Drought Risk and You

Dr Ivan Grove & Dr Jim Monaghan

Harper Adams University

Funded by:

NERC DRY project Report and Results from HAU Agricultural Mesocosms

Abstract

The ‘drought and water scarcity’ programme was a £12 million+ Natural Environment Research Council (NERC) programme, in collaboration with ESRC, EPSRC, BBSRC and AHRC. The key concern for drought was that ‘our ability to characterise and predict their occurrence, duration and intensity, as well as minimise their impacts, is often inadequate’. Within this program the Drought Risk and You, DRY, project was funded and included an investigation involving crop production, which was based at Harper Adams University, Shropshire. For this element of the investigation the team at HAU chose not to simply repeat the extensive research already published on crop responses to drought, but to investigate if cropping within the UK could tolerate the most severe climate change projected under the high emissions scenario for the UK in 2050. This work investigated effects on the mainstay cereals of common wheat and barley, the lesser grown triticale, and the current niche crops durum wheat and quinoa which favor warmer climates. In addition, as the UK uses significant amount of land for forage the performance of perennial ryegrass and its suggested drought tolerant equivalent Lucerne were also included as important crops for the study.

Overriding findings are that acceptable crop yields were still achieved in the main cereal crops of wheat and barley, and the lesser grown triticale, even with the 38% lower spring and summer rainfall quantities projected under the 2050 high emissions for the midlands region. Durum wheat performed less well and quinoa performed inconsistently. Lucerne however outperformed perennial ryegrass in all three seasons demonstrating its better suitability to drier and warmer climates. However, as this work simulated the monthly average Central England rainfall pattern by using a 3x week application strategy this ensured a constant, if small, regular water supply which is not a true reflection of within month precipitation. However, as the soil moisture deficits did not become severely limiting until past the yield critical stages for the cereals this would have been influential of the maintenance of acceptable yields in the DRY scenario. Notably, this work also identified the importance of the return of the soil to field capacity from the increased winter rainfall which is also a key element within this climate change scenario. Replenishing the soil moisture, even at only a 4% precipitation increase, during this slow plant growing period from October to March, ensures significant soil water reserves are available to support plants during the active cereal growing period of April to July. In respect of the forage crops the effect of this scenario on PRG was substantial both in terms of yield loss and ultimately a failure of soils to return back to FC in the final winter, in contrast to the return to FC and and high yields of Lucerne. Water productivity was shown to be superior for the spring sown crops but as the winter rainfall in the UK adds little to the yield of winter sown crops the inclusion of this precipitation in the calculation is debatable.

Soil analysis before and after the investigation revealed that pH was significantly reduced in the DRY scenario whereas soil K and P were both significantly lower in

the CEave scenario, thus suggesting a link with nutrient availability or movement in the moister environment and crop removal by the greater yielding plants.

This work did mimic the normal monthly rainfall pattern for Central England so it did provide some measure of semblance to historic rainfall patterns. The overall conclusion from this work however suggests that should the UK experience the reduced summer rainfall and increased winter rainfall investigated, whilst maintaining the same pattern of rainfall, our mainstay cereals and Lucerne should not encounter significant yield reductions. For other crops which have active growing seasons from April to October, such as those in the fresh produce sector, the issues would be more critical unless the winter rainfall was sufficient to also recharge depleted aquifers so that adequate irrigation was then available in the drier April to September growing period.

Headline:

The projected rainfall pattern for the 2050 high emissions 10% probability, plus 3% winter rain & minus 38% summer rainfall, did not significantly reduce cereal, wheat, barley, triticale, durum, quinoa, yields but did substantially reduce perennial ryegrass yield in comparison to lucerne.

In progress publication outputs:

Paper 1: Mesocosm simulation of climate change impacts on cereal and forage crops in the UK

Paper 2: Cereal and forage crop climate change simulation using the Saltmed model.

Technical outputs:

How do cereals and forage crops respond to predicted UK summer droughts? Project report 131. Harper Adams University, Shropshire.

Knowledge transfer outputs and planned outputs:

Dissemination of results at the DRY catchment meetings at Bevills Leam and Eden (Scotland).

Dissemination of the results at appropriate conferences.

Use of material within HAU postgraduate and undergraduate teaching programme

Use of material within BASIS ‘Soil and Water management’ modules.

Contents Page no.

List of Tables

List of figures

1. Background to the project and the HAU contribution

The UK Drought and Water scarcity programme is a £12 million+ National Environment Research Council (NERC) programme, in collaboration with ESRC, EPSRC, BBSRC and AHRC. The concern was that both drought and water scarcity are a significant threat to 'the environment, agriculture, infrastructure, society and culture in the UK'. However, the concern remains that 'our ability to characterise and predict their occurrence, duration and intensity, as well as minimise their impacts, is often inadequate'. Consequently a five- year interdisciplinary UK Droughts & Water Scarcity research program was initiated to 'support improved decision-making in relation to droughts and water scarcity by providing research that identifies, predicts and responds to the interrelationships between their multiple drivers and impacts' (NERC, 2018).

Five projects were funded under the UK Droughts & Water Scarcity program including the Drought risk and you, DRY:

- DRY: Drought risk and you, which uses narrative, modelling and physical investigations to create a utility which enabled decision makers to foresee drought/water scarcity impacts at both social and physical levels.

1.1 The HAU proposal for DRY

This text is a direct extract from the proposal: 'Agricultural mesocosms: The second set of mesocosm experiments involves agricultural crop species in large polytunnel style structures. The wide ranging implications of drought for food security extends from the direct loss of yield in arable and horticultural crops, to the less obvious reduced forage production and subsequent lower milk and meat production, and consequent impacts on farm income and the rural economy. This part of WP4B will address the foremost issue, loss of yield and food production for both human and animal use that results from reduced precipitation. Wheat, the UK"s staple food, requires up to 650mm of water for optimum yield. In the arable areas around Cambridge and Shropshire, annual rainfall since 1961 has been below 550mm for 44% and 23% of the time, respectively, putting excessive pressure on food supplies. Breeding crops for drought tolerance is a slow and difficult process, and so strategies must include alternate cropping to cope with future drought events - a common practice in Australia. Commercially grown drought resistant alternatives to wheat, include pearl millet, sorghum, amaranth and quinoa. These crops may provide suitable alternatives but research is required to determine both their potential and productivity in UK soils. Other 'intermediate crops" include Durum wheat (pasta wheat), a Mediterranean crop which survives the hotter climates and is currently only grown in the south of England. Work with anti-transpirants (Harper Adams) has demonstrated their potential to increase wheat yields under drought conditions. The proposed research will investigate the production of a range of crops using mesocosms under controlled (polytunnel) conditions to assess crop production under drought conditions. This system will also enable a range of water supply, fresh, brackish and waste water to be tested as supplementary water. It is planned that 5-8 crops, anti-transpirants and 2-3 water sources will be investigated. Drought will be simulated through irrigation closely linked to soil moisture monitoring and data capture will include growth parameters, fresh/dry weight, stomatal conductance, leaf area, crop yield and harvest index. Information on environmental conditions, soil types, organic matter content, air temp (max and min), RH, wind speed, transpiration rates, simulated rainfall, soil moisture, plus the plant growth characteristics such as stomatal conductance, relative growth rates, yield, harvest index, leaf area index and leaf area duration. This data will allow modelling of how the plants might perform and allow predicts of the minimum water requirement (rainfall). As the mesocosms are covered, irrigation in the experimental work will mimic rainfall conditions. This matches the drought conditions when all abstraction for overhead agricultural irrigation is stopped so that public and industrial water supply is maintained, Establishing drought effects on the UK‟s rain-fed agriculture is therefore the priority. WP4B(b) will be linked to stakeholder engagement (see WP5). Stakeholder engagement (visits to site) would be expected to be May/June as they would be during the most informative of the growing periods. Media outputs will involve on-going web presence in the style of a photographic diary (crop progress) and research updates.'

2.0 General introduction to the experimental work at HAU

The UK is categorised as having a temperate maritime climate, with relatively cool summers and mild winters. From Thornthwaite's climate classification the UK would be 'microthermal', having cold winters and low potential evapotranspiration whereas the Köppen system, which includes vegetation, would classify the UK as 'temperate oceanic' with warm summers and mild winters. The UK patterns for temperature and rainfall however are quite variable for an island of only 93,628 miles^2; the western Scottish mountains average 4000mm precipitation p.a, the Lake District averages 3000mm p.a., whilst parts of eastern England receive less than 700mm p.a. The mean annual temperature is also reported as approximately 7°C in the Scottish Shetland isles to over 11°C in the South-west and the channel islands of Guernsey and Jersey (Met Office, 2018). In 2018, following on from a wet winter, it was reported that Northern and Western England had experienced unusually dry spring and early summer weather in contrast to Eastern and Southern England which experienced very wet conditions (UKIA, 2018). For agriculture these variations certainly affect the crops grown, their management and potential productivity and have a considerable impact on the need for supplemental water from irrigation for higher value crops. Crop choice therefore is inextricably linked to climate and then further refined by other considerations such as soil type, market availability and its volatility, labour availability, notwithstanding personal and practical preferences. Increasingly however there is concern about changing climate and weather patterns. According to many of the projections produced by the Intergovernmental Panel on

Climate Change (IPCC) there is significant potential for an increase in the occurrence of drought due to changes in the global climate (Intergovernmental Panel on Climate Change [IPCC] 2007). It was reported by Chaves and Oliveira (2004) that drought was already one of the greatest limitations to crop expansion beyond the 2004 agricultural area. Therefore any increasing occurrences or expansions of drought could only reduce our ability to feed an ever increasing world population, estimated to reach 9 billion by 2050 (Godfray *et al.* 2010). During 2017 Spain was reported to have experienced significant drought and received substantially less rain than normal for the last 3 years. Whereas Portugal have experienced significant droughts with 94% of the country in 'extreme drought' (Vicente, 2017).

At the present time it is reported that the UK is 76% self-sufficient in indigenous type food and 60% self-sufficient in all food (Defra, 2017), and therefore retains some degree of food security. Although the UK is classed as a temperate climate it is not unknown for drought, table 1.1.

Table 1.1 Major droughts in England and Wales 1800-2006 (Marsh *et al.,* 2007)

Major droughts in England and Wales.

Year	Duration	Comments
1854–1860	Long Drought	Major long-duration drought. Sequence of dry winters in both the Lowlands (seven in succession at Oxford) and northern England. Major and sustained groundwater impact.
1887–1888	Late winter 1887–summer 1888	Major drought. High ranking rainfall deficiencies across a range of timeframes. Very widespread (across most of British Isles). Extremely dry five-month sequence in 1887. Primarily a surface water drought – severe in western Britain (including the North-West).
1890–1910	Long Drought	Major drought – long duration (with some very wet interludes, 1903 especially). Initiated by a sequence of notably dry winters. Latter half of the period features a cluster of dry winters. Major and sustained groundwater impact, with significant water supply problems. Most severe phases: 1893, 1899, 1902, 1905. Merits separate investigation.
1921–1922	Autumn 1920–early 1922	Major drought. Second-lowest 6-month and third-lowest 12-month rainfall totals for England and Wales. Very severe across much of England and Wales (including East Anglia and the South-East; parts of Kent reported <50% rainfall for the year, 1921); episodic in north-west England.
1933–1934	Autumn 1932–autumn 1934	Major drought. Intense across southern Britain. Severe surface water impacts in 1933 followed by severe groundwater impacts in 1934, when southern England heavily stressed (less severe in the more northerly, less responsive, Chalk outcrops).
1959	Feb–Nov	Major drought. Intense three-season drought – most severe in eastern, central and north- eastern England. Significant spatial variation in intensity. Modest groundwater impact.
1976	May 1975 – Aug 1976	Major drought. Lowest 16-month rainfall in England and Wales series (from 1766). Extreme in summer 1976. Benchmark drought across much of England and Wales – particularly the Lowlands; lowest flows on record for the majority of British rivers. Severe impact on surface water and groundwater resources.
1990–1992	Spring 1990–summer 1992	Major drought. Widespread and protracted rainfall deficiencies – reflected in exceptionally low groundwater levels (in summer 1992, overall groundwater resources for England and Wales probably at their lowest for at least 90 years). Intense phase in the summer of 1990 in southern and eastern England. Exceptionally low winter flows in 1991/1992.
1995–1997	Spring 1995–summer 1997	Major drought. Third-lowest 18-month rainfall total for England and Wales (1800–2002). Long-duration drought with intense episodes (affecting eastern Britain in the hot summer of 1995). Initial surface water stress, then very depressed groundwater levels and much diminished lowland stream network.

Note: Pre-1850 droughts have not been included here due to the limited hydrological evidence of their severity.

In addition to these events droughts have also been recorded for 2004-06 and 2010-12 (Met Office, 2018) and concerns surrounding an drought development were reported in the farming press in 2017 (Burns, 2017).

Although there are several key factors which can affect the manner, severity and timescale of the changes, such as global carbon dioxide emissions, the central estimates using current models tend towards increased temperature and reduced summer rainfall for the UK. Whether this just leads to drier summers or a greater frequency or severity of droughts in the UK is difficult to predict. However, as drought is the most serious abiotic stress which can limit crop productivity to levels far below their genetic potential (Boyer, 1982; Cattivelli et al., 2008) this may require that UK growers include the impact of drier weather or drought conditions when making crop choices. Whether this can be achieved simply by adopting different management strategies, utilising varieties from drier countries or requiring new breeding lines from UK varieties is yet to be determined. In Europe, a study by Brisson et al. (2010) reported that although some countries achieve significant cereal breeding advances, the yields remained static under hostile environments such as drought which occurred during key growth stages such as stem elongation. Similarly in Australia (Turner, 2004a, 2004b) indicated that both agronomic management contributed 50% of yield maintenance to overcome the problems of crop production as soils dry and temperature and evapotranspiration increase in early summer. As these same climatic conditions are projected for the UK these same approaches will no doubt form the mainstay of our own approaches to drying summer conditions. A recent study by El Chami *et al*. (2015) considered the potential for irrigation of the common wheat (*Triticum aestivum* L.) in the East of England, a key producing area. Although economically it was deemed feasible for the higher value milling wheats the qualification was that with water abstraction limitations the competing demands for the water would make it unsustainable and therefore not an option. Investigations regarding the response of a range of crops to one of the most severe UK projected scenarios was therefore designed to be run for DRY within a protected environment, polytunnel, utilising mesocosms. These mesocosms allow a small representative crop stand to be achieved whilst experiencing the same environmental conditions but can receive different irrigation quantities without affecting the neighbouring mesocosm. This system also then allowed a randomised complete block design without confounding issues. Mesocosms can offer the potential for reduced water, drought experiments, in a temperate climate and are a good bridge between protected glasshouse work and unprotected field experiments as long as their limitations are recognised (Stewart *et al*., 2013).

In relation to plants the importance of water cannot be overstressed. It is a major component of cells, it is a solvent for the uptake and transport of nutrients, an essential medium for biochemical reactions, a reactant in biochemical processes such as photosynthesis, creates the pressure (turgor) which causes cell elongation, growth and structural integrity and is a thermal buffer whereby the plant is cooled by the process of transpiration.

2.1 Dry weather and drought

Drought is often shown as a progressive phenomenon classified into several key types from meteorological to agricultural and then to hydrological drought along with economic, social and environmental impacts, figure 2.1. Drought can also be classified using 'drought monitoring indices' related to drought severity, figure 2.2. For the purpose of this report the main concern is the impact of agricultural drought which focuses on reduced 'soil moisture deficit' (SMD) and its effect on reduced crop growth and yield. However, as the next 'level' of drought, the hydrological drought' impacts on river flow and ground water (aquifer) availability it must be considered due the impact on growers ability to utilise these water sources for irrigation of crops. For growers in the UK a drought risk web based tool, D-Risk, has been launched by Cranfield University to allow growers of irrigated crops to understand and planning of their drought and water abstraction risks (D-Risk, 2018).

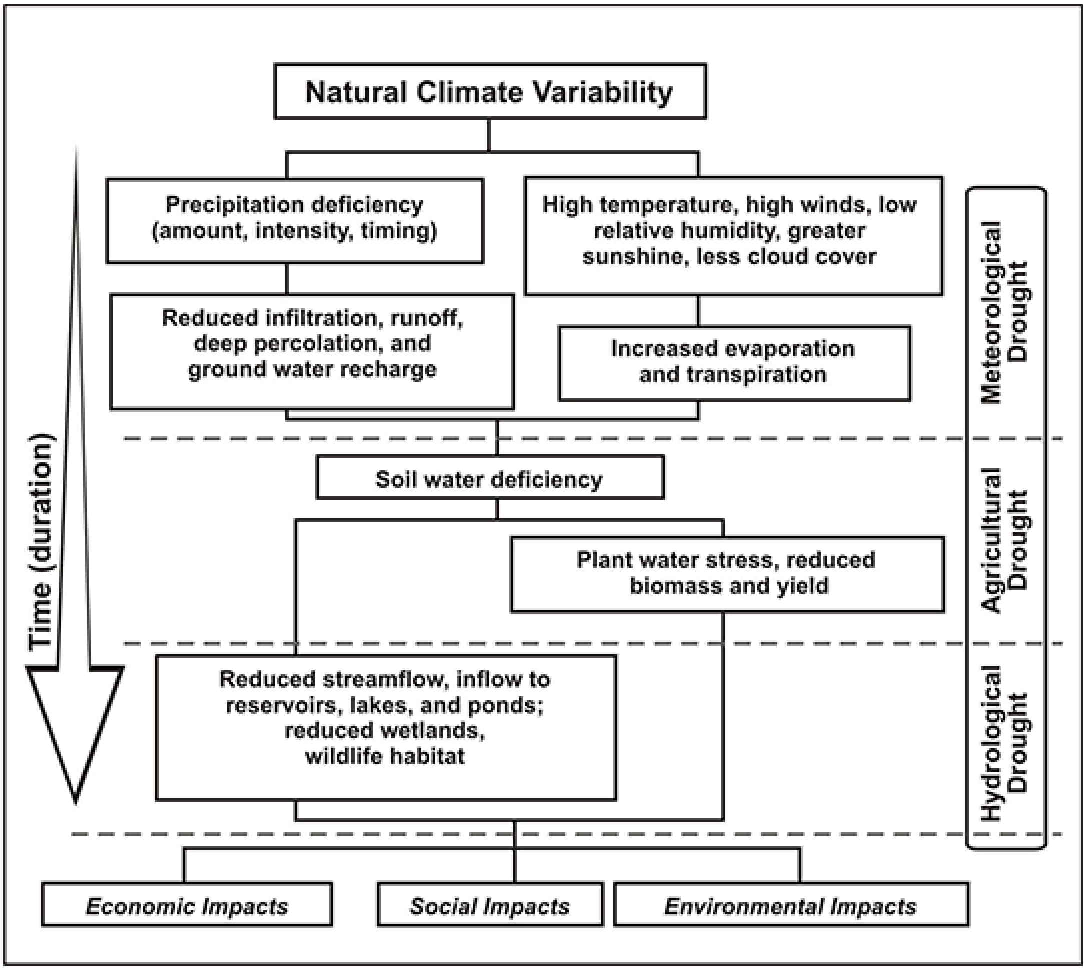

Figure 2.1. Drought type related to drought progression over time.
(Source: National Drought Mitigation Centre, 2013)

Drought Severity	Return Period (years)	Description of Possible Impacts	Drought Monitoring Indices		
			Standardized Precipitation Index (SPI)	NDMC* Drought Category	Palmer Drought Index
Minor Drought	3 to 4	Going into drought; short-term dryness slowing growth of crops or pastures; fire risk above average. Coming out of drought; some lingering water deficits; pastures or crops not fully recovered.	-0.5 to -0.7	D0	-1.0 to -1.9
Moderate Drought	5 to 9	Some damage to crops or pastures; fire risk high; streams, reservoirs, or wells low, some water shortages developing or imminent, voluntary water use restrictions requested.	-0.8 to -1.2	D1	-2.0 to -2.9
Severe Drought	10 to 17	Crop or pasture losses likely; fire risk very high; water shortages common; water restrictions imposed.	-1.3 to -1.5	D2	-3.0 to -3.9
Extreme Drought	18 to 43	Major crop and pasture losses; extreme fire danger; widespread water shortages or restrictions.	-1.6 to -1.9	D3	-4.0 to -4.9
Exceptional Drought	44 +	Exceptional and widespread crop and pasture losses; exceptional fire risk; shortages of water in reservoirs, streams, and wells creating water emergencies.	less than -2	D4	-5.0 or less

*NDMC - National Drought Mitigation Center

Figure 2.2. Drought severity related to drought monitoring indices.

3.0 UK cropping

The UK has a land area of approximately 24.5 million ha, of which 18.4 million is agricultural but only 17.5 million ha are ‘Utilised Agricultural Area’, 72% of the total area. Of this total there was 11.2 million ha of grassland of which 7.1 million ha was either temporary or permanent grassland and from which the national dairy herd of 1.9 million head would partly depend for forage. There were 4.67 million ha of arable and horticultural crops, of which 3.1 million ha were cereal crops, which includes 1.8 million ha of wheat and 1.1 million ha of barley, the dominant crops by volume and area in the UK (Defra, 2018), key crops are listed, table 3.1.

There are a range of forage/fodder crops grown such as the maize (194,000ha), forage turnips, Lucerne and fodder beet and a substantial number of ‘minority’ crops such as borage (1,000ha), Quinoa, calendula and evening primrose, these crops are seldom irrigated.

The UK has a wide range of crops which can be grown with the majority being C3 plants which function well in our temperate climate, requiring an optimum temperature range of 15-25°C. There are several C4 crop plants which have been bred specifically for production in Europe and the UK, such as the forage crop Maize (*Zea mays* ssp *mays*) which normally require an optimum temperature range of 30-40°C.

Table 3.1 Key crops grown in the UK by land area, production amount and use. (Source Defra, 2017a, 2017b)

Crop	**Area ‘000 ha**	**Production ‘000t**	**Irrigated in UK**	**Main uses**
Wheat	1, 823	14, 383	No	Bread, biscuits and animal feed
W. Barley S. Barley	439 683	2, 823 3, 832	No	Brewing and animal feed
Oats	141	816	No	Milling & animal feed
Minor cereals	45	113	No	Rye, triticale & mixed corn.
Oilseed rape	579	1, 775	No	Cooking oil, lubricants & biodiesel
Linseed	27	48	No	Technical oils & animal feed
Sugar beet	86	5, 687	Yes	Sugar, animal feed & bioethanol
Field beans	177	649	No	Animal consumption (human consumption not included)
Potatoes	139	5, 373	Yes	All food uses (not stockfeed)
Fresh Veg	113 (a) 1 (b)		Yes Yes	Cabbages, carrots, cauliflower, calabrese, lettuce, mushrooms, onions & tomatoes.
Fresh fruit	25 (c) 10 (d)		Yes Yes	Apples, pears, raspberries & strawberries.

Notes: (a) Fresh vegetables grown in the open or (b) grown under protection but does not include mushrooms. Fresh fruit: (c) Orchard fruit and (d) soft fruit.

3.1 Irrigated cropping and water requirements

According to Chaves and Oliveira (2004) approximately 70% of the available water globally is employed in agriculture and 40% of food production is done under irrigation. As seen in table 3.1 many of the main UK arable crops rely on rainfall as their sole water source but others require supplemental water. This is normally abstracted from surface or groundwater sources, applied as irrigation, and used to maintain yield and meet the ever increasing crop quality demanded by buyers, retailers and consumers. One of the most comprehensive sources of information for crop water requirements is published by the Food and Agriculture Organisation (FAO, 2012). The information contained in the publication is extensive but information pertaining to the key UK crops is provided, table 3.2.

When considering the annual rainfall pattern in the UK for 2017, figure 3.3, it could be predicted that in terms of the crop water required, table 3.2, these needs can be easily met. However, the UK climate is extremely variable, as the annual rainfall map for 2011, figure 3.4, demonstrates that in some years the crop water requirements cannot be met from rainfall alone. In addition, as the peak plant growth and water demand from crops in the UK is during the warmer months from April to September the availability of water is considerably below the requirements identified.

Table 3.2. Water requirements of key crops (adapted from Brouwer & Heibloem, 1986)

Crop	Water required (mm)
Winter Wheat Spring Wheat	450 – 650
Spring Barley Winter Barley	450 - 650
Lucerne	800-1600
Potatoes	500 – 700 (FAO: 400-700)
Sorghum	450 - 650
Grass	600 - 90

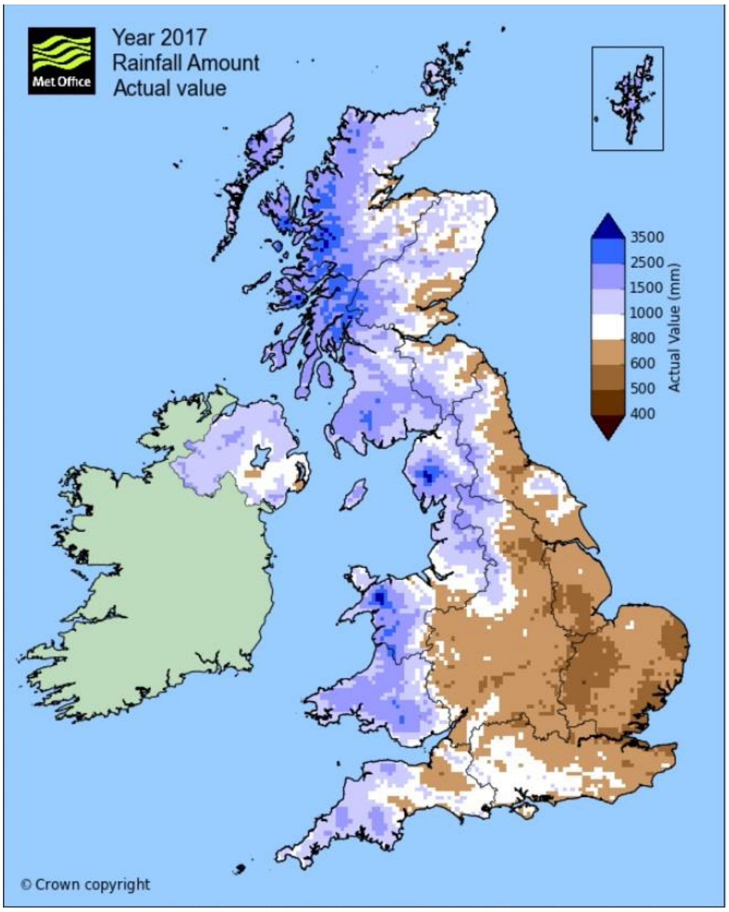

Figure 3.3. Annual rainfall map for the UK 2017 (Met Office, 2018)

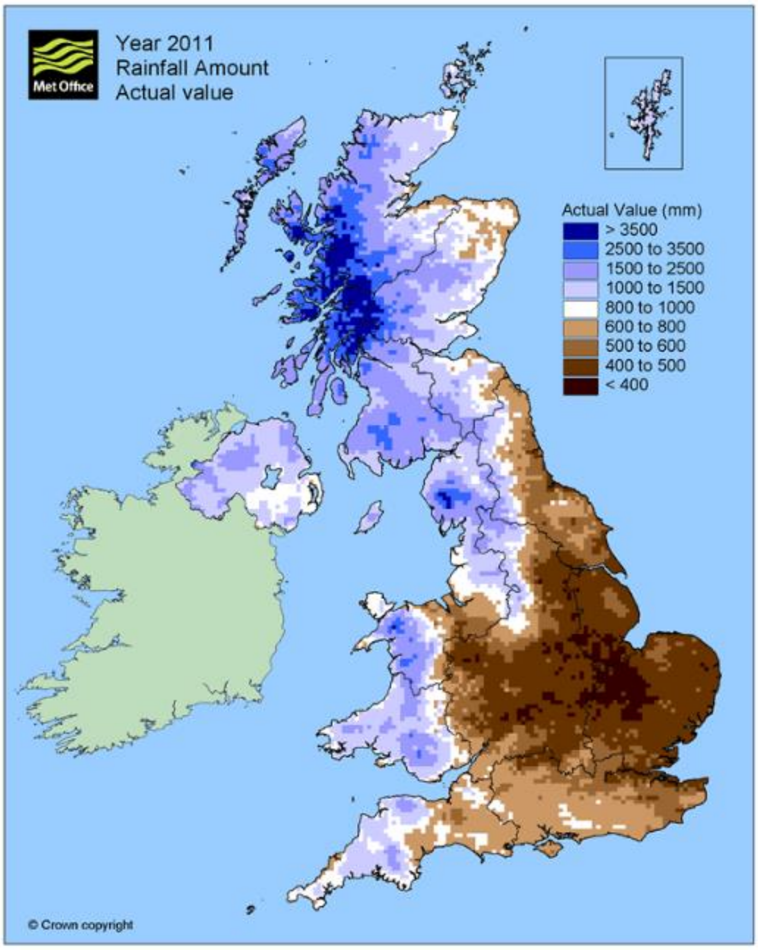

Figure 3.4 Rainfall map for the UK 2011

When crop water demand cannot be met by rainfall the higher value crops such as potatoes and vegetables can be irrigated if an appropriate abstraction permit is held and there is sufficient water available for abstraction. In England, Defra (2017) report that water abstraction for all agricultural uses is less than 1% of the total abstraction by volume. For spray irrigation alone the Environment Agency reported that there were 9,437 spray irrigation licences abstracting 84 million m^3 from surface and groundwater sources in 2016, of which the Anglian, also known as Eastern, region abstracted 53 million m^3, equating to approximately 63% of spray irrigation abstraction. This regional abstraction bias exists as the area has a beneficial climate, landscape and fertile soils (NFU, 2016) suitable to higher value cropping which reached output values of £1, 756 million, 25% of the England crop output in 2016, of which £339 million was from fresh vegetables alone (Defra, 2018). Over the period of 2000 – 2016 the variability of the rainfall and thus spray irrigation water demand in England is demonstrated by the range of abstractions from 118 million m^3 in 2011 to only 50 million m^3 in 2012 (Environment Agency, 2017). The close link between the peak irrigation periods of spring and summer in the Anglian region and rainfall in the east Anglian region is demonstrated by a strong correlation, r = 0.77, between the two, figure 3.5. This emphasises both the supplemental nature and the requirement for the irrigation.

