	7.2	7.2	7.2
days to emergence	13	15	11	15
days to max canopy	119	110	110	120
days to senescence	158	135	138	139
days to maturity	197	182	180	180
days to flowering	127	120	116	120
length of flowering	15	12	11	13
days building up HI	67	56	45	56
max root depth (m)	1.5	0.6	0.6	0.6
days to max root depth	93	90	91	90
reference harvest index	48%	36%	37%	40%
water productivity (kg/m2)	15	15	15	15
Kctr (transpiration co-efficient)	1.1	1.1	1.1	1.1
Sink strength	50%	20%	20%	20%

17. *Soil profile characteristics for Merchouch, as entered in AquaCrop*



AquaCrop only generates values for *dry* yield and biomass, and the ICARDA measurements were taken from samples with 15-17% moisture content. Therefore the yields for the ICARDA data were reduced by 16% before being compared to the AquaCrop outputs. Three statistical indicators were chosen to test the model, Root Mean Square Error (RMSE), Nash-Sutcliffe Efficiency (NSE) and Willmott's Index of Agreement (d), as shown in figure 18. Figure 19 compares the observed and simulated results using these three indicators, as well as displaying the difference between observed and simulated results and percentage error.

18. Formulas for three statistical methods used to compare observed and simulated yields

- Root Mean Square Error (RMSE) *measures the difference between observed and simulated values. A smaller RMSE value indicates smaller error and therefore closer agreement*

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (P_i - O_i)^2}{n}}$$

- Nash-Sutcliffe Efficiency (NSE) *calculates the ratio of error variance of simulations to variance of observations. NSE = 1 means a perfect agreement between model and observations, NSE = 0 means no agreement*

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} (O_i - \bar{O})^2}$$

- Willmott's Index of Agreement (d) *measures degree of model prediction error as a ratio of mean square error to potential error, d = 1 means perfect agreement, d = 0 means no agreement*

$$d = 1 - \frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} (|P_i - \bar{O}| + |O_i - \bar{O}|)^2}$$

P = simulated, O = observed, Obar = mean of observations, N = number of observations

19. *The yields simulated by AquaCrop shown compared to those observed in field trial. Field trial yields have been reduced by 16%*

Rainfed	Yield ton/ha		Difference	Standard	Prediction	NSE	RMSE	Willmott (d)
2016-17	Observed	Simulated	ob / sim	deviation ob.	error %			
G1. JAWAHIR-1	4.095	4.153	0.058	0.124	1.42	0.990711	0.03983	0.997580
G2. BOW/3/ATTILA	5.068	5.081	0.013	1.015	0.26			
G3. AMAD	4.340	4.375	0.035	0.311	0.81			
			Difference	Standard	Prediction	NSE	RMSE	Willmott (d)
2017-18	Observed	Simulated	ob / sim	deviation ob.	error %			
G1. JAWAHIR-1	5.992	5.963	-0.029	0.535	-0.48	0.967945	0.033774	0.991676
G2. BOW/3/ATTILA	6.440	6.410	-0.030	1.295	-0.47			
G3. AMAD	6.118	6.159	0.041	1.061	0.67			
Irrigated 100% FC			Difference	Standard	Prediction	NSE	RMSE	Willmott (d)
2016-17	Observed	Simulated	ob / sim	deviation ob.	error %			
G1. JAWAHIR-1	5.194	6.279	1.085	0.937	20.89	-2.44946	1.43405	0.462705
G2. BOW/3/ATTILA	6.531	6.735	0.204	0.704	3.12			
G3. AMAD	4.704	6.929	2.225	0.943	47.30			
			Difference	Standard	Prediction	NSE	RMSE	Willmott (d)
2017-18	Observed	Simulated	ob / sim	deviation ob.	error %			
G1. JAWAHIR-1	7.070	5.964	-1.106	0.146	-15.64	-4.2685	0.66666	0.319775
G2. BOW/3/ATTILA	6.447	6.413	-0.034	0.684	-0.53			
G3. AMAD	6.461	6.131	-0.330	0.586	-5.11			

Once calibrated AquaCrop was tested for its accuracy in simulating observed yields. As irrigation to 100% FC most frequently produced the highest yields which were identified as statistically significant, it was chosen as the irrigation regime to test. As shown in figure 19, AquaCrop was able to simulate rainfed yields in both seasons with a high degree of accuracy, with NSE and d values close to 1, and simulated values well within the range of the replications for each genotype. RMSE was 0.039 ton/ha in 2016-17 and 0.033 ton/ha in 2017-18, less than 1% of observed yields, indicating a very close match. In other studies AquaCrop was also found to accurately simulate crop yields in India, when tested with RMSE (Dubey, 2018). When tested with Willmott's index AquaCrop was found to accurately simulate wheat yields, with d values close to 1 (Kumar et al., 2014). AquaCrop was also found to accurately simulate wheat grain yields when tested with RMSE and Willmott's index in a semi-arid climate in Australia (Zeleke and Nendel, 2019).

AquaCrop was unable to accurately simulate the effects of irrigation for Jawahir and Amad, with very high prediction error percentages and negative values for NSE, but was reasonably accurate for Attila, with errors of +3.12% for season 1 and -0.53% for season 2. AquaCrop significantly overestimated yields under irrigation for the other two genotypes in the dry season 1. AquaCrop did not project any increase in yield under irrigation in season 2, but doubts as to the statistical significance of these values in the field data have already been discussed.

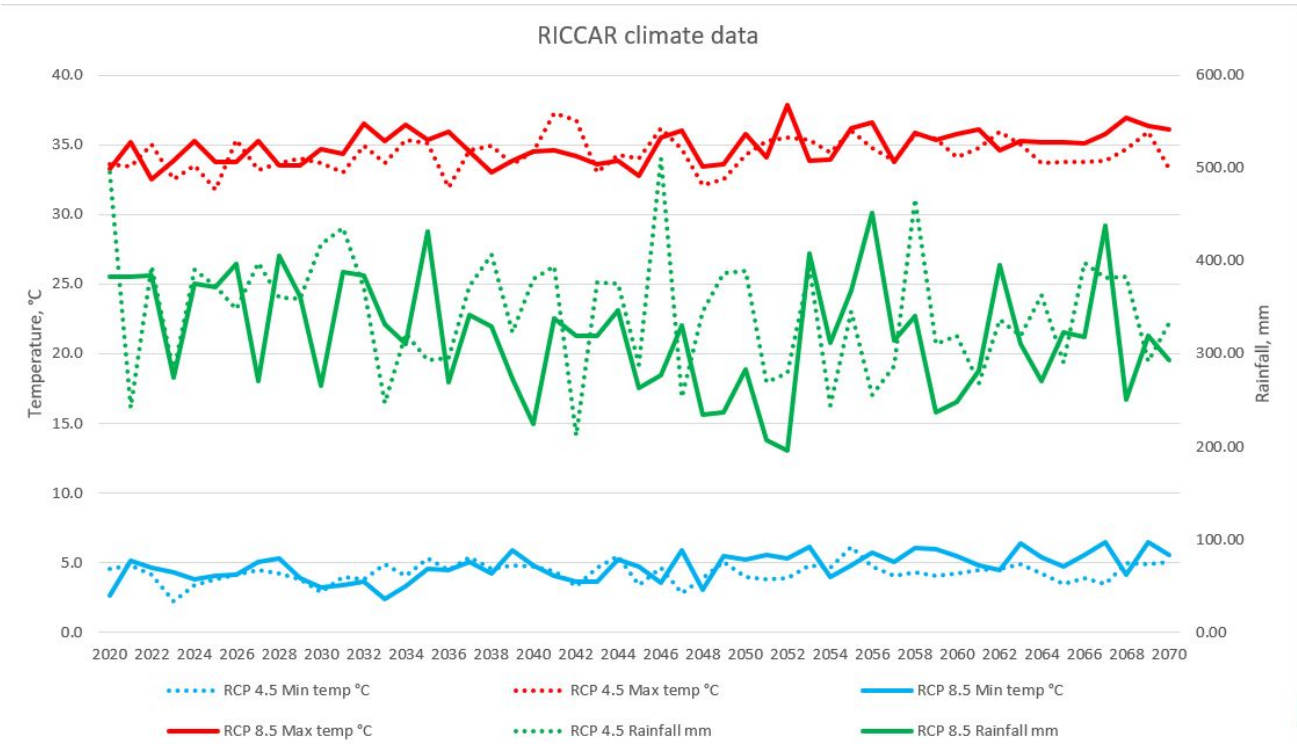
5: Climate simulation

5:1. RICCAR climate data

Since 2007 the Intergovernmental Panel on Climate Change bases future climate scenarios on Representative Concentration Pathways (RCPs), which represent a projected level of radiative forcing (difference between incoming and outgoing radiation to the earth) by the year 2100, due to a particular trend in greenhouse gas emissions. Climate models are enormously complex, and modern climate projections use an ensemble of different models to take into account uncertainties.

AquaCrop was run using downscaled climate data from the RICCAR ensemble of climate models for the period 2020 to 2070. RICCAR consists of the outputs of three GCMS (CNRM-CM5; SMHI-RCA4 and GFDL-ESM2M), downscaled to a resolution of $50km^2$ and bias-corrected for two different climate change scenarios (RCP 4.5 and RCP 8.5). Values for maximum and minimum temperature and rainfall were taken from the RICCAR models, and ETo was calculated based on historical averages for wind speed and solar radiation for the area. The projected rainfall and temperatures over the fifty year period for each RCP are displayed below.

20. *Projected temperatures and rainfall for RCP 4.5 and 8.5 compared*



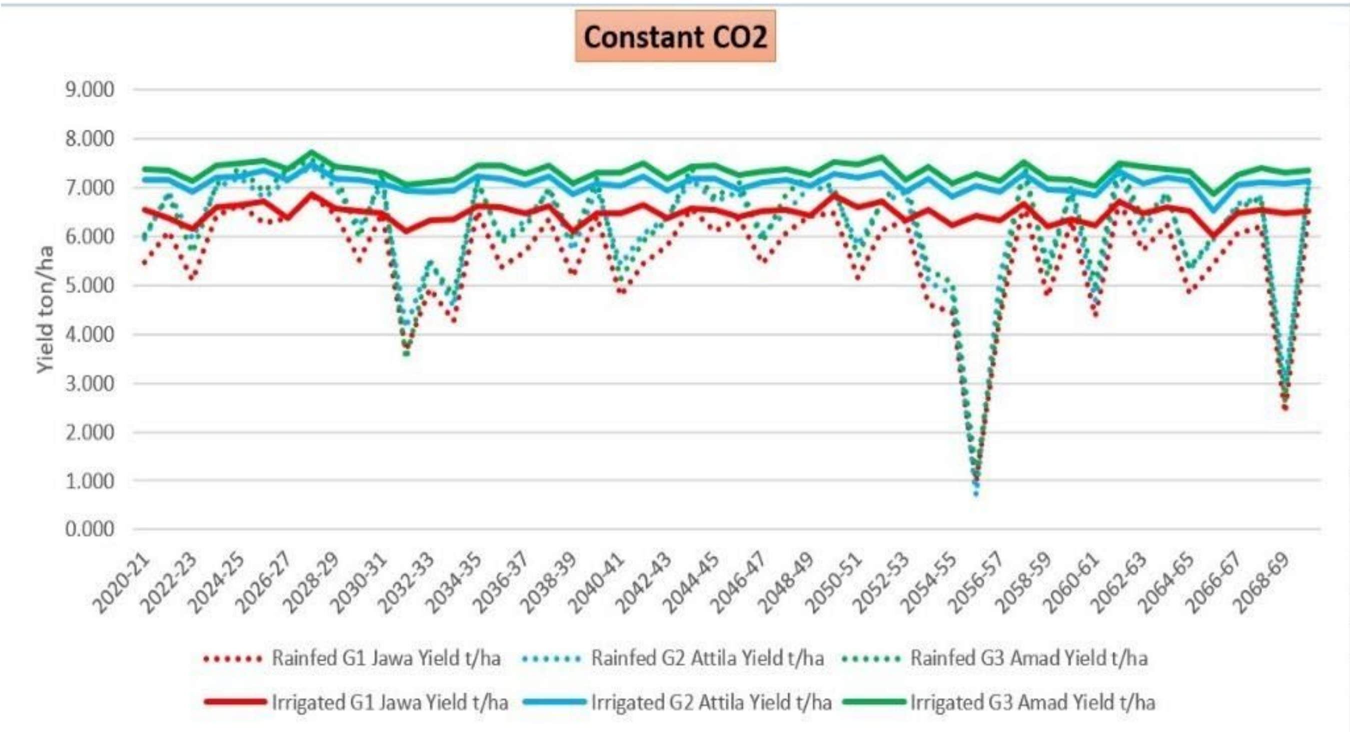
AquaCrop can automatically determine planting dates based on a threshold of rainfall before the seeding date. However this was not found to reliably result in satisfactory yields, and so a fixed date of 17th November was used throughout. For irrigation AquaCrop can automatically generate irrigation schedules based on user selected criteria. For this study, irrigation was specified to start when 100% of readily available water was depleted at intervals of twenty days after day 60 from seeding, and for the soil to be wetted to 100% of field capacity. Through trial and error this irrigation scheme was found to result in the most reliably high yields in the simulations. The simulated method was drip irrigation, as in the field trials.

All three genotypes were run for both irrigated and rainfed scenarios. To take into account the uncertainty surrounding CO_2 enrichment, many modelling studies on crop response to climate change carry out two sets of trials, one with CO_2 enrichment and one without, as well as simulating several different emissions scenarios (Liu et al., 2018; Rosenzweig et al. 2014).