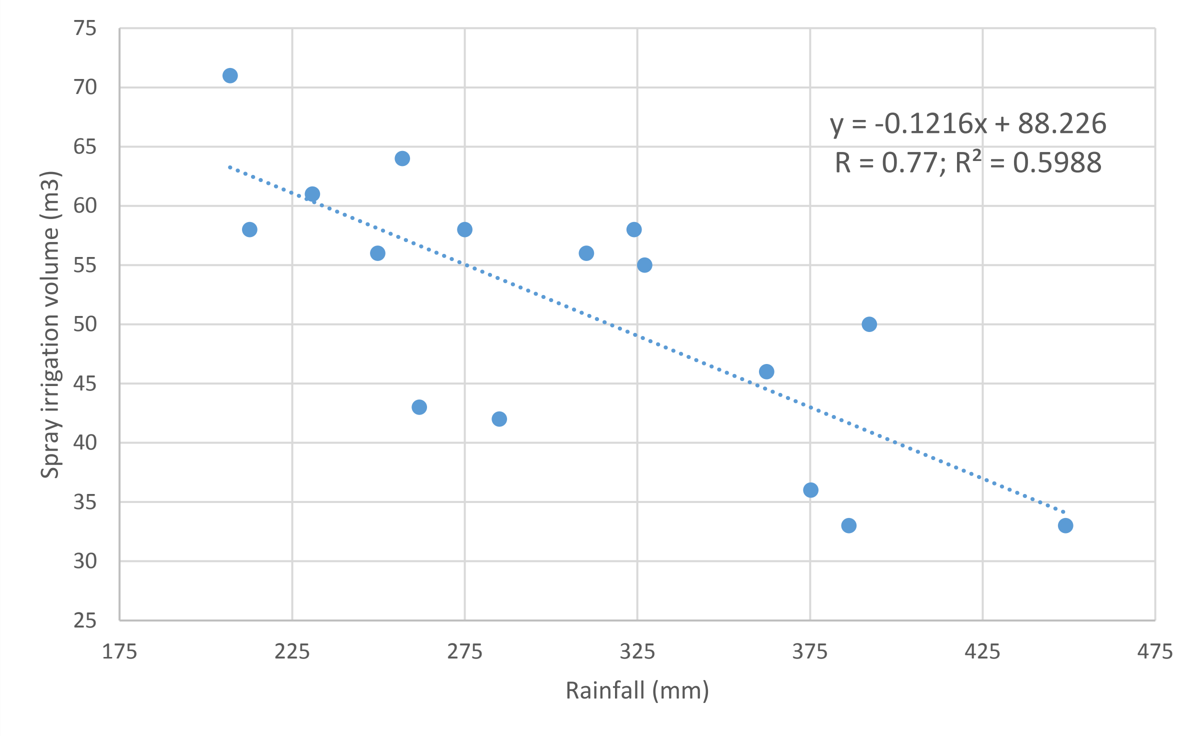

Figure 3.5. Summer & Spring rainfall (mm) in East Anglia vs spray irrigation volume (m^3) in the Anglian Region (Data sourced from: Environment Agency, 2017).

In contrast to the actual recorded 53 million m^3 abstracted however, the amount of water 'licenced' for abstraction for spray irrigation in 2016 was 325 million m^3, indicating that only 26% of the licenced quantities was actually used. Whereas in a wet year of 2012 only 10% of potential abstraction was used. These current figures do not cover the abstraction for trickle tape (drip) irrigation, which until 2018 has not required a licence and which could add up to 5% additional abstraction to the total.

In years where rainfall does not meet requirements for commodity (relatively non-perishable, storable, transportable, and undifferentiated) crops, such as cereals and oilseed rape, and for forage crops the yields and quality will decline as they experience drought. For these crops irrigation is neither economic nor available in the UK due to the restrictions on water abstraction for spray irrigation.

3.2 Crop water use

Plants need water for both structural and physiological reasons. Structurally water provides cell turgor as it fills the cell vacuoles creating pressure and a type of flexible rigidity. This pressure drives cell expansion and is important for plant growth. Physiologically water is important as a carrier for nutrients and hormones through the plant, is essential for biochemical reactions and all importantly for its role as hydrogen provider in the process of photosynthesis.

The amount of water required by plants can be broadly calculated by use of the FAO Penman-Monteith formula (FAO, 2012a), figure 3.6:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)} \quad (6)$$

where

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],
Δ slope vapour pressure curve [kPa °C^{-1}],
γ psychrometric constant [kPa °C^{-1}].

Figure 3.6. FAO Penman-Monteith reference crop evapotranspiration ETo (FAO, 2012a)

This equation is based on climatic data and provides a reference value for a defined short grass crop. To calculate actual crop values crop coefficients are used to refine the predictions based on individual crop growth parameters (FAO, 2012a). The need for these type of calculations arises from the prediction of crop water requirements for either irrigation or modelling purposes. In the UK water management *per se* is only considered for irrigated crops as the application of irrigation is only carried out where an economic return is possible, driven by the constraints of water availability, licence restrictions and in water limited situations then irrigation is based on the most financially responsive crops (Knox, 2012). In water limited situations the key goal should be to maximise the use of the water available and improvement of crop water productivity whereby the greatest production of usable material, food, is produced from the least amount of water. This is often classified as 'water use efficiency' (UWE) or 'irrigated water use efficiency' (IWUE) for predominantly irrigated crops, as opposed to rain-fed crops.

3.2.1 **Water use efficiency**

WUE has been defined in several, if not many, variations. Stanhill (1986) suggested the ratio of the volume of water used productively. Steduto (1996) suggested that ‘Water use Efficiency’ as a term is rather ambiguous because it can be related to many aspects of water use such as the efficiency of the water conveyance system from the source to the application equipment, the efficiency of the application of that water by the application equipment or other use. Steduto (1996) therefore suggested that in all other instances the term ‘efficient use of water’ should be used and ‘water use efficiency’ should only be used where the term is relates to the carbon gained via Ps relative to the input of the water lost via transpiration, figure 3.7.

$$\text{Water} - \text{Use Efficiency} = \text{WUE} = \frac{\text{carbon gained through photosynthesis}}{\text{water lost by transpiration}}$$

Figure 3.7. Equation used for WUE as proposed by Steduto, 1996.

Machibya *et al*. (2004) defined Water use efficiency (WUE) “as the ratio between the amount of water that is used for an intended purpose and the total amount of water supplied within a spatial domain of interest”.

Medrano *et al*. (2015) expand the WUE whilst working on grapevine to include instantaneous WUE (leaf level, whole plant WUE and productivity WUE), figure 3.8.

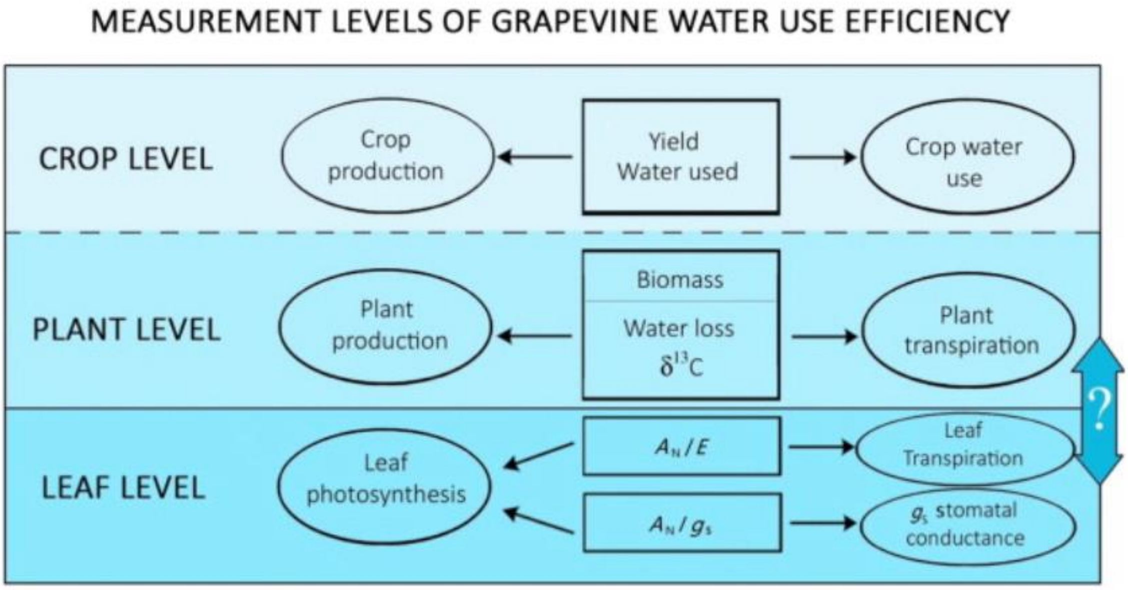

Figure 3.8. Measurement levels of grapevine water use efficiency (Medrano *et al*, 2015)

From these considerations therefore it can be suggested that although WUE is generally regarded as the ratio of the water used in plant metabolism to the amount of water lost by the plant through transpiration, the term should be clarified contextually before use and would take the form of:

WUE (kg/mm) = Yield of plant (kg/ha) / ET (mm) Actual transpiration from seedling to harvest.

French and Schultz (1984) proposed WUE as a benchmark for wheat production in Australia and gave a guide of 20kg/ha/mm water applied from equation1. This was developed further and an improved formula was suggested eqaution2

*Yield = ET * T/ET * TE * HI eq. 1*

*Yield/ET = WUE = T/ET * TE * HI eq. 2*

"Where ET (evapo-transpiration) is the total water used in growing a crop (mm), ET consists of productive water use (transpired water), and water losses i.e. primarily soil water loss through soil evaporation, though in some cases run-off and deep drainage below the rooting depth of the crop could also be significant. T/ET is the fraction of ET captured as productive water use by the crop (i.e. taken up by the roots and transpired through the leaves); TE is the efficiency with which the plant can accumulate total growth for a given amount of transpired water (kg/ha.mm); and HI, is the harvest index, which is the fraction of total crop mass at harvest allocated to the grains i.e. grain yield divided by the total crop mass (excluding roots)"

3.2.2 **Water Productivity**

In contrast to WUE there is an increasing call for use of the term water productivity, WP. Sharma *et al.* (2015), Machibya *et al.* (2004) and Ragab (undated) suggest that the current use of WUE is actually inappropriate because 'efficiency' is expressed as a ratio or percent: i.e. if 10mm of water is applied and only 8mm is used, the efficiency of water use is 80%. Whereas reports which indicate the quantity of crop returned from a given application/quantity of water such that 'kg per cubic meter of water" there is no ratio implied and therefore should be reported as WP kg/m^3.

3.2.3 **Irrigation Water Use Efficiency**

In contrast to WUE a modified term can be used when dealing with irrigated crops, IWUE. The equation is given as:

IWUE (kg m^3) = Yield of total dry biomass (kg/ha / T_{WA} total amount of water used including irrigation and rainfall from planting to harvest (m^3 ha)

3.3 Effect of drought on crop production

Haverkort and Goudriaan (1994) stated that one of the most limiting factors for crop production in north-western Europe was lack of water even though rainfall was relatively abundant. This has been reiterated and updated by BarnabáS *et al.* (2008) who agreed that drought was a major limitation to crop production coupled with global warming and a greater frequency and intensity of droughts was affecting the most productive areas in the world. In some countries droughts or very dry conditions are common and are considered in cropping plans. For instance in Australia growers are advised to change crop types based on predictions for El nino or La nina weather phases of the El Nino Southern Oscillation (ENSO). Wheat requires significantly less water, 450-650 mm, than cotton, 700-1300 (FAO, 2012. El Nino generally leads to drier and hotter conditions, while La Nina usually leads to cooler and wetter conditions. Although the UK is connected to the North Atlantic oscillation (NOA) the effects are less predictable and droughts are more sporadic and difficult to accommodate. In 2017 it was reported that cereal production was reduced by up to 70% in the Castilla Y Leon region of Spain where they experienced the 3rd driest year on record (Euronews, 2017).

As discussed earlier the term drought has several layers, figure 2.1, but for agriculture it is predominantly connected to soil moisture depletion, figure 2.2, and growers ability to access and use irrigation water for high value crops. Drought is associated with reductions of crop production or yield beyond those experienced within typical seasonal variability and also reductions in crop quality (Stagnari *et al.*, 2016; Lopez *et al*, 2012; Balla *et al*., 2011). All reductions of soil-water availability to plants/crops below an optimum range restricts their ability to satisfy the demands from evapotranspiration (ET), reducing plant growth and functioning until cellular collapse and death occurs. For xerophytic plants such as cacti, which exhibit survival mechanisms over prolonged droughts, the overall aim is plant survival. Whilst with the mesophytes used for food production, suited to neither prolonged wet or dry conditions, the ability to produce a optimum and usable yield is paramount. A significant exception within the major food crops group however is rice, *Oryza sativa* (Asian rice) or *Oryza glaberrima* (African rice) the 2nd most important food crop worldwide (740 Mt), which is suited to prolonged wet conditions and is classed as a hydrophyte.

Within the mesophytes there is considerable variation relating to their ability to withstand dry conditions, generally termed ‘drought resistance’ or ‘drought tolerance’ which must be defined for agriculture in terms of yield in relation to a limiting water supply (Passioura, 1997). It was further suggested by Passioura (1997) that drought should not be seen only as prolonged periods when rainfall fails to keep up with ET but should be viewed at ontogenetic time scales, being weeks to months for an annual crop and with floral initiation and rate of development of leaf area key considerations. Furthermore it was suggested that plants also need the ability to respond to rapid environmental changes, such as daily temperature rises, with short term physiological and biochemical responses to overcome temporary deficits, table 3.3.

Table 3.3. Plant response to environment conditions at different timescales (Source: Passioura, 1997)

Time scale	In the plant	In the environment
Minutes or less	Turnover of some proteins, stomatal movement	Movement of shadows, rain or irrigation
Hours	Production of heat shock proteins or dehydrins, leaf movement, wilting, osmotic adjustment, response to ABA	Diurnal evaporative demand, rundown of surface soil water, rewetting of previously dry topsoil
One to two days	Cellular "hardening" – induction of housekeeping genes, seedset, floral initiation, flowering	Weather (cool to hot, dry winds), rundown of water in the topsoil
Several days to weeks	Canopy development, leaf senescence, root system development	Rundown of soil water throughout the profile
Weeks to months	Clocks controlling development (e.g. vernalisation, time to flowering), grain filling	Seasonal evaporate demand, prevailing rainfall pattern

Farooq (2009) also outlines some of the effects ontogenetically as: impaired germination and poor crop establishment (probably from low soil moisture and thus low imbibition and low available water for early growth); reduced or slow crop growth resulting from poor cellular growth/elongation linked to reduction in turgor pressure; reduced plant height and leaf area due to impaired mitosis, cellular elongation and expansion. Subsequent effects then occur in relation to specific crops and yield forming components: Water stress pre-anthesis in triticale reduced time to anthesis but post anthesis stress reduced the grain filling period; In barley (*Hordeum vulgare*) drought stress reduced the number of tillers, spikes and grains per plant and grain weight thus reducing overall yield, whilst any level of drought stress post-anthesis reduced yield; Drought stress in maize delayed silking and increased kernel abortion; soybean total and branch seed yield was reduced. As many of these effects were related to timing and duration of the drought stress Farooq (2009) produced a table giving the economic yield reduction by drought stress in Barley, Maize, Rice, chickpea, pigeon pea, common bean, soybean, cowpea, sunflower, canola and potato. Other effects reported include reductions in wheat pollen viability (Weerasinghe *et al.,* 2016) and grain quality (Balla *et al.,* 2011).

Sinclair and Ludlow (1986), working on four tropical legumes, suggested that plants response to soil water deficit can be split into 3 phases, figure 3.9:

Stage 1 covers the range of soil moisture when water is freely available and transpiration is at its maximum related to the prevailing environmental conditions. This would encompass approximately 30 -50% of available water capacity, when the soil moisture is held at less than 2 bars (0.2MPa). Leaf gas exchange and leaf growth are affected towards the latter part of stage 1 and into stage 2.

Stage 2 begins when the rate of uptake cannot match the rate of potential transpiration and stomatal conductance declines to match water uptake, thus maintaining plant water balance.

Stage 3: Minimum transpiration occurs and water loss relates to epidermal conductance. Plant available soil water content is then minimal and plant death occurs at the latter part of stage 3.

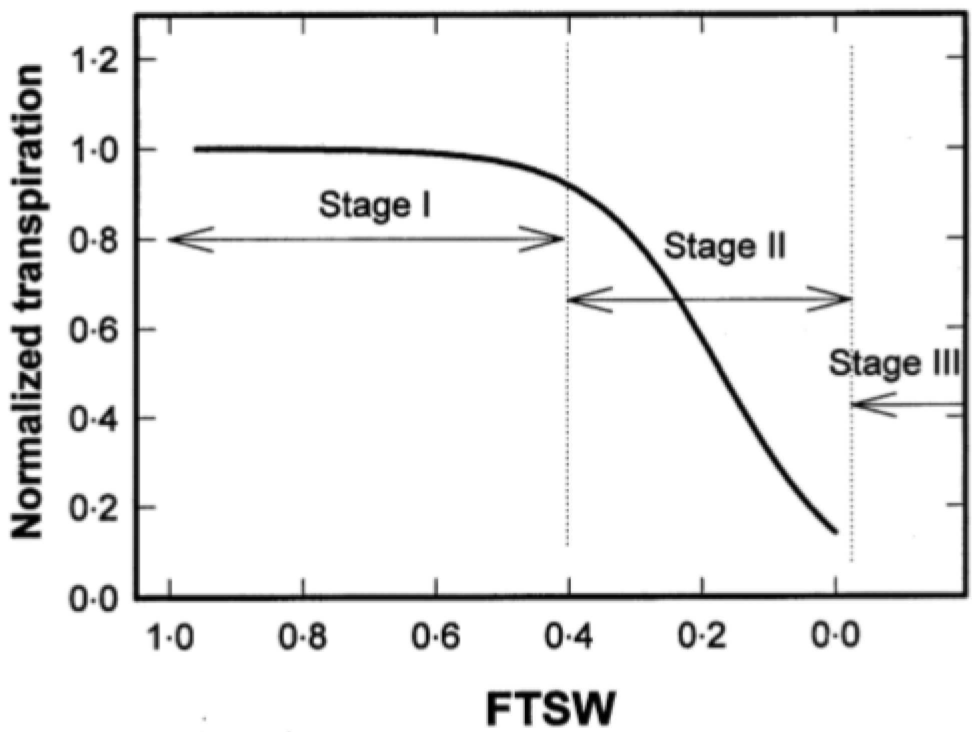

Figure 3.9. Normalised transpiration against the fraction of transpirable soil water (FTSW) adapted by Serraj and Sinclair (2002) from the data of Sinclair & Ludlow (1986).

3.3.1 Quantifying crop responses to drought

Any reduction in water availability below that required by the evaporative demand of the crop will reduce the ability of the crop to produce its maximum yield within the constraints of other limiting factors, e.g. crop nutrient demand and solar radiation. The primary or ultimate effect of reduced water availability on crop production is a reduction in total production or crop yield. In order to quantify this effect the Food and Agriculture Organisation (FAO) related the relative yield reduction to the corresponding relative reduction in evapotranspiration and expressed it as in equation 3 (FAO, 2012):

$$\left(1-\frac{Y_a}{Y_x}\right)=K_y\left(1-\frac{ET_a}{ET_x}\right)$$

Equation 3: Relative yield response to ET

“where Yx and Ya are the maximum and actual yields, ETx and ETa are the maximum and actual evapotranspiration, and Ky is a yield response factor representing the effect of a reduction in evapotranspiration on yield losses. Equation 3 is a water production function and can be applied to all agricultural crops, i.e. herbaceous, trees and vines” (FAO, 2012). The various parameters within the equation include differences between crops allowing it to be related directly to potential and actual evapotranspiration, which is linked to productivity. These crop yield reductions are however the result of physical, physiological and biochemical changes within the plant as a result of reduced water availability and uptake.

Crop models

Carrying out physical research on all the crops of interest, under different soil, climatic conditions and water availability scenarios would not only be extremely difficult and time consuming it would also be extremely expensive due to the vast number of permutations. For this reason the use of computer models has become an acceptable method of investigating scenarios based on data collected in many experiments in those climates and soils. Key models available include FAO-CROPWAT, DSSAT (Including CERES), Aquacrop, CropSyst, InfoCrop, APSIM and SaltMed, all varying in complexity and input requirements. Some of these are reviewed by Palosuo *et a*l, 2011) AquaCrop (FAO, 2018a) is a well-known simulation model that works for herbaceous plants and can predict yield relative to the water supply without any other yield limiting factors but does have a fertility model. Although it can be used to investigate responses in a wide range of environments it should be calibrated and validated with physical experimental data from that region. SaltMed (Ragab, 2002) is a program principally designed as a generic model which can accommodate a variety of irrigation systems, soil types, soil layers, crop, trees, water management strategies leaching and water quality parameters. It has a wide range of background data files from a wide range of environments. As part of the DRY project at HAU the SaltMed program will be used to investigate the data produced from the mesocosms.

Harvest Index

As drought not only affects yield but also dry matter partitioning it is useful to investigate this with harvest index, HI. Kay (1995) suggested that several approaches or calculations had been proposed over the preceding years to identify the cereal productivity of new varieties. The Harvest Index is therefore designed to quantify the fraction of ‘useful’ (grain) plant material relative to the total mass produced ‘above ground’ and as such is now recognised as the decimal fraction of wheat grain yield to the above ground biological yield or biomass. The crop should be cut by hand, at maturity at ground level, dried to constant weight, threshed and the component parts weighed. Indications of HI for a range of crop is given, table 3.4.

Table 3.4. Reported Harvest Indices for a range of crops (Hay, 1995)

Species	Type	Area	Harvest index	Source
Triticum aestivum, wheat	Winter	UK	0.43–0.54	McLaren, 1981 Darby, Widdowson & Hewitt, 1984 Austin *et al.*, 1989
		USA	0.31–0.51	Gent & Kiyomoto, 1989
	Spring	Canada	0.38–0.41	Hucl & Baker, 1987
		Australia	0.37–0.47	Stapper & Fisher, 1990
Hordeum vulgare, barley	Winter	UK	0.43–0.57	Ellis & Russell, 1984
	Spring	UK	0.55–0.63	Ellis & Russell, 1984
		Canada	0.33–0.49	Foster *et al.*, 1991 Ma & Smith, 1992
Triticale		UK	0.45–0.47	Ford *et al.*, 1984
Oryza sativa, rice	wetland	Philippines	0.55–0.62*	Anon., 1978
		India	0.35–0.59	Sahu *et al.*, 1980
Zea mays, maize	hybrid	Nigeria	0.36–0.46	Remison & Fajemisin, 1982
		USA	0.42–0.49	Deloughery & Crookston, 1979
		Canada	0.47–0.57	Place & Brown, 1987
Glycine max, soybean		USA	0.35–0.53	Schapaugh & Wilcox, 1980
Cicer arietinum, chickpea	desi, Winter-sown	Australia	0.28–0.36	Siddique, Sedgeley & Marshall, 1984
Vigna unguiculata, cowpea	determinate	USA	0.44–0.64	Fernandez & Miller, 1985
	indeterminate		0.15–0.29	
Brassica napus, oilseed rape	Winter	Germany	0.22–0.38	Huhn, Grosse & Leon, 1991
Manihot esculenta, cassava		India	0.30–0.65	Ramanujam, 1985
Solanum tuberosum, potato	maincrop	Canada	0.47–0.62	Knowles & Botar, 1992

* Values for ‘rough rice’ before dehulling.

4.0 Drought Tolerance/resistance mechanisms

Basu *et al.* (2016) summarises the mechanisms behind drought resistance as mainly morpho-physiological changes which are ultimately controlled by the molecular mechanisms which control gene expression. In addition they suggested that when breeding new variety lines the selection for drought tolerance cannot be the only consideration as under normal growing conditions these tolerant varieties often have a yield penalty when grown under non-drought conditions. The work went on to suggest that as there is a direct correlation between their performances in the two environments the selection process should be tested simultaneously to gain the best insights.

Drought resistance is generally a broad term used to describe the plant adaptions which help them to survive shortage of water. From an agronomic viewpoint Sade *et al.* (2012) suggest that it could be classed as enhanced productivity under stressful conditions. According to Basu *et al.* (2016) these adaptions can be split into three broad categories:

'Drought escape' is an adaption which avoids drought (arguably therefore this could be called drought 'avoidance'). However, 'drought escape' is the ability of the plant to complete its life cycle before the onset of drought and so has no requirement for physical, physiological or biochemical drought resistance or tolerance mechanisms. The lifecycle needs to be matched to the time of more favourable environment and then involves one of two key mechanisms: rapid phenological development, which encompasses very rapid plant growth, and the production of minimal seed number before the onset of the dry period, or developmental plasticity whereby plants produce few seeds in dry periods but can produce significant seed numbers in wetter periods. As the time of flowering is critical for most crop reproduction the adaption which uses short duration varieties is an effective strategy to reduce yield losses to terminal drought (Kumar and Abbo, 2001) but may significantly reduce overall yield potential in infrequent drought areas.

'Drought avoidance' typically is the term used to describe a plants ability to maintain a relatively higher tissue water content even when the soil moisture content is lower than optimum for the plant. This trait has two mechanisms: minimisation of water loss by reduced transpiration, transpiration area and radiation absorption, and/or optimisation of water uptake by increased rooting, maintenance of xylem hydraulic conductance by regulation of stomatal conductance (*g*s) and thus prevention of xylem cavitation due to embolism (Nardini and Salleo, 2000), the hydraulic disconnection between leaves/aerial parts and roots (Vilagrossa *et al.,* 2012). Glaucousness, classed as the bluish-grey or green bloom of epicuticular wax seen on the surfaces of leaves, sheaves and spikes, has also been associated with drought avoidance and increased wheat yields in droughted soils (Richards *et al.,* 1986).

'Drought tolerance' (DT) is a plants ability to grow, flower and display an economic yield under sub-optimal water supply (Farooq *et al.,* 2009). However it is also described as the ability of the plant to 'tolerate' low tissue water content through traits such as maintenance of cell turgor through osmotic adjustment and cellular elasticity, and increasing protoplasmic resistance (Basu *et al.,* 2016). Bartlett *et al.* (2016) investigated the correlations and sequences of drought tolerance responses of 262 woody angiosperms and 48 gymnosperm species and suggested that the plant drought tolerance trait triggered by water potential thresholds at minimum leaf water potential (ψ_{leaf}) follows a sequence that limits severe tissue damage through stomatal closure, wilting, and substantial stem embolism.

'Resurrection': another more extreme type of drought resistance is found in the resurrection plants which are capable of substantial water conservation over prolonged droughts. These plants use a survival mechanism where seed production is foregone and so is not a mechanism that is immediately suitable for food production (Basu *et al.,* 2016).

In addition to the drought resistance/tolerance adaptions other drought mechanisms may be achieved in some or all of these adaptions:

4.1 **Morphological mechanisms:**

When soil moisture becomes limiting it is the shoot and roots which are most affected, whereby the number and area of leaves are reduced to limit plant water requirement (Farooq *et al.*, 2009) but root growth, density, proliferation and size all increase to access more water (Kavar *et al.*, 2008). Work reported by Nguyen *et al.* (1997) shows that the ability of root systems in rice to meet evaporative demand from deep soil moisture is a major drought resistant trait. Drought stress is also suggested to increase the number of trichomes, fine hairs, on both sides of wheat leaves but this was not suggested as a mechanism to lower leaf temperature or transpiration in wheat, unlike in other species, but merely a response to it.

Xu and Zhou (2008) reported key changes in stomatal density on grass, *Leymus chinensis*, in response to drying soil conditions. Under moderate water deficits there was an increase in stomatal density whereas more severe water deficits the stomatal number decreased per leaf area. In addition stomatal size declined with increased water deficit. The conclusions were that both stomatal density and stomatal guard cell size would change in response to the degree of water deficit experienced.

Root morphology:

Root systems in the majority of plants are the mechanisms by which water and nutrients are procured. Ultimately therefore their ability to locate, absorb and transport water is fundamental to plant functioning. In water limited environments Schenk & Jackson (2002) highlighted that availability of water and nutrients depends both on the size and shape of the root system and root competition. Their work identified that absolute rooting depth of a range of plant types generally reduced with aridity but relative root depth (relative to above ground biomass) increased with aridity. These differences between plant types or crop species are well documented but Dardenelli *et al.* (1997) also showed that differences exist between varieties of the same crop species. Example root depths from the work include: Soybean cultivars 85, 112 and 230cm and sunflower cultivars 250 and 290cm.

Basu *et al*. (2016) suggests that primary root growth is not affected by drought stress in contrast to lateral root growth which is significantly affected. However, small root production is apparently increased in order to provide a greater absorptive surface area for water uptake and the presence of specialised thickened/suberised cell walls occurs as a drought stress survival adaption. Work by Chaiwanon and Wang (2015) agree that optimal root growth rate is necessary for drought survival and demonstrated the antagonistic roles of brassinosteroids and auxins in the root growth process of cell division and cell elongation which is crucial for sustainable and optimum root growth. Bao *et al.* (2014) also demonstrated how different root-zones are dedicated to different functions. Their work on root patterning, termed hydropatterning, highlighted that growth around the circumference of roots can be influenced by contact with moisture or air which stimulates the root to induce lateral root growth towards the moisture or root hairs.

Overall, the importance of deep rooting in plants and the greater need for emphasis on these traits within breeding programs was recommended for wheat by Wasson *et al.* (2012) and also by Kell (2011) due to their key role in carbon, nutrient and water sequestration.

4.2 **Physiological & biochemical mechanisms:**

Under mild drought or variable soil moisture Yordanov *et al* (2003) and Cornic and Massacci (1996) suggest that plants have the ability to maintain leaf relative water content (RWC) by regulating the balance between water loss and water uptake with little or no change to Ps capacity. This will initially be through the closure of the stomatal aperture, reducing stomatal conductance (gs), for which the mechanisms are suggested to be achieved through ABA modulation (Zhang *et al.,* 2006; Dodd, 2003; Cornic and Massacci, 1996). Dodd (2003) suggested at that time that there was limited evidence to support key roles for other hormones in the stomatal responses, however work by Chen (2013) has since identified reduced stomatal sensitivity to ABA due to reduced stomatal sensitivity to ethylene in aged wheat leaves, demonstrating the complexity of the interactions. Basu *et al*. (2016) show the ABA gene dependent pathway in rice, figure 4.1 but suggest that under severe drought stress several mechanisms will interact to protect the plant largely dependent on the plant species affected.

Although this identifies the key ABA relationship for drought stress other hormones such as cytokinin (CK), gibberellic acid (GA), auxin, ethylene, Jasmonic acid (JA), Salicylic acid (SA) and strigolactone are now also thought to have key roles in moderating drought stress. Cytokinins can delay premature leaf senescence whereas Gibberellins promote growth inhibition and ethylene can increase embryo and grain abortion and reduce grain filling rate (Basu *et al*., 2016). The most recent work in this area (Takashi *et al.*, 2018) also highlights the role of the peptide CLE25 which is reported to move from roots to shoots in response to drying soil and induces ABA synthesis in leaves, which then leads to stomatal closure and reduced water loss to the atmosphere.

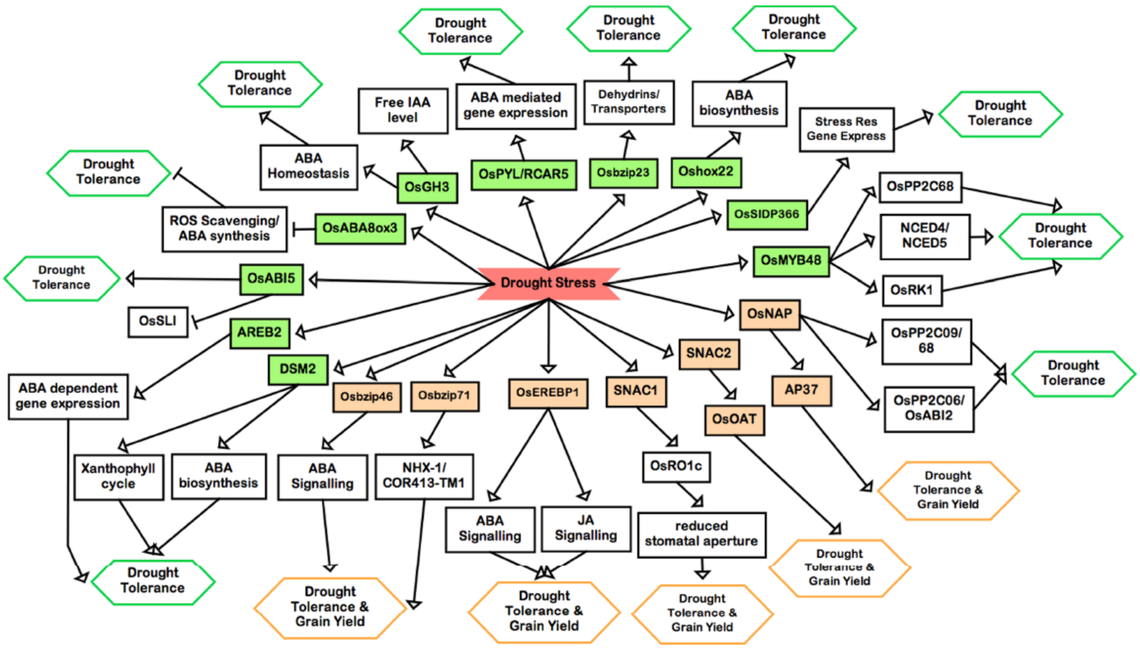

Figure 4.1. The abscisic acid (ABA)-dependent gene regulatory pathway in rice. (source: Basu *et al,* 2016)

Although the primary role of stomatal closure for the plant is a survival 'strategy' to reduce water loss to the atmosphere and maintain an adequate plant water status, plant productivity and yield can be reduced. The primary effect of stomatal closure is reduced CO_2 diffusion into the leaf and thus reduced CO_2 for metabolism. Work by Tezara *et al.* (1999) on sunflower (*Helianthus annuus* L.) however shows that although drought stress decreased the CO_2 diffusion into the leaf it was not the cause of the reduced CO_2 assimilation. It was the inhibition of ribulose biphosphate synthesis by the stress which was related to lower adenosine triphosphate (ATP) content as a result of loss of ATP synthase. This suggesting therefore that other drought stress reactions were contributing to Ps reduction. Manivannan *et al*. (2007), Mafakheri *et al.* (2010) and Nyachiro *et al*. (2001) also showed that drought stress significantly reduced chlorophyll *a*, *b* and total chlorophyll content in sunflower, chickpea and wheat respectively. It was noted that the photosynthetic apparatus themselves however appear to be resistant to drought. In contrast to these reductions the osmolyte proline has been shown to accumulate in drought stressed plants debatably as a stress adaptive response to aid osmoregulation (Maggio et al. 2002).

Stomatal closure can be assessed by measurement of stomatal conductance, gs, using porometry or infrared gas analysis which quantify water vapour or carbon dioxide fluxes. However, although there was, and still is, some debate as to usefulness of stomatal conductance as a direct reference parameter for drought (Medrano *et al.,* 2002) it is still used in many studies e.g. Ouyang *et al.* 2017; Bartlett *et al.*, 2016), where high stomatal conductance indicates a good water supply and low stomatal conductance indicating drought stress or low water availability.

The actual response of stomata to water availability is also linked to the plant type, whether anisohydric or isohydric traits. Plants which exhibit isohydric behaviour maintain good midday leaf water potential (ψleaf) during abundant soil moisture conditions but also under drying soil moisture by reducing stomatal aperature and loss of moisture to the atmosphere. Plants which exhibit anisohydric behaviour exhibit variable midday leaf water potential (ψleaf) over a much wider range of soil drying soil conditions by maintaining more open stomatal apertures. It is suggested that the latter approach can actually be beneficial at least under moderate soil drying but can be detrimental under more extensive soil drying (Sade *et al*., 2012). Examples of plants which demonstrate isohydric behaviour include Potato (Liu et al., 2005), iceberg Lettuce (Gallardo et al., 1996), Bean (Wakrim et al., 2005), Barley (Jones, 2004), Sorghum (Jones and Tardieu, 1998) and common wheat (Tardieu and Simmonneau, 1998). Whereas anisohydric plant examples include Cauliflower (Kochler et al., 2007), Tomato (Sobeih et al, 2004), Lupin and Pea (Tardieu and Simmonneau, 1998) and Maize (Jones, 2007).

4.3 **Osmotic adjustment (OA)**

Osmotic adjustment or 'osmoregulation' is a biochemical mechanism that helps to maintain water uptake in response to drying or saline soils. A wide range of solute types including sugars, cyclitols, proline and glycine betaine accumulate in cell cytoplasm making the osmotic potential more negative which can increase cell hydration and maintains turgor in leaf tissue and other metabolically active cells. As the process is based on uptake of solutes it is suggested as a slow process which is sensitive to the timing and intensity of the stress but is a drought adaption and not a drought response (Sanders and Arndt, 2012). Serraj and Sinclair (2002) investigated the effect of OA on crop yield as a proposed tolerance mechanism worthy of inclusion in plant breeding. They reported that in most cases except for very severe drought, yield was not generally improved by OA except for improvement in root development which would subsequently improve yield.

4.4 **Source-sink relationships**

The strength of the source to sink relationship has long been known to be a key factor in crop yield, which is mainly regulated by water and nutrients (Wenting *et al.* (2016). In cereals the primary sink is the grain and the main sources being the two upper leaves, flag leaf and leaf 2 which together contribute up to 70% of the photosynthetic activity (AHDB, 2016) and thus assimilates for grain filling (Hirota *et al*., 1990). Several studies in wheat propose that grain yield is sink-limited during the grain filling stage and by increasing sink capacity a corresponding increase in grain yield would occur. As drought stress during pollen mother cell meiosis in wheat substantially reduces the number of grain sites on the developing ear (Weersinghe *et al.*, 2016), a significant reduction of 'sink' potential would occur. However, even if the sinks were protected during their initiation an ongoing drought would still prevent the attainment of yield potential by failing to fill that grain. One must conclude however that protecting sink development allows the potential yield to be attained should the drought fade. Although a reduction of sink strength due to drought can be the result of reduced leaf size, leaf number, nutrient and water deficiency through reduced uptake, the negative effect of drought on physiological and biochemical reactions would be critical to source performance. In contrast to wheat, Wenting *et al.* (2016) suggest that in potatoes (*Solanum tuberosum* L.) tuber growth appears to be source limited rather than sink limited during the tuber bulking stage and that that reduced water (and nitrogen) availability affected yield by reducing net photosynthetic rate, total leaf area and leaf area duration. To increase yield in potatoes therefore the Ps assimilate source must be improved rather than the sink potential. Again however this cannot be so easily separated as it is imperative to produce optimum sink number during tuber initiation in order for these sinks to make use of the assimilates produced in the source. Consequently, as with all plant yield relationships would not the development and maintenance of both source and sink be critical to maximum yield potential, and identifying critical growth stages important such as pollen mother cell meiosis in wheat and tuber initiation in potatoes?

4.5 **Agronomic intervention: the use of antitranspirants**

Transpiration is a key part of a plants functioning whereby water and nutrients are drawn into and through the plant, exiting at the stomata. It is an integral part of plant functioning where the water not only creates turgidity within the plant but also carries essential nutrients and phyto-hormones from roots. Unfortunately the process also leads to significant loss of soil-water through the stomata to the atmosphere. As the amount of water retained by the plant is only around 1% of the total used (Jensen, 1968) the resulting deficit from reserves in the soil can be significant, especially during drier periods. In order to reduce this water loss various chemicals and materials, termed anti-transpirants (AT) can be applied to the plant in order to retard transpiration (Gale and Hagen, 1966). The majority of the early use of AT was not focused towards reducing drought effects on crop but towards prevention of desiccation of trees and shrubs during transplantation (Gale, 1961). Additionally, later work by Davenport *et al.* (1972) suggested that AT were actually unsuitable for crop production because they reduced CO_2 uptake, photosynthesis and thus yield. Since that time however AT's have been investigated on a wide range of crops including, common wheat (Kettlewell and Holloway, 2010), Durum wheat (Bhahma *et al.*, 2007), Oilseed rape (Faralli, *et al*., 2017), rice (Yamamoto, 1990), coffee (Akunda & Kumar, 1980) and potatoes (Khalel, 2015). A key element in much of these works is the identification of key drought sensitive growth stages where yield protection is more important than reductions in CO_2 uptake. Weerasinghe *et al. (*2016*)* identified that pollen mother cell meiosis around early booting (GS41) in common wheat was significantly affected by dry growing conditions, well before the yield producing upper leaves were formed (GS33). Although it is not clear why the maintenance of plant water status at GS33 achieved the protection of the pollen mother cells the work had demonstrated that AT applied at this time improved grain yield. Similarly work in oilseed rape showed that water stress during flowering produces a significant yield loss (Faraji *et al.,* 2009; Sinaki *et al.,* 2007) but that an antitranspirant applied at flowering, can alleviate the water stress and give positive yield benefits (Faralli *et al,* 2017).

Anititranspirant types

There are several types of AT which utilise different modes of action;
Stomatal closing type: These induce stomatal closing or decrease the size and number of stomata thus reducing water loss but also photosynthesis through a reduction in CO_2 uptake, e.g. Abscisic Acid (ABA) or Phenyl Mercuric Acetate;
Film forming types: where a plastic, oil or waxy material is sprayed onto the leaf surface to form a thin colourless film over the leaf surface giving a physical barrier to water loss including blockage of stomata primarily on the adaxial surface;
Reflecting type: mostly clay based materials which coat the leaf surface, increase light reflection and reduce heating and water losses.
Sometimes growth retardants are considered as AT as they can induce stomatal closure, their main effect however is to change the plant growth pattern to favour root growth thus enabling better soil moisture exploration and therefore a drought avoidance response (Basu *et al.*, 2016). Currently the water emulsifiable organic polymers of the film forming type of AT are most common in agriculture.

5.0 Key UK arable crops and drought

5.1 Wheat

According to the FAO (2018) the production of wheat, including common, durum and spelt, was recorded at 749 Mt and occupied over 220 M ha in 2016, making it the most important cereal worldwide. In the UK wheat production is almost all from the common wheat, *Tritcum aestivum* L. and is the mainstay of arable crop rotations where it occupies 1.8 M ha and produces between 14 – 16 Mt p.a. In the UK wheat is split into four main groups based on its use; Group 1 is bread wheat, Group 2 wheat with bread potential for some grists, group 3 for biscuit production and group 4 for animal feed (NABIM, 2017).

Wheat response to drought or dry conditions.

Wheat production in the UK is classed as rain-fed because it is seldom irrigated due to the relatively low value per ha in comparison to vegetable crops and also due to the limitations of water abstraction quantities (El Chami *et al*, 2015). For this reason therefore all wheat growth depends on stored soil moisture which falls as precipitation throughout the year. As the crop water requirements of winter and spring wheat is suggested as 450-650mm (FAO, 2012) any crop grown in dry environments is unlikely to achieve its maximum yield potential. The temperate UK for instance has an average yield of 7.9 t/ha (FAO, 2018) with mean rainfall ranging from 600 – 3000mm p.a. (Met Office, 2018b) whilst in Australia the average yield is only 1.95 t/ha (FAO, 2018), with mean rainfall ranging from 249-1182mm p.a. (Bureau of Meteorology, 2018). Byerlee and Morris (1993) suggested drought has the potential to affect 65 million ha wheat with yield reductions of up to 50% of the potential irrigated yield. This would be a considerable concern if taken at face value as this equates to almost 30% of the 220 M ha of current global wheat area and thus a potential reduction of 112 Mt. However, as significant proportions of the global production is grown in less than ideal conditions, including drought, the current total production of 749 Mt is probably a fair reflection of the environmental limitations that currently exist across the many growing regions. To determine if the water use efficiency (WUE) of some Australian production was solely the result of dry conditions Sadras and Angus (2006) compared the WUE of south-eastern Australian wheat with other dry production areas of the North American Great Plains, the China Loess Plateau, and the Mediterranean Basin crops using meta-analysis of 691 data sets. This demonstrated a commonality between wheat grain yield and evapotranspiration in low rainfall environments and concluded that whereas the maximum $WUE_{Y/ET}$ attainable was 22kg grain/ha/mm the averages found were only 9.9 for south-eastern Australia, 9.8 for the China Loess Plateau, 8.9 for the northern Great Plains of North America, 7.6 for the Mediterranean Basin, and 5.3 for the southern-central Great Plains. The work went on to suggest that the loss of yield was partially due to the effect of Et at the time of flowering, but also that low availability of phosphorus, late sowing, and subsoil chemical constraints were also key factors due to their interaction with soil evaporation.

If the maximum $WUE_{Y/ET}$ attainable is taken 22kg grain/ha/mm (French and Schultz, 1984) then a crop receiving 400mm rainfall could be expected to attain 8800 kg or 8.8 t/ha and a crop receiving 650mm could achieve 14.3 t/ha. Although the latter is well above the world average of 3.4 t/ha it is closer to the UK average of 7.9 t/ha and where yields greater than 10 t/ha are not uncommon. The benchmark or threshold set by French and Schultz (1984) is primarily used for Mediterranean type climates and has since been amended by other authors such as (Rodriguez and Sadras, 2008).

Balla *et al*. (2011) investigated the response of five winter wheat varieties to drought and heat (in controlled environment cabinets), one each from the USA and Russia, and three from Hungary. They found that drought at 40-45% pot capacity reduced yield by 57% and drought plus high temperature by 76%. The work also demonstrated reductions in grain quality.

5.2 **Barley**

Worldwide production of barley, *Hordeum vulgare* was reported as 141 Mt and occupied 47 Mha in 2016 (FAO, 2018), making this a significant contributor to world food production for animal feed or for the brewing industry. Significant quantities of barley are grown in the Russian Federation 18 Mt, Spain 7.9 Mt, and the UK at 6.6 Mt. The dominant type of barley is the hulled, covered, barley but 'naked' barley is grown to a lesser extent. Barley types are also classified by the grain position on the ear, with six or two rows. Until recently six row types were grown for feed and the lower protein two row being used for the brewing industry. In the UK there are winter and spring types with sowing times of pre-winter for winter types and March/April for spring types, both accounting for approximately 50% of plantings. The sowing time is linked to the plants need for vernalisation. The crop can be very productive especially in the UK where it averages 6 t/ha although the majority of countries achieve 2.3 to 4.4 t ha and a world average of 3.1 t ha.

Barley is reported to be useful as a dryland crop and is extensively grown in Mediterranean areas for livestock feed which is borne out by its production in Spain of 7.9 Mt from 2.8 M ha (FAO, 2018). Yield is significantly reduced by water stress post-anthesis where it reduces the duration of the grain-filling period (Brookes *et al*., 1982), the effect on grain number is less clear and probably linked to timing of the water stress. Work by Czyz *et al.* (2001) demonstrated a positive correlation between barley yield and total root mass, which is in line with other crops. It has been noted however, that yield can be also be slightly enhanced in some drought cases, all dependent on the timing, duration and severity of the drought (FAO, paper 66).

5.3 **Triticale**

Triticale (x *Triticosecale*) is a hybrid of wheat (*Triticum*) and Rye (*Secale)* and was produced to combine the grain qualities of common wheat with the low input requirements and hardiness of rye. Production in the UK is only given as a combined area with rye and mixed corn of 52,000ha by Defra (2018a) but is reported to have produced 42,936t on 11,058 ha in 2016 (FAO, 2018) It is reported to generally out-yield common wheat by c. 8% when grown as a second cereal on all soil types and seasons. The markets include animal feed, bioethanol and anaerobic digestion plants (Clarke *et al.,* 2016; Roques *et al*, 2017). According to Basu *et al.* (2011) triticale often out-yields wheat in both favourable and unfavourable environments. Triticale has demonstrated good drought tolerance as shown by the works of Giunta *et al.* (1993) where droughted durum wheat yields were reduced by 25, 54 and 87% compared to only an 8% reduction for triticale, and Estrado-

Campuzano *et al.* (2012) where triticale produced 40%+ greater yield than an Argentinian common wheat.

5.4 **Perennial Ryegrass**

Perennial ryegrass *(Lolium perenne* L.) (PRG) is the most important and widely grown grass species in Britain and has been adopted around the world in other temperate grassland forage systems such as New Zealand (Frame, 1992). It is a highly productive grass, up to 17.7 tons of dry matter per ha (British Grassland, 2017), which responds well to nitrogen, has high digestibility and stock acceptability (Frame, 1994) and is major constituent of both permanent pastures (grass over 5 years old) and temporary grass (less than 5 years old) in the UK. It is reported to have an effective rooting depth of 0.8 m (Garwood and Sinclair, 1979) which may be important for its ability to reach water under dry growing conditions. Within the species there are diploid, tetraploid and early to late heading varieties which allow it to be used for either silage or grazing or a combination of the two. Unlike most crops PRG is always sown as a mixture of varieties in order to provide increased production over the growing season and reduced pest and disease problems. The crop does not perform well under dry conditions where its persistence/longevity is reduced. This is supported by Garwood and Williams (1967) who suggested that PRG growth is severely restricted when soil moisture deficits exceed 40-50mm and also to Hopkins (2000) who reports a good response to irrigation of 15-25 kg DM mm^{-1} of water ha when SMD exceeds 100mm.

The actual water requirements of PRG is less well documented than for many arable crops but Frame (1994) suggests 25mm water per tonne dry matter, equating to 300 - 450mm for average to high yielding crops. Smith (2012) however suggests 600mm p.a. or 25mm p.w. over the growing season. In the UK the growing season for grassland is linked to ‘site class’ which is informed by rainfall, soil type and temperature, which is also affected by altitude, with an optimum growing temperature of 18 - 24°C and a minimum of 5°C. In south-western coastal regions of England the growing season should be 300-350 days whereas in colder eastern-Scotland it will be closer to 200-250 days. As Frame (1994) suggests that the actual grazing season is 5 – 6 weeks less than this, arguably the most productive part of the season, the growing season would be 160 – 310 days (23 – 44 weeks) and the water requirement would therefore be 575 – 1100mm. This is supported by work in New Zealand by Murray-Cawte (2013) who demonstrated the potential of fully irrigated PRG at 18.7 t DM ha compared with 8.29 t DM ha for unirrigated. Although no linear response was reported the yield and water use suggests such a relationship as production rose from 8.9 t DM ha at 386mm water to ~13 t DM ha at 557mm, ~14.5 at 606mm and 18.7 t DM ha at 692mm water. Work on a range of grass species by Garwood and Sinclair (1979) reported PRG yield of only 2.3t/ha in unirrigated plots under rainout shelters in the UK.

Obviously there is some disparity between the figures but with April to September rainfall of less than 350mm from central to the east of England (Frame, 1994) any reduction of rainfall can only reduce the quantity and quality of grass forage produced. Consequently it can therefore be concluded that in order for PRG to remain productive in the UK under a drying summer climate the water requirement would need to be met from irrigation in a significant part of England.

5.5 **Lucerne (Alfalfa)**

Medicago sativa L. known as lucerne (syn. Alfalfa) is the widest grown leguminous forage crop in Europe with production worldwide of approximately 30M ha (FAO, 2012). Cotswold (2018) suggest that the figure is closer to 13M ha for forage and Julier *et* al. (2017) suggest 2.5 million ha in Europe. but unfortunately there is no definitive FAO information to support either figure. Frame *et al.* (1998) reported that it was grown extensively in the USA, Russian federation and Argentina which made up 70% of the total area which is supported by Cook (2018) which reports that 42 states in the USA produced 57.5 Mt. In comparison, Keogh *et al.* (2018) suggests one Mt in Australia but research continues into its value as a replacement for traditional ryegrass sward under dry conditions in New Zealand (Murray-Cawte, 2013). Currently the crop is not widely grown in the UK, approximately 6,000ha, but is suggested as suitable for around 0.4Mha and is being promoted for suitable UK forage systems (Cotswold, 2018).

The crop is very productive, up to 12 - 16 tons of dry matter per ha at an average protein content of 18.1% (Julier *et al.* 2017, British Grassland, 2017; Genever and McConnell, 2014) and is mainly used for conservation as silage in the UK.

Lucerne is recognised as a drought tolerant crop due to its ability to extract water from significant depths (Peterson *et al,* 1992). Frame *et al.* (1998) reports an average of 2 - 4m depth but cites other work which claimed 39m.

Optimum conditions for development and growth are reported as between 5°C minimum and 45°C as the upper limit, with little increase beyond 30°C (FAO, 2012), and with radiation use efficiency rising from 0.6 to 1.6 g DM/Mj as mean air temperatures rose from 6 to 18°C (Brown *et al.*, 2006).

The Lucerne growers guide from the Agricultural and Horticultural Development Board in the UK suggests that the crop does not grow well below 8°C and so the main growth period would be between April/May – September (Genever and McConnell, 2014). In addition it was suggested that the cold tolerance of the varieties is a key point where they suggest using the Northern French ‘Flemish’ varieties are more cold tolerant but probably not as drought resistant as the southern ‘Provence’ varieties.

6.1 **Alternative drought tolerant crops for the UK**

Commercially grown drought resistant alternatives to our mainstay wheat crop, include pearl millet, sorghum, amaranth and quinoa. These crops may provide suitable alternatives but their useful products are not the traditional 'breads' that UK crops have been bred for. Other 'intermediate crops‟ include Durum wheat (a pasta wheat not a UK bread wheat), a Mediterranean crop which survives the hotter climates and is currently only grown in the south of England but struggles to meet the continental quality requirements.

If irrigation is not an option to supplement or provide total precipitation due to climate change then any crop selection must be based on their suitability to be grown in dry or drying conditions. To determine which crops are suitable the principles of crop production apply and are based on several factors: Suitability to the climate, in particular precipitation, humidity and temperature, with C3 plants and C4 plants having optimum ranges for photosynthesis at 20-25° and 30-45° respectively; Soils, soil texture and soil depth; Market, farmers can only grow a product if there is a financially rewarding market for the product; Labour, some crops are very labour intensive and the availability of that labour may be a limiting factor; Machinery, growers will need the appropriate machinery if they wish to plant, manage and harvest the crops at suitable timescales. Where there is a lack of available labour the machinery becomes ever more important; Knowledge, this may only be limiting for the short duration of education. For the UK currently the growers possess or use contractors for all of the machinery required for the majority of mainstay cropping. Any combinable crop would pose no issues and most tuber crops could be quickly adapted to. Labour however, is a significant challenge for many vegetable/fruit growers and the UK very much depends on migrant European labour (Grant, 2017).

The basic requirements for wheat and barley (as comparisons):

Wheat (*Triticum aestivum* L.) (C3) also known as common wheat is grown in the majority of countries around the world. Wheat is a long day plant that needs a cold dry climate with optimum temperatures for growth of 20-25°C and grain formation 14-16°C. Water requirement of 450-650mm (|Spring and summer varieties).

Barley (*Hordeum Vulgare* L.) (C3) is grown quite extensively in the UK but in significant quantities in drier countries around the world. Barley is a long day plant which requires cool temperatures for growth but is not tolerant of frosts generally. Water requirements are similar to wheat, 450-650mm (spring and winter varieties).

Alternative 1: Sorghum (*Sorghum bicolor*). Sorghum is the fifth most widely cultivated cereal crop in the world at 63 Mt in 2016, behind wheat, rice, maize and barley (FAO, 2018). It is a staple food for over 500 million people mostly in the rain-fed arid and semi-arid regions of Africa and Asia (Reddy *et al.,* 2009). Compared with other cereals, like maize, sorghum is a drought tolerant crop (Kholova, *et al*., 2013; Ogbaga, 2014) with higher water use efficiency. With water requirement of 450 – 650mm, similar to wheat, would arguably fair no better than wheat in a drier UK.

Sorghum species are C4 short day plants, flowering only when sunlight periods are less than 12 hours, which for the UK would be in cooler autumn/winter and spring temperatures far below the 27-32°C required for growth. This crop would not be a simple replacement for UK bread wheat and would not suit the UK climate unless a severe change occurred.

Alternative 2: Pearl Millet *(Pennisetum glaucum)*: (C4) Pearl millet was planted on 14 million ha in Africa and 31 million ha worldwide. Global production of its grain exceeds 28 million tons p.a. (FAO, 2018). It classed as a warm weather crop and is also classed as a short day plant but there are varieties which are day neutral. The plant requires temperatures of 27-30°C for germination and growth, is not cold tolerant and requires high temperatures for grain maturity. It is suggested as drought resistant and a water requirement of 250-650mm (DAFF, 2011). This crop would not be a replacement for UK bread wheat especially with it climatic requirements.

Alternative 3: Grain amaranth (Amaranthus spp.) (C4) is classed as a warm season pseudocereal. It is a grain or green leaf crop and it is not a direct replacement for UK bread wheat, but can be mixed with it normally at 10% inclusion. Temperatures required for seed germination are reported to be 18-25°C, growth is restricted at 18°C and requires above 25°C for optimum growth. Low temperatures and short days induce early flowering with accompanying yield reduction. As with most plants amaranth growth is limited by reduced soil moisture or stress when production concentrates on vegetative rather than grain production, and irrigation is seldom economic. The crop is suggested as drought tolerant (DAFF, 2014) and water requirements are suggested to be only 42-47% of that for wheat, 51 – 62% of that of corn and 79% of cotton (Weber, 1990). Yields are extremely variable due to the variability of the types used, an average of 2250 kg/ha and a range from 500 – 6000 kg/ha has been reported. Williams and Brenner (1995) suggest that grain amaranths will never compete with cereals as a staple crop but do have a place in hill areas around the world. Due to the climatic requirements of this crop it is unlikely to be suitable for the projected climate in the UK for some considerable time.