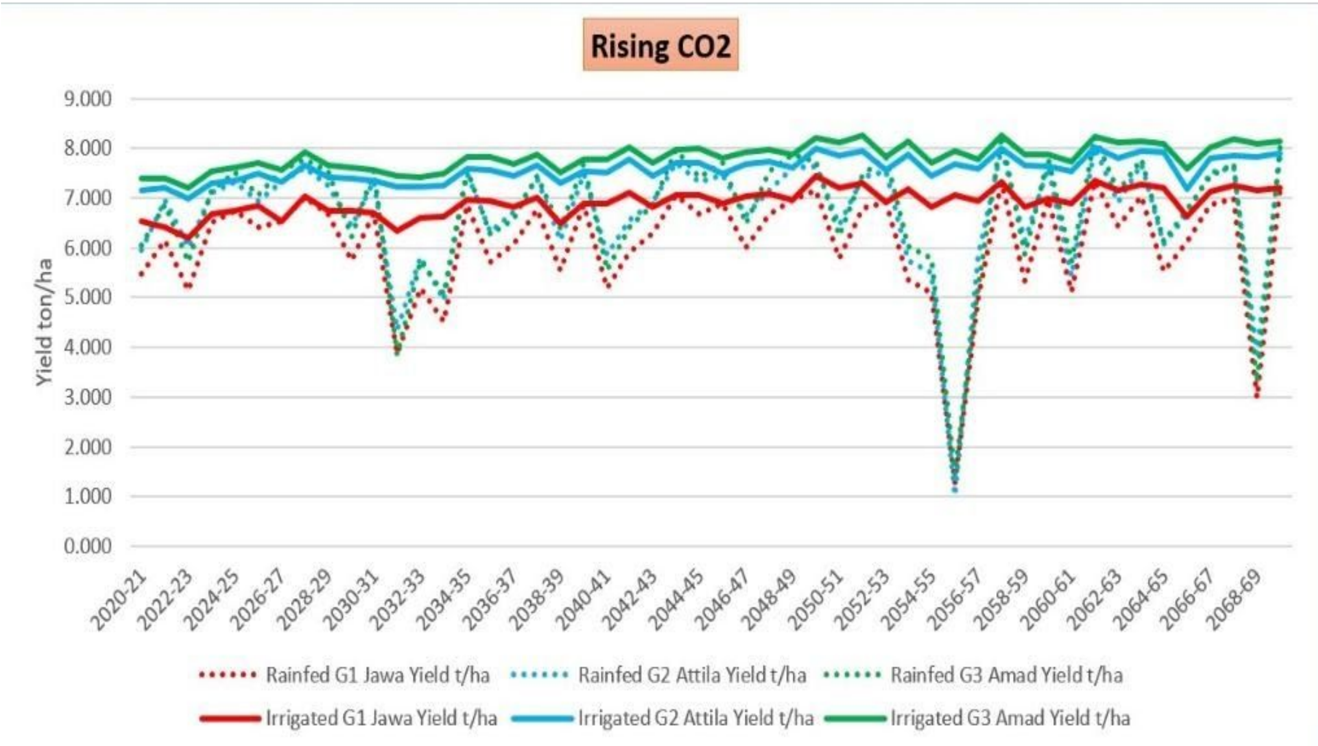
5:2. Yield results from simulations using project climate data

Each RCP was run both with the projected increases in atmospheric CO2 and with a constant concentration of 412 parts per million throughout the scenario, in line with the most recent figures for atmospheric CO_2 (Mauna Loa observatory). This resulted in four scenario simulations for each crop in each RCP, for a total of twenty-four scenarios, the key results of which are summarised below. Figures 21 and 22 show yields under RCP 4.5 with constant and rising CO_2, respectively, whiles figures 23 and 24 show the same for RCP 8.5. Figure 25 averages all of the yields into five decade periods for all four scenarios, with seasonal variability calculated as standard deviation. This is done so that long-term trends may be identified, and the projected average yield for the period 2060-70 may be compared with earlier projections and the field trial results.

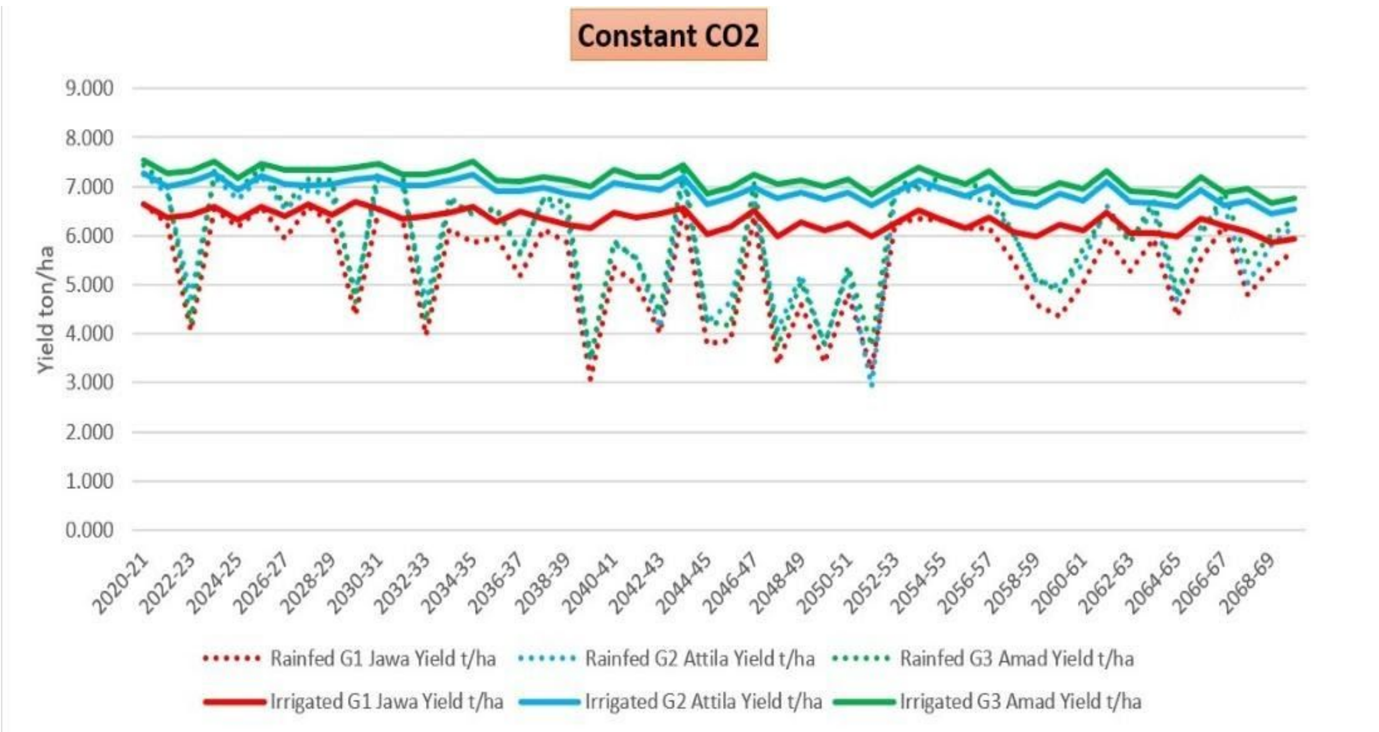
21. *Projected yields for RCP 4.5 with* CO_2 constant throughout



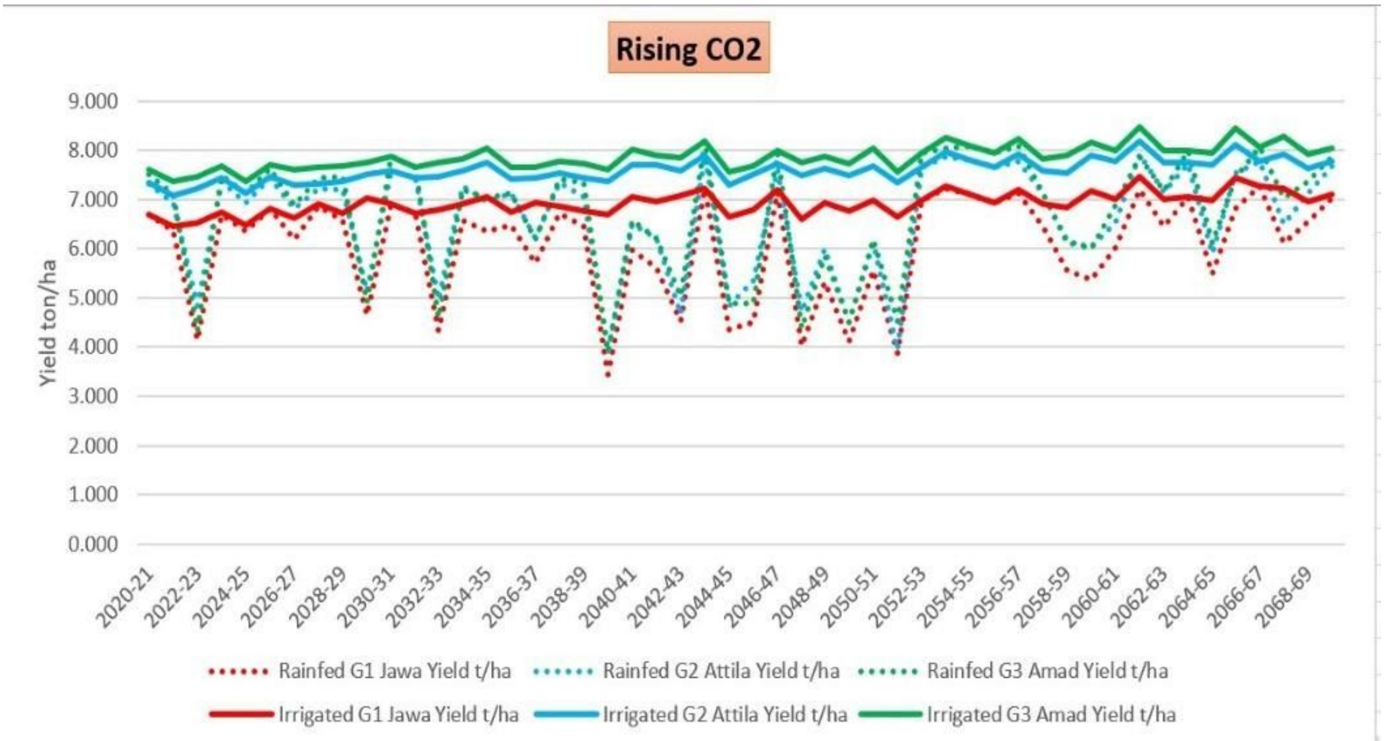
22. *Projected yields for RCP 4.5 with* CO_2 simulated to rise



23. *Projected yields for RCP 8.5 with* CO_2 constant throughout



24. *Projected yields for RCP 8.5 with* CO_2 simulated to rise



25. *Yields for both RCP scenarios, averaged into five decade periods with seasonal variability calculated as standard deviation*

RCP 4.5		Rising CO2 rainfed			Rising CO2 irrigated			Constant CO2 rainfed			Constant CO2 irrigated		
	Genotype	G1 Jawa	G2 Attila	G3 Amad	G1 Jawa	G2 Attila	G3 Amad	G1 Jawa	G2 Attila	G3 Amad	G1 Jawa	G2 Attila	G3 Amad
Decade		Yield t/ha	Yield t/ha	Yield t/ha	Yield t/ha	Yield t/ha	Yield t/ha	Yield t/ha	Yield t/ha	Yield t/ha	Yield t/ha	Yield t/ha	Yield t/ha
2020-30	Average	6.239	6.893	6.948	6.3	7.327	7.559	6.127	6.770	6.822	6.541	7.206	7.434
	Std Dev	0.569	0.542	0.683	0.225	0.178	0.190	0.537	0.508	0.645	0.187	0.135	0.144
2030-40	Average	5.814	6.404	6.418	6.741	7.419	7.646	5.49	6.040	6.044	6.419	7.060	7.273
	Std Dev	0.999	1.053	1.197	0.211	0.156	0.165	0.946	1.012	1.162	0.184	0.130	0.143
2040-50	Average	6.483	7.091	7.160	7.039	7.67	7.929	5.961	6.523	6.580	6.539	7.117	7.367
	Std Dev	0.594	0.562	0.753	0.165	0.149	0.138	0.549	0.520	0.696	0.131	0.108	0.106
2050-60	Average	5.590	6.127	6.194	7.053	7.725	7.980	4.982	5.489	5.535	6.444	7.061	7.310
	Std Dev	1.659	1.905	1.867	0.181	0.173	0.191	1.573	1.801	1.760	0.173	0.167	0.179
2060-70	Average	6.163	6.769	6.826	7.129	7.779	8.035	5.448	5.977	6.033	6.462	7.055	7.295
	Std Dev	1.271	1.248	1.410	0.202	0.233	0.199	1.236	1.261	1.353	0.187	0.212	0.184
Overall Average		6.058	6.657	6.709	6.852	7.584	7.830	5.602	6.160	6.203	6.481	7.100	7.336
RCP 8.5		Rising CO2 rainfed			Rising CO2 irrigated			Constant CO2 rainfed			Constant CO2 irrigated		
	Genotype	G1 Jawa	G2 Attila	G3 Amad	G1 Jawa	G2 Attila	G3 Amad	G1 Jawa	G2 Attila	G3 Amad	G1 Jawa	G2 Attila	G3 Amad
Decade		Yield t/ha	Yield t/ha	Yield t/ha	Yield t/ha	Yield t/ha	Yield t/ha	Yield t/ha	Yield t/ha	Yield t/ha	Yield t/ha	Yield t/ha	Yield t/ha
2020-30	Average	6.131	6.721	6.796	6.700	7.316	7.588	5.943	6.516	6.584	6.510	7.109	7.374
	Std Dev	0.898	0.888	1.113	0.173	0.133	0.135	0.893	0.886	1.103	0.129	0.113	0.108
2030-40	Average	5.966	6.585	6.631	6.836	7.503	7.759	5.507	6.088	6.124	6.385	7.007	7.240
	Std Dev	1.100	1.164	1.275	0.111	0.107	0.123	1.069	1.127	1.230	0.135	0.141	0.156
2040-50	Average	5.278	5.834	5.847	6.921	7.601	7.852	4.641	5.141	5.137	6.291	6.897	7.145
	Std Dev	1.129	1.166	1.299	0.207	0.159	0.174	1.104	1.126	1.260	0.199	0.165	0.170
2050-60	Average	6.220	6.814	7.010	7.001	7.705	7.994	5.378	5.861	6.050	6.214	6.840	7.091
	Std Dev	1.035	1.199	1.169	0.179	0.182	0.197	1.011	1.241	1.156	0.160	0.160	0.177
2060-70	Average	6.599	7.184	7.381	7.152	7.843	8.118	5.410	5.887	6.039	6.112	6.698	6.935
	Std Dev	0.552	0.642	0.579	0.179	0.171	0.194	0.544	0.642	0.573	0.175	0.179	0.187
Overall Average		6.039	6.628	6.733	6.922	7.594	7.862	5.376	5.899	5.987	6.302	6.910	7.157