Alternative 4: Quinoa (*Chenopodium quinoa* spp): (C3) is classed as a pseudocereal, a non-grass used as grains in the same way (ground into flour) as the cereal crops. It has gained popularity in the UK as a 'superfood', is high in protein, useful for human and animal feed and can provide good nutritive value in breads required in gluten free diets (Alvarez-Jubete *et al.*, 2009; Fleming and Galwey, 1995), although it is not a direct replacement for UK bread wheat. There are many subspecies of this plant which suit a wide variety of climates. It is suggested as a cool climate plant which can be grown in temperatures ranging from -4°C to 35°C. Similarly water requirements are also subspecies/variety dependent, from 300-1000mm, but the crop has been reported as drought tolerant (Bosque Sanchez *et al.*, 2003; Jacobsen *et al.,* 2003) able to withstand high evaporative demands and low soil moisture (Fleming and Galwey, 1995). Reports suggest that it can be successfully grown in many parts of Europe including the UK. Currently the 'The British Quinoa Company' is the only UK based supplier of commercial quinoa seed. Although Quinoa is reported as both drought tolerant and intolerant Dr Stephen Jones (Personal communication: Stephen Jones is the owner of The British Quinoa Company) suggests that varieties currently used in the UK do not appear to be drought tolerant from his experience. Yields are reported up to 5 t/ha in Britain (Risi and Galwey, 1991).

Alternative 5: Durum wheat, *Triticum turgidum* ssp. *Durum,* synonym *Triticum durum*, (C3) widely known as pasta wheat, has projected global production of 39 M t currently which is approximately 5% of total wheat production (IGC, 2018). Durum wheat is known as a Mediterranean crop but has been grown in southern latitudes of the UK. Peak production of 19,000t was attained in 2002, declined to 12,000t in 2004 and has no values shown in EU production records from 2005 – 2017, probably because any production was below the minimum 1,000 t threshold for display in the database (EUCMO, 2018). Seed suppliers Elsoms seeds Ltd of Lincolnshire in the UK, do supply the variety 'Miradoux' for use in the UK. Durum wheat is not a direct replacement for UK bread wheat but can be used for flat breads. Durum wheat is a long day plant but some varieties show daylength insensitivity. Temperature requirements are similar to the common wheats but are not frost hardy and new varieties are being developed which can grow and yield up to 35-40°C (SLU, 2017). Durum is better suited to regions of low annual rainfall than common wheat with minimum water requirements of 250mm (Prota, 2006).

7.1 Selection of crops for the experiment.

Wheat

As the mainstay of UK arable crop rotations, occupying 1.8 M ha and producing between 14 – 16 Mt p.a this crop is a major dietary component and any drought effects on its production need to be investigated. The UK wheat crop is seldom irrigated but not classed as drought tolerant. Investigation of the response of wheat to the predicted climate change impacts will provide a benchmark for comparisons with other crops.

Barley

UK production of barley, *Hordeum vulgare* was reported as 6.6 Mt (FAO, 2018) making this a significant contributor to UK food production for animal feed or for the brewing industry. The crop can be very productive in the UK where it averages 6 t/ha. Barley is reported to be useful as a dryland crop and is extensively grown in Mediterranean areas for livestock feed which is borne out by its production in Spain of 7.9 Mt from 2.8 M ha (FAO, 2018). Yield is significantly affected by stresses such as water availability during early grain filling where it affects both the grain number and grain filling. It has been noted however that yield can be also be slightly enhanced in some drought cases, all dependent on the timing, duration and severity of the drought (FAO, paper 66). A key contributor to UK food production it should be included in the experiment.

Triticale

Triticale is a good substitute for common wheat as animal feed but would be less suitable for UK bread making. It is already grown and adapted for the UK but is regarded as a far more drought tolerant crop than the common wheat grown here. Subsequently it would be a good candidate for inclusion in the experiment.

Durum wheat

Durum wheat, *Triticum turgidum* ssp. *Durum,* synonym *Triticum durum*, widely grown in hotter and drier Mediterranean areas but has only been grown in southern latitudes of the UK. Although not a replacement for UK bread wheats pasta is part well-established within UK diets and with increasing temperatures it could well be grown over a wider UK area in drier and warmer climates.

Quinoa

Quinoa (*Chenopodium quinoa* spp) can and is grown on a small scale in the UK. It should suit our current and projected increased temperatures and it can be use our current harvesting technology without any increased labour requirements. It is a broadleaf crop and would make a useful 'break' crop for any of the true cereals (Fleming and Galwey, 1995). The British Quinoa Company grow the crop but the variety grown has questionable drought tolerance. Inclusion of this crop within the experiment could help to determine its drought tolerance.

Perennial Ryegrass

Perennial ryegrass *(Lolium perenne* L.) (PRG) is the most important and widely grown grass species in Britain. It is a highly productive grass and is major constituent of both permanent pastures and temporary grass in the UK. The crop is reported to under-perform under dry conditions where its persistence/longevity is reduced. As much of the UK grazing livestock, and thus animal production, depends on this forage it would be a sensible inclusion within the experiment

Lucerne (Alfalfa)

Lucerne (syn. Alfalfa) is the widest grown leguminous forage crop in Europe with production worldwide of approximately 30M ha (FAO, 2012). Currently the crop is not widely grown in the UK, approximately 6,000ha, but is suggested as suitable for around 0.4Mha and is being promoted for suitable UK forage systems (Cotswold, 2018). The crop is very productive, up to 12 - 14 tons of dry matter per ha which compares well with PRG. Lucerne is recognised as a drought tolerant crop due to its ability to extract water from significant depths. The Lucerne growers guide from the AHDB in the UK suggests that the crop does not grow well below 8°C and is suggested to be cold intolerant. As a potential more drought tolerant crop than PRG it is a valuable consideration for the experiment.

8.0 Experimental work (Mesocosms at HAU)

Introduction to the experimental work

The physical, phrenological, biochemical and molecular effects of drought on crops have been studied for many years and is documented in part earlier in this report. Consequently the value of this research should be to add to this knowledge and not simply replicate it. As for all crops it is not simply the amount of drought but also the timing of the drought in relation to specific growth stages or processes which is important, the design of the experiment/s should not be centered on the critical stage of one crop. For the purpose of the research required within the DRY project therefore consideration was given to the potential of the need to change cropping in light of climate change projections and so what would be the driver for change. To determine this the investigation focused on the effects of a severe climate change scenario for the 2050 period, on three concurrent years, which the UK may face and which would be applicable to all crops grown. Within this work the effects on the mainstay UK arable crops was important and also the inclusion of three minor but potentially more drought tolerant alternatives, triticale, Durum wheat and Quinoa. In addition to these a decision was made to include the main UK forage crop, perennial ryegrass and a drought tolerant replacement, Lucerne, to the same scenario. In order to achieve the latter however, and maintain a robust experimental design within the confines of the mesocosms, the proposed inclusion within the experiment of alternative water sources was foregone. Although this is out with the original 'case for support' it is believed that the benefits of inclusion of the forage crops for this climate change scenario far outweigh the loss of a 'brackish water' component. To support this it was also felt that our knowledge of the effects of salinity on crops is considerable unlike our knowledge on the potential need to consider changing our cropping practices in the non-too distant future.

Climate change scenario:

The UKCP09 climate change projections used in this work are accessed through the UK Met Office portal (Met Office, 2018c). Utilising the High Emissions 2050 time period rainfall datasets for the 'Change at 10% probability' the changes in percentage rainfall for the combined East and West Midland datasets produced: An increase of 3% of average winter rainfall and a 38% decrease of summer rainfall. The base dataset selected from which to make these changes were then based on published Central England rainfall information (Alexander & Jones, 2001; HadUKP Data, 2018) utilising the 50 year period from 1961 – 2010 period.

Crop mesocosms using two scenarios:
Central England 50 year average rainfall (CE50)
UKCP09 High Emissions 2050 changes (Dry)
(Plus 3% Winter rain & minus 38% summer rainfall for the Midlands)

The overall objectives of this work were:

1) to determine the yield response of the chosen crops to 'average' rainfall and to the predicted 'dry' scenario
2) to collect environmental data to allow modelling work to be carried out using the SaltMed model.

The overall hypothesis for the work was:

'That crop growth in the mesocosms would not be affected by changes in the simulated rainfall amounts'.

8.1 General materials and methods

The site for the research was at the Crop and Environment Research Centre at Harper Adams University, Shropshire, UK (52°46'37.17"N, 2°25'42.87"W).

Crops were grown under the protection of a large polytunnel which acted as a rain-out shelter. The ends of the polytunnel were left free from polythene but were netted to prevent access to birds. Within the tunnel 96 'mesocosms' were created from deep wheelie bin container of an average height of 76.45 cm and a surface area of 40 cm x 44.5 cm = 1780 cm^2, giving a total capacity was 136l. In the base of each container six 25mm holes were drilled to allow drainage before they were buried to a depth of 50 cm leaving approximately 30 cm above the soil surface, figure 5.1. The soil, sandy loam, excavated for the burial of the mesocosms was then mixed with peat before being used to provide the growing media within them. At the beginning of this experiment the OM% and main nutrient analysis was performed for each mesocosms and into each a moisture sensor access tube was installed in the centre to allow regular moisture measurements to be taken to 70cm depth at 10 cm intervals. Field capacity (FC) was achieved following saturation during the set-up period over the first winter before the polythene cover was fitted. All crops were grown using standard UK agronomic practices.

Figure 8.1. The basic set up of the crop mesocosms in the DRY experiment at HAU, 2015-2017 (Source: Grove I, 2015)

Nutrient Analysis

Soil sample analysis was conducted on all mesocosms individually by taking soil samples using a cheese corer style auger, 20mm diameter x 20cm deep. Samples were either carried out at Princess Margaret laboratories at HAU or sent for analysis at NRM laboratories, Bracknell, Berkshire, UK. Analysis included soil pH, available P, K, Mg and organic matter. Nutrients were applied as required based on recommendations (AHDB, 2010).

Crops and crop rotations utilised.

As the rationale and background for the crop selection has been covered, section 7.1, tables 8.1a & b provides a list of crop and varieties, whereas tables 8.2 and 8.3 provide information on the rotations used within the mesocosms.

Table 8.1a. Crop and variety information for the DRY mesocosm experiment at HAU 2015-2017.

Crop	Variety Spring 2015	Variety 2015 - 2016	Variety 2016 - 2017
Common Wheat	Belvoir	Evolution	Evolution
Common wheat AT[1]	Belvoir	Evolution	Evolution
Barley	Winchester	Volume	Volume
Triticale	Trimour	Agostino	Agostino
Durum wheat	Anvergur	Anvergur	Aventadur
Quinoa	Atlas	Atlantis	Atlas
Perennial ryegrass[2]	2014/034/9a	2014/034/9a	2014/034/9a
Lucerne	Neptune	Neptune	Neptune

Note[1]. Common wheat AT denotes common wheat plus application of antitranspirant.

Note[2]. Seed supplied by Herbiseed, Hardwick Organic Estate, Oxford.

Table 8.1b Planting & harvest dates

	2015 Crop		2015/2016 Crop		2016/2017	
	Sown	Harvested	Sown	Harvested	Sown	Harvested
Spring Wheat +AT	10/04/2015	05/08/2015	27/11/2015	26/07/2016	10/10/2016	11/07/2017
Spring Wheat -AT	10/04/2015	05/08/2015	27/11/2015	26/07/2016	10/10/2016	11/07/2017
Spring Barley	10/04/2015	30/07/2015	27/11/2015	05/07/2016	10/10/2016	15/06/2017
Durum	20/04/2015	25/08/2015	21/03/2016	27/07/2016	14/03/2017	11/07/2017
Triticale	10/04/2015	25/08/2015	27/11/2015	25/07/2016	10/10/2016	11/07/2017
Quinoa	10/04/2015	23/09/2015	21/03/2016	06/09/2016	14/03/2017	14/09/2017
PRG	21/04/2015	3 harvests	21/04/2015	6 harvests	21/04/2015	3 harvests
Lucerne	02/04/2015	3 harvests	02/04/2015	8 harvests	02/04/2015	3 harvests

Table 8.2 Crop rotation used in the ‘average rainfall’ scenario within the mesocosm experiment at HAU 2015-2017.

Year 1	**S. wheat AT**	**S. wheat**	**S Barley**	**Durum (S)**	**S Triticale**	**Quinoa (S)**	**PRG**	**Lucerne**
Year 2	**W Barley**	**Durum (S)**	**W Triticale**	**Quinoa (S)**	**W wheat AT**	**W wheat**	**PRG**	**Lucerne**
Year 3	**W Triticale**	**Quinoa (S)**	**W wheat AT**	**W wheat**	**W Barley**	**Durum (S)**	**PRG**	**Lucerne**

Table 8.3 Crop rotation used in the ‘DRY rainfall’ scenario within the mesocosm experiment at HAU 2015-2017.

Year 1	**S wheat AT**	**S wheat**	**S Barley**	**Durum (S)**	**S Triticale**	**Quinoa (S)**	**PRG**	**Lucerne**
Year 2	**W Barley**	**Durum (S)**	**W Triticale**	**Quinoa (S)**	**W wheat AT**	**W wheat**	**PRG**	**Lucerne**
Year 3	**W Triticale**	**Quinoa (S)**	**W wheat AT**	**W wheat**	**W Barley**	**Durum (S)**	**PRG**	**Lucerne**

Rainfall scenarios and Irrigation regimes:

As each mesocosm was required to be at field capacity before the experiment started the polytunnel covers were removed to allow rainfall to fall onto all the mesocosm at the same rate and until soil moistures were measured and determined to be at field capacity. As the value of field capacity for each mesocosm would be expected to be different due to slight soil structural and textural differences, each was monitored with a diviner 2000 probe (Sentek Technologies, Australia) to a depth of 70cm, to obtain a soil moisture curve pertaining solely to that mesocosm. The values were taken at least weekly during the initiation period (September 2014 to February 2015) and FC categorised when the average soil moisture content remained constant for two weeks after heavy rainfall. This is similar to the method as used by Hall *et al*. (1977).

Irrigation treatments were commenced at planting of year 1. Water was applied on Monday, Wednesday and Friday every week using drip irrigation or watered by hand whilst the irrigation system was drained for frost protection from November to March, with a measured volume of water for each mesocosm to add the required quantity of water. Soil moisture content was measured in each mesocosm using the Diviner probe every Friday morning.

Climate data

Temperature and relative humidity data was collected using Tinytag® View 2 or Plus 2 temperature (-25°C to + 85°C) and relative humidity (0 – 100%) loggers (Gemini dataloggers (UK) Ltd). Wind speed was recorded with a DS-2 sonic anenometer and a Decagon Em50 datalogger (Labcell, Hants). Solar radiation was collected using four Skye Instruments par energy sensors recording at 15 minute intervals, Watts/m^2 and converted to Mj/M^2/day, logged with a datahog logger (Skye Instruments). Three of sensors were positioned inside the polytunnel and one outside of the tunnel to determine the effect of the polytunnel cover on the solar energy reaching the plants through plastic.

Polytunnel

The plastic cover of the polytunnel was removed between December 2014 and Mid-February 2015 and again between December 2015 and mid-February 2016 as the soil moisture in all mesocosms had returned to field capacity and also to protect the structures. However, the covers were left in place from February 2016 until September 2017, no overwinter uncovered period, as some of the mesocosms containing perennial crops had not returned to field capacity.

Agronomy and Anti-transpirants

All crops were grown using standard UK practices. Weed control was by hand removal. Crops received disease control measures only for mildew in cereal crops as advised and applied by the trials dept at HAU. Anti-transpirant was applied to the wheat+AT, around GS 33, as di-1-p-methene (as Vapour guard, Miller Chemical, Hanover) at 1 litre/ha in 200 l/ha volume, with F110-03 nozzles at 2 bar pressure using compressed air propellant with a Lunchbox sprayer (Trials Equipment UK).

9.0 Results

9.1 Results year 1

There were no significant field capacity differences between crops or scenarios and no interactions. This suggests that no crop or scenario responses would be influenced by the background amount of water available in the soils. Therefore a uniform background had been achieved. With an overall mean value of 128.6mm over 70cm depth, table 9.1, this equates to 183.7mm per m and thus 18.7% total water by volume which is within the range for this soil type (Hall *et al*., 1977).

Table 9.1. Field capacity quantification (total mm for all depths to 70cm) at experiment initiation (March 2015) in the HAU mesocom experiment

		Scenarios		
Crops		CEAve	Dry	**Mean Crop**
SWheat+AT		131.6	125.4	**128.5**
SWheat-AT		131.2	130.4	**130.8**
SBarley		131.5	132.4	**132**
Durum		125.2	138.7	**131.9**
STriticale		118	121.4	**119.7**
Quinoa		136.4	125.4	**130.9**
PRG		134.8	121.6	**128.2**
Lucerne		127.2	126.5	**126.8**
	Mean Sc	**129.5**	**127.7**	
		Overall mean		**128.6**
Crops		*P* =	0.456	
Scenarios		*P* =	0.545	
Crops.Scenarios		*P* =	0.395	
	Crops	Scenarios	Cr* Sc	
s.e.d.	5.83	2.91	8.24	

Table 9.2. Field capacity quantification (total mm for 10cm depth) at experiment initiation (March 2015) in the HAU mesocom experiment

		Scenarios		
Crops		CEAve	Dry	**Mean Crop**
SWheat+AT		14.47	14.35	14.41
SWheat-AT		14.43	14.4	14.42
SBarley		14.7	14.72	14.71
Durum		14.15	15.57	14.86
STriticale		13.1	14.13	13.62
Quinoa		15.02	14.15	14.58
PRG		14.02	13.93	13.98
Lucerne		14.07	14.65	14.36
	Mean Sc	14.24	14.49	
		Overall mean		**14.37**
Crops		*P* =	0.659	
Scenarios		*P* =	0.47	
Crops.Scenarios		*P* =	0.762	
	Crops	Scenarios	Cr* Sc	
s.e.d.	0.671	0.335	0.948	

There were no significant field capacity differences between crops or scenarios and no interactions in the 10 cm zone of soil. This suggests that no crop or scenario responses would be influenced by the background amount of water available in the soils at 10cm. A uniform background with a mean of 14.4mm, 14.4% total water by volume, which is within the range for this soil type (Hall *et al*., 1977), table 9.2.

There were no significant field capacity differences between crops or scenarios and no interactions in the 20 cm zone of soil. A uniform background with a mean of 17.5mm, 17.5% total water by volume, which is within the range for this soil type (Hall *et al*., 1977), table 9.3

Table 9.3. Field capacity quantification (total mm for 20cm depth) at experiment initiation (March 2015) in the HAU mesocom experiment

		Scenarios		
Crops		CEAve	Dry	**Mean Crop**
SWheat+AT		17.92	17.18	17.55
SWheat-AT		17.38	18.83	18.11
SBarley		18.68	18.28	18.48
Durum		15.88	17.62	16.75
STriticale		17.08	16.32	16.7
Quinoa		18.4	18.1	18.25
PRG		17.43	15.8	16.62
Lucerne		18.32	16.63	17.47
	Mean Sc	17.64	17.35	
		Overall mean		**17.49**
Crops		*P* =	0.659	
Scenarios		*P* =	0.47	
Crops.Scenarios		*P* =	0.762	
	Crops	Scenarios	Cr* Sc	
s.e.d.	0.671	0.335	0.948	

There were no significant field capacity differences between crops or scenarios and no interactions in the 30 cm zone of soil. This suggests that no crop or scenario responses would be influenced by the background amount of water available in the soils at 30cm. A uniform background with a mean of 18.1mm, 18.1% total water by volume, which is within the range for this soil type (Hall *et al*., 1977), table 9.4.

There were no significant field capacity differences between crops or scenarios and no interactions in the 40 cm zone of soil. This suggests that no crop or scenario responses would be influenced by the background amount of water available in the soils at 40cm. A uniform background with a mean of 18.1mm, 18.1% total water by volume, which is within the range for this soil type (Hall *et al*., 1977), table 9.5.

Table 9.4. Field capacity quantification (total mm for 30cm depth) at experiment initiation (March 2015) in the HAU mesocom experiment

		Scenarios		
Crops		CEAve	Dry	**Mean Crop**
SWheat+AT		17.48	18.32	17.9
SWheat-AT		18.42	19.18	18.8
SBarley		18.35	19.33	18.84
Durum		17.45	18.13	17.79
STriticale		17.28	16.18	16.73
Quinoa		18.98	18.57	18.77
PRG		18.65	17.93	18.29
Lucerne		17.77	17.53	17.65
	Mean Sc	18.05	18.15	
		Overall mean		**18.1**
Crops		*P* =	0.602	
Scenarios		*P* =	0.864	
Crops.Scenarios		*P* =	0.974	
	Crops	Scenarios	Cr* Sc	
s.e.d.	1.167	0.583	1.65	

Table 9.5. Field capacity quantification (total mm for 40cm depth) at experiment initiation (March 2015) in the HAU mesocom experiment

		Scenarios		
Crops		CEAve	Dry	**Mean Crop**
SWheat+AT		18.83	19.22	19.03
SWheat-AT		19.95	19.02	19.48
SBarley		19.53	19.15	19.34
Durum		17.98	20.5	19.24
STriticale		16.43	17.15	16.79
Quinoa		20.9	17.95	19.43
PRG		19.93	18.63	19.28
Lucerne		17.2	18.5	17.85
	Mean Sc	18.85	18.76	
		Overall mean		**18.81**
Crops		*P* =	0.27	
Scenarios		*P* =	0.893	
Crops.Scenarios		*P* =	0.452	
	Crops	Scenarios	Cr* Sc	
s.e.d.	1.208	0.604	1.709	

There were no significant field capacity differences between crops or scenarios and no interactions in the 50 cm zone of soil. This suggests that no crop or scenario responses would be influenced by the background amount of water available in the soils at 50cm. A uniform background with a mean of 19.3mm, 19.3% total water by volume, which is within the range for this soil type (Hall *et al*., 1977), table 9.6.

Table 9.6. Field capacity quantification (total mm for 50cm depth) at experiment initiation (March 2015) in the HAU mesocom experiment

		Scenarios		
Crops		CEAve	Dry	**Mean Crop**
SWheat+AT		21.12	18.48	19.8
SWheat-AT		19.05	19.78	19.42
SBarley		20.29	19.05	19.67
Durum		18.77	21.63	20.2
STriticale		16.77	18.28	17.53
Quinoa		21.02	18.42	19.72
PRG		21.02	18.2	19.61
Lucerne		18.2	18.07	18.13
	Mean Sc	19.53	18.99	
		Overall mean		**19.26**
Crops		*P =*	0.336	
Scenarios		*P =*	0.378	
Crops.Scenarios		*P =*	0.164	
	Crops	Scenarios	Cr* Sc	
s.e.d.	1.213	0.607	1.716	

There were no significant field capacity differences between crops or scenarios and no interactions in the 60 cm zone of soil.   This suggests that no crop or scenario responses would be influenced by the background amount of water available in the soils at 60cm. A uniform background with a mean of 1.9.8mm, 19.8% total water by volume, which is within the range for this soil type (Hall *et al*., 1977), table 9.7.

There were no significant field capacity differences between crops or scenarios and no interactions in the 70 cm zone of soil.   This suggests that no crop or scenario responses would be influenced by the background amount of water available in the soils at 70cm. A uniform background with a mean of 20.8mm, 20.8% total water by volume, which is within the range for this soil type (Hall *et al*., 1977), table 9.8.

Table 9.7.Field capacity quantification (total mm for 60cm depth) at experiment initiation (March 2015) in the HAU mesocom experiment

		Scenarios		
Crops		CEAve	Dry	**Mean Crop**
SWheat+AT		21.47	19.02	20.24
SWheat-AT		20.08	19.45	19.77
SBarley		19.69	19.98	19.84
Durum		19.68	22.12	20.9
STriticale		18.7	18.68	18.69
Quinoa		20.8	18.57	19.68
PRG		21.25	17.72	19.48
Lucerne		20.3	19.5	19.9
	Mean Sc	20.25	19.38	
		Overall mean		**19.81**
Crops		*P* =	0.675	
Scenarios		*P* =	0.107	
Crops.Scenarios		*P* =	0.165	
	Crops	Scenarios	Cr* Sc	
s.e.d.	1.064	0.532	1.504	

Table 9.8. Field capacity quantification (total mm for 70cm depth) at experiment initiation (March 2015) in the HAU mesocom experiment

		Scenarios		
Crops		CEAve	Dry	**Mean Crop**
SWheat+AT		20.33	18.78	19.56
SWheat-AT		21.9	19.75	20.82
SBarley		20.23	21.92	21.07
Durum		21.3	23.1	22.2
STriticale		18.58	20.62	19.6
Quinoa		21.25	19.63	20.44
PRG		22.53	19.33	20.93
Lucerne		21.3	21.62	21.46
	Mean Sc	20.93	20.59	
		Overall mean		**20.76**
Crops		*P* =	0.151	
Scenarios		*P* =	0.505	
Crops.Scenarios		*P* =	0.055	
	Crops	Scenarios	Cr* Sc	
s.e.d.	1.001	0.5	1.415	

There were no significant organic matter (OM) differences between crops or scenarios and no interactions. This suggests that no crop or scenario responses would be influenced by the background amount of OM within the soil. The mean of 3.8% is within the range for an arable soil of this type (Hall *et al*., 1977), table 9.9.

Table 9.9. Soil organic matter % at experiment initiation (March 2015) in the HAU mesocom experiment

		Scenarios		
Crops		CEAve	Dry	**Mean Crop**
SWheat+AT		4.4	3.3	**3.8**
SWheat-AT		3.6	3.8	**3.7**
SBarley		3.4	3.6	**3.5**
Durum		3.9	4.1	**4.0**
STriticale		4.5	3.6	**4.0**
Quinoa		3.2	3.3	**3.3**
PRG		4.4	3.5	**3.9**
Lucerne		3.9	4.0	**3.9**
	Mean Sc	**3.9**	**3.6**	
		Overall mean		**3.8**
Crops		*P* =	0.538	
Scenarios		*P* =	0.174	
Crops.Scenarios		*P* =	0.389	
	Crops	Scenarios	Cr* Sc	
s.e.d.	0.39	0.19	0.56	

Table 9.10. Soil K (mg/l) at experiment initiation (March 2015) in the HAU mesocom experiment

		Scenarios		
Crops		CEAve	Dry	**Mean Crop**
SWheat+AT		120.8	164.9	**142.9**
SWheat-AT		150.7	129.5	**140.1**
SBarley		153.2	177.7	**165.4**
Durum		169	137.7	**153.3**
STriticale		157.1	160.4	**158.7**
Quinoa		167	162.8	**164.9**
PRG		153.1	176.3	**164.7**
Lucerne		145.9	146.7	**146.3**
	Mean Sc.	**152.1**	**157**	
		Overall mean		**154.6**
Crops		*P* =	0.682	
Scenarios		*P* =	0.582	
Crops.Scenarios		*P* =	0.448	
	Crops	Scenarios	Cr* Sc	
s.e.d.	17.76	8.88	25.12	

There were no significant differences in soil K (mg/l) between crops, scenarios or interactions. No crop or scenario responses would be influenced by the background amount of K (mg/l). The mean of 154.6 mg K/l equates to an UK index of 2-, which is the target soil index for arable, forage & grass crops (AHDB, 2017), table 9.10.

Table 9.11. Soil pH at experiment initiation (March 2015) in the HAU mesocom experiment

		Scenarios		
Crops		CEAve	Dry	**Mean Crop**
SWheat+AT		6.0	6.0	**6.0**
SWheat-AT		6.1	6.1	**6.1**
SBarley		6.1	6.1	**6.1**
Durum		6.0	6.0	**6.0**
STriticale		5.8	6.2	**6.0**
Quinoa		6.3	6.0	**6.1**
PRG		5.9	6.0	**6.0**
Lucerne		5.9	6.0	**6.0**
	Mean Sc.	**6.02**	**6.05**	
		Overall mean		**6.03**
Crops		*P* =	0.75	
Scenarios		*P* =	0.507	
Crops.Scenarios		*P* =	0.146	
	Crops	Scenarios	Cr* Sc	
s.e.d.	0.11	0.055	0.1555	

There were no significant differences in soil pH between crops, scenarios or interactions. No crop or scenario responses would be influenced by the background soil pH. The mean of pH 6.0 is within the normal pH range of 6.00 – 6.5 for arable, forage & grass crops on mineral soils (AHDB, 2017), table 9.11.

Within the first season crops of the experiment the soil moisture was monitored on a weekly basis. Tables9.12, 9.13 and 9.14 illustrate the development of the soil moisture deficits on 2nd June, 30th June and 11th August respectively.

On 2nd June there were no significant differences between the scenarios, P = 0.909, but there were significant, $P < 0.001$, differences between mean values for the individual crops. PRG and lucerne had developed the least soil moisture deficits, 15 and 21mm respectively. Spring triticale, quinoa and durum wheat moderate soil moisture deficits, and spring wheats and barley the greatest soil moisture deficits. There were no interactions, table 9.12. The overall mean of 44.7mm equated to 35% of total water volume to 70cm.

Table 9.12. Soil moisture deficit as of 2nd June 2015 in the HAU mesocom experiment, mm total water to 70cm.

		Scenarios		
Crops		CEAve	Dry	**Mean Crop**
SWheat+AT		62.83	57.50	60.17
SWheat-AT		60.67	62.67	61.67
SBarley		63.83	65.67	64.75
Durum		33.67	39.00	36.33
STriticale		49.67	49.33	49.50
Quinoa		50.50	46.17	48.33
PRG		16.67	14.00	15.33
Lucerne		20.50	22.17	21.33
	Mean Sc.	44.79	44.56	
		Overall mean		**44.68**
Crops		*P* =	<.001	
Scenarios		*P* =	0.909	
Crops.Scenarios		*P* =	0.89	
	Crops	Scenarios	Cr* Sc	
s.e.d.	3.994	1.997	5.649	

Soil moisture deficits had increased in all crops by the 30th June 2015 but there was still no significant scenario effect. There were significant differences between mean values for crops. The overall mean of 69mm equated to 54% of available water content being used at this point, table 9.13.

Table 9.13. Soil moisture deficit as of 30th June 2015 in the HAU mesocom experiment, mm total water to 70cm.

		Scenarios		
Crops		CEAve	Dry	**Mean Crop**
SWheat+AT		77.8	73.2	75.5
SWheat-AT		78	78.4	78.2
SBarley		75.4	81.3	78.4
Durum		71.9	81.2	76.6
STriticale		63.7	66.5	65.1
Quinoa		70.1	65.8	68
PRG		51.6	43.6	47.6
Lucerne		59	67.9	63.5
	Mean Sc.	68.4	69.8	
		Overall mean		**69.10**
Crops		*P* =	<.001	
Scenarios		*P* =	0.538	
Crops.Scenarios		*P* =	0.318	
	Crops	Scenarios	Cr* Sc	
s.e.d.	4.23	2.11	5.98	

Table 9.14. Soil moisture deficit as of 11th August 2015 in the HAU mesocom experiment, mm total water to 70cm.

		Scenarios		
Crops		CEAve	Dry	**Mean Crop**
SWheat+AT		73.7	76.9	75.3
SWheat-AT		78.4	81.4	79.9
SBarley		72.2	82.8	77.5
Durum		72.9	85.1	79
STriticale		63.5	70.9	67.2
Quinoa		77.6	74.3	75.9
PRG		73.5	63.2	68.3
Lucerne		66.6	75	70.8
	Mean Sc.	72.3	76.2	
		Overall mean		**74.20**
Crops		*P* =	0.023	
Scenarios		*P* =	0.079	
Crops.Scenarios		*P* =	0.181	
	Crops	Scenarios	Cr* Sc	
s.e.d.	4.36	2.18	6.16	

Soil moisture deficits had increased further in all crops by the 11th August 2015 but with no significant scenario effect. There were significant differences between mean values, $P = 0.023$. The overall mean of 74.2mm equated to 58% of available water content being used at this point, tables 9.14. A key point here however is that at this point the soil moisture at all depths had been constant for several weeks suggesting maximum soil water extraction had occurred.

Soil moisture was recorded on 7 day intervals and the progression is shown in figures 9.1 for barley, 9.2 triticale, 9.3 durum wheat, 9.4 spring wheat and 9.5 lucerne.

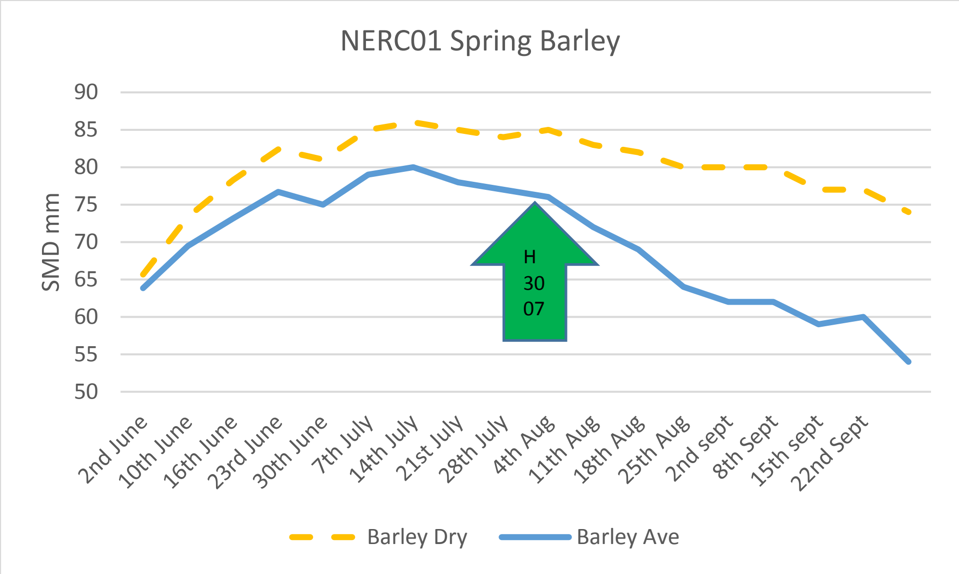

Figure 9.1. Soil moisture deficit progression for the spring barley crop from 2nd June 2015 to 29th September 2015. Crop harvested on 30th July 2015.

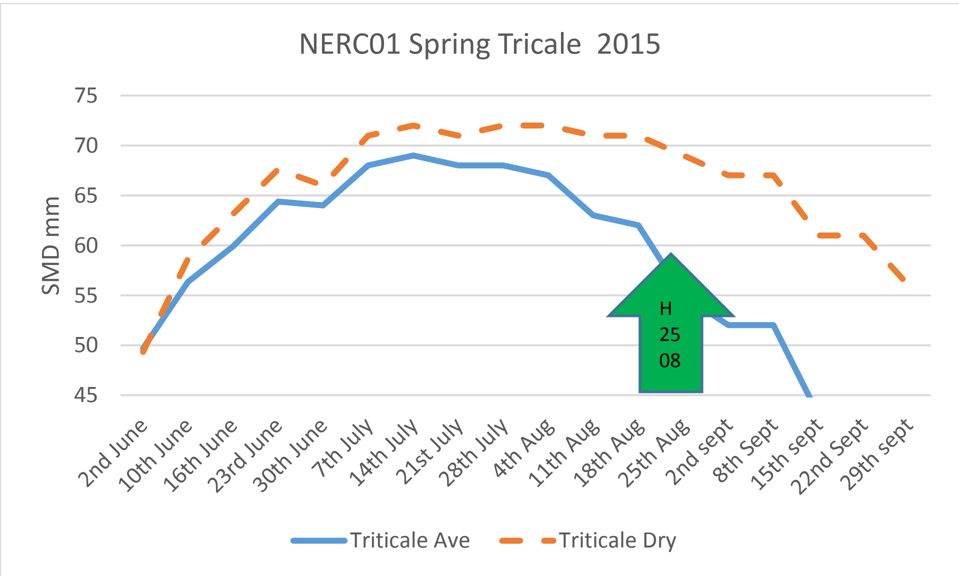

Figure 9.2. Soil moisture deficit progression for the spring triticale crop from 2nd June 2015 to 29th September 2015. Crop harvested on 25th August 2015.

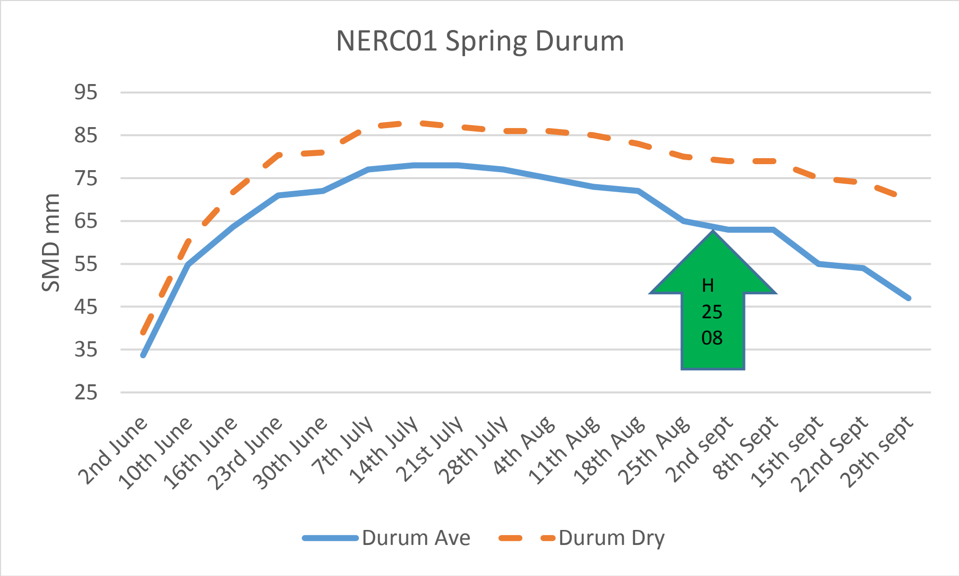

Figure 9.3. Soil moisture deficit progression for the durum wheat crop from 2nd June 2015 to 29th September 2015. Crop harvested on 25th August 2015.

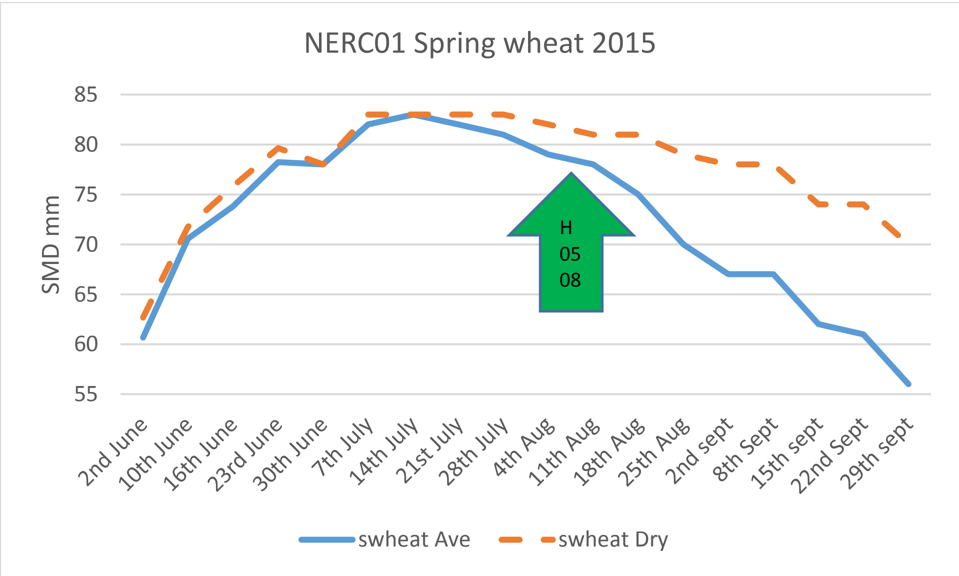

Figure 9.4. Soil moisture deficit progression for the durum wheat crop from 2nd June 2015 to 29th September 2015. Crop harvested on 25th August 2015.

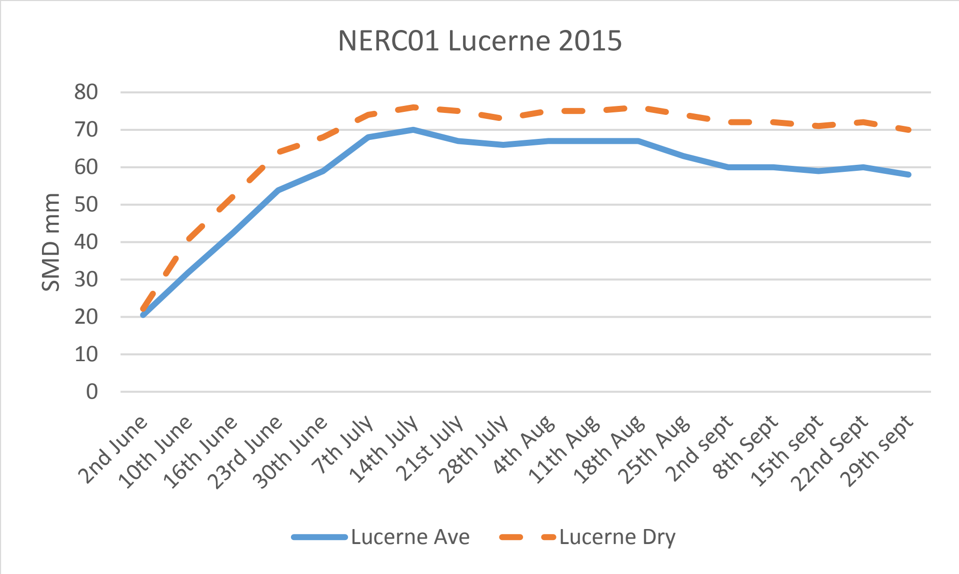

Figure 9.5. Soil moisture deficit progression for the lucerne crop from 2nd June 2015 to 29th September 2015. Crop harvested on 25th August 2015.

As can be seen from figures 9.1 to 9.4, once the crop has senesced and is harvested the soil moisture quickly increases in the CEave scenario but much more slowly in the DRY scenario. For the perennial crops PRG and lucerne however, the crop continues to extract water and thus the soil moisture deficits continue to be maintained, figure 9.5.

Table 9.15. Biomass yield Ln(x) transformed t/ha (dryweight basis) from the HAU mesocom experiment 2015 spring planted crops (t/ha equivalent)

	Scenario		
Crop	CEave	DRY	**Mean crop**
Durum	2.308 (10.4)	2.242 (9.5)	2.275
Lucerne	2.383 (11.2)	2.395 (11.1)	2.389
PRG	1.854 (6.5)	1.548 (4.7)	1.701
Quinoa	5.948 (387.5)	5.524 (311.2)	5.736
Spring Barley	2.263 (9.7)	2.34 (10.5)	2.302
Spring Wheat +AT	2.984 (19.9)	2.641 (14.7)	2.812
Spring Wheat -AT	2.84 (17.3)	2.788 (16.6)	2.814
Triticale	2.787 (16.9)	2.814 (17.0)	2.8
Mean Scenarios	**2.921**	**2.786**	
	Overall mean		2.854
Crop	*P*	<.001	
Scenario	*P*	0.017	
Crop.Scenario	*P*	0.172	
SE	Crop	Scenario	Interaction
	0.1105	0.0553	0.1563

Note: Backtransformed data in parantheses

When total biomass dry weight was considered the data were skew and required transformation by natural log Ln(x) to gain normality. Total above ground fresh biomass was measured at harvest except for the PRG and lucerne which was combination of all first year harvests up to November 2015. There were significant crop differences with PRG having significantly lower biomass than all other crops and quinoa significantly greater biomass than all other crops. The wheats and triticale also produced significantly greater biomass than durum wheat and barley. There were significant differences between the scenarios, *P* = 0.017, where the CEAve scenario produced significantly greater biomass than the DRY scenario, there were no significant interactions. Quinoa produced the greatest amount of biomass, equivalent to a mean of 349 t/ha, which is considerably more than would be expected. Lucerne produced significantly greater dry matter than PRG. Although there were no significant interactions both spring barley and spring triticale appeared to be least affected by the drier conditions, table 9.15.

When separated from the forage crops the grain yields from the cereal crops could be analysed separately. There were significant differences between the cereal crop yields and significantly lower mean values for the DRY scenario. There were no significant interactions and so no emphasis can be placed on differences within crops and scenarios, however spring triticale and spring barley appears to be least affected by the lower water application in the DRY scenario, table 9.16

Table 9.16. Final cereal crop yields t/ha Ln(x), and (back-transformed), from the HAU mesocom experiment 2015 (t/ha equivalent)

Yield t/ha Ln(x) (Untrans)			
	Scenario		
Crop	CEave	DRY	Mean crop
Durum	1.591 (5.04)	1.303 (3.73)	**1.447 (4.39)**
Quinoa	2.728 (18.85)	2.536 (16.2)	**2.632 (17.53)**
Spring Barley	1.826 (6.34)	1.774 (6.12)	**1.8 (6.23)**
Spring Wheat +AT	2.032 (7.7)	1.583 (5.14)	**1.807 (6.42)**
Spring Wheat -AT	1.932 (6.93)	1.688 (5.53)	**1.81 (6.23)**
Triticale	1.979 (7.61)	1.955 (7.57)	**1.967 (7.59)**
Mean Scenarios	**2.015 (8.74)**	**1.806 (7.59)**	
	Overall mean		**1.911 (8.06)**
Crop	*P*	<.001	
Scenario	*P*	0.038	
Crop.Scenario	*P*	0.824	
SE	Crop	Scenario	Interaction
	0.1694	0.0978	0.2396

Due to difficulties quantifying leaf area within the mesocosms as destructive analysis was not an option, and differences between crop leaves, the area of the main leaf was quantified to determine if there were any effects of the scenarios. There were significant differences between crops, which is to be expected, but no significant effect of rainfall scenario or interactions, table 9.17.

Table 9.17. Leaf area of main leaf Ln(x) transformed cm^2 from the HAU mesocom experiment on 23rd to 26th June 2015 spring planted crops.

	Scenario		
Crop	CEave	DRY	**Mean crop**
Durum	2.526	2.838	2.682
Lucerne	1.707	1.618	1.663
PRG	2.546	2.522	2.534
Quinoa	3.273	3.398	3.336
Spring Barley	4.926	4.435	4.681
Spring Wheat +AT	2.663	2.859	2.761
Spring Wheat -AT	2.771	2.871	2.821
Triticale	2.109	1.967	2.038
Mean Scenarios	2.815	2.813	
	Overall mean		2.81
Crop	*P*	<.001	
Scenario	*P*	0.983	
Crop.Scenario	*P*	0.218	
SE	Crop	Scenario	Interaction
	0.1483	0.0741	0.2097

Table 9.18 Stem number m^2 for the cereal crops in the HAU mesocom experiment on 23rd to 26th June 2015 spring planted crops.

	Scenario		
Crop	CEave	DRY	Mean crop
Durum	521	530	526
Spring Barley	1168	1288	1228
Spring Wheat +AT	540	564	552
Spring Wheat -AT	568	527	547
Triticale	552	526	539
Mean Scenarios	670	687	
	Overall mean		678
Crop	*P*	<.001	
Scenario	*P*	0.552	
Crop.Scenario	*P*	0.433	
SE	Crop	Scenario	Interaction
	45.4	28.7	64.2

There were significantly different stem numbers between crops, which again is to be expected, but no significant effects of the scenarios and no significant interactions, table 9.18, suggesting that the different water regimes had no effect on stem numbers produced and retained at that time. The height of plants were also checked at this time and although there were significant height differences between the crops there was no scenario effect of interactions.

As a measure of grain quality the effect of scenario on thousand grain weight was quantified. There were significant thousand grain weight differences between the crops, which is to be expected, but there were no significant effects of the scenario and no significant interactions, table 9.19.

Table 9.19. Thousand grain weight (g) for the cereal crops in the HAU mesocom experiment for spring planted crops 2015.

	Scenario		
Crop	CEave	DRY	Mean crop
Durum	50.95	49.2	50.08
Quinoa	2.9	2.52	2.71
Spring Barley	47.32	46.77	47.04
Spring Wheat +AT	53.37	51.83	52.6
Spring Wheat -AT	55.23	53.9	54.57
Triticale	46.28	49.07	47.67
Mean Scenarios	42.67	42.21	
	Overall mean		42.44
Crop	*P*	<.001	
Scenario	*P*	0.517	
Crop.Scenario	*P*	0.461	
SE	Crop	Scenario	Interaction
	1.223	0.706	1.73

Harvest index, the fraction of ‘useful’ (grain) plant material relative to the total biomass produced ‘above ground’. There were significant Harvest Index differences between crops with spring barley showing the greatest HI of all crops at 0.62, which is at the upper range of normal. All of the cereals were within the normal range. Quinoa had a significantly low HI but this was largely the result of the extensive above ground canopy growth. There was also a significantly lower HI for the DRY scenario compared to the CEave scenario suggesting that crops in the DRY scenario produced significantly less useful fraction (grain) as a proportion of the total plant production. As no ‘below ground’ production is accounted for however, it is plausible that crops in the DRY scenario invested in greater root production in order to scavenge more soil moisture. There were no significant interactions. Triticale and the spring wheat + AT showed the smallest HI variation between scenarios, table 9.20, suggesting that in the drier scenario these crops continued to produce useful grain.

Table 9.20. Harvest indices from the HAU mesocom experiment 2015 spring planted crops

Harvest index			
	Scenario		
Crop	CEave	DRY	**Mean crop**
Durum	0.50	0.39	0.45
Quinoa	0.05	0.05	0.05
Spring Barley	0.65	0.59	0.62
Spring Wheat +AT	0.39	0.35	0.37
Spring Wheat -AT	0.41	0.33	0.37
Triticale	0.46	0.44	0.45
Mean Scenarios	0.408	0.359	
	Overall mean		0.384
Crop	*P*	<.001	
Scenario	*P*	0.013	
Crop.Scenario	*P*	0.66	
SE	Crop	Scenario	Interaction
	0.03315	0.01914	0.04688

The difference in water application between the CEave and the DRY scenarios are shown, table 9.21.

Table 9.21. Water applied per treatment and scenario (mm) for the spring 2015 planted crops in the HAU mesocom experiment.

Water applied mm	Scenario		
Crop	CEave	DRY	Mean crop
Durum	245	152	198.5
Lucerne	446	324	385
PRG	416	306	361
Quinoa	300	186	243
Spring Barley	193	120	156.5
Spring Wheat +AT	213	132	172.5
Spring Wheat -AT	213	132	172.5
Triticale	245	152	198.5
Mean Scenarios	283.9	188	
	Overall mean		239.5

Table 9.22. Water productivity kg yield per m^3 for the spring planted 2015 crops in the HAU mesocom experiment.

Water productivity kg m3			
	Scenario		
Crop	CEave	DRY	Mean crop
Durum	2.05	2.45	2.25
Quinoa	6.29	8.71	7.5
Spring Barley	3.28	5.1	4.19
Spring Wheat +AT	3.62	3.89	3.75
Spring Wheat -AT	3.25	4.19	3.72
Triticale	3.1	4.98	4.04
Mean Scenarios	3.22	4.38	
	Overall mean		4.24
Crop	*P*	<.001	
Scenario	*P*	0.007	
Crop.Scenario	*P*	0.697	
SE	Crop	Scenario	Interaction
	0.726	0.419	1.027

There were significant differences between crops and between scenarios whereby all crops produced more useful grain per m^3 water used in the DRY scenario, table 9.22.

9.2 Results year 2

Table 9.23. Yield (t/ha) of all crops in the HAU mesocom experiment 2015-2016.

	Scenarios		
Crops	CEAve	Dry	**Mean Crop**
W. Barley	10.52	10.68	10.6
Durum	6.15	4.31	5.23
Lucerne	29.25	27.74	28.5
PRG	9.06	6.47	7.76
Quinoa	2.16	1.87	2.01
W. Triticale	12.45	14.1	12.45
W. Wheat +AT	9.8	9.32	9.8
W. Wheat -AT	15.28	15.87	15.28
Mean Sc.	11.61	11.3	
	Overall mean		**11.45**
Crops	*P =*	<.001	
Scenarios	*P =*	0.613	
Crops.Scenarios	*P =*	0.357	
	Crops	Scenarios	Cr* Sc
s.e.d.	1.259	0.629	1.78

Note: Lucerne & PRG yields t/ha DM, all other crops at 14% MC.

There were significant yield differences between crops but not between scenarios and there were no significant interactions. Winter triticale, winter barley and winter wheat – AT produced greater yields in the DRY scenario, these were not significant increases, table 9.23.

Table 9.24. Thousand grain weight for cereal crops in the HAU mesocom experiment 2015-2016.

	Scenarios		
Crops	CEAve	Dry	**Mean Crop**
Barley	50.83	46.07	48.45
Durum	66.4	64.38	65.39
Quinoa	2.15	2.15	2.15
Triticale	56.8	59.28	58.04
W Wheat +AT	53.57	52.52	53.04
W Wheat -AT	54.45	55.2	15.28
Mean Sc.	47.37	46.6	54.83
	Overall mean		**46.98**
Crops	*P* =	<.001	
Scenarios	*P* =	0.462	
Crops.Scenarios	*P* =	0.446	
	Crops	Scenarios	Cr* Sc
s.e.d.	1.793	1.035	2.536

There were significant differences in grain weight between crops but not between scenarios and there were no interactions. The increase in yield from triticale, table 9.23, could be linked to the increased thousand grain weight, table 9.24, but this would not appear to be the case for barley.

Table 9.25. Individual grain weight (g) for cereal crops in the HAU mesocom experiment 2015-2016.

	Scenarios		
Crops	CEAve	Dry	**Mean Crop**
Barley	0.051	0.046	0.048
Durum	0.066	0.064	0.065
Quinoa	0.002	0.002	0.002
Triticale	0.057	0.059	0.058
W Wheat +AT	0.054	0.053	0.053
W Wheat -AT	0.054	0.055	0.055
Mean Sc.	0.047	0.047	
	Overall mean		**0.047**
Crops	*P* =	<.001	
Scenarios	*P* =	0.462	
Crops.Scenarios	*P* =	0.446	
	Crops	Scenarios	Cr* Sc
s.e.d.	0.001793	0.001035	0.002536

There were significant differences between crops but not between scenarios and there were no significant interactions, table 9.25.

Table 9.26. Total biomass (t/ha) for cereal crops in the HAU mesocom experiment 2015-2016.

Biom tha	**Scenarios**		
Crops	CEAve	Dry	**Mean Crop**
Barley	24.3	25.2	24.7
Durum	13.2	9.6	11.4
Quinoa	45.4	59.3	52.3
Triticale	23.5	34.2	28.9
W Wheat +AT	19.9	18.8	19.4
W Wheat -AT	26.3	28.4	27.3
Mean Sc.	25.4	29.2	
	Overall mean		**27.300**
Crops	*P =*	<.001	
Scenarios	*P =*	0.28	
Crops.Scenarios	*P =*	0.66	
	Crops	Scenarios	Cr* Sc
s.e.d.	6.05	3.49	8.55

There were significant crop differences but there were no significant differences between scenarios and no significant interactions, table 9.26.

Table 9.27. Water productivity for cereal crops in the HAU mesocom experiment 2015-2016

WP kg m3	**Scenarios**		
Crops	CEAve	Dry	**Mean Crop**
Barley	2.355	2.78	2.568
Durum	2.761	3.05	2.905
Quinoa	0.704	0.952	0.828
Triticale	2.243	3.491	2.867
W Wheat +AT	2.121	2.295	2.208
W Wheat -AT	3.032	3.909	3.47
Mean Sc.	2.203	2.746	
	Overall mean		**2.474**
Crops	*P =*	<.001	
Scenarios	*P =*	<.001	
Crops.Scenarios	*P =*	0.282	
	Crops	Scenarios	Cr* Sc
s.e.d.	0.2658	0.1535	0.3759

There were significant differences between the water productivity of the crops and also a significantly greater water productivity from crops in the DRY scenario. There were no significant interactions, table 9.27

Table 9.28. Leaf area of flag leaf (cm2) on 14th June 2016 for cereal crops in the HAU mesocom experiment 2015-2016.

Leaf area cm2	**Scenarios**		
Crops	CEAve	Dry	**Mean Crop**
Barley	9.71	9.42	9.56
Durum	18.15	15.78	16.96
Triticale	10.14	8.7	9.42
W Wheat +AT	19.82	13.39	16.61
W Wheat -AT	20.16	14.01	17.09
Mean Sc.	15.59	12.26	
	Overall mean		**13.930**
Crops	*P =*	<.001	
Scenarios	*P =*	0.002	
Crops.Scenarios	*P =*	0.226	
	Crops	Scenarios	Cr* Sc
s.e.d.	1.632	1.032	2.308

The leaf area of the flag leaves were significantly different between crops and also between scenarios, where the DRY scenario produced substantially reduced leaf areas in most crops. There were no significant interactions, table 9.28.

Table 9.29. Height of plants (cm) on 14th June 2016 for cereal crops in the HAU mesocom experiment 2015-2016

Ht cm	**Scenarios**		
Crops	CEAve	Dry	**Mean Crop**
Barley	67.57	68.17	67.87
Durum	60.5	57.58	59.04
Triticale	93.43	96.68	95.06
W Wheat +AT	60.8	61.27	61.03
W Wheat -AT	68.05	70.47	69.26
Mean Sc.	70.07	70.83	
	Overall mean		**70.450**
Crops	*P =*	<.001	
Scenarios	*P =*	0.604	
Crops.Scenarios	*P =*	0.716	
	Crops	Scenarios	Cr* Sc
s.e.d.	2.313	1.463	3.271

There were significant differences of plant height but there were no significant effects of scenario and no significant interactions, table 9.29

Table 9.30. Number of ears m^2 on 14th June 2016 for cereal crops in the HAU mesocom experiment 2015-2016

Ears m2	Scenarios		
Crops	CEAve	Dry	**Mean Crop**
Barley	635	607	621
Durum	425	395	410
Triticale	525	678	602
W Wheat +AT	526	507	516
W Wheat -AT	662	673	667
Mean Sc.	554	572	
	Overall mean		**563.0**
Crops	*P* =	<.001	
Scenarios	*P* =	0.402	
Crops.Scenarios	*P* =	0.037	
	Crops	Scenarios	Cr* Sc
s.e.d.	32.9	20.8	46.5

The number of ears m^2 were significantly different between crops but there were no differences due to scenario. There was a significant interaction however, whereby triticale produced significantly more ears in the DRY scenario in contrast to durum which produced significantly less ears in that scenario, table 9.30.