5:3. Discussion of yields projected by AquaCrop

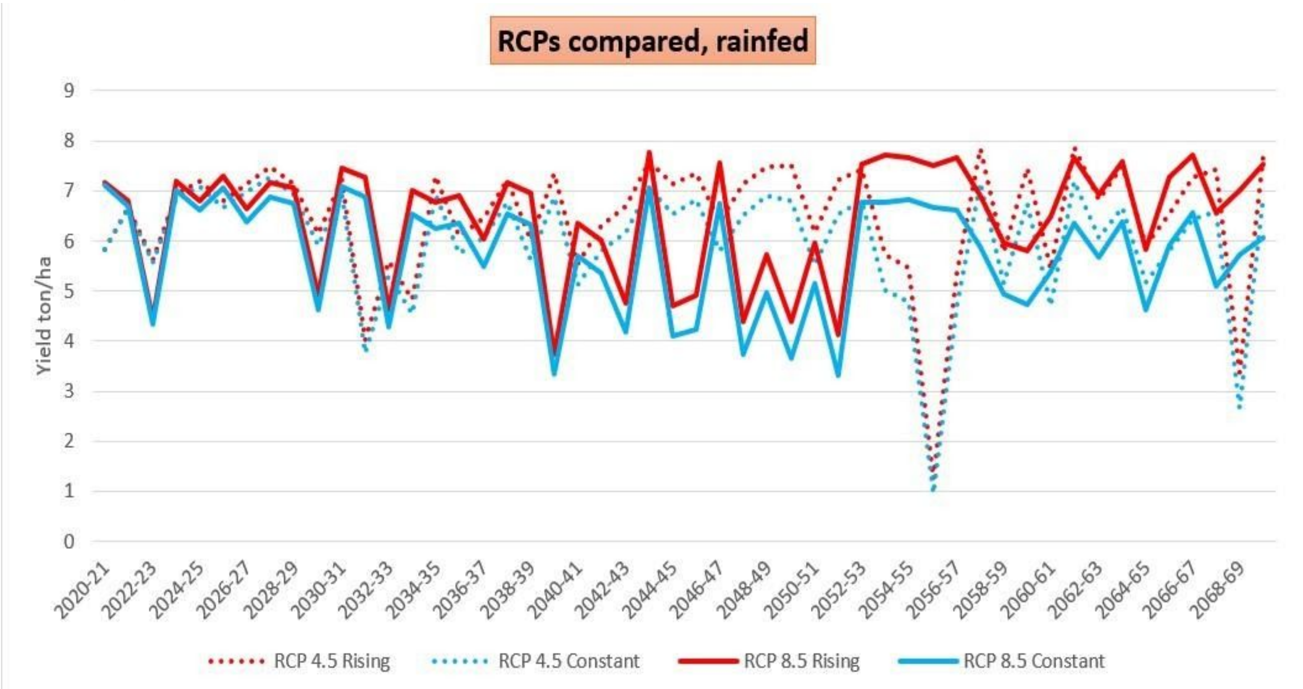
It may be seen that in all scenarios, a similar hierarchy of yields among the genotypes is displayed. Jawahir-1 almost always has the lowest yields, while Attila and Amad were fairly closely matched, with Amad usually having slightly higher yields. This contrasts with the field trial results and validation simulations, where Attila yielded higher than Amad, and may be due to Amad's higher HI.

It must be emphasised that these yields are far in excess of typical yields of 2-3 ton/ha in Morocco, particularly when it is considered that these are *dry* yields and so an extra percentage for moisture must be added. However, they can provide a useful insight into possible future trends due to rainfall variability, CO_2 enrichment and irrigation practices.
In RCP 4.5, taking the field trial period 2017-18 as a reference period and averaging yields across all genotypes, by the decade 2060-70 yields are projected to increase by 6.5% for rainfed and 14.8% for irrigated with elevated CO_2; with constant CO_2 rainfed yields decline by 5.9%, while irrigated still increase by 4.2%. In RCP 8.5 by 2060-70, rainfed yields increase by 14.1% and irrigated by 15.7% while under elevated CO_2, while without it rainfed yields decline by 6.6% and irrigated by 1.2%. For RCP 4.5 inter-season variability seems to increase over time without irrigation, while this effect is less clear RCP 8.5.

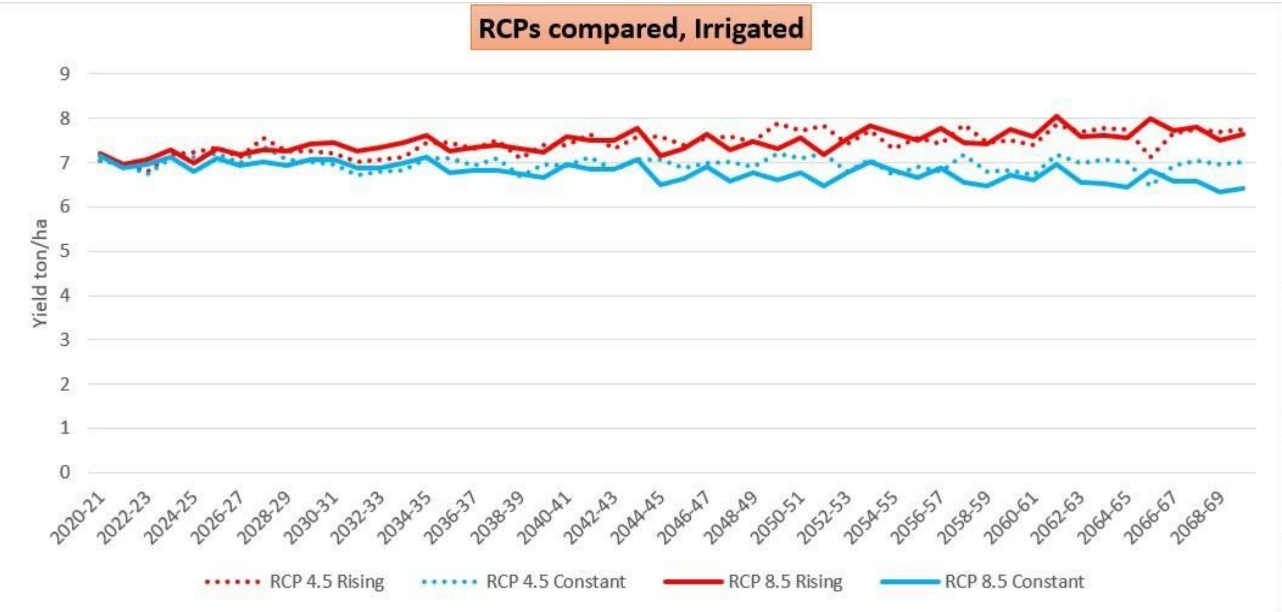
5:4. Effects of CO_2

As expected, by the period 2060-70 all scenarios with rising levels of CO_2 had significantly higher yields than those with constant. When averaged across all genotypes, rainfed yields in the 2060-70 period for RCP 4.5 were 13.2% higher with CO_2 enrichment as compared to without it. For RCP 8.5 they were 22% higher, reflecting the greater concentrations of CO_2. In RCP 4.5 by the 2060-70 period the constant CO_2 irrigated scenario had average yields 19.2% higher than the constant rainfed, and 5.3% greater than the rising CO_2 rainfed scenario. For RCP 8.5 by 2070, irrigated yields in the constant CO_2 scenario were 13.8% higher than rainfed but 6.7% lower than those for rainfed yields with elevated CO_2
All genotypes were assigned the same sink strength and so responded equally to CO_2 enrichment. In figures 26 and 27 below, all the genotypes have been averaged together for ease of comparison between the two RCPs. The greater gap in yields between CO_2 elevated and CO_2 constant is particularly obvious in RCP 8.5. When CO_2 enrichment and irrigation are considered, both RCPs project similar yield towards the end of the simulation period. Over the course of the whole simulation, the rainfed RCP 4.5 scenarios show a slightly greater inter-season variability, with a standard deviation among the seasons of 1.22 for rising CO_2 and 1.2 for constant, while for RCP 8.5 these figures are 1.13 and 1.11, respectively.

26. *Projected yields for RCP 4.5 and 8.5 compared in the rainfed scenarios, with all genotypes averaged together*



27. *Projected average yields for RCP 4.5 and 8.5 compared in the irrigated scenarios*



5:5. Irrigation

As expected, for all varieties irrigation results in significantly higher yields than rainfed. However the irrigated yields must be taken with caution, as it was found in calibration that AquaCrop overestimated the response of Jawahir-1 and Amad to irrigation in dry years, and there is considerable uncertainty as to effect of irrigation in wet years. As an overall average Jawahir-1 increased its yield by 14.3%, Attila by 13.9% and Amad by 16.7% when irrigated, in both RCPs with elevated CO_2. When CO_2 enrichment was not considered the percentage increase for all genotypes in RCP 4.5 under irrigation was higher (15.7, 15.2 and 18.2%), and higher still for RCP 8.5 (17.2, 17.1 and 19.5%) due to the lower average yields for rainfed scenarios. As expected, irrigation was most effective in dry years, as evidenced by the much lower inter-season variability and lack of failure seasons under all irrigated scenarios. AquaCrop did not simulate irrigation in very wet seasons; when moderate irrigation was applied in moderately wet seasons the yield increases were marginal. Yield variation among the genotypes was also much less pronounced during seasons of low rainfall. Even taking into account over-estimation error, irrigation still provides Jawahir-1 and Amad with some protection against yield losses in dry years.

5:6. Water Use Efficiency

AquaCrop can also calculate WUE as water transpired. WUE was found to be positively affected by CO_2 enrichment and by irrigation. Irrigation was found to increase WUE by an average of 8%, with the greatest difference being between irrigated and rainfed for RCP 4.5 without CO_2 enrichment. By 2060-70 in RCP 4.5 WUE was found to be an average of 15% higher with CO_2 enrichment than without it for rainfed crops, and 12% higher for irrigated. In RCP 8.5 these figures were 25% and 22%, respectively. Without the effects of elevated CO_2 no long-term change in WUE was projected for either RCP. Due to the crops greater WUE, irrigation demands by 2060-70 were also observed to decline with CO_2 enrichment as opposed to without, by 14% for RCP 8.5 but only by 5% for RCP 4.5.

6: Discussion

6:1. CO_2 enrichment

As a C3 plant wheat uses CO_2 less efficiently, and so is further from its saturation point than C4 crops such as maize; thus C3 plants are expected to show greater yield increases in response to elevated CO^2 (Leakey et al., 2009). FACE trials by Long et al. (2006) in 2006 found that conventional wheat yields could increase by 13% under 550 ppm CO^2 levels compared to yields at ambient CO^2, as opposed to a theoretical maximum of 31% achieved in enclosure studies and this has since been supported by a review of other FACE trials (Leakey et al., 2009). At Long's reference point in 2006, atmospheric CO_2 concentrations were at 381 ppm, with 550 ppm representing an increase of 44%. For the reference point of this study in 2018, concentrations were at 408.5 ppm (Mauna Loa observatory), thus an increase of 44% represents concentrations of 589.7ppm, levels reached in 2058 under RCP 8.5. In this study the average yield in the period 2060-70 was 14.1%, in agreement with Long et al.

However a FACE study carried out for wheat in a semi-arid environment (O'Leary et al. 2015) found yields to increase by a mean of 26% under 50% greater concentrations of CO_2, a considerably greater increase in yield. Crop water use efficiency was observed to increase by 31%, while in this study AquaCrop projected increases of 25% in WUE under a 50% increase in CO_2. O'Leary et al. observed irrigated crops to benefit more from elevated CO_2, in contrast to this study when irrigated yields increased 3-5% less than rainfed ones under elevated CO_2. This may be explained by AquaCrop's substantial overestimation of irrigated yields.
A FACE trial by Fitzgerald et al. (2016) on dryland wheat also observed considerably greater yield increases in response to elevated CO_2, ranging from 25% to 53%. They also observed irrigated wheat to experience much greater yield increases than rainfed, in agreement with O'Leary. They did not observe any difference in yield response among the varieties to CO_2 in agreement with the findings of this study.

In contrast, some FACE studies have observed the CO_2 enrichment effect to be greater under water stress (Kimball et al., 2002;). This effect was also observed in this study, as under the highest concentrations of CO_2 the percentage difference in yield between CO_2 enriched and non-enriched scenarios could be nearly twice as high in a year with low rainfall compared to one with higher rainfall.

6:2. Uncertainty around FACE studies

It should be noted that AquaCrop bases its calculation of CO_2 enrichment responses on FACE trials in the literature (Vanuytrecht et al. 2011). Therefore differences in AquaCrop's simulation of yields under elevated CO_2 and observed results may also reflect the above-mentioned variation in among FACE trials. AquaCrop supports a range of sink strengths for each crop, dependent on varieties and management, and wheat has an indicative sink strength range between 0-20%, with this variance depending both on management and on soil and climate factors. Wheat grown with ample soil nutrients is able to assimilate more carbon than those under fertility stress. Due the perfect soil fertility of the ICARDA trials, the bread wheat genotypes were assigned a sink strength of 20%, while under typical Moroccan agronomic practices a value of 0% may be more realistic. Running the genotypes with a sink strength of 0% assigned resulted in yields 2.2% lower by 2060-70 under RCP 4.5, while for RCP 8.5 this was 5.4%, but in both cases yields by 2060-70 were still significantly higher with sink strength 0% than without any CO_2 enrichment.

FACE studies have never achieved the yields gains which may be achieved in enclosed trials, suggesting the real-world effect of CO_2 enrichment will be less than the theoretical maximum. However a recent review found that fluctuations in CO_2 concentration using current FACE techniques are more than ten times greater than natural conditions (Allen at al., 2020). Allen et al. calculated that increases in photosynthesis under fluctuating elevated CO_2 concentrations were only 65% of those under constant CO_2 of the same concentration, although the exact cause for this is still unknown. Therefore FACE trials may underestimate crop yield increases due to increased CO_2 concentrations, and the true increases under natural conditions may in fact be closer to the theoretical maximum than thought. Allen et al. calculated that a correction factor of 1.5 should be applied to FACE results. As crop CO_2 response in AquaCrop is based on FACE trials, this could greatly increase AquaCrop simulated yield gains under elevated CO_2. However these findings are very recent and further research will be necessary.

As is common practice in crop-climate simulations, scenarios in this study were run both with and without elevated CO_2 to take into account the uncertainty and to understand how great an impact this uncertainty will have on yields. It should be emphasised that while this is a useful practice in modelling studies, almost all field experiments indicate some yield response to CO_2 levels (a crop with a sink strength of 0% will still respond) and therefore it is not realistic to expect no response at all.

6:3. Effects of temperature and rainfall change

A similar crop-climate simulation based on a semi-arid site in Pakistan by Ahmad et al. (2020), projects that without CO_2 enrichment, wheat yields will decrease by 11-18%, by the 2060s for RCP 4.5, and by 11-20% for RCP 8.5, far greater decreases than projected in this study. They concluded that the effect of CO_2 enrichment could offset much, but not all, of the negative climate change effect on yields.

Bouras et al. (2019) also assessed future wheat production in Morocco for RCP pathways 4.5 and 8.5. They found that the rise in air temperature shortens the growing cycle by up to 50 days, an effect also observed by Ahmad et al., but not observed this study due to the milder temperatures of the RICCAR data. Without the CO_2 enrichment effect wheat yields are expected to decrease by between 7 and 30% by the middle of the 21st century, considerably greater than in this study. With CO_2 enrichment considered Bouras et al. project yields to increase by 7% for RCP 4.5 and 13% for RCP 8.5, a similar range as projected in this study. The greater maximum yield declines projected by Bouras and Ahmad may be due to greater projected temperatures in the mid-21st century in their climate data as opposed to the RICCAR data. Due to the shortening of life cycle Bouras et al. project water requirements could decrease with WUE increasing by up to 93% for RCP 8.5 by 2090, a much greater increase than the greatest projected in this study. They also project a decrease in irrigation demands of up to 20% by 2090, again a greater decrease than projected in this study.

Rosenzweig et al. (2014) carried out an ensemble study of seven crop and five GCM climate models. By the end of the 21st century most models under RCP 8.5 showed an increase in yield for wheat in higher latitudes when CO_2 enrichment was taken into account, but a decrease without it. However for lower latitudes, including Morocco, a decline in wheat yield is expected even with enrichment considered due to increases in water demand and a shortening of the growing cycle.

An ensemble-model study on the impacts on global wheat production at 1.5°C and 2°C above pre-industrial warming projects that in the absence of CO_2 enrichment wheat yields could decrease by 5% for every 1.0°C of warming (Liu et al. 2018). Liu et al. considered local cultivars across 60 representative sites, including Sidi El Aydi in Morocco and took into account changes in rainfall as well as temperature. For both scenarios they project global wheat yields to increase in most wet temperate regions (5-10%) and decrease for arid, hot regions (up to -2.4%), even with CO_2 enrichment considered, and Morocco is adversely affected in both. They also project yearly variability and frequency of extremely low yields will increase under both scenarios for hotter locations, due to more frequent extreme weather events. However they did not consider adaptation strategies such as irrigation or changes in varieties.

6:4. Irrigation and other adaptation measures

According to a meta-analysis of 1700 published simulations (Challinor et al. 2014), warming without any adaptation would lead to yield losses for wheat in both temperate and tropical regions. However adaptation measures could prevent wheat yield losses above 2°C in tropical areas. In the simulations analysed, irrigation was found to be the most reliably effective strategy, with changes in genotype and planting date having a positive effect in some studies and a negative effect in others. They also found increasing yield variability due to warming is more likely, although this prediction is less certain than the others.

Bouras et al. (2019) examined seeding dates in mid-November, mid-December and mid-January and found that yields for early sowing were most adversely affected by climate change without CO_2 enrichment and benefited least when enrichment was considered, suggesting a January seeding date might be optimal under climate change scenarios. However in this study, a seeding date in December or January resulted in greatly reduced yields, due to the lesser rainfall received over the season.

Irrigated wheat field trials carried out by Costa et al. (2013) in Portugal under similar climatic conditions to Merchouch found a sowing date on the 21st December increased yields between 15 and 30%, over the 5th of December, in spite of the later sowing date receiving slightly less rainfall and irrigation. The higher yields for the later sowing date indicate that yields and can be stimulated by moderate water stress, as found in the ICARDA trial.
Due to the increasing vulnerability of the Mediterranean and North Africa to drought under climate change, supplement irrigation has been suggested as an effective adaptation strategy, due to its relatively low water demands and increase of plant WUE (Oweis and

Hachum, 2006). However it must be emphasised that currently most wheat production in Morocco is rainfed, and that introducing widespread irrigation would involve significant investment in infrastructure, as well requiring farmers to learn new agronomic practices. In Morocco such an undertaking may not be financially possible and furthermore Morocco faces a significant water deficit (Taheripour et al., 2020). Therefore while there is a strong motivation to ensure current irrigation practices use water as efficiently as possible, widespread use of SI may not be a viable adaption strategy to climate change induced drought across the whole country.

6:5. Limitations

No measurements of transpiration are available for the ICARDA trials. It is possible to calculate this based on the known characteristics of the crop and soil, but without precise measurements it is impossible to know with certainty how much water was transpired by the crops and so contributed to productivity. With the ICARDA data, it is only possible to calculate the yield per unit of water applied, not the ET water productivity. AquaCrop can calculate the ET water productivity of crops, but without field data to compare with the simulated values, the accuracy of these calculations cannot be known.
There are also various other possible effects of climate change in the region which are outside the scope of this study. The reproduction of weeds, insect pests and pathogens may be stimulated by rising temperatures (and also CO^2 enrichment in the case of weeds), and this could negatively affect yields. As temperatures increase and precipitation becomes more erratic top-soil can dry out and become blown away and permanently lost. These indirect effects of climate change may have a serious negative impact on crop yields but are not simulated by AquaCrop.

The RICCAR climate data may also under-estimate temperature increases due to climate change. It may be seen that both the predicted maximum temperatures for RCP 4.5 and 8.5 are not significantly greater than those recorded at Merchouch research station in the years 2015-19, even by the year 2070, in contrast to many other climate studies. This climate data predicts average daily maximums, and so does not take into account occasional extreme heatwaves, such as those recorded in 2016, which can severely affect yields even if they are only a few days in duration. Moderate increased temperatures may stimulate plant growth, but heat stress can negatively affect yields. The milder temperatures of RICCAR data may explain why the projected yield losses and gains under climate change with and without CO_2 enrichment are not as great as other studies in the literature. Climate change is also likely to alter cloud formation, and hence solar radiation and ETo, but this was not considered in the study.

The yield results should be seen as indicative values only, as in the ICARDA field trial fertilisation was perfect and may be considered non-limiting, and the crops were also not subject to weeds, pests and diseases or salinity stress. Even in dry years, yields per hectare were far higher than is typical in Morocco. If these crops were to be widely adopted by Moroccan farmers, considerably lower yields should be expected under non-field trial conditions. Trials using agronomic practices typical of Morocco and comparing local bread as well as durum wheat varieties with ICARDA varieties would give an idea of the performance of the ICARDA varieties under more realistic conditions.

In order to achieve the optimal calibration of AquaCrop, or any crop model, further field trials are suggested. As can be seen from the standard deviations, there was often considerable variation among the three different replications for each crop. In some of the trials this variation was evenly spread, but in others there were outliers with either much higher or much lower yields. There are also some aspects of the field trials, such as the increased yields of bread and durum wheat genotypes under irrigation in the wet season of 2017-18 which AquaCrop was unable to simulate. Some of the yields in the trials may be due to factors not recorded in the available data. Exact dates for the canopy growth stages in the field trial are necessary for the most accurate calibration of AquaCrop, but these were not available in the field trial. Further trials with a greater number of replications, and precise measurements of the canopy growth stages, as well as soil moisture levels at seeding and other factors affecting yield are suggested for the optimum calibration of AquaCrop.

7: Conclusion

ICARDA genotypes show excellent performance, with many of the durum wheat varieties having equally as high yields as the locally popular Karim, and most of them significantly outperforming the locally derived Faraj. Bread wheat genotypes also achieved high yields, although in this case no field trial data on locally used genotypes was available for comparison. Supplemental irrigation was found to significantly boost yields during 2016-17 season for both bread and durum genotypes, and so can help buffer against crop failure in a dry year. Yield increases were also observed under supplemental irrigation in the wetter season 2017-18, but it is not clear that these are statistically significant. A later seeding date was found to significantly increase yields for durum wheat during the wetter season, but to greatly decrease them during the dryer season. As total rainfall over a season cannot yet be reliably forecast in advance, it is not clear from these trials that altering seeding dates is a viable adaptation strategy to drought. However supplemental irrigation was found to provide very effective protection against drought at comparatively little cost in water.

AquaCrop was found to be able to simulate rainfed wheat yields with a high degree of accuracy, but significantly overestimated yields under supplemental irrigation in a dry year. There were also high levels of variation among some of the replications for each genotype during the trials. In order to optimally calibrate AquaCrop, further trials are suggested, with a higher number of replications across several seasons, so that the behaviour of these genotypes under varying conditions may be fully understood. Precise measurements on canopy development and soil moisture content will also help the model to accurately simulate yields.

Using RICCAR climate model data, AquaCrop simulate future yields to decline due to the effects of climate change, but much of the negative impacts may be offset by CO_2 enrichment. Yields may significantly increase under both RCP 4.5 and 8.5 with CO_2 enrichment considered, but decline without it. Both RCPs project a considerable year-to-year variability of rainfall which can negatively affect yields. Irrigation has the potential to offset much of the losses during dry years, but it may not be a viable adaptation strategy on a national scale in Morocco due to on-going water shortage crisis the country faces, and limits on the amount of irrigated agriculture which may realistically be installed. There are considerable uncertainties as to the response of all crops to elevated CO_2 including the results of a very recently published study which may have a considerable impact on how CO_2 is calculated in the future. ICARDA genotypes have been found to have high potential yields, and further research is suggested to fully assess their future performance.