Soil moisture deficits during 2015-2016:

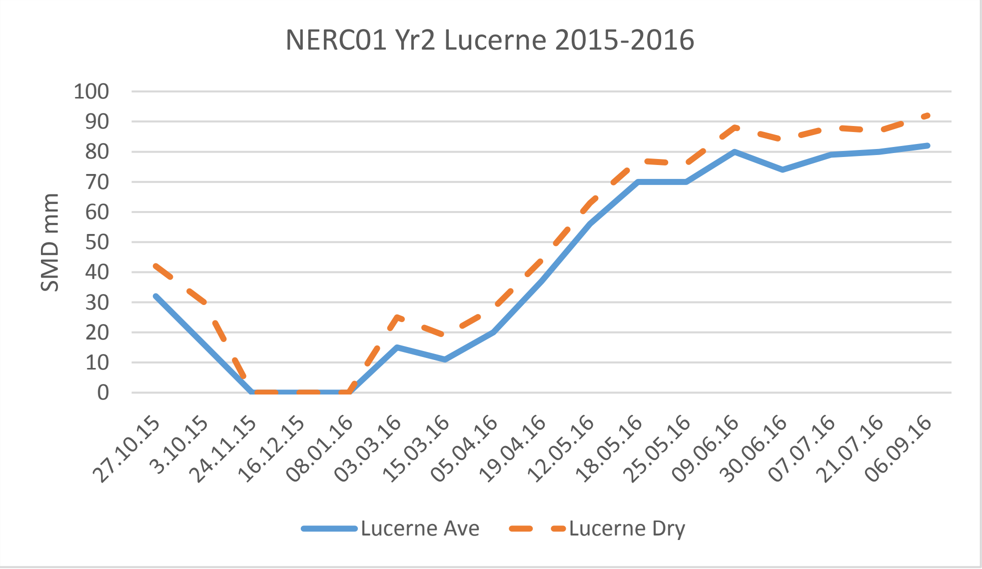

Figure 9.6. Soil moisture deficit progression for the lucerne crop from 27th October 2015 to 6th September 2016. Perennial crop, no terminal harvest date.

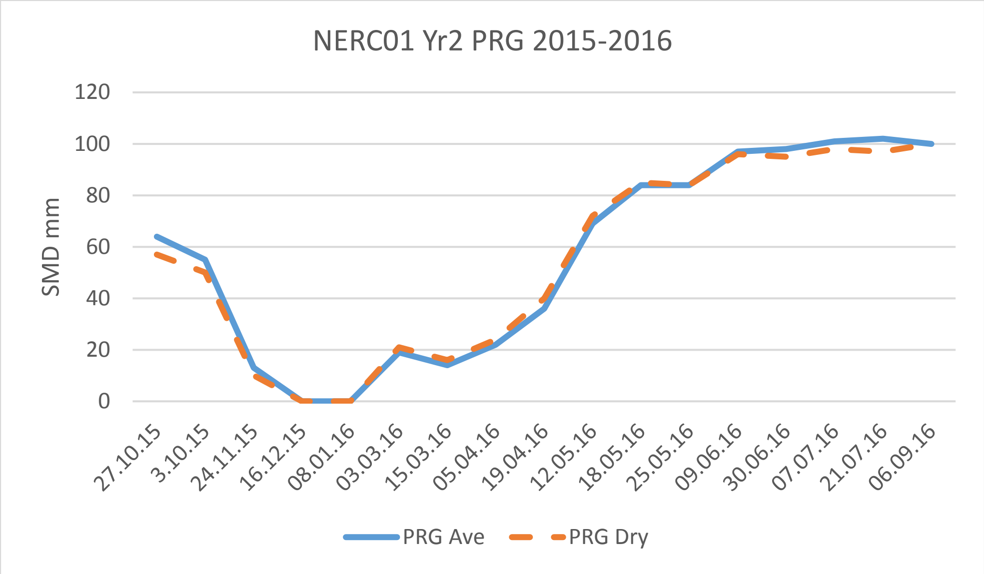

Figure 9.7. Soil moisture deficit progression for the perennial ryegrass crop from 27th October 2015 to 6th September 2016. Perennial crop, no terminal harvest date.

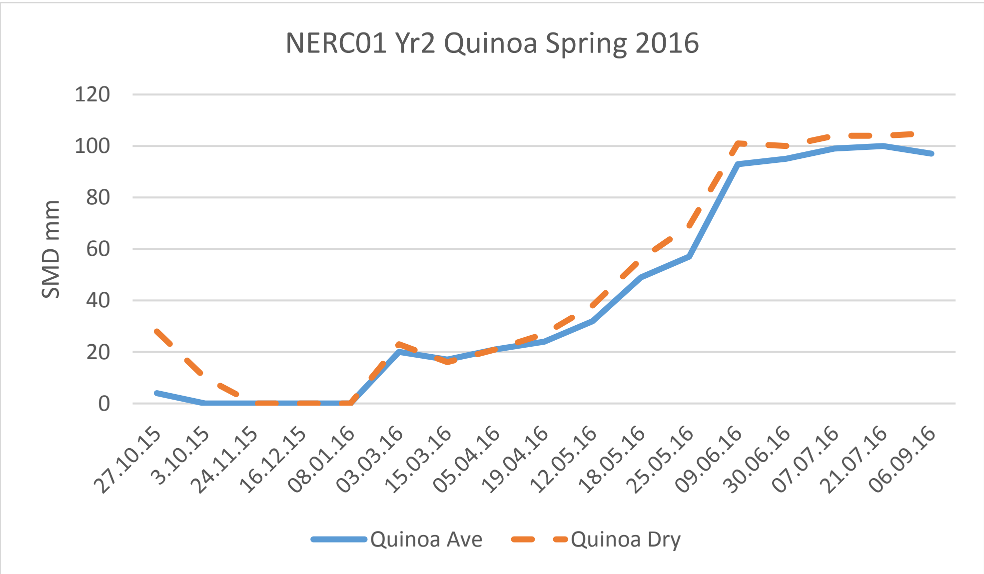

Figure 9.8. Soil moisture deficit progression for the quinoa crop from 27th October 2015 to 6th September 2016. Crop harvested 6th September 2016

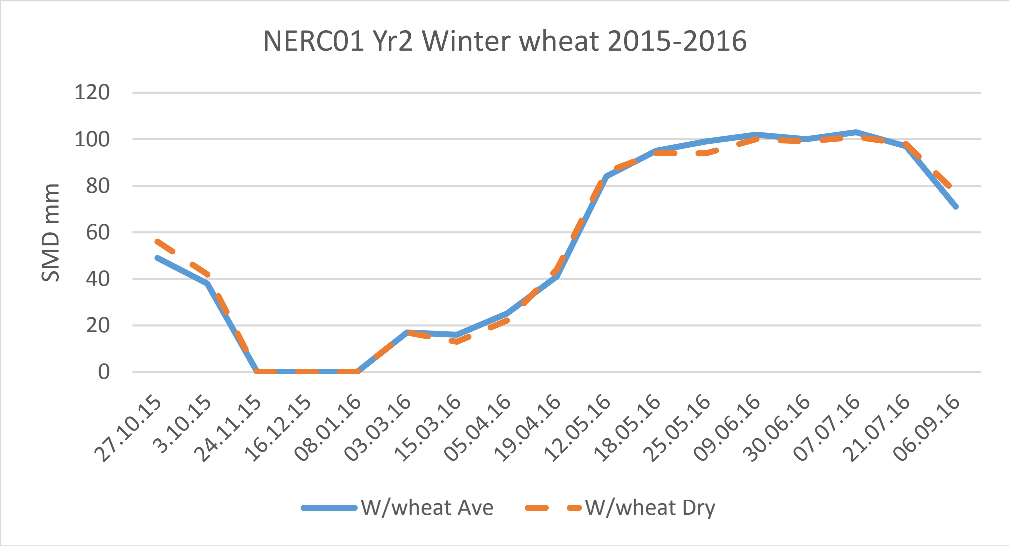

Figure 9.9. Soil moisture deficit progression for the winter wheat (-AT) crop from 27th October 2015 to 6th September 2016. Crop harvested 26th July 2016

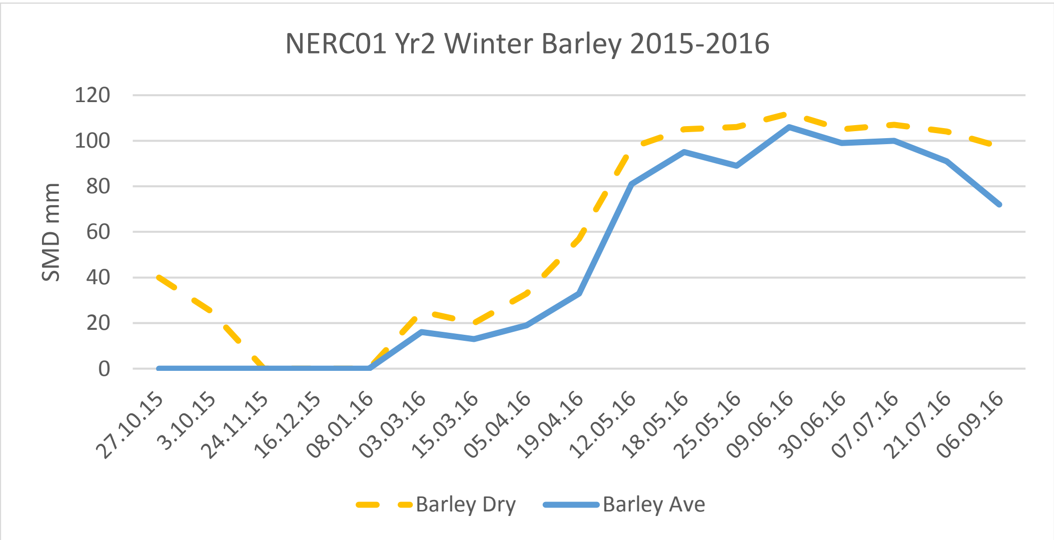

Figure 9.10. Soil moisture deficit progression for the winter barley crop from 27th October 2015 to 6th September 2016. Crop harvested 5th July 2015

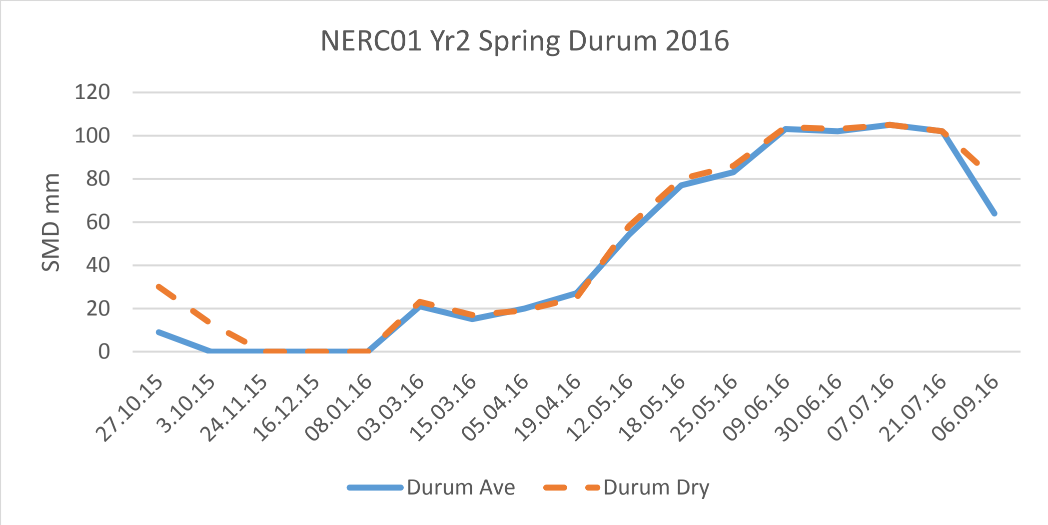

Figure 9.11. Soil moisture deficit progression for the spring durum crop from 27th October 2015 to 6th September 2016. Crop harvested 27th July 2016.

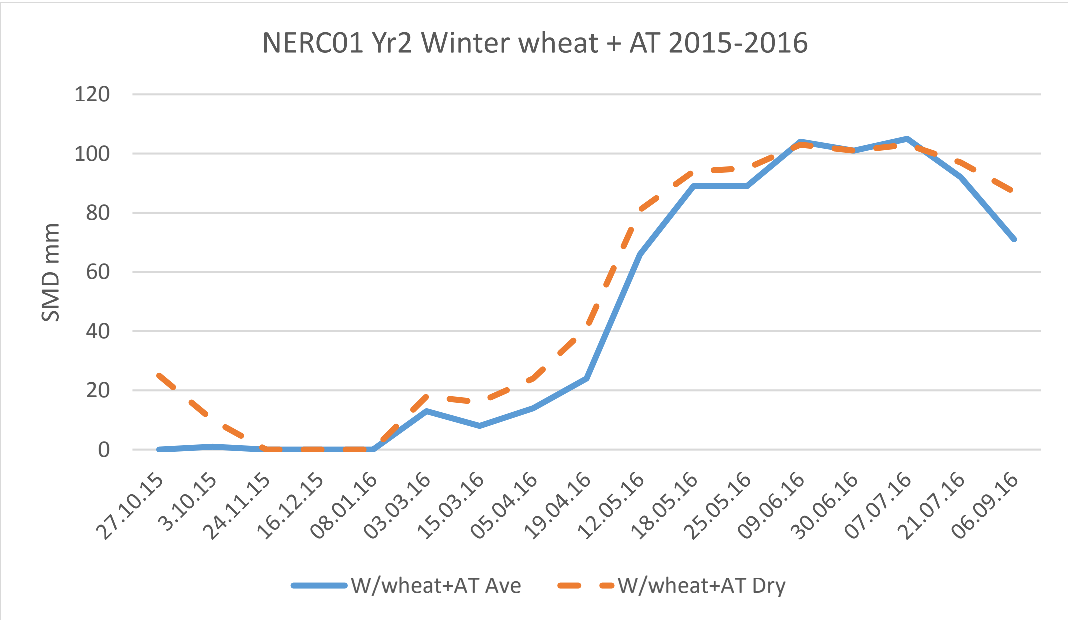

Figure 9.12. Soil moisture deficit progression for the winter wheat (+AT) crop from 27th October 2015 to 6th September 2016. Crop harvested 26th July 2016

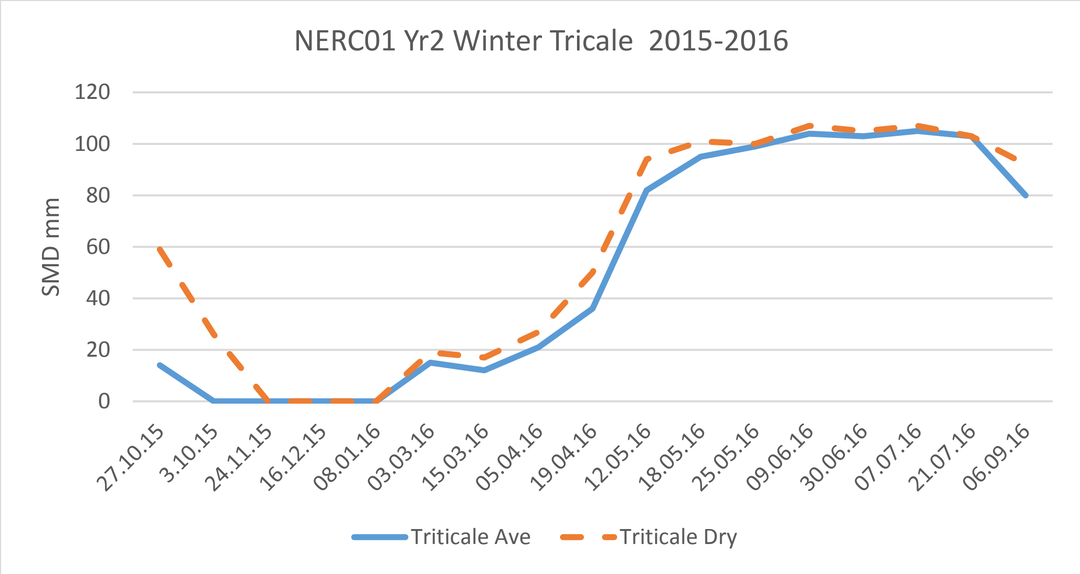

Figure 9.13. Soil moisture deficit progression for the winter triticale crop from 27th October 2015 to 6th September 2016. Crop harvested 25th July 2016

Table 9.31. Soil moisture deficits (mm) in the HAU mesocosm experiment at 30th June 2016

SMD 30/06/16	Scenarios		
Crops	**CEAve**	**Dry**	**Mean Crop**
Barley	99.17	104.8	102.0
Durum	102	102.5	102.3
Lucerne	73.83	84.3	79.1
PRG	98.33	95.3	96.8
Quinoa	94.67	100.0	97.3
Triticale	102.67	104.5	103.6
W Wheat +AT	100.5	100.6	100.6
W Wheat -AT	99.5	98.5	99.0
Mean Sc.	96.33	98.8	
	Overall mean		**97.6**
Crops	*P* =	<.001	
Scenarios	*P* =	0.144	
Crops.Scenarios	*P* =	0.449	
	Crops	Scenarios	Cr* Sc
s.e.d.	3.124	1.562	4.417

Soil moisture deficits on the 30th June 2016, when only quinoa, PRG and lucerne remained growing as other crops were harvested, showed a significantly lower SMD for lucerne than any other crop, achieving a mean of only 79mm. There were no significant scenario differences or interactions, table 9.31.

Most of the cereal crop mesocosms in the CEave scenario had returned back to FC by early October 2015 whereas those in the DRY scenario did not achieve FC until late November 2015. This was similar for the lucerne mesocosms but not for the PRG which did not return to FC until mid-December. FC was then maintained until mid-February 2016 when the polytunnels were re-covered. However during this period a problem with the soil moisture probe was detected and a new sensor was fitted. After recalibration the sensor gave a higher reading in all mesocosms leading to a small deficit. As the readings are relative rather than absolute the measurements were continued with the higher readings. From mid-March SMDs developed up to a maximum of 100mm, approximately 15mm greater than in 2015 but following the same patterns. Once the wheat, barley, triticale and durum wheat crops were harvested in July 2016 the SMD reduced with those of the CEave scenario reducing more quickly. The SMDs in the lucerne, PRG and quinoa mesocosms contained to increase until the last measurement of that season on 6th sept 2016, figures 9.6 - 9.13, table 9.31.

Table 9.32. Soil moisture deficits (mm) in the HAU mesocosm experiment at 21st September 2016

SMD 21/09/16	**Scenarios**		
Crops	**CEAve**	**Dry**	**Mean Crop**
Barley	55.1	89.7	72.4
Durum	47.7	69.1	58.4
Lucerne	81.7	91.6	86.6
PRG	105.9	102.7	104.3
Quinoa	86.3	100.7	93.5
Triticale	60.5	83.2	71.8
W Wheat +AT	50.6	76.9	63.8
W Wheat -AT	55.5	64.1	59.8
Mean Sc.	67.9	84.8	
	Overall mean		**76.3**
Crops	*P* =	<0.001	
Scenarios	*P* =	<0.001	
Crops.Scenarios	*P* =	0.022	
	Crops	Scenarios	Cr* Sc
s.e.d.	5.28	2.64	7.47

The later season SMDs showed significant crop effects. PRG maintained the greatest SMD of 104mm which was only similar to quinoa at harvest on the 6th September. Lucerne SMD was significantly lower than PRG at this time. There was also a significantly greater SMD in the DRY scenario and a significant interaction, table 9.32..

9.3 Results year 3

Table 9.33. Crop yield in the HAU mesocom experiment 2016-2017

Yield t/ha	Scenarios		
Crops	CEAve	Dry	**Mean Crop**
Barley	12.92	12.57	**12.75**
Durum	4.13	3.7	**3.92**
Lucerne	38.33	36.87	**37.6**
PRG	10.74	9.36	**10.05**
Quinoa	6.48	6.95	**6.72**
Triticale	10.85	11.06	**10.96**
W Wheat +AT	11.24	12.79	**12.02**
W Wheat -AT	17.26	16.28	**16.77**
Mean Sc.	13.99	13.7	
	Overall mean		**13.85**
Crops	*P* =	<.001	
Scenarios	*P* =	0.688	
Crops.Scenarios	*P* =	0.972	
	Crops	Scenarios	Cr* Sc
s.e.d.	1.458	0.729	2.062

There were significant differences in yield between crops, as would be expected, but no significant effect of the scenario and no significant interaction, table 9.33

Table 9.34. Water productivity (kg ha per m^3 water applied ha) for all crops in the HAU mesocom experiment 2016-2017

WP kg m3	Scenarios		
Crops	CEAve	Dry	**Mean Crop**
Barley	3.023	3.202	3.113
Durum	2.154	3.452	2.803
Lucerne	8.655	11.095	9.875
PRG	2.425	2.816	2.62
Quinoa	2.031	3.398	2.715
Triticale	2.291	2.636	2.463
W Wheat +AT	2.373	3.049	2.711
W Wheat -AT	3.643	3.879	3.761
Mean Sc.	3.325	4.191	
	Overall mean		**3.76**
Crops	*P* =	<0.001	
Scenarios	*P* =	<0.001	
Crops.Scenarios	*P* =	0.058	
	Crops	Scenarios	Cr* Sc
s.e.d.	1.458	0.729	2.062

There were significant differences of water productivity between crops with Lucerne showing the greatest amount of dry matter production per ha per m^3 water applied. Crops grown in the DRY scenario also produced significantly greater quantities of crop per m^3 water than crops in the CEave scenario. There was no significant interaction between crop and scenario, P = 0.058, table 9.34.

Table 9.35. Cereal crop yield in the HAU mesocom experiment 2016-2017

Yield t/ha	**Scenarios**		
Crops	CEAve	Dry	**Mean Crop**
Barley	12.92	12.57	12.75
Durum	4.13	3.7	3.92
Quinoa	6.48	6.95	6.72
Triticale	10.85	11.06	10.96
W Wheat +AT	11.24	12.79	12.02
W Wheat -AT	17.26	16.28	16.77
Mean Sc.	10.48	10.56	
	Overall mean		**10.52**
Crops	*P* =	<.001	
Scenarios	*P* =	0.903	
Crops.Scenarios	*P* =	0.912	
	Crops	Scenarios	Cr* Sc
s.e.d.	1.145	0.661	1.619

There were significant differences between the mean yields of crops with Winter wheat – AT showing a significantly greater yield than all other crops. There was no significant scenario affect, table 9.35.

Table 9.36. Harvest Index for cereals in the HAU mesocom experiment 2016-2017

HI	**Scenarios**		
Crops	CEAve	Dry	**Mean Crop**
Barley	0.5834	0.5173	0.5504
Durum	0.3252	0.3506	0.3379
Quinoa	0.0353	0.0584	0.0469
Triticale	0.4109	0.3862	0.3986
W Wheat +AT	0.4612	0.4575	0.4593
W Wheat -AT	0.4518	0.4297	0.4407
Mean Sc.	0.378	0.3666	
	Overall mean		0.3723
Crops	*P* =	<.001	
Scenarios	*P* =	0.22	
Crops.Scenarios	*P* =	0.054	
	Crops	Scenarios	Cr* Sc
s.e.d.	0.01587	0.00916	0.02244

There were significant harvest index (HI) differences between crops but not between scenarios. The interactions were close to significance, P = 0.55, where Durum and quinoa gave a higher HI in the DRY scenario than in the CEave scenario, table 9.36.

Table 9.37. Ears m^2 in the HAU mesocom experiment 2016-2017

Ears m2	**Scenarios**		
Crops	CEAve	Dry	**Mean Crop**
Barley	601	687	644
Durum	397	384	391
Quinoa	59	52	56
Triticale	606	649	628
W Wheat +AT	524	550	537
W Wheat -AT	666	669	667
Mean Sc.	475	499	
	Overall mean		**487**
Crops	*P =*	<.001	
Scenarios	*P =*	0.096	
Crops.Scenarios	*P =*	0.305	
	Crops	Scenarios	Cr* Sc
s.e.d.	23.8	13.7	33.6

There were significant variation of the number of ears m^2 between crops with quinoa having substantially less ears (heads). This is normal as the growth habit of quinoa is substantially different to the other cereals grown. There was no difference between scenarios and no interactions, table 9.37.

However, as grain yield is influenced by ear number m^2 in cereals the use of ears m^2 were investigated as a covariate, table 9.38.

When the yield of cereals were analysed with ears m^2 as a covariate the covariate effect was shown to be highly significant. The overall effect was to normalise the crop yields as can be seen in table 9.38.

Table 9.38. Cereal crop yield analysed with ears per m^2 as covariate in the HAU mesocom experiment 2016-2017

Yield t/ha	**Scenarios**		
Crops	CEAve	Dry	**Mean Crop**
Barley	10.31	8	9.16
Durum	6.19	6.05	6.12
Quinoa	16.25	16.89	16.57
Triticale	8.14	7.35	7.74
W Wheat +AT	10.41	11.36	10.88
W Wheat -AT	13.17	12.12	12.65
Mean Sc.	10.75	10.3	
	Overall mean		**10.52**
Crops	*P* =	<.001	
Scenarios	*P* =	0.51	
Crops.Scenarios	*P* =	0.654	
Covariate	*P* =	< 0.001	
	Crops	Scenarios	Cr* Sc
s.e.d.	2.167	0.602	2.33

Table 9.39. TGW for the cereal crops in the HAU mesocom experiment 2016-2017

TGW (g)	**Scenarios**		
Crops	CEAve	Dry	**Mean Crop**
Barley	41.37	41.05	41.21
Durum	55.83	58.42	57.13
Quinoa	3.38	3.43	3.41
Triticale	49.15	45.52	47.33
W Wheat +AT	44.37	45.37	44.87
W Wheat -AT	48.3	46.6	47.45
Mean Sc.	40.4	40.06	
	Overall mean		**40.23**
Crops	*P* =	<.001	
Scenarios	*P* =	0.766	
Crops.Scenarios	*P* =	0.689	
	Crops	Scenarios	Cr* Sc
s.e.d.	1.943	1.122	2.747

There were significant differences of TGW between crops but no significant scenario effects or interactions, table 9.39.

There were significant flag (main) leaf area differences between crops, with barley having the least and quinoa the greatest. There were no effects of the scenarios and no interactions, table 9.40.

Table 9.40. Flag leaf area (cm^2) on 24th May 2017 in the HAU mesocom experiment 2016-2017

Flag leaf cm2	**Scenarios**			
Crops	CEAve		Dry	**Mean Crop**
Barley	6.5		6.6	6.6
Durum	21.1		22.4	21.8
Quinoa	27.8		32	29.9
Triticale	15.3		17.7	16.5
W Wheat +AT	19.7		22.9	21.3
W Wheat -AT	19.8		21.1	20.4
Mean Sc.	18.4		20.5	
	Overall mean			**19.4**
Crops	*P* =	<.001		
Scenarios	*P* =	0.321		
Crops.Scenarios	*P* =	0.994		
	Crops	Scenarios		Cr* Sc
s.e.d.	3.56	2.06		5.04

There were significant differences between crops with quinoa giving the highest NDVI in comparison to triticale which produced significantly less. There were no significant effects from the rainfall scenarios and no significant interactions, table 9.41.

Table 9.41. NDVI as measured with a hand-held green-seeker on 24th May 2017 in the HAU mesocom experiment 2016-2017

NDVI	**Scenarios**		
Crops	CEAve	Dry	**Mean Crop**
Barley	0.4083	0.4767	0.4425
Durum	0.48	0.45	0.465
Quinoa	0.6067	0.52	0.5633
Triticale	0.385	0.35	0.3675
W Wheat +AT	0.46	0.4417	0.4508
W Wheat -AT	0.4567	0.4533	0.455
Mean Sc.	0.4661	0.4486	
	Overall mean		**0.4574**
Crops	*P* =	<.001	
Scenarios	*P* =	0.368	
Crops.Scenarios	*P* =	0.346	
	Crops	Scenarios	Cr* Sc
s.e.d.	0.03339	0.01928	0.04722

There were significant differences in plant height, as would be expected from the varied range of crops. There were no significant effects of rainfall scenario and no significant interactions, table 9.42.

Table 9.42. Plant height (cm) on 24th May 2017 in the HAU mesocom experiment 2016-2017

Ht (cm)	Scenarios		
Crops	CEAve	Dry	**Mean Crop**
Barley	80.5	77	78.8
Durum	69.2	70.7	69.9
Quinoa	98	87.3	92.7
Triticale	96.5	94.2	95.3
W Wheat +AT	77.2	80.8	79
W Wheat -AT	86.5	83.7	85.1
Mean Sc.	84.6	82.3	
	Overall mean		**83.5**
Crops	*P* =	<.001	
Scenarios	*P* =	0.269	
Crops.Scenarios	*P* =	0.484	
	Crops	Scenarios	Cr* Sc
s.e.d.	3.67	2.12	5.18

The soil moisture deficits after harvest of the cereal crops showed significant crop differences with PRG having the greatest SMD which was substantially greater than the other forage crop lucerne. Quinoa, durum wheat and winter wheat also showed very high SMDs, substantially greater than those of triticale and barley. The DRY scenario was also significantly drier than the CEave scenario, and there were significant interactions, table 9.43

Table 9.43. Soil moisture deficits (mm) at after harvest of all cereal crops, 10th August 2017.