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9: Appendices

Appendix 1A: bread wheat 2016-17

average and standard deviations for yield, biomass, HI, WUE

Bread wheat 2016-17 (seeding 17th Nov)	Yield (ton/ha)				Total Biomass (ton/ha)			
Water regime / total applied (inc. rain) →	Rainfed	100% FC	66% FC	33% FC	Rainfed	100% FC	66% FC	33% FC
Genotype ↓	263.4mm	483.4mm	410.4mm	336.4mm	263.4mm	483.4mm	410.4mm	336.4mm
G1. JAWAHIR-1	4.875	6.183	5.442	4.925	15.833	18.458	16.292	15.292
G2. BOW/3/ATTILA	6.033	7.775	7.008	6.308	17.958	20.417	18.292	17.375
G3. SERI.1B//KAUZ/HEVO/3/AMAD/4	5.167	5.600	6.158	5.967	15.208	17.708	16.792	15.750
G4. MILAN/DUCULA//AL-ZEHRAA-1	5.033	6.133	5.375	4.600	16.333	17.333	15.792	15.458
G5. JAWAHIR-1/3/PASTOR/SERI//PFAU	4.850	5.758	4.983	6.100	16.542	17.125	16.375	18.625
G6. FLAG-3/ICARDA-SRRL-5	4.442	6.251	5.850	5.900	14.542	17.125	18.792	17.083
G7. 3/AMAD/4/ESDA	3.667	6.083	6.017	5.958	11.667	18.083	16.167	16.333
G8. Attila-7	4.100	6.858	5.425	4.975	13.667	18.667	15.167	15.958
G9. Arrehane	6.017	4.692	5.608	4.900	16.542	14.792	15.708	15.417
G10. Achtar	4.825	6.125	5.533	5.317	15.000	16.750	16.792	16.250
Average across genotypes	4.901	6.146	5.740	5.495	15.329	17.646	16.617	16.354
Standard Deviation across genotypes	0.707	0.758	0.532	0.584	1.674	1.384	1.076	1.004
Standard Deviation across replications								
G1. JAWAHIR-1	0.147	0.637	0.349	0.289	0.680	2.611	1.192	2.297
G2. BOW/3/ATTILA	1.208	1.542	0.633	1.424	2.858	2.566	1.276	3.383
G3. SERI.1B//KAUZ/HEVO/3/AMAD/4	0.370	1.263	0.479	0.617	0.059	0.680	1.650	0.612
G4. MILAN/DUCULA//AL-ZEHRAA-1	0.796	0.198	0.816	0.728	1.910	0.059	1.378	2.420
G5. JAWAHIR-1/3/PASTOR/SERI//PFAU	0.340	0.565	1.455	0.682	1.312	3.144	0.306	1.327
G6. FLAG-3/ICARDA-SRRL-5	0.460	1.014	1.928	0.449	1.883	2.252	3.478	1.218
G7. 3/AMAD/4/ESDA	0.467	1.749	0.283	0.812	1.582	1.393	1.284	2.097
G8. Attila-7	0.823	0.635	0.108	0.623	1.589	1.296	0.358	2.003
G9. Arrehane	1.105	0.511	0.502	0.147	1.559	1.047	1.595	0.562
G10. Achtar	0.537	1.779	1.074	1.032	0.204	2.808	1.786	1.771

Genotype ↓	Harvest Index %				Water Use Efficiency kg/m3 per ha			
G1. JAWAHIR-1	30.8	33.7	33.6	32.7	1.851	1.279	1.326	1.385
G2. BOW/3/ATTILA	33.5	37.7	38.3	36.0	2.291	1.608	1.708	1.783
G3. SERI.1B//KAUZ/HEVO/3/AMAD/4	34.0	31.9	36.8	37.8	1.962	1.158	1.501	1.674
G4. MILAN/DUCULA//AL-ZEHRAA-1	30.7	35.4	33.9	29.8	1.911	1.269	1.310	1.294
G5. JAWAHIR-1/3/PASTOR/SERI//PFAU	29.3	34.2	30.4	32.7	1.841	1.191	1.214	1.716
G6. FLAG-3/ICARDA-SRRL-5	30.8	36.4	30.1	34.5	1.686	1.293	1.425	1.663
G7. 3/AMAD/4/ESDA	31.6	33.1	37.6	36.5	1.392	1.258	1.466	1.681
G8. Attila-7	29.7	36.7	35.8	31.2	1.557	1.419	1.322	1.391
G9. Arrehane	36.2	31.6	35.8	31.9	2.284	0.971	1.367	1.378
G10. Achtar	32.1	35.8	32.8	32.4	1.832	1.267	1.348	1.489
Average across genotypes	31.9	34.6	34.5	33.5	1.861	1.271	1.399	1.546
Standard Deviation across genotypes	2.0	2.0	2.7	2.4	0.268	0.157	0.13	0.167
Standard Deviation across replications								
G1. JAWAHIR-1	1.0	1.4	3.3	3.1	0.065	0.143	0.094	0.097
G2. BOW/3/ATTILA	3.2	3.2	2.5	1.6	0.535	0.346	0.170	0.476
G3. SERI.1B//KAUZ/HEVO/3/AMAD/4	2.4	8.2	1.3	2.5	0.164	0.283	0.128	0.206
G4. MILAN/DUCULA//AL-ZEHRAA-1	2.2	1.1	2.2	1.6	0.352	0.044	0.219	0.244
G5. JAWAHIR-1/3/PASTOR/SERI//PFAU	0.8	3.2	8.8	2.7	0.150	0.127	0.390	0.228
G6. FLAG-3/ICARDA-SRRL-5	2.9	1.5	5.4	1.0	0.204	0.227	0.517	0.150
G7. 3/AMAD/4/ESDA	2.5	7.5	4.7	0.9	0.206	0.392	0.076	0.272
G8. Attila-7	2.6	0.9	0.2	0.4	0.364	0.142	0.029	0.208
G9. Arrehane	4.4	1.3	0.9	2.1	0.489	0.115	0.135	0.049
G10. Achtar	3.2	4.6	3.7	2.6	0.237	0.399	0.288	0.345

Appendix 1B: bread wheat 2017-18

average and standard deviations for yield, biomass, HI, WUE

Bread wheat 2017-18 (seeding 17th Nov)	Yield (ton/ha)				Total Biomass (ton/ha)			
Water regime / total applied (inc. rain) →	Rainfed	100% FC	66% FC	33% FC	Rainfed	100% FC	66% FC	33% FC
Genotype ↓	493.4mm	518.1mm	509.9mm	501.6mm	493.4mm	518.1mm	509.9mm	501.6mm
G1. JAWAHIR-1	7.133	8.417	7.942	7.242	19.542	19.625	21.167	19.250
G2. BOW/3/ATTILA	7.667	7.675	6.817	7.800	20.667	19.542	19.250	20.583
G3. SERI.1B//KAUZ/HEVO/3/AMAD/4	7.283	7.692	6.975	8.217	17.625	19.667	20.750	21.042
G4. MILAN/DUCULA//AL-ZEHRAA-1	6.550	7.142	7.392	6.775	20.083	18.792	20.875	18.542
G5. JAWAHIR-1/3/PASTOR/SERI//PFAU	7.183	6.092	6.425	6.908	20.733	19.500	18.258	20.000
G6. FLAG-3/ICARDA-SRRL-5	6.883	7.233	6.392	6.525	19.375	19.750	18.750	18.833
G7. 3/AMAD/4/ESDA	6.958	7.258	7.458	6.133	19.375	18.667	18.542	16.425
G8. Attila-7	6.575	7.633	8.400	8.067	17.667	19.583	21.583	19.833
G9. Arrehane	6.742	6.533	6.533	7.158	19.125	18.292	18.250	19.083
G10. Achtar	6.900	7.617	7.717	6.308	21.000	20.583	22.208	18.417
Average across genotypes	6.988	7.329	7.205	7.113	19.400	19.400	19.963	19.201
Standard Deviation across genotypes	0.324	0.618	0.652	0.688	0.620	0.620	1.429	1.235
Standard Deviation across replications								
G1. JAWAHIR-1	1.115	0.174	1.161	0.587	0.868	1.429	2.435	1.890
G2. BOW/3/ATTILA	0.838	0.814	1.215	0.391	2.122	1.218	2.041	1.284
G3. SERI.1B//KAUZ/HEVO/3/AMAD/4	1.123	0.698	1.220	0.190	1.744	1.359	1.339	0.312
G4. MILAN/DUCULA//AL-ZEHRAA-1	0.532	0.338	0.377	1.012	0.695	1.549	1.137	1.022
G5. JAWAHIR-1/3/PASTOR/SERI//PFAU	0.444	0.955	0.799	0.277	0.486	0.270	1.258	2.413
G6. FLAG-3/ICARDA-SRRL-5	0.429	1.517	0.950	0.786	0.736	3.478	1.544	0.328
G7. 3/AMAD/4/ESDA	0.150	0.292	1.104	0.347	0.354	0.948	3.376	0.691
G8. Attila-7	0.227	0.527	0.532	0.224	2.283	0.766	1.621	0.562
G9. Arrehane	1.014	1.198	0.554	0.552	1.744	1.888	1.686	1.953
G10. Achtar	0.297	1.796	2.032	0.444	0.919	0.386	1.815	1.559

Genotype ↓	Harvest Index %				Water Use Efficiency kg/m3 per ha			
G1. JAWAHIR-1	36.6	43.2	37.6	37.7	1.446	1.625	1.557	1.444
G2. BOW/3/ATTILA	37.1	39.2	35.2	38.2	1.554	1.481	1.337	1.555
G3. SERI.1B//KAUZ/HEVO/3/AMAD/4	41.1	39.6	33.8	39.0	1.476	1.485	1.368	1.638
G4. MILAN/DUCULA//AL-ZEHRAA-1	32.6	38.1	35.4	36.7	1.328	1.378	1.450	1.351
G5. JAWAHIR-1/3/PASTOR/SERI//PFAU	34.6	31.3	35.7	35.0	1.456	1.176	1.260	1.377
G6. FLAG-3/ICARDA-SRRL-5	35.5	36.5	34.0	34.6	1.395	1.396	1.254	1.301
G7. 3/AMAD/4/ESDA	35.9	38.9	40.5	37.4	1.410	1.401	1.463	1.223
G8. Attila-7	37.7	39.0	39.0	40.7	1.333	1.473	1.647	1.608
G9. Arrehane	35.1	35.4	35.8	37.6	1.366	1.261	1.281	1.427
G10. Achtar	33.0	37.0	34.3	34.6	1.398	1.47	1.513	1.258
Average across genotypes	35.9	37.8	36.1	37.1	1.415	1.415	1.413	1.418
Standard Deviation across genotypes	2.3	2.9	2.1	1.9	0.119	0.119	0.128	0.137
Standard Deviation across replications								
G1. JAWAHIR-1	6.2	3.8	4.3	1.7	0.226	0.034	0.228	0.117
G2. BOW/3/ATTILA	2.2	2.8	4.0	4.1	0.170	0.157	0.238	0.078
G3. SERI.1B//KAUZ/HEVO/3/AMAD/4	2.3	6.6	6.7	0.4	0.228	0.135	0.239	0.038
G4. MILAN/DUCULA//AL-ZEHRAA-1	1.6	1.5	0.2	6.3	0.108	0.065	0.074	0.202
G5. JAWAHIR-1/3/PASTOR/SERI//PFAU	1.9	5.3	7.0	4.4	0.090	0.184	0.157	0.055
G6. FLAG-3/ICARDA-SRRL-5	1.6	3.0	3.4	3.7	0.087	0.293	0.186	0.157
G7. 3/AMAD/4/ESDA	0.9	0.9	2.8	2.1	0.030	0.056	0.216	0.069
G8. Attila-7	3.5	2.8	2.5	0.9	0.046	0.102	0.104	0.045
G9. Arrehane	2.5	3.0	1.3	1.0	0.206	0.231	0.109	0.110
G10. Achtar	2.5	9.0	7.0	4.2	0.060	0.347	0.399	0.088

Appendix 2A: durum wheat 2016-17

average and standard deviations for yield, biomass, HI, WUE

Durum Wheat 2016-17	Seeding date 1 (mid Nov) 220mm irr.				Seeding date 2 (late Dec) 220 mm irr.			
	Yield (t/ha)		Tot. Biomass (t/ha)		Yield (Ton/ha)		Tot. Biomass (t/ha)	
Water regime / total applied (inc. rain) →	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated
Genotype ↓	266 mm	486 mm	266 mm	486 mm	154 mm	374 mm	154 mm	374 mm
G1. DAWRyT106	4.408	7.617	15.875	20.083	2.658	5.783	7.875	15.667
G2.Dawryt 104	4.717	6.475	15.958	17.667	2.983	5.525	9.125	14.500
G3. Dwayt 214	4.550	6.750	14.958	18.792	3.642	4.567	10.833	12.542
G4.Berghouata1	4.467	6.717	14.542	17.583	3.258	6.758	10.625	16.833
G5. Icambel	4.150	6.667	14.708	18.917	2.833	5.367	10.250	15.667
G6. Secondroue	4.892	5.950	16.125	18.792	2.400	5.200	8.125	13.708
G7. Icamoram7	4.658	7.258	16.083	19.917	2.842	6.050	9.958	15.083
G8. Karim	4.817	7.067	15.375	17.792	4.238	4.783	10.667	12.875
G9. Louiza	3.850	6.825	12.833	18.250	3.300	5.108	11.417	13.250
G.10 Faraj	3.175	5.275	12.458	19.458	2.325	4.958	10.458	14.500
Standard Deviation across replications								
G1. DAWRyT106	0.386	0.330	1.503	1.247	0.575	0.501	1.242	1.002
G2.Dawryt 104	0.545	1.477	2.887	0.514	0.554	0.601	0.935	3.898
G3. Dwayt 214	1.084	0.212	2.042	1.226	0.031	0.869	0.212	2.394
G4.Berghouata1	0.266	1.076	0.524	1.969	0.150	0.633	1.429	1.684
G5. Icambel	0.806	0.895	1.355	2.297	0.368	1.409	1.005	2.350
G6. Secondroue	1.143	1.000	1.659	0.598	0.389	1.157	1.643	3.710
G7. Icamoram7	1.143	0.976	1.659	2.635	0.764	0.361	1.697	2.301
G8. Karim	0.412	0.729	1.939	1.832	0.038	0.906	4.053	2.252
G9. Louiza	0.134	0.503	2.166	1.403	0.294	0.293	0.412	0.612
G.10 Faraj	0.521	0.868	0.386	2.223	0.147	0.923	0.926	3.572
Average across genotypes	4.368	6.660	14.892	18.725	3.048	5.410	9.933	14.463
Standard Deviation across genotypes	0.496	0.627	1.249	0.858	0.553	0.618	1.121	1.310

Average across genotypes	4.368	6.660	14.892	18.725	3.048	5.410	9.933	14.463
Standard Deviation across genotypes	0.496	0.627	1.249	0.858	0.553	0.618	1.121	1.310
	Harvest Index %		**WUE kg/m3/ha**		**Harvest Index %**		**WUE kg/m3/ha**	
Genotype	**Rainfed**	**Irrigated**	**Rainfed**	**Irrigated**	**Rainfed**	**Irrigated**	**Rainfed**	**Irrigated**
G1. DAWRyT106	27.8	38.0	1.657	1.567	33.5	36.9	1.726	1.546
G2.Dawryt 104	29.9	36.5	1.773	1.332	32.4	39.7	1.937	1.477
G3. Dwayt 214	30.0	36.1	1.711	1.389	33.6	36.5	2.365	1.221
G4.Berghouata1	30.7	38.0	1.679	1.382	31.4	40.2	2.116	1.807
G5. Icambel	28.0	35.4	1.560	1.372	27.6	35.5	1.840	1.435
G6. Secondroue	30.2	31.6	1.839	1.224	29.8	38.7	1.558	1.390
G7. Icamoram7	28.8	36.8	1.751	1.493	28.1	40.8	1.845	1.618
G8. Karim	31.5	39.7	1.811	1.454	31.5	39.5	2.262	1.279
G9. Louiza	30.9	37.5	1.447	1.404	29.0	38.6	2.143	1.366
G.10 Faraj	25.6	27.1	1.194	1.085	22.3	34.8	1.510	1.326
Average across genotypes	29.3	35.7	1.642	1.370	29.9	38.1	1.930	1.447
Standard Deviation across genotypes	1.7	3.5	0.187	0.129	3.2	2.0	0.274	0.165
Standard Deviation across replications								
G1. DAWRyT106	0.3	1.6	0.145	0.068	3.1	0.9	0.373	0.134
G2.Dawryt 104	1.9	7.3	0.205	0.304	2.8	6.1	0.360	0.161
G3. Dwayt 214	4.0	3.3	0.408	0.044	0.5	1.6	0.020	0.232
G4.Berghouata1	1.5	2.0	0.100	0.221	5.2	0.8	0.098	0.169
G5. Icambel	2.8	3.1	0.303	0.184	1.4	12.2	0.239	0.377
G6. Secondroue	2.3	4.7	0.264	0.206	2.2	3.3	0.253	0.309
G7. Icamoram7	1.4	5.4	0.353	0.201	3.1	5.3	0.496	0.097
G8. Karim	1.6	1.4	0.155	0.150	1.5	13.5	0.693	0.242
G9. Louiza	5.6	2.2	0.050	0.103	3.4	1.4	0.191	0.078
G.10 Faraj	4.8	3.2	0.196	0.179	0.6	3.3	0.096	0.247

Appendix 2B: durum wheat 2017-18

average and standard deviations for yield, biomass, HI, WUE

Durum Wheat 2017-18	Seeding date 1 (19th Nov) 34.8 mm irr.				Seeding date 2 (24th Dec) 28.2 mm irr.			
	Yield (t/ha)		Tot. Biomass (t/ha)		Yield (Ton/ha)		Tot. Biomass (t/ha)	
Water regime / total applied (inc. rain) →	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated
Genotype ↓	493.4 mm	528.2 mm	493.4 mm	528.2 mm	416 mm	444.2 mm	416 mm	444.2 mm
G1. DAWRyT106	7.708	8.492	16.958	21.125	8.067	9.617	21.000	21.042
G2.Dawryt 104	7.525	7.058	20.583	18.792	8.275	8.183	19.458	18.125
G3. Dwayt 214	6.367	6.883	17.375	19.625	8.267	8.858	20.333	20.500
G4.Berghouata1	7.067	7.417	18.833	17.458	8.358	7.508	19.542	17.583
G5. Icambel	5.742	4.392	15.667	18.292	8.042	8.425	17.250	20.875
G6. Secondroue	5.350	4.225	17.875	19.750	7.925	7.817	19.667	17.000
G7. Icamoram7	6.758	6.475	20.208	19.958	8.650	8.617	19.042	17.500
G8. Karim	7.917	7.792	17.333	18.167	8.367	8.925	18.333	21.250
G9. Louiza	7.842	7.608	18.125	15.125	7.817	6.675	17.333	18.833
G.10 Faraj	5.650	7.025	18.875	22.208	7.667	7.858	19.625	21.042
Average across genotypes	6.793	6.737	18.183	19.050	8.143	8.248	19.158	19.375
Standard Deviation across genotypes	0.921	1.323	1.417	1.878	0.280	0.790	1.147	1.637
Standard Deviation across replications								
G1. DAWRyT106	1.347	0.316	2.315	1.794	0.310	0.082	1.418	2.712
G2.Dawryt 104	0.359	0.286	1.487	2.003	0.061	0.777	1.047	2.084
G3. Dwayt 214	1.424	0.537	1.912	1.768	0.698	0.734	2.446	2.215
G4.Berghouata1	0.481	0.379	2.425	2.027	0.630	1.399	0.059	0.257
G5. Icambel	1.022	0.445	2.003	1.559	0.399	0.790	1.483	2.564
G6. Secondroue	1.364	0.448	0.935	0.714	0.308	0.143	1.948	1.150
G7. Icamoram7	0.239	1.111	1.637	2.693	0.288	0.827	1.841	1.705
G8. Karim	0.575	1.026	2.392	2.682	0.399	0.786	2.195	0.797
G9. Louiza	0.930	1.263	0.714	4.320	0.914	2.440	0.664	1.209
G.10 Faraj	0.495	0.804	1.780	2.092	0.492	0.165	2.143	1.276

	Harvest Index %		WUE kg/m3/ha		Harvest Index %		WUE kg/m3/ha	
Genotype	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated
G1. DAWRyT106	45.2	40.4	1.562	1.608	38.7	46.4	1.939	2.165
G2.Dawryt 104	36.8	38.0	1.525	1.336	42.6	45.8	1.989	1.842
G3. Dwayt 214	37.6	35.6	1.29	1.303	41.5	43.6	1.987	1.994
G4.Berghouata1	38.4	43.4	1.432	1.404	42.8	42.8	2.009	1.690
G5. Icambel	36.7	24.2	1.164	0.831	47.0	41.2	1.933	1.897
G6. Secondroue	30.3	21.4	1.084	0.800	40.7	46.2	1.905	1.760
G7. Icamoram7	33.7	33.0	1.37	1.226	45.7	49.6	2.079	1.940
G8. Karim	46.6	43.0	1.605	1.475	46.3	42.2	2.011	2.009
G9. Louiza	43.2	52.8	1.589	1.440	45.0	36.1	1.879	1.503
G.10 Faraj	30.1	31.6	1.145	1.330	39.3	37.5	1.843	1.769
Average across genotypes	37.9	36.3	1.377	1.275	43.0	43.1	1.958	1.857
Standard Deviation across genotypes	5.4	8.9	0.187	0.25	2.8	3.9	0.067	0.178
Standard Deviation across replications								
G1. DAWRyT106	2.0	2.5	0.273	0.060	3.7	5.1	0.074	0.019
G2.Dawryt 104	4.1	4.1	0.073	0.054	2.1	7.1	0.015	0.175
G3. Dwayt 214	11.5	5.6	0.289	0.102	7.3	5.4	0.168	0.165
G4.Berghouata1	6.9	7.6	0.098	0.072	3.3	8.5	0.151	0.315
G5. Icambel	5.0	3.0	0.207	0.084	5.2	7.3	0.096	0.178
G6. Secondroue	9.1	2.5	0.277	0.085	4.7	2.6	0.074	0.032
G7. Icamoram7	3.4	7.5	0.048	0.210	2.9	6.1	0.069	0.186
G8. Karim	7.7	1.1	0.116	0.194	6.4	5.0	0.096	0.177
G9. Louiza	3.9	9.0	0.188	0.239	3.6	14.5	0.220	0.549
G.10 Faraj	2.8	1.1	0.1	0.152	2.5	2.9	0.118	0.037

Appendix 3A: daily recorded weather data, November 2016 – June 2017

Date	Rainfall mm	Average temp °C	Min temp °C	Max temp °C	Eto mm
01/11/2016	0	22.3	15.7	30.1	3.2
02/11/2016	0	21.4	13.2	31.3	3.6
03/11/2016	0.2	22.1	15.3	31.4	5.2
04/11/2016	0	20.5	17.5	23.6	2.7
05/11/2016	0	19.3	13.7	25.4	2.7
06/11/2016	0	16.8	13.5	21.7	2
07/11/2016	1.2	13.9	11.2	17.5	1.7
08/11/2016	3	12.3	7.6	18.1	1.6
09/11/2016	0	10.8	2.1	19.3	2.1
10/11/2016	0	12.0	3.9	18.8	1.4
11/11/2016	0	13.3	8.6	19.1	2
12/11/2016	0	12.8	6.1	20.3	1.9
13/11/2016	0	12.9	5.7	21.2	1.8
14/11/2016	0	13.5	4.9	23.1	2.2
15/11/2016	0	14.3	4.5	23.7	3
16/11/2016	0	15.9	6.8	24.2	3.1
17/11/2016	0	14.6	6	25	2.6
18/11/2016	0	13.1	4.5	22.1	2.1
19/11/2016	0	13.1	6.7	20.8	1.7
20/11/2016	0	13.8	6.1	21	1.8
21/11/2016	1	15.8	11.2	21.4	2.6

22/11/2016	11.6	12.9	10.4	16.1	0.9
23/11/2016	0.2	10.2	8.6	13.6	1.6
24/11/2016	3.4	10.9	8.9	16	1.8
25/11/2016	0.2	13.7	10.8	18.2	2.6
26/11/2016	10.2	12.9	10.1	16.7	1.8
27/11/2016	9.4	13.4	11.7	16.5	1.5
28/11/2016	3.6	12.5	9.4	17.1	1.1
29/11/2016	0.2	12.5	6.1	19.2	1.3
30/11/2016	0	13.4	9.3	18.5	1.2
01/12/2016	0	15.0	8.8	23.4	2.2
02/12/2016	2.8	15.5	11.4	20.1	1.4
03/12/2016	2.4	16.5	13.9	20.8	1.4
04/12/2016	4.2	15.6	12.7	17.6	1.5
05/12/2016	15.6	15.2	14.1	17.5	1
06/12/2016	0.4	15.2	12.7	19.6	0.9
07/12/2016	0.4	13.9	8.9	20.3	1.5
08/12/2016	0.2	14.3	7.5	22.3	1.7
09/12/2016	0	14.7	8.8	22.3	1.9
10/12/2016	0	13.1	6.7	20.6	1.5
11/12/2016	0	12.1	6.8	19.7	1.4
12/12/2016	0.2	11.7	5.8	19	1.3
13/12/2016	0.4	11.0	5.9	18	1.1
14/12/2016	8.6	11.6	5.5	18.6	1.7

15/12/2016	0.6	11.5	8.4	15	1.1
16/12/2016	27.4	9.3	6.4	13	0.8
17/12/2016	1.8	8.2	6	11.4	1
18/12/2016	0.2	8.1	1.1	14.6	1.1
19/12/2016	3.4	10.4	8.2	14.6	1.2
20/12/2016	2.4	10.6	6.2	13.6	0.8
21/12/2016	0.2	9.3	3	15.7	1
22/12/2016	0.4	9.5	3.9	15.7	1.2
23/12/2016	0.2	9.8	3.3	18.1	1.2
24/12/2016	0	10.2	2.9	18.9	1.3
25/12/2016	0	11.3	4.7	20.2	1.8
26/12/2016	0	10.3	3.9	18.1	1.3
27/12/2016	0	10.0	3.4	17.6	1.2
28/12/2016	0	9.9	2.6	19.1	1.4
29/12/2016	0	10.5	3.4	19.6	1.7
30/12/2016	0	10.5	3.5	19.3	1.4
31/12/2016	0.2	10.0	2.5	19	1.5
01/01/2017	0.2	9.7	2.9	19.4	1.5
02/01/2017	0	10.2	2.5	19.7	2.1
03/01/2017	0	10.7	3.1	20.6	2.4
04/01/2017	0	10.3	2.9	20.2	2.2
05/01/2017	0	9.7	1.6	18.7	1.6
06/01/2017	0.2	10.1	1.4	19.8	1.4

07/01/2017	0	10.6	2.3	20.9	1.7
08/01/2017	0	9.3	2	18.3	1.3
09/01/2017	0	8.8	2.1	16.6	1.1
10/01/2017	0.2	9.4	1.4	15.5	1.2
11/01/2017	0	12.4	8.7	17.7	1.2
12/01/2017	0	12.0	4.8	20.2	2.5
13/01/2017	0	9.8	1.8	17.5	1.2
14/01/2017	0.2	10.9	4.9	15.5	1.2
15/01/2017	0	7.9	1.6	15.3	2.3
16/01/2017	0	6.3	-2.4	16.6	1.7
17/01/2017	0	6.9	-2.4	17	1.7
18/01/2017	1.8	8.3	2.4	15.4	1.3
19/01/2017	4.8	5.8	2.7	10.7	1.1
20/01/2017	9.2	5.5	2.6	9.2	0.8
21/01/2017	0.4	7.2	2.5	11.4	1.1
22/01/2017	1	7.7	1.8	11.7	1
23/01/2017	7.4	8.5	6.6	12.9	1.1
24/01/2017	0	8.5	2.1	14.4	1.3
25/01/2017	0.2	7.0	-0.8	15.4	1.3
26/01/2017	5.8	11.1	4.8	17.8	2.7
27/01/2017	12.6	11.6	9.8	14.6	1
28/01/2017	0.8	11.1	6.8	16.8	1.2
29/01/2017	0.2	9.5	2.4	17.1	1.3