SMD 10/08/17	Scenarios		
Crops	CEAve	Dry	**Mean Crop**
Barley	50.3	119.3	84.8
Durum	92.2	115	103.6
Lucerne	80.5	94.7	87.6
PRG	125	121	123
Quinoa	117.8	113	115.4
Triticale	70.8	112.7	91.8
W Wheat +AT	95.7	124	109.8
W Wheat -AT	103	119.7	111.3
Mean Sc.	**91.9**	**114.9**	
	Overall mean		**103.4**
Crops	*P* =	<0.001	
Scenarios	*P* =	<0.001	
Crops.Scenarios	*P* =	<0.001	
	Crops	Scenarios	Cr* Sc
s.e.d.	6.99	3.49	9.88

Soil moisture deficits through the 2016 – 2017 growing season

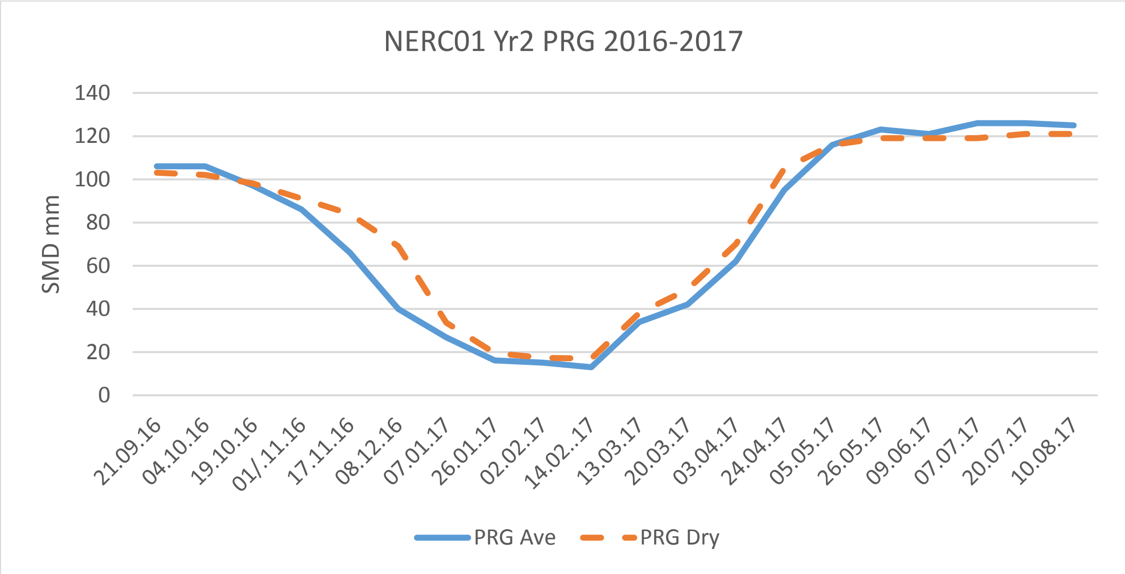

Figure 9.14. Soil moisture deficit progression for the perennial ryegrass crop from 21st September 2016 to 10th August 2017. Final harvest date 14th September 2017

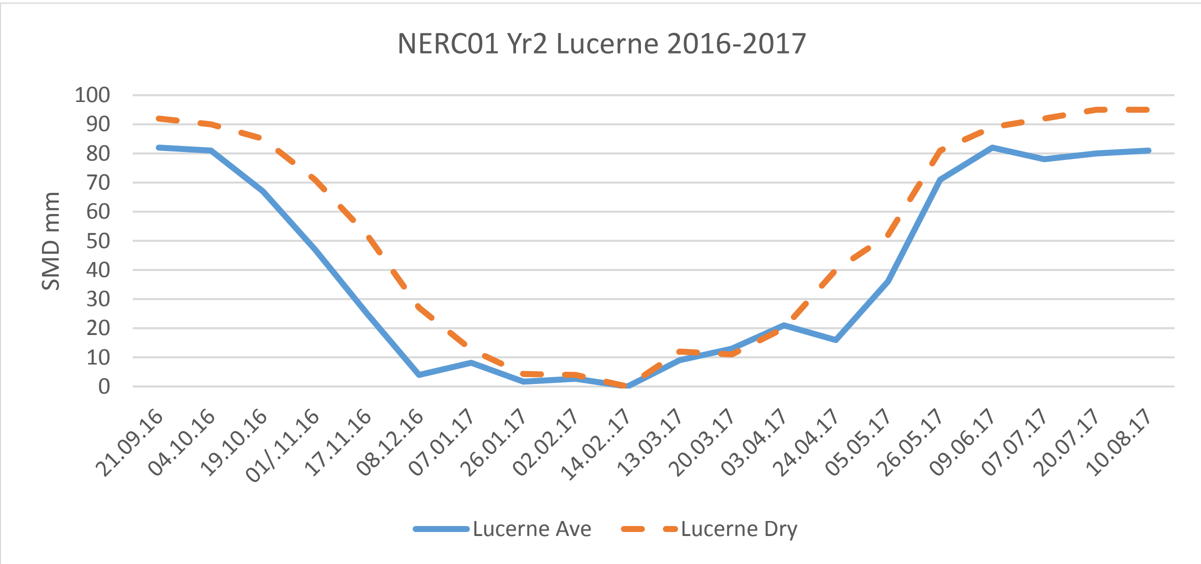

Figure 9.15. Soil moisture deficit progression for the perennial lucerne crop from 21st September 2016 to 10th August 2017. Final harvest date 14th September 2017.

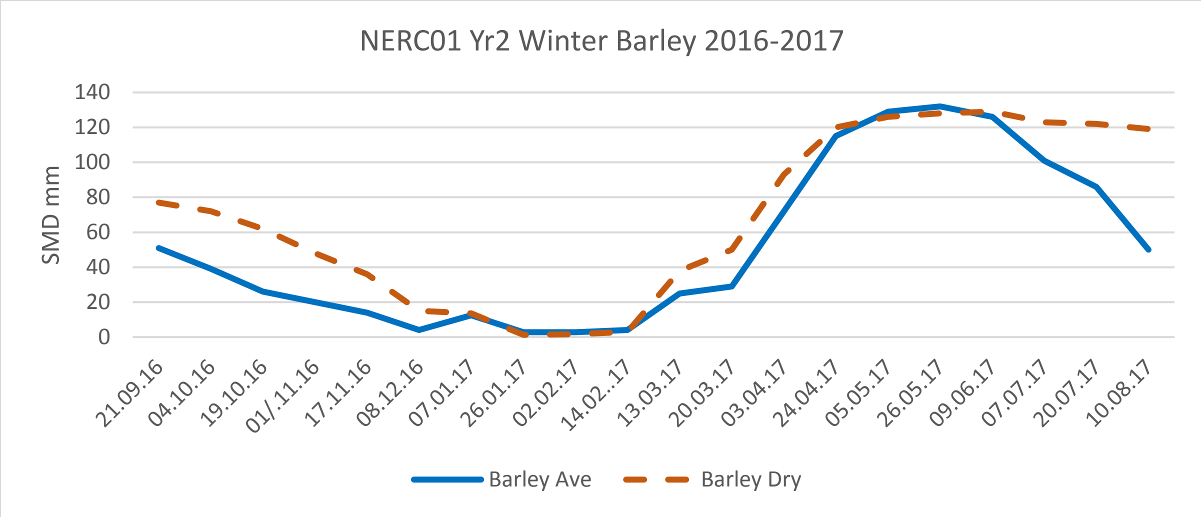

Figure 9.16. Soil moisture deficit progression for the winter barley crop from 21st September 2016 to 10th August 2017. Harvest date 15th June 2017

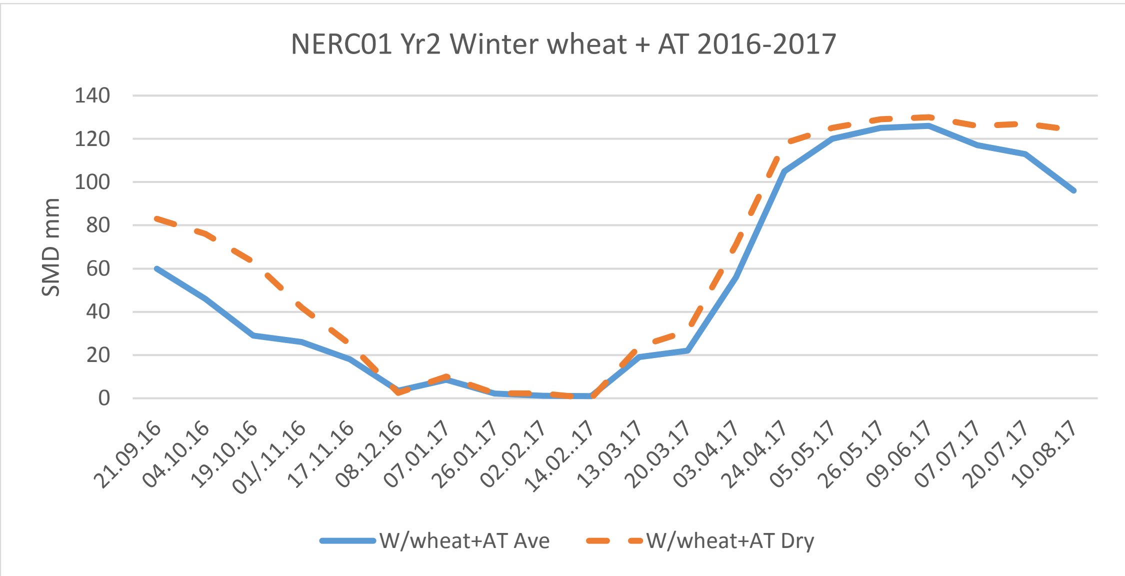

Figure 9.17. Soil moisture deficit progression for the winter wheat crop from 21st September 2016 to 10th August 2017. Harvest date 11th July 2017.

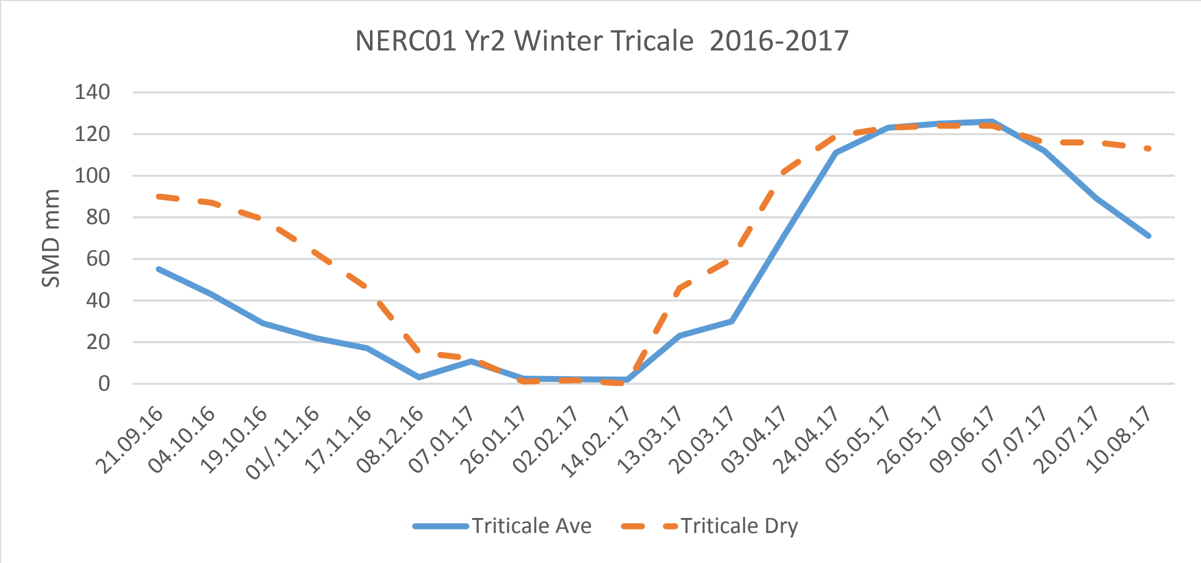

Figure 9.18. Soil moisture deficit progression for the winter triticale crop from 21st September 2016 to 10th August 2017. Harvest date 11th July 2017.

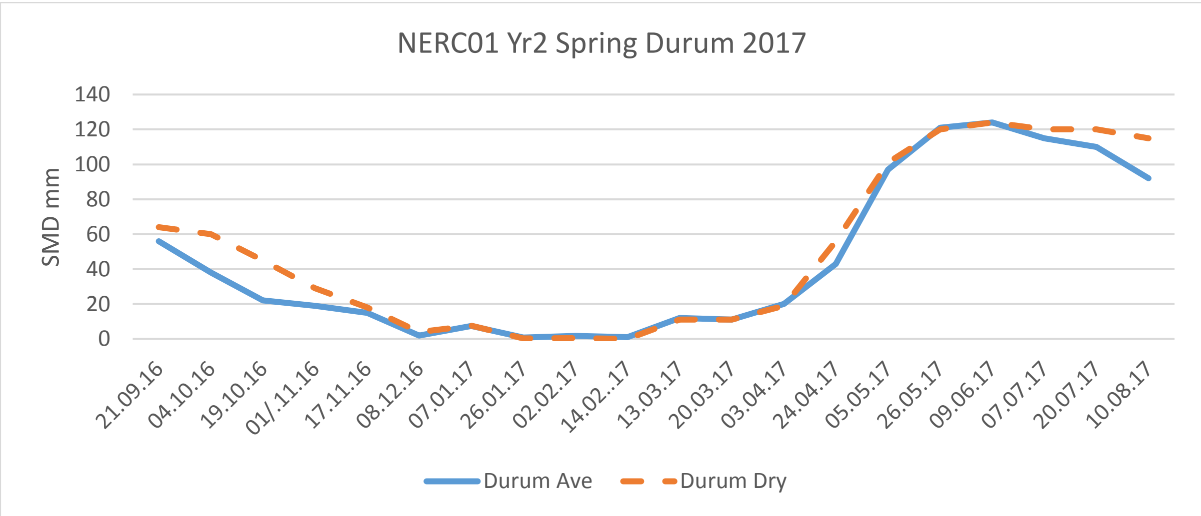

Figure 9.19. Soil moisture deficit progression for the winter wheat crop from 21st September 2016 to 10th August 2017. Harvest date 11th July 2017.

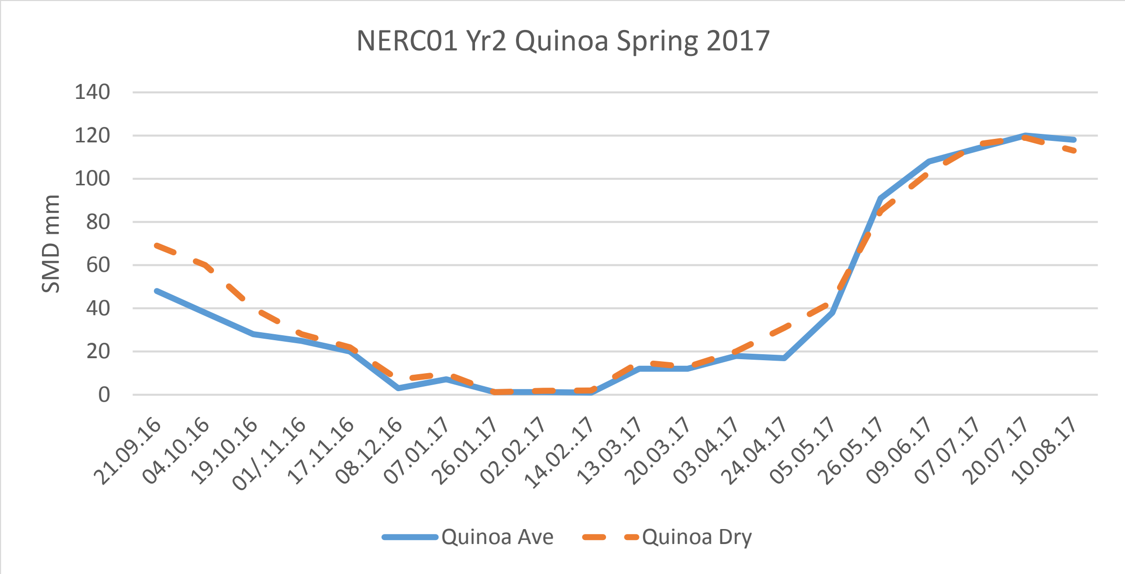

Figure 9.20. Soil moisture deficit progression for the quinoa crop from 21st September 2016 to 10th August 2017. Harvest date 14th September 2017.

Figures 9.14 – 9.20 show the progression of soil moisture deficits in the mesocosm experiments at HAU from 21st September to 10th August 2017. The cereal crops and lucerne show a return back to FC by late December even in the DRY scenario. It should be noted however that this scenario does include a small increase in rainfall over the average CEave scenario in the climate change projection. It can be envisaged however that if the climate DRY climate projections were to become more severe then a return to FC by springtime may not occur and the consequences for the next season could be similarly severe. The only exception to this trend was the PRG which never returned to FC, figure 9.14 and followed this with an exceptionally high SMD in the following August of 2017. Unexpectedly, the spring sown crops of quinoa and durum wheat both reached substantial SMDs similar to those within the winter sown crops of triticale, wheat and barley. Although the soil moisture deficits for both scenarios are very similar in figures 9.14 – 9.20 the effect on the crops was still important.

Rotational Effects

Abbreviations for the two rotations applied in the two scenarios as described in tables 8.2 and 8.3.

Two basic rotations: 1) Wheat+ AT, barley and triticale, or 2) wheat-AT, durum, quinoa. Used in both scenarios.

Table 9.44 Crops and rotational positions in both CEave and DRY scenarios.

Year 1	**S. wheat AT**	**S. wheat**	**S Barley**	**Durum (S)**	**S Triticale**	**Quinoa (S)**	**PRG**	**Lucerne**
Year 2	**W Barley**	**Durum (S)**	**W Triticale**	**Quinoa (S)**	**W wheat AT**	**W wheat**	**PRG**	**Lucerne**
Year 3	**W Triticale**	**Quinoa (S)**	**W wheat AT**	**W wheat**	**W Barley**	**Durum (S)**	**PRG**	**Lucerne**

Table 9.45.Water productivity (kg ha per m^3 water applied ha) for rotations in the HAU mesocom experiment 2016-2017

WP kg m3	Scenarios		
Rotations	CEAve	Dry	**Mean Rotation**
D Q WW-AT	66.3	56.8	3.761
Lucerne	81.8	112.8	9.875
PRG	75.3	111	2.62
Q WW-AT D	61.3	54.7	2.803
SB WT WWAT	102	171.5	2.711
ST WWAT WB	65.3	71.5	3.113
SW-AT D Q	76.7	76.2	2.715
SWAT WB WT	122.7	157	2.463
Mean Sc.	3.325	4.191	
	Overall mean		**3.76**
Rotations	*P* =	<0.001	
Scenarios	*P* =	< 0.001	
Rotation * Scenarios	*P* =	0.058	
	Rotations	Scenarios	Rotation* Scenario
s.e.d.	0.3862	0.1931	0.5462

Water productivity was significantly affected by rotation where Lucerne and Durum/Quinoa/Winter wheat-AT gave significantly greater productivity (kg) per m^3 water applied. Similarly the DRY scenario also provided a greater water productivity across the rotation than the CEave scenario, table 9.45.

Table 9.46.Soil organic matter percentage after harvest of the 2016-2017 crops in the HAU mesocosm experiment

OM%	Scenarios		
Rotations	CEAve	Dry	**Mean Rotation**
D Q WW-AT	3.1	2.633	2.867
Lucerne	2.683	2.983	2.833
PRG	3.633	3.017	3.325
Q WW-AT D	2.467	2.933	2.7
SB WT WWAT	2.617	2.917	2.767
ST WWAT WB	3.15	3	3.075
SW-AT D Q	2.833	2.5	2.667
SWAT WB WT	2.6	2.983	2.792
Mean Sc.	2.885	2.871	
	Overall mean		**2.88**
Rotations	*P* =	0.245	
Scenarios	*P* =	0.914	
Rot* Scen	*P* =	0.28	
	Rotations	Scenarios	Rotation* Scenario
s.e.d.	0.2684	0.1342	0.3796

Soil organic matter percentage was not significantly influenced by the crop rotation or the rainfall scenarios, table 9.46

Soil pH was significantly affected by the rotation used in the experiment and the scenario affect was close to significance, *P* = 0.055, where it appeared to be reduced within the DRY scenario. There were no interactions, table 9.47.

Table 9.47.Soil pH after harvest of the 2016-2017 crops in the HAU mesocosm experiment

Soil pH	**Scenarios**		
Rotations	**CEAve**	**Dry**	**Mean Rotation**
D Q WW-AT	6.567	6.283	6.008
Lucerne	5.967	5.867	6.392
PRG	6.4	6.383	6.2
Q WW-AT D	6.133	6.267	5.917
SB WT WWAT	6.333	6.183	6.325
ST WWAT WB	6.533	6.133	6.425
SW-AT D Q	6.617	6.033	6.317
SWAT WB WT	5.983	6.033	6.148
Mean Sc.	**6.317**	**6.148**	
	Overall mean		**6.23**
Rotations	*P* =	0.041	
Scenarios	*P* =	0.055	
Rotation * Scen.	*P* =	0.459	
	Rotations	Scenarios	Rotation* Scenario
s.e.d.	0.1728	0.0864	0.2444

Crop rotation significantly affected the soil K content (mg/l) over the 3 crop seasons whereby the soil under the Spring barley/Winter triticale/WW+AT rotation contained significantly more K than any other rotation. The soil in the quinoa/Winter wheat-AT/durum rotation retained significantly less K than lucerne and the Spring wheat+AT/winter barley/winter triticale rotation. The DRY rainfall scenario also showed a significantly greater quantity of soil K than the CEave scenario, table 9.48

Rotation also significantly affected the soil P status with the perennial crops of lucerne and PRG having the lowest soil P content and the quinoa//winter wheat-AT/durum rotation having the greatest soil P content. There were no significant effects of the rainfall scenarios, table 9.49.

Table 9.48.Soil K mg/l after harvest of the 2016-2017 crops in the HAU mesocosm experiment

K mg/l	Scenarios		
Rotations	CEAve	Dry	**Mean Rotation**
D Q WW-AT	66.3	56.8	61.6
Lucerne	81.8	112.8	97.3
PRG	75.3	111	93.2
Q WW-AT D	61.3	54.7	58
SB WT WWAT	102	171.5	136.8
ST WWAT WB	65.3	71.5	68.4
SW-AT D Q	76.7	76.2	76.4
SWAT WB WT	122.7	157	139.8
Mean Sc.	81.4	101.4	
	Overall mean		**91.40**
Rotations	*P* =	< 0.001	
Scenarios	*P* =	0.017	
Rotation * Scen.	*P* =	0.228	
	Rotations	Scenarios	Rotation* Scenario
s.e.d.	16.46	8.23	23.27

Table 9.49.Soil P mg/l after harvest of the 2016-2017 crops in the HAU mesocosm experiment

P mg/l	Scenarios		
Rotations	CEAve	Dry	**Mean Rotation**
D Q WW-AT	47.03	50.43	48.73
Lucerne	43.9	41.5	42.7
PRG	43.73	42.87	43.3
Q WW-AT D	48.3	52.6	50.45
SB WT WWAT	46.9	46.27	46.58
ST WWAT WB	43.1	44.8	43.95
SW-AT D Q	46.93	52.57	49.75
SWAT WB WT	44.1	46.87	45.48
Mean Sc.	45.5	47.24	
	Overall mean		**46.37**
Rotations	*P* =	< 0.001	
Scenarios	*P* =	0.092	
Rotation * Scen.	*P* =	0.475	
	Rorations	Scenarios	Rotation* Scenario
s.e.d.	2.037	1.019	2.881

Soil Mg content was not affected by the rotation but the DRY scenario retained significantly less soil K than the CEave rainfall scenario. There were no significant interactions, table 9.50.

Table 9.50. Soil Mg mg/l after harvest of the 2016-2017 crops in the HAU mesocosm experiment

Mg mg/l	**Scenarios**		
Rotations	CEAve	Dry	**Mean Rotation**
D Q WW-AT	119.2	104.2	111.7
Lucerne	108.2	111.3	109.8
PRG	124.2	116	120.1
Q WW-AT D	105.7	109.2	107.4
SB WT WWAT	118	102.5	110.2
ST WWAT WB	119.8	110.7	115.2
SW-AT D Q	113.2	100.2	106.7
SWAT WB WT	108.8	101.3	105.1
Mean Sc.	114.6	106.9	
	Overall mean		**110.80**
Rotations	*P* =	0.295	
Scenarios	*P* =	0.016	
Rotation * Scenarios	*P* =	0.666	
	Rorations	Scenarios	Rotation* Scenario
s.e.d.	6.26	3.13	8.86

10 Overall Discussion

The main question which this research aimed to investigate was 'how would the selected mainstay arable and forage crops perform under the climate change scenario identified for this investigation'? The ultimate or key indicator for this was the crop yield response to the drier conditions, a 38% reduction in rainfall from April to September. The differences in yield between the individual crops was not the key factor in this work but the performance and yield of the individual crops in the two scenarios. For the UK crops such as winter wheat, which is the mainstay of many UK arable crop rotations, crop yield and total production reductions due to drought could seriously impact on the UK food supply chain.

The responses of the crops to the reduced water application and the small differences of soil moisture deficit at each time point was shown to be considerable for some of the crops over the course of the experiment. Soil moisture deficits recorded in the two scenarios followed a similar trend but generally only differed significantly post-harvest of the arable crops. Over the majority of the post-winter and fast growing period of May and June the 38% reduction of applied water in the DRY scenario led to small but important soil moisture deficits during this period.

These SMD differences were more pronounced in the 2015 where all crops were spring planted. In subsequent crops only Durum wheat and quinoa were spring planted, as is normal, and the scenario SMD differences within the winter planted crops were not so pronounced over the same periods. The August SMD similarities between the spring and winter sown crops however can be expected as root growth for winter cereals is reported as only 5mm per day^{-1} whereas for spring planted cereals it is 15-25mm day^{-1} (Lucas *et al*., 2000) thus allowing the roots of the spring planted crops to explore the same soil volumes. However, unlike the establishment phase of the winter cereals, which occurred during reducing SMDs, the spring durum crop was planted into increasing SMDs conditions especially in the DRY Scenario compared to that in the CEave mesocosms. In the 2015 crop SMDs in both scenarios reached approximately 69mm in late June and progressed to only 72mm in the Ceave and 76mm in the DRY scenario by mid-August. This minimal SMD progression over that period would be expected as crop growth would have ceased in July as the crop would have been in the senescing/drying phase (AHDB, 2015). In the 2015 – 2016 season the late June SMDs had reached 96mm (CEave) and 99mm (DRY), greater than in 2015, which would be attributed in part to the earlier planting of the spring durum (mid-march in 2016 as opposed to mid-April in 2015) and also to a greater ET demand arising from the greater demand, yield and biomass production in the winter planted crops. In 2016 – 2017 the late June SMDs for both scenarios were between 110-120 mm, greater than in 2016, being in part be due to the change of sensor alluded to earlier where slight increases were noted from the new sensor and variations in crop growth and environmental factors between years. Although the soil moisture deficits in the DRY scenario did become more negative as a result of the lower quantity of water applied, 188mm, compared to the CEave scenario, 284mm, the soil moisture deficits at each sampling point were seldom significantly different. As soils dry out from field capacity, when water is held at - 0.05 to -0.33 bar, and soil moisture deficits increase, the water is held at greater and greater tensions until becoming unavailable at approximately - 15 bar (pF 4.2), permanent wilting point (Hall *et al*, 1977, Ritchie, 1981). However, during the early phases of the drying-down the plant can access water without experiencing significant stress or loss of production thus producing similar extraction. This fraction of the total available water is classed as the ‘readily available water’ and its value varies between soils, crops and environmental conditions. As a guide the FAO (1998) suggest that the fractions of readily available water range from 0.3 for shallow rooted crops at high rates of ETc to 0.7 for deep rooted crops at low rates of ETc. Overall a figure of 0.5 (50%) is often used for planning but wheat, barley, oats and lucerne is given as 0.55 (55%). The point when readily available water ceases is also classed as the point of ‘limited availability’ which is suggested as pF 3.0–3.3 (Novak and Havrila, 2006). The amount of water available to the plant at these tensions however will depend on the soil type, figure 10.1 and 10.2.