30/01/2017	0.4	10.8	1.8	21.1	1.6
31/01/2017	0	12.3	6.6	18.8	1.9
01/02/2017	0	11.3	4.5	17.2	1.3
02/02/2017	0.6	11.6	5.5	18.5	1.6
03/02/2017	0.2	12.9	7.3	18.9	1.4
04/02/2017	0.2	12.8	6.4	18.4	1.5
05/02/2017	0	12.7	8.1	18.1	1.4
06/02/2017	0.2	12.1	5.5	20.8	2.2
07/02/2017	0.2	11.8	3.5	20.8	2.1
08/02/2017	0	10.2	3.4	18.4	1.8
09/02/2017	0	11.9	1.4	23.3	2.9
10/02/2017	6.4	9.4	6.7	11.8	0.7
11/02/2017	13	10.4	5.5	16.5	1.4
12/02/2017	11.4	13.4	10.7	16.1	1.3
13/02/2017	0.2	11.9	6.4	17	1.7
14/02/2017	0.2	10.7	3.4	18.6	1.6
15/02/2017	0.2	12.1	4	21.3	1.6
16/02/2017	0.4	13.7	4.8	23.8	1.7
17/02/2017	0	12.3	3.9	22.6	2.2
18/02/2017	0.2	10.9	3.9	17.9	1.4
19/02/2017	22.8	9.7	7.2	11.4	0.6
20/02/2017	6.8	10.3	7.1	15.6	0.8
21/02/2017	0.2	12.0	9.1	16	1

22/02/2017	0.2	11.8	6.8	16.5	1
23/02/2017	13.6	11.9	9.8	14.7	0.9
24/02/2017	5.6	13.1	11.7	16.1	0.9
25/02/2017	0.2	13.0	10.5	16.8	1.1
26/02/2017	0	12.8	7.6	18.7	1.5
27/02/2017	0	12.1	7.2	18.1	1.3
28/02/2017	0	12.6	7.2	17.7	1.6
01/03/2017	0.4	10.7	4.1	19.2	1.7
02/03/2017	0.2	12.6	3.5	22.1	1.6
03/03/2017	0.6	10.4	4.6	15.7	1.1
04/03/2017	0.6	9.8	3.1	15.2	1.5
05/03/2017	0.2	13.7	6.6	20.2	1.7
06/03/2017	0.4	11.3	6.1	17.2	0.9
07/03/2017	0.2	13.8	5.7	22.4	2.1
08/03/2017	0.4	16.2	5.8	28.3	2.3
09/03/2017	0.2	18.8	8.8	30.6	2.7
10/03/2017	0	17.7	7.9	30.2	2.8
11/03/2017	0	15.8	5.7	29.7	2.8
12/03/2017	0.2	12.3	4.8	20.1	1.4
13/03/2017	0	10.9	3.3	16.6	1.9
14/03/2017	0.2	10.7	3.4	19.2	1.9
15/03/2017	0.6	11.4	2.9	20.7	2.1
16/03/2017	0.2	13.6	10.5	19.2	1.4

17/03/2017	1	13.6	6.2	21.1	1.7
18/03/2017	0.2	14.1	5.9	23.8	2.2
19/03/2017	0.4	13.8	6.1	23.1	2.3
20/03/2017	0.2	13.9	7.2	22.3	2.3
21/03/2017	0	12.9	8.6	19.4	1.5
22/03/2017	0	11.3	2.8	18.4	1.8
23/03/2017	9.8	8.6	4.8	13.3	1.1
24/03/2017	4.2	8.0	3.4	14.2	1.4
25/03/2017	0.2	8.5	0.3	17.8	2.1
26/03/2017	0.2	11.8	0.8	21.7	2.9
27/03/2017	0	13.5	6.7	21	1.8
28/03/2017	0.2	13.3	4.3	23.1	2.7
29/03/2017	0.2	14.5	3.8	25.9	2.6
30/03/2017	0.2	16.7	6.8	29.2	3
31/03/2017	0	15.7	5.4	26.9	2.7
01/04/2017	0	15.1	8.1	23.9	2.6
02/04/2017	0.2	13.6	3.9	25.1	2.8
03/04/2017	0.2	14.7	3.5	26.9	3
04/04/2017	0.2	15.4	4.9	27.2	3.1
05/04/2017	0	15.3	4.4	28.2	3.3
06/04/2017	0	17.0	3.5	29.2	3.9
07/04/2017	0	19.0	7.6	30.2	4.8
08/04/2017	0	16.5	4.7	29.7	3.4

09/04/2017	0	19.0	7	32.5	3.7
10/04/2017	0	20.0	9.8	32.2	4.1
11/04/2017	0	18.3	9.2	29.1	3.2
12/04/2017	0	18.0	14	26.6	2.6
13/04/2017	0	16.7	12.3	25.4	2.8
14/04/2017	0	17.1	10.9	26	2.9
15/04/2017	0	18.9	11.6	29.5	3.2
16/04/2017	0	18.6	10.4	29.5	3.2
17/04/2017	0	21.4	8.2	33.8	4
18/04/2017	0	24.9	14.4	37.5	5.2
19/04/2017	0	23.1	12	34.5	3.9
20/04/2017	0	19.3	13.5	28.6	3.4
21/04/2017	0	17.8	15.3	22.4	1.8
22/04/2017	0	18.0	12.9	25.4	2.6
23/04/2017	0	17.8	10	26.9	2.9
24/04/2017	0	18.4	14.7	26.1	2.9
25/04/2017	0	17.7	11.8	26.8	3
26/04/2017	0	17.0	8.1	26.3	3.1
27/04/2017	0	18.4	9.1	28.9	3.9
28/04/2017	1.6	19.2	14.9	27	3.8
29/04/2017	0	17.2	10.7	24.5	2.8
30/04/2017	0	16.0	9	22.6	2.4
01/05/2017	0	15.5	5.6	25.4	3.4

02/05/2017	0	19.3	6	32.4	4
03/05/2017	0	24.1	12.9	36.8	5
04/05/2017	0	18.3	14.9	25.6	2.6
05/05/2017	0	18.3	11.5	25.2	3
06/05/2017	0	18.5	10.2	28	3.6
07/05/2017	0	20.4	9.2	33.3	4
08/05/2017	0	21.2	11.5	33.1	4.2
09/05/2017	0	18.7	10.7	29.1	4.2
10/05/2017	0	18.3	9.2	27.4	4.1
11/05/2017	0	19.2	14.5	25.1	3.4
12/05/2017	0.6	18.6	12	26.8	3.9
13/05/2017	0	17.7	9.4	26.8	3.5
14/05/2017	0	18.7	10.5	28.4	4.1
15/05/2017	0	21.4	10.2	33.4	3.9
16/05/2017	0	25.0	13	36.9	4.4
17/05/2017	0	24.8	14	35.4	4.7
18/05/2017	0	19.5	13.1	26.6	3.7
19/05/2017	0	19.2	8.7	30.8	4.9
20/05/2017	2	28.7	11.4	43	5.8
21/05/2017	0	26.4	18	33.1	5.1
22/05/2017	0	20.0	15.8	26.8	2.8
23/05/2017	0	20.9	14.3	29.2	3.6
24/05/2017	0	20.9	16.5	29.9	3.9

25/05/2017	0	20.7	17.1	28.1	2.8
26/05/2017	0	20.4	17.7	26.6	2.6
27/05/2017	0	21.3	17.5	27.1	3.1
28/05/2017	0	19.5	14.7	24.1	2.1
29/05/2017	0	19.0	11.2	27.3	3.4
30/05/2017	0	19.2	11.1	27.4	3.8
31/05/2017	0	21.2	13.4	29	3.6
01/06/2017	0	23.4	18	32.2	4.1
02/06/2017	0	22.6	18.1	30.6	4
03/06/2017	0	22.0	16.5	29.3	3.9
04/06/2017	0	19.6	14.5	27.1	4
05/06/2017	0.2	18.7	9.5	28.6	4.4
06/06/2017	0.2	19.7	11	28.9	4.6
07/06/2017	0	23.9	14.2	36.5	5.8
08/06/2017	0	25.9	19.1	35.7	5.5
09/06/2017	0	22.9	17	30.3	4.2
10/06/2017	0	25.7	15.8	35.8	
11/06/2017	0	28.3	17.6	40.4	5.5
12/06/2017	0	25.6	18.2	33.8	4.9
13/06/2017	0	22.4	18.7	29.8	4.2
14/06/2017	0	21.1	16.9	27.3	3.2
15/06/2017	0	23.1	17.5	30.8	4
16/06/2017	0	29.6	17.4	41.5	6.5

17/06/2017	0	31.6	22.7	42	6.6
18/06/2017	0	29.5	20.9	39.9	6.4
19/06/2017	0	28.8	22.1	35.7	5.5
20/06/2017	0	23.8	18.6	31.6	3.9
21/06/2017	0	23.9	18.9	31.3	4.2
22/06/2017	0	23.7	17.1	33	4.2
23/06/2017	0	27.3	15.6	40.5	6.7
24/06/2017	0	29.3	16.1	44.1	7.6
25/06/2017	0	28.3	21.7	41.6	8.2
26/06/2017	0	23.9	19.5	30.5	3.5
27/06/2017	0	21.8	17.7	28.7	3.9
28/06/2017	0	21.3	14.7	29	4.4
29/06/2017	0	18.4	14.1	24.7	2.9
30/06/2017	0	18.3	11.1	25.3	4.1

Appendix 3B: daily recorded weather data, November 2017 – June 2018

Date	Rainfall mm	Average Temp °C	Min Temp °C	Max Temp °C	ETo
01/10/2017	0	22.53	16.3	31.7	3.3
02/10/2017	0	25.05	15.3	35.1	4.1
03/10/2017	0	26.81	16.1	36.1	5.5
04/10/2017	0	26.76	17.1	35.6	5
05/10/2017	0	25.27	16.1	34	4.4
06/10/2017	0	25.12	18.6	32.2	3.8
07/10/2017	0	22.42	14.8	33	3.3

08/10/2017	0	22.70	14.9	31.9	3.4
09/10/2017	0	24.58	15.5	34.4	4
10/10/2017	0	25.83	15.9	35.2	4.3
11/10/2017	0	27.75	19.6	36.7	5
12/10/2017	0	29.03	21.7	37.6	5
13/10/2017	0	28.31	18.8	37.4	5.4
14/10/2017	0	28.39	18.3	36.7	5.2
15/10/2017	0	27.24	19.7	35	5
16/10/2017	0	25.68	20.8	29.7	3
17/10/2017	0	24.45	19.6	31.5	3.7
18/10/2017	0.4	19.65	17.7	22.5	2.5
19/10/2017	10.4	18.29	16.4	21.7	1.4
20/10/2017	0	18.64	14.4	24.3	2.1
21/10/2017	0	18.36	11.1	25.8	1.9
22/10/2017	0	19.32	13.5	26.3	2.2
23/10/2017	0	19.04	10.8	28.9	2.1
24/10/2017	0	20.93	12	31.8	3
25/10/2017	0	21.18	11.4	31	2.8
26/10/2017	0	22.02	12.5	32.4	3
27/10/2017	0	21.18	13	30	3
28/10/2017	0	19.57	10	29.8	2.8
29/10/2017	0	18.08	10.4	27.2	2.4
30/10/2017	0	17.04	7.3	28.3	2.5

31/10/2017	0	16.05	8.6	24.9	1.9
01/11/2017	0	16.50	8.3	25.8	2.2
02/11/2017	0	17.65	10.2	27.2	2.4
03/11/2017	0	17.83	13	23.2	1.9
04/11/2017	0	17.83	11	22.7	2.2
05/11/2017	0	15.14	7.3	22.3	2
06/11/2017	0	14.63	5.2	23.9	2.1
07/11/2017	0	14.78	5.5	25.5	2.4
08/11/2017	0	15.05	6.7	23.2	1.9
09/11/2017	0	13.74	6.1	21	1.9
10/11/2017	0	14.18	6.7	20.9	1.9
11/11/2017	0	14.70	5.6	24.3	3.4
12/11/2017	0	13.03	4	23.7	2
13/11/2017	0	12.28	3.5	21.7	1.8
14/11/2017	0	12.75	4.5	21.4	1.9
15/11/2017	0	12.52	3.4	21.8	1.8
16/11/2017	0	13.17	4.3	23.4	2.1
17/11/2017	0	13.63	5.1	23.4	1.9
18/11/2017	0	14.19	5.5	24.7	2.2
19/11/2017	0	14.48	4.8	25.3	2.6
20/11/2017	0	15.22	5.8	26.4	2.7
21/11/2017	0	15.56	6	26.1	2.7
22/11/2017	0	15.28	6.8	25.5	2.9

23/11/2017	0	15.67	6.2	26.2	2.5
24/11/2017	0	16.61	7.8	26.9	2.5
25/11/2017	0	16.95	7.6	27.1	2.8
26/11/2017	0	18.16	8.9	27.8	3.8
27/11/2017	0	18.62	12.1	26.7	2.4
28/11/2017	0	20.13	12.7	27.4	3.5
29/11/2017	1.4	19.32	16.2	24.1	4
30/11/2017	28	12.85	9	17.2	1.2
01/12/2017	0	9.62	5.6	14	1.3
02/12/2017	0	8.26	2.3	14.6	1.2
03/12/2017	0.2	7.55	0.9	14.9	1.3
04/12/2017	0	8.65	0	17.8	1.3
05/12/2017	0	10.42	2.6	20	1.9
06/12/2017	0	10.75	3.4	19.3	1.7
07/12/2017	0	9.32	1.8	18	1.5
08/12/2017	0	9.15	1.1	18.9	1.7
09/12/2017	0	10.37	2.5	19.2	1.6
10/12/2017	0	11.80	5	19.7	1.3
11/12/2017	30.2	11.22	8.2	14.4	0.8
12/12/2017	7	9.18	4.7	12.9	1
13/12/2017	0.2	7.22	1.2	13.4	0.9
14/12/2017	0.2	9.06	2.6	15.8	1
15/12/2017	0	11.80	5.7	17	1.2

16/12/2017	9.4	12.19	8.9	13.7	0.6
17/12/2017	0.2	9.19	2.9	14.6	0.8
18/12/2017	0.4	8.73	2.5	14.9	0.8
19/12/2017	0.2	8.88	2.3	14.9	1
20/12/2017	0	10.62	6.3	16.2	2.2
21/12/2017	0	10.36	2.3	18.3	2.2
22/12/2017	0	10.53	5.5	17.1	1.9
23/12/2017	0	9.01	1.2	17.4	1.3
24/12/2017	0.2	9.30	2.1	17.1	1.1
25/12/2017	0.2	10.12	4	16.9	1.4
26/12/2017	0	11.30	5.2	16.8	1.4
27/12/2017	2.2	12.68	11	14.6	0.8
28/12/2017	1.8	13.43	11.7	16.7	0.9
29/12/2017	0.2	11.48	6.6	16.3	0.9
30/12/2017	0.4	13.37	7.2	21.8	1.5
31/12/2017	0	14.44	10.1	18.2	1.2
01/01/2018	0.2	11.94	7.5	16.3	1
02/01/2018	0.4	10.46	3.4	19.7	1.5
03/01/2018	0.2	10.92	4.1	17.6	1
04/01/2018	0	12.29	10.3	17.6	1
05/01/2018	0.2	11.55	5.9	19.8	1.5
06/01/2018	19	8.92	5.7	12.5	1
07/01/2018	14.2	6.34	3.9	9.5	0.7

08/01/2018	37.8	7.65	5.2	9.9	0.6
09/01/2018	0.2	11.93	8.8	14.5	1.1
10/01/2018	12.4	12.20	7.2	15.5	0.6
11/01/2018	0.4	9.87	5.3	16.3	0.8
12/01/2018	0.2	9.00	3.9	15.6	1.3
13/01/2018	4.6	10.42	3.8	15.4	1
14/01/2018	8.6	9.95	7.8	13.9	0.8
15/01/2018	0	8.15	4.4	11.8	1.1
16/01/2018	0	9.20	3.4	16.4	1.3
17/01/2018	0.2	9.21	3	14.8	0.9
18/01/2018	0	10.09	6.3	12.8	0.5
19/01/2018	0	11.73	7.8	16.3	1
20/01/2018	0.4	10.44	3.8	17.1	1
21/01/2018	0.4	10.69	2.8	19.5	1.4
22/01/2018	0.2	9.21	3.2	15.1	0.9
23/01/2018	0.2	9.68	8.4	11.4	0.5
24/01/2018	0	9.68	7.8	12.9	0.7
25/01/2018	0	11.19	8.9	15.1	1
26/01/2018	7.2	9.55	6	12.9	1.1
27/01/2018	1.4	7.90	3.4	12.5	1.2
28/01/2018	0.2	6.13	0.4	12.2	1.2
29/01/2018	0	9.23	5.2	15	1.4
30/01/2018	0	11.81	5	19.4	2.2

31/01/2018	0	9.75	4.7	13	0.7
01/02/2018	0	11.24	5.4	16.2	1.2
02/02/2018	2	9.15	2.8	12.6	1.3
03/02/2018	0.2	5.70	-1.7	12.4	1.2
04/02/2018	15.8	5.47	0.2	10	1
05/02/2018	16.2	5.73	3.5	10	0.7
06/02/2018	13	5.39	2.7	8.7	0.6
07/02/2018	0.6	6.68	3.6	10.6	1
08/02/2018	1.8	7.51	4.2	12.4	1
09/02/2018	0	8.36	4.6	12.6	1.2
10/02/2018	2.8	9.82	6.9	14	1.1
11/02/2018	0.2	8.79	3.1	15.2	1.3
12/02/2018	0.2	9.49	1.9	16.9	1.4
13/02/2018	0.2	11.18	5.2	16.6	1.4
14/02/2018	0.2	8.89	2.2	17.5	1.5
15/02/2018	0.4	9.54	1.4	18.5	1.6
16/02/2018	0.2	10.00	3	17.5	1.3
17/02/2018	0	11.78	6.2	16.7	1.4
18/02/2018	0.2	10.15	2.5	17.7	1.4
19/02/2018	0.2	9.76	2.4	16.2	1.2
20/02/2018	0.2	10.55	4.5	17.2	1.4
21/02/2018	0.2	10.42	3.4	17.7	1.7
22/02/2018	0.2	11.61	5.8	18.1	1.9

23/02/2018	0.2	10.81	3.9	17.5	1.8
24/02/2018	0	10.48	5.4	16	1.3
25/02/2018	0.2	11.48	3.4	20.4	1.8
26/02/2018	4.8	11.93	7.5	19.4	1.6
27/02/2018	0	13.24	8.3	19.2	2.3
28/02/2018	3.8	12.03	4.7	22.1	2.8
01/03/2018	18.8	14.95	12.6	18.3	1.7
02/03/2018	0	16.07	12.7	21	2.2
03/03/2018	29	12.76	10.9	15.8	0.7
04/03/2018	0.8	14.17	12	17.7	2.1
05/03/2018	13.4	13.08	11.3	15.2	1
06/03/2018	8	13.63	10.9	16.9	0.6
07/03/2018	4.8	15.83	13.7	19.9	1.1
08/03/2018	0.4	15.75	12.6	20.3	1.7
09/03/2018	6.8	15.84	9.9	21.4	1.8
10/03/2018	0.6	15.70	13.1	20.8	1.8
11/03/2018	0.8	13.13	10	17	1.8
12/03/2018	3.6	13.08	7.6	20.5	2
13/03/2018	0.2	12.46	6.2	18.9	1.4
14/03/2018	0.2	13.87	8.2	19.9	1.8
15/03/2018	7.4	12.08	8.4	13.9	0.8
16/03/2018	4.6	10.15	7.7	13.8	1.3
17/03/2018	0.4	11.63	7.5	16.5	2.1

18/03/2018	10	13.50	11.2	17.8	1.7
19/03/2018	0.4	13.01	10.1	17.8	1.7
20/03/2018	4.8	10.84	6.2	13.8	1.7
21/03/2018	0.2	8.71	3.9	14.3	1.6
22/03/2018	0.2	8.04	0.2	14.8	1.7
23/03/2018	0.2	9.59	1.6	17.5	2.1
24/03/2018	5	11.04	6.4	13.8	0.9
25/03/2018	1.6	10.60	5	16.2	1.3
26/03/2018	1	11.32	4.6	17.6	2
27/03/2018	0.2	12.44	4	21.1	2.5
28/03/2018	0.2	13.40	5.4	21.8	2.1
29/03/2018	0.2	12.59	7.2	19.2	1.7
30/03/2018	0.2	12.51	8	17.6	1.9
31/03/2018	0	12.85	6.3	20.3	2.2
01/04/2018	0.4	13.99	5.5	23.7	2.4
02/04/2018	0	13.44	7.4	19.8	1.8
03/04/2018	0.2	13.28	6	21.3	1.9
04/04/2018	0	14.60	8.3	21	2.4
05/04/2018	0	14.00	6.1	22.7	2.2
06/04/2018	0	14.30	9.9	20.7	2.4
07/04/2018	8.6	12.22	8.4	18	2
08/04/2018	0.6	12.08	9.4	16.7	1.4
09/04/2018	8.8	10.83	7.1	15.9	1.7

10/04/2018	0.4	11.58	5.9	16	1.8
11/04/2018	8.6	11.78	9.6	15.6	1.5
12/04/2018	8.4	12.25	8.9	17.9	2.1
13/04/2018	16.2	10.18	7.7	13.3	1
14/04/2018	18.2	11.47	6.8	17	1.2
15/04/2018	1.8	11.54	3.7	19.7	2.3
16/04/2018	0.2	14.27	6.7	22.5	2.5
17/04/2018	0.2	16.68	9.7	25.3	2.7
18/04/2018	0.2	17.40	8.6	27.8	2.7
19/04/2018	0.2	19.73	10.4	28.6	3
20/04/2018	0	16.63	13.9	22.2	2.4
21/04/2018	0.4	13.83	10.2	16.5	1.1
22/04/2018	0	14.33	8	20.7	2.2
23/04/2018	0.4	14.93	9.9	21.4	2.3
24/04/2018	7.2	15.21	11.7	21.4	1.8
25/04/2018	24.2	15.15	11.7	21.1	2
26/04/2018	0	16.40	12.9	20.9	2
27/04/2018	0.2	16.20	11.9	22.5	1.9
28/04/2018	1	14.73	10.8	19.2	1.6
29/04/2018	0.2	12.69	7	17.8	2.2
30/04/2018	0	11.04	3.5	17.8	2.1
01/05/2018	5.6	11.38	7	17	2
02/05/2018	0	11.38	4.2	18.9	2.2

03/05/2018	0	12.53	7.2	18.8	2
04/05/2018	0	13.42	6	20.5	2.3
05/05/2018	0	14.78	6.7	23.1	2.5
06/05/2018	0	15.81	8.7	23.3	2.4
07/05/2018	0.4	16.61	13.3	21.1	2.2
08/05/2018	0	17.20	13.7	22.7	2.3
09/05/2018	0	15.41	11	21	1.6
10/05/2018	0	15.81	10.2	22.2	2.4
11/05/2018	0	15.51	10	23.2	2.3
12/05/2018	0	15.82	12.1	21.8	2.7
13/05/2018	0	15.50	7.4	23.1	3.2
14/05/2018	0	14.68	5.2	25.7	3.2
15/05/2018	0	16.65	6.8	27.5	3.3
16/05/2018	0	18.29	8.8	27.2	3.1
17/05/2018	1.4	18.38	14.6	24.4	2
18/05/2018	0.2	17.70	11.6	24.8	2.4
19/05/2018	0	16.57	12.8	21.1	1.7
20/05/2018	0	17.72	13.2	25.3	2.9
21/05/2018	0	16.10	9.6	24.1	2.2
22/05/2018	0	17.75	13.4	26.5	3.1
23/05/2018	0.2	15.98	14.1	19.5	1.1
24/05/2018	0.2	15.30	10.8	20.1	1.4
25/05/2018	0	16.48	10.9	24	2.4

26/05/2018	0	15.95	8.4	24.6	2.4
27/05/2018	0	17.30	11.7	23.6	2.2
28/05/2018	0	15.80	8.3	23	2.4
29/05/2018	0	16.11	9.9	23.3	2.6
30/05/2018	0	15.88	8.1	24.3	2.8
31/05/2018	0	16.68	9.3	24.9	2.7
01/06/2018	0	17.23	11.4	25.9	3
02/06/2018	0	16.64	9.2	22.9	2.6
03/06/2018	0	16.66	6.8	26.3	3.4
04/06/2018	0	17.93	12.7	25	3.2
05/06/2018	0	17.90	12.5	24.2	3.3
06/06/2018	0	18.07	12.6	25.3	3.2
07/06/2018	0	18.50	11.7	28	3.4
08/06/2018	0	18.11	11.5	27.9	3.3
09/06/2018	0	17.99	15	23.5	2.4
10/06/2018	0	17.27	10.1	24.9	2.7
11/06/2018	0	16.38	8.1	24.2	2.9
12/06/2018	0	18.22	11.3	25.3	3.1
13/06/2018	0	19.02	15.7	26.5	3.4
14/06/2018	0	19.73	11.4	28.7	3.7
15/06/2018	0	21.11	10.9	31.3	3.8
16/06/2018	0	20.56	14	29.6	3.7
17/06/2018	0	20.80	12.4	30.3	3.3

18/06/2018	0	22.11	16.4	32	3.8
19/06/2018	0	20.90	12.6	31.7	3.8
20/06/2018	0	19.77	15.2	27.5	2.8
21/06/2018	0	19.81	16.4	26	2.9
22/06/2018	0	19.88	15.9	26.8	2.6
23/06/2018	0	19.20	13.6	26.9	2.7
24/06/2018	0.2	17.93	16.8	20.4	0.9
25/06/2018	0	18.46	16.2	22.5	1.5
26/06/2018	0	20.27	16.9	27.2	3.1
27/06/2018	0	20.12	14.2	28.5	3.1
28/06/2018	0	20.05	14.1	27.9	3.4
29/06/2018	0	20.78	14.6	29.5	3.7
30/06/2018	0	20.30	14	27.7	2.7