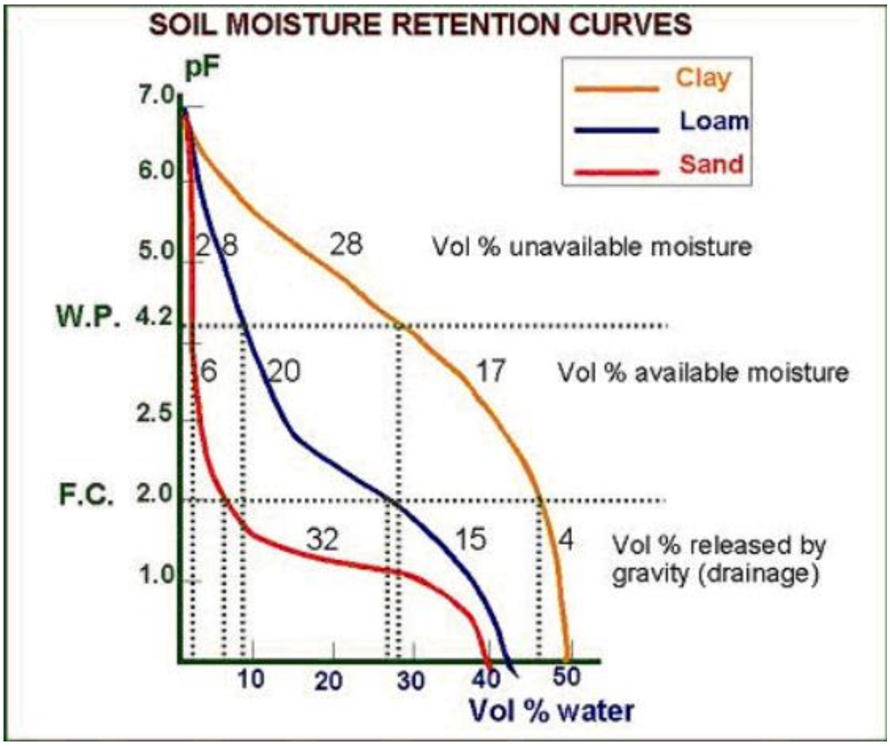

Figure 10.1. Soil moisture retention and availability for the three main soil type classifications (Brady and Weil, 2016)

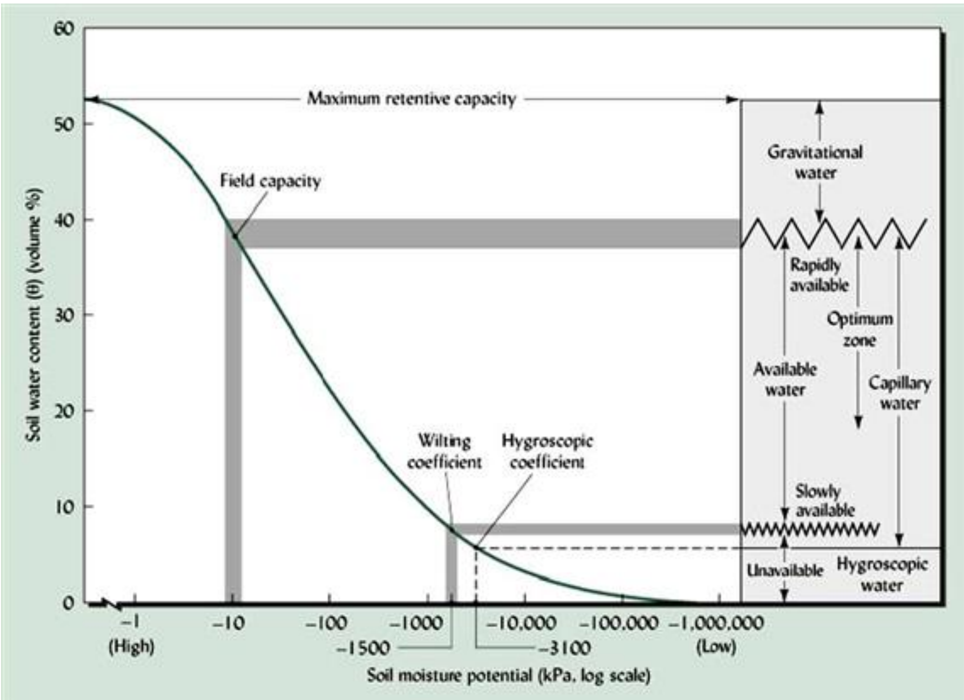

Figure 10.2. Soil moisture availability curve (Brady and Weil, 2016)

The soils in this experiment are classed as loamy sand and therefore a significant proportion of the total available water will be easily available. Consequently only when the soil moisture deficit reached a significant proportion of the total available water would the crops become stressed, growth reduced and crop yield reduced (Novak and Havrila, 2006). For the crops in the mesocosm experiments therefore the 55% readily available water would cease at an SMD of approximately 70mm, and so the spring planted 2015 crops would always have been within the readily available water range. In the 2015 – 2016 crop SMDs reached 70mm by mid-June and would have been during the grain filling period of the cereals, thus potentially limiting. For the 2016 – 2017 crops the SMDs reached 70mm by mid-May and should therefore have been limiting crop yield. However, the 0.55 fraction is based on a daily 5mm ETc value which was the upper value in this experiment. In this situation the readily available fraction may approach the upper value of 0.7 (70%) and put the limiting SMD at 90mm which would prevent stress until much later in the season and beyond the critical growth phases for crops such as wheat, GS 41 (Weerasinghe *et al.,* 2016*).* Additionally, when ET occurs at a low rate the root zone soil moisture has more time to be replenished (FAO, 2012) thus maintaining active soil moisture uptake into the plant and allowing root growth to extend into wetter soil (Bao *et al*., 2014). The similarity of SMD between the CEave and DRY scenarios during rapid plant growth would also be justified as the rate of Etc is driven by water availability (FAO, 1998). As the CEave received a total of 197, 199 and 178mm water over April to July over the three years compared to DRY which received 122, 120 and 106mm over the same periods, there would be water available for uptake. If this was indeed the case it would be represented by increased growth and yield within the CEave scenario in the absence of other limiting factors.

In 2015, season 1, results showed substantial reduction of both biomass and yield for the majority of spring planted arable crops in the DRY scenario. The exceptions were spring barley and triticale which produced similar biomass and grain yield in both scenarios, but with triticale showing almost identical HI in both. Comparison of the HI reported here with Hay (1995) suggest that the barley 0.65 CEave and 0.59 DRY was in the upper range, triticale 0.46 CEave and 0.44 DRY is identical, whereas the wheats were slightly below those reported. For triticale therefore the effect of the substantially lower water application was almost inconsequential to productivity and only slightly negative for spring barley. This could be the result of osmotic adjustment as outlined by Pask *et al.* (2012) but should then also have been a factor for wheat which was reported by Zhang *et al*. (1999). In addition the water productivity of triticale and spring barley achieved 61% and 55% increases by rising from 3.1 to 4.38 and 3.28 to 5.1 kg m^3 water applied respectively. Quinoa did achieve a WP increase of 38% which was substantially better than both durum wheat and the common wheat and maintained a similar HI. Forage growth during this first season was slow due to the need for its establishment, but lucerne outperformed PRG over the 3 forage harvests. Lucerne achieved a mean of 11.1 t/ha FW (11.2 CEave and 11.1 DRY) whereas PRG only achieved a mean of 5.6 t/ha FW, with 6.5 in CEave and only 4.7 in the DRY scenario. Unlike PRG the Lucerne was not as affected by the reduced water which is similar to findings by Murray-Cawte (2013).

In the second season the wheat, barley and triticale were planted as winter varieties in late autumn of 2015 whilst Durum and quinoa were spring planted as normal for the UK. Biomass production was similar in both scenarios for wheat and barley, greater in the DRY scenario for triticale and quinoa and lower for barley in the DRY.

The grain yields overall showed similar patterns to those of the 2015 spring planted crops of similar yields for winter varieties of wheat (+ AT and -AT), triticale and barley but decreased yields for the spring planted durum and quinoa in the DRY scenario. These results for the winter planted crops could have been an effect of the pre-winter establishment of the root system making them less sensitive to the conditions in the DRY scenario, unlike the 2015 spring varieties which would have needed to develop roots whilst experiencing drier soil, figures 5.13-5.16, which is supported by the work of Li *et al*. (2001) . The yield of quinoa was however substantially lower than in the first season achieving approximately 2 t/ha in both scenarios, substantially less than the 18 t/ha seen in the first season. The 2 t/ha is considerably lower than Risi and Galwey (1991b) suggest where a range of 4 - 7 t/ha was achieved in the UK. During this season however there were considerable aphid problems with this crop which resulted in substantial leaf roll and leaf loss attributed to the quinoa leaf aphid, *Hayhurstia atriplicis*. In 2017 crop only the potato aphid, *Macrosiphum euphorbiae*, was seen and little damage occurred. Harvest indices in the 2015/2016 crops were within the normal ranges as specified by Hay (1995) but triticale produced both a better grain yield and excessive stem and leaf in the DRY scenario which led to a reduced HI for this crop in the DRY scenario. This greater biomass was identified by taller plants and a substantially greater number of ears (stems) m^2, 525 in CEave compared to 678 in the DRY scenario, greater individual grain weight and TGW, and greater seed yield but lower leaf area. As none of these differences were statistically significant however the increased biomass and yield should only be considered as a function of the greater stem/ear numbers as these are key determinants in the components of yield as described by Hay and Porter (2006). There were significant reductions in leaf area for all crops in the DRY scenario which is a normal response to reduced water availability with reduced cellular elongation and expansion but it would also be expected to be accompanied by height reductions (Farooq, 2009). Effects on wheat can influence the potential of the crop to be accepted at mill intake (NABIM, 2018). Low water uptake during grain fill can result in small or shriveled grains, changes to protein and starch structure and content ((Balla, *et al*., 2011). Weerasinghe *et al*., *(*2016*)* showed how important adequate soil moisture was to pollen mother cell meiosis in common wheat around early booting (GS41), which affected grain set and ultimately seed number. A key consideration within these results however as the differences in varietal tolerance to drought within each of the crops species (Thrapa *et al.* 2018; Abouu-Dief *et al.*, 2015). However, Yordanov *et al.* (2003) also suggest that although mild drought can affect plant physiology the response is often maintenance of relative leaf water content (RWC) within limits where no or little change occurs to photosynthetic capacity and quantum yield. However, one of the drought tolerance mechanisms is reduced stomata density or production (Zu and Zhou, 2008) which would then lead to reduced CO_2 uptake and reduced dry matter production. In addition Hepworth *et al*, (2015) agree that stomatal density is affected but then suggests that our knowledge of reduced nutrient uptake in droughted plants is limited and this could also be a contributory factor for reduced yield. As plant analysis for nutrient content was not investigated in this work it remains an unconfirmed possibility but this could be included in future work of this nature. In terms of water productivity winter triticale outperformed other crops by increasing WP from 2.24 in the CEave up to 4.98 kg/m^3 water applied in the DRY scenario (56% increase) similar to 2015 spring crop 3.1 and 4.98 kg/m^3 water applied, 61% increase. Quinoa also maintained a similar WP improvement in the DRY scenario WP achieving a 35% increase in 2015-2016 compared to 38% in 2015 spring. The WP of barley was better again in the DRY scenario but the effect was not so exaggerated, with improvements of only 18%, as compared to 55% with the 2015 spring planted crop. Wheat crop WP improvements in the DRY scenario was similar in both years. Considering the factors which make up the WP calculation however the winter crop calculation accounts for the additional water (precipitation) crops receive during their slow growing phases of winter and early spring, which could be misleading. For UK crops therefore although WP may appear to be better for spring planted crops than winter planted, the additional water is not at any cost to the grower or the environment as the majority of rainfall add to the soil water reserves and aquiifers. Comparisons between winter planted crops however suggests that the WP of both triticale and wheat are substantially better than for barley. In terms of crop selection therefore wheats and triticale should take preference should our climate become drier to the extent investigated. For the forage crops Lucerne outperformed PRG for the second year running. Lucerne produced 29 t/ha DM in the CEave and reduced by only 5% to 28 t/ha DM in the DRY scenario, all achieved from 8 harvests which is just above the norm of 3 to 7 harvests taken at 5-8 week intervals (Julier *et al.,* 2017). In contrast PRG produced 9 t/ha DM in CEave and reduced by 29% to 6.47 t/ha DM in the DRY scenario, produced from only 6 harvests. The Lucerne yields are high as yields are reported to be normally be 12 - 16 t/ha dry matter in the UK and Europe (Julier *et al.,* 2017; British Grassland, 2017; Genever and McConnell, 2014) but up to 19 t/ha dry matter in New Zealand (Murray-Cawte, 2013). However, temperatures within the protected environment of the polytunnel averaged 13ºC over the 3 years, an average maximum temperature of 19ºC and an average minimum of 7ºC, and reached over 35ºC during the summer months. These conditions would be closer to the range of 5°C minimum and 45°C (FAO, 2012). Early growth was also suggested to be fast as mean air temperatures rises from 6 to 18°C (Brown *et al.*, 2006). In addition, Lucerne is reported to have a substantial root system with records suggesting depths of up to 4m (Frame *et al.*, 1998). The importance of deep rooting in plants has been reported by many researchers (Gao *et al.*, 2016; Wasson *et al.,* 2012; Kell, 2011; Manschadi and Hammer, 2006; Schenk and Jackson, 2002) due to their key role in carbon, nutrient and water sequestration. The difference in harvest number was determined by the growth and development of the crops to match optimum harvest times.

In the third season winter varieties of wheat, barley and triticale and spring varieties of quinoa and durum were used again. Lucerne and PRG continued to grow for a third year. Crop yields were not significantly different between the scenarios and all crops except for durum wheat produced above average yields for the UK, which can be expected in these type of experiments where edge effects and less adverse weather can promote growth. Average barley, and wheat yields exceeded 12.75 t/ha whereas triticale averaged almost 11 t/ha and quinoa 7 t/ha. However, there was considerable differences of ears m^2 with both barley and triticale having substantially greater numbers in the DRY scenario. Durum wheat and quinoa were again the only crops whose yields were appeared to be reduced by the reduced water application. Harvest indices were also not significantly different between scenarios with most crops following the trend of lower HI in the DRY scenario. The spring crops and durum wheat however had greater HI than any of the winter cereals. Water productivity was again significantly improved within the DRY scenario and as in the 2015/2016 season WP was greatest in the spring crops of quinoa and durum wheat.

The differences in the yields of the winter crops between 2016 and 2017 could not be simply related to environmental conditions during the peak growing period of April to late June. The total solar radiation during these periods was almost identical between 2016 and 2017, being 1148 and 1125 mj m^2 respectively, whereas in 2015 it was considerably greater at 1278 mj m^2. Variations in maximum temperatures between years could have been influential as photosynthetic capacity is significantly influenced by temperature and varies between species (Sage and Kubien, 2007). Maximum, minimum and average temperatures between 10th April and 30th June were: 2015 40, -4 and 16.4°C, 2016 35, - 1 and 16°C, 2017 41, -4 and 16°C. The yield response of the crops did not follow the patterns of solar radiation or maximum temperatures however and consequently these crops all appeared to be able to produce good yields under the increased temperatures experienced during the fast growing periods. This is useful information as climate change scenarios encompass both precipitation and increased temperature.

The result of the addition of the antitranspirant, AT, was disappointing as previous work by Kettlewell *et al.* (2010) and Abdullah *et al.* (2015) all showed yield improvement in drought conditions. However, insufficient drought during the critical growth period, as was probably the case in this experiment, could negate the AT effect as water is not sufficiently limiting and even impair growth as noted by earlier researchers. In addition Weerasinghe *et al.* (2016) showed the importance of applying the AT at the critical growth stage GS33 in order to protect pollen mother cell meiosis. Within this experiment the resulting yield reductions seen from the application of the AT are most likely a result of insufficient 'drought' at the time of application and consequent reduced CO_2 uptake due to stomatal coverage with the AT film as suggested by Davenport *et al*. (1972)

At the end of the experiments soil samples were taken to determine the effect of the scenarios on the rotations employed within them. Organic matter, a key component for water retention and soil stability (FAO, 2005) was not affected by the scenarios. However, soil pH was lower in the DRY scenario which could be related to Ca mobility and appeared to be reduced more in rotations predominantly spring planted but there was no consistent pattern. In contrast to this, the other soil nutrients measured all showed significant reductions from the CEave rather than the DRY scenario. Available soil K (mg/l) was substantially and significantly reduced by the CEave scenario and also where spring cropping dominated the rotation. There were no significant interactions and it was difficult to identify any real patterns within and between crops. Similarly soil P availability also shown a significant reduction in the CEave scenario but again no real patterns could be seen. Further analysis linked to crop offtake may identify is that is the cause of the variation as nutrient offtake is linked inextricably to soil reserves (AHDB, 2010).

In order for the mesocosms in the experiment to be stabilised and brought up to field capacity using natural rainfall rather than irrigation, the first season began post winter and all crops were sown as spring crops. In years two and three winter sown varieties for wheat, barley and triticale were utilised which would follow conventional UK practice. Prior to planting the uniformity of the soils was shown with no differences found between FC values, organic matter %, pH and available K (mg/l), so provided a good even starting conditions for the experiment. A sub-sample of soils were tested for phosphate availability and were also found to be similar. Crops grew well through the season and soil moisture deficits (SMDs) became more negative in all crops and scenarios up until harvest of the annual crops. The perennial crops continued to grow through the first year and were harvested at times to match their growth.

The purpose of this work overall was to determine the effect of a rainfall reduction as suggested by the UKCP09 2050 high emissions 10% probability projection (Met Office, 2018c) rather than a complete pattern change. One of the key reasons for this approach was that under the projection selected not only are 'drier' summer weather projected but also wetter winters. For the UK, the notable droughts of 1976 and 1992 were problematical because each was preceded by drier than normal winters. The 1976 drought is related to the period from May 1975 to August 1976, whereas the 1992 drought is related to the period from spring of 1990 to the summer of 1992 (Marsh *et al.,* 2007). If climate change includes warmer and drier summers but also wetter winters therefore both needed to be included within the work. Achieving this rainfall reduction in an equitable manner however could realistically only be achieved by mimicking the normal monthly rainfall amounts and applying the 38% reduction. This was then converted to daily amounts per month and applied on a Monday, Wednesday and Friday morning throughout the experiment. As a process this was easily achieved using drip irrigation but also provided the plants with a regular rather than sporadic supply as would normally be experienced. Plants are driven by a daily Etc demand dependent on environmental conditions and take up water to satisfy this (FAO, 1998). Providing plants with a regular water supply therefore more closely follows their requirements than irregular rainfall patterns which may have led to adaptions to growth or physiology in this investigation. In the experiments there were few significant clear indications that basic morphology was changed by the DRY scenario as would be expected from droughted plants (Farooq *et al.*, 2009) with the variations of leaf area, height and tiller production between scenarios neither consistent between scenarios or years. However, under mild drought or variable soil moisture Yordanov *et al* (2003) and Cornic and Massacci (1996) suggest that plants have the ability to regulate the balance between water loss and water uptake with little or no change to Ps capacity. With soil moisture deficits within the scenarios following a similar pattern and intensity the plant adaption appears to be one of adaption to a considerable ongoing reduction in available water rather than an absence or alternating supply.

11 Conclusions

Initially the use of mainstay UK crops within this work rather than crops from significantly drier environments is supported for this investigation as the growth and yield of the UK cereals within the investigation were not significantly affected by the severe high emission 2050 scenario.

Overall the net yield effect of the climate change scenario imposed within this experiment was small for the mainstay UK crops but reductions of yield of durum wheat and perennial ryegrass were consistent. The proviso under these results however is that only one variety of each crop was grown and varietal drought tolerance would need to be investigated to optimize variety selection for the environments which dominate at that time. Clearly, Lucerne produced substantially better yield and was less affected in the DRY scenario compared to PRG, undoubtedly due to a substantially better rooting system and suitability to the higher temperatures arising in the polytunnel. When considering the impact of the PRG and Lucerne results for the UK forage production it is apparent that under the projected climate change scenario used in this work the higher temperature and reduced April-September rainfall would favour Lucerne better and thus provide a more stable forage source for these temperature and rainfall projections.

The water productivity of all of the crops was improved in the DRY scenario over all three seasons which was due mainly to the similar yields achieved in both scenarios. The lower water productivity of the winter planted crops, compared to the spring planted, is to be expected due to the additional growing period when the crops received additional water without commensurate growth. In the UK however the precipitation falling over the winter adds little to the yield of the crop and, as it adds to the soil and aquifer reservoir, should debatably be used in the calculation of water used/applied.

A crucial finding within this work is that as the soils returned back to field capacity each winter, due to slow crop growth and higher precipitation from October through to March, limiting SMDs did not develop during critical yield limiting growth stages of the cereals. In contrast the more severe SMDs from July onwards would have been a key component of the reduced PRG yield compared to the Lucerne.

Soil analysis post investigation also revealed that pH was significantly reduced in the DRY scenario whereas soil K and P were both significantly lower in the CEave scenario suggesting some link with nutrient availability or movement in the moister environment.

Obviously this investigation took place inside a protected environment using a simulated regular rainfall pattern which would not occur in reality. The work did however mimic the normal monthly rainfall pattern for Central England so it did provide some measure of historic rainfall patterns. The overall conclusion from this work suggests that should the UK experience the reduced summer rainfall and increased winter rainfall investigated, whilst maintaining the same pattern of rainfall, our mainstay cereals and Lucerne should not encounter significant crop failure.

11.0 Recommendations for future work

- The capability of common wheat to grow in a wide range of climates suggests that it would be very useful to investigate the performance of a wide range of global common wheat varieties rather than look for 'new crops'.

- Similarly, there is a dearth of information relating to the drought tolerance of current UK cultivars and therefore research to identify breeding would be beneficial.

- Although UK barley performed well under this investigation it would be sensible to investigate a wider range of Mediterranean barley genotypes for use in a warmer and drier UK.

- As triticale performed extremely well in this investigation, it may be useful to further investigate the potential for it to replace the lower quality feed wheats in animal feed rations.

- The antitranspirant work did not show any benefit in this work, in contrast to other studies, however as the previous work has focused on wheat under severe stress it may be necessary to investigate if the timing of application under lower stress situations may elucidate a better response.

- The outstanding performance of Lucerne (alfalfa) in contrast to PRG, both in yield and water productivity, suggests that greater research is needed to investigate the soil and climatic limitations that currently exist in the UK. The aim would be to increase water productivity in both the short and longer term.

Acknowledgements:

This work was funded by the Natural Environment Research Council in collaboration with ESRC, EPSRC, BBSRC and AHRC and overseen by the Principal Investigator Professor Lindsey McEwen at the University of the West of England.

Thanks must go to the staff at the Crop and Environment Research Centre at Harper Adams University who maintained the experiment and facilities for this investigation.

Thanks also to Dr Stephen Jones of the British Quinoa Company for both the quinoa seed and also his advice.

References

Abdullah, A.S., Aziz, M.M., Siddique, K.H.M. and Flower, K.C., 2015. Film antitranspirants increase yield in drought stressed wheat plants by maintaining high grain number. *Agricultural Water Management*, *159*, pp.11-18.

Abou- Deif MH, Rashed MA, Sallam MAA,Mostafa EAH and Ramadan WA, 2015. Response of Twenty Wheat Varieties to Drought Stress Based on Some Agronomic Traits and Molecular Analysis. *Asian Journal of Plant Sciences*, **14**: 1-10. DOI: 10.3923/ajps.2015.1.10

AHDB. 2015. Wheat growth guide. AHDB, Stoneleigh Park, Warwickshire.

AHDB. 2016. Wheat disease management guide. AHDB, Stoneleigh Park, Warwickshire.

AHDB. 2017. Nutrient management guide (RB209) updated May 2017. AHDB, Stoneleigh Park, Warwickshire.

Akunda EM and Kumar D. 1980. Studies with antitranspirants on coffee (Coffea arabica L.). *East African Agricultural and Forestry Journal* **45** (3), 230-235

Alexander, L.V. and Jones, P.D. 2001. Updated precipitation series for the U.K. and discussion of recent extremes. *Atmospheric Science Letters* doi:10.1006/asle.2001.0025

Alvarez-Jubete L, Arendt EK and Gallager E. 2009. Nutritive value and chemical composition of pseudocereals as gluten-free ingredients. *International Journal Food Science Nutrition* **60** (4), 240-257.

Balla K, Rakszegi M, Li Z, Bekes F, Bencze S and Veisz O. 2011. Quality of winter wheat in relation to heat and drought shock after anthesis. *Czeck. Journal of Food Science* **29** (2), 117-128.

Bao Y, Aggarwal P, Robbins NE, Sturrock CJ, Thompson MC, Tan HQ, Tham C, Duan L, Rodriguez PL, Vernoux T, Mooney SJ, Bennett MJ and DinnenyJR. 2014. Plant roots use a patterning mechanism to position lateral root branches toward available water. *PNAS June 24*, **111,** (25). 9319 – 9324: www.pnas.org/lookup/suppl/doi:10.1073/pnas.1400966111

Bartlett MK, Klein T, Jansen S, Choat B and sack L. 2016. The correlations and sequence of plant stomatal. Hydraulic, and wilting responses to drought. *PNAS* **113**, (46)13098-13103.

BarnabáS B., Jäger K. & Fehér A. 2008. The effect of drought and heat stress on reproductive processes in cereals. *Plant, Cell & Environment* **31**, 11–38.

Basu S, Ramegouda V, Kumar A and Pereira A. 2016. Plant adaption to drought stress. F1000Research 5. ncbi.nlm.nih.gov. Doi: 10.12688/f1000research.7678.1

Bhahma R, Janawade, A. D and Palled YB. 2007. Water use studies in durum wheat as influenced by irrigation schedules, mulch and antitranspirant application in black soils of northern transitional zone of Karnataka. *Karnataka Journal of Agricultural Sciences* **20** (1) 120-122

Bell, M.A., Fischer, R.A., Byerlee, D. and Sayre, K., 1995. Genetic and agronomic contributions to yield gains: A case study for wheat. *Field Crops Research*, **44** (2-3), pp.55-65.

Brady NC and Weil RR. 2016. The nature and properties of soil. Harlow: Pearson.

British Grassland. 2017. Recommended grass and clover lists for England and Wales 2017/18. www.britishgrassland.com/RGCL

Brown, H.E., moot, D.J. & Teixeira, E.I. 2006. Radiation use efficiency and biomass partitioning of lucerne (Medicago sativa) in a temperate climate. *European Journal of Agronomy* **25**: 319-327.

Bosque Sanchez H, Lemeur R, van Damme P and Jacobsen SE. 2003. Ecophysiological analysis of drought and salinity stress of quinoa (*Cheopodium quinoa* Willd.). *Food Reviews International* **19**, (1&2). 111-119

Boyer, J.S., 1982. Plant productivity and environment. *Science*, **218** (4571), pp.443-448.

Brisson, N., Gate, P., Gouache, D., Charmet, G., Oury, F.X. and Huard, F., 2010. Why are wheat yields stagnating in Europe? A comprehensive data analysis for France. *Field Crops Research*, **119** (1), pp.201-212.

Brookes A, Jenner CF and Aspinall D. 1982. Effects of water deficit on endosperm starch granules and on grain physiology of wheat and barley. Australian Journal of Plant Physiology **9** (4), 423 – 436.

Bureau of Meterology. 2018. Annual Climate statement 2017. http://www.bom.gov.au/climate/current/annual/aus/#tabs=Rainfall

Burns J. 2017. Drought could slash crop yields by up to 50%. Farmers weekly April 29, 2017: http://www.fwi.co.uk/arable/concerns-grow-drought-will-slash-crop-yields.htm

Byerlee D and Morris M. 1993. Research for marginal environments: Are we underinvested? Food Policy 18 (5), 381-393

Cattivelli, L., Rizza, F., Badeck, F.W., Mazzucotelli, E., Mastrangelo, A.M., Francia, E., Marè, C., Tondelli, A. and Stanca, A.M., 2008. Drought tolerance improvement in crop plants: an integrated view from breeding to genomics. *Field Crops Research*, **105** (1), pp.1-14.

Chaiwanon J and Wang ZY. 2015. Spatiotemporal Brassinosteroid Signaling and Antagonism with Auxin Pattern Stem Cell Dynamics in Arabidopsis Roots. *Current Biology,* April 2015 DOI: 10.1016/j.cub.2015.02.046

Chaves MM and Oliveira MM. 2004. Mechanisms underlying plant resilience to water deficits: prospects for water saving agriculture. *Journal of Experimental Botany* **55** (407). 2365-2384.

Clarke S, Roques S, Weightman R and Kindred D. 2016. Understanding triticale. AHDB: Stonleigh: https://cereals.ahdb.org.uk/media/897536/pr556-understanding-triticale.pdf

Cook R. 2018. States that produce the most alfalfa (ranking). FarmCentric.

Cornic G and Massacci A. 1996. Leaf photosynthesis under drought stress. In: Baker N (Eds) *Photosynthesis and the environment*. Kluwer: Netherlands. Pp 347-366

Cotswold. 2018. Cotswold seeds: Accessed on 11th March 2018: https://www.cotswoldseeds.com/seed-info/lucerne-also-known-alfalfa

Czyz EA, Tomaszewska J and Dexter AR. 2001. Response of spring barley to changes of compaction and aeration of sandy soil under model conditions. *International Agrophysics* **15**, 9 – 12.

Dardenelli JL, Bachmeier, Sereno R and Gil R. 1997. The rooting depth and soil water extraction patterns of different crops in a silty loam haplustoll. *Field Crops Research* **54**: 29-38

DAFF. 2011. Pearl Millet production guidelines. Department of Agriculture, Forestry and Fisheries. Pretoria, SA.

DAFF. 2014. Amaranth production guidelines. Department of Agriculture, Forestry and Fisheries. Pretoria, SA.

Das, V.S.R. and Raghavendra, A.S., 1979. Antitranspirants for improvement of water use efficiency of crops. *Outlook on Agriculture*, **10**, pp 92-98.

Davenport, D.C., Fisher, M.A. and Hagan, R.M., 1972. Some counteractive effects of antitranspirants. *Plant Physiology*, **49** (5), pp.722-724.

Defra. 2017a. Agriculture in the United Kingdom 2016. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/672119/AUK-2016-08jan18.pdf

Defra. 2017b. Farming Statistics Provisional crop areas, yields and livestock populations at June 2017 - United Kingdom. Accessed on 2nd Feb 2018: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/651173/structure-jun2017prov-UK-12oct17.pdf

Defra. 2018. Regional level aggregate farm accounts for England, Second estimate for 2016. National Statistics publication.

Defra. 2018a. Agriculture in the United Kingdom 2017.: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/712317/AUK-2017-31may18.pdf

Dodd, I.C. 2003. Hormonal interactions and stomatal responses. *J Plant Growth Regul.* **22** (1) 32 - 46. https://doi.org/10.1007/s00344-003-0023-x

D-Risk. 2018. A planning tool to help you manage your irrigation and abstraction and drought risks: http://www.d-risk.eu/index.php

El Chami D, Knox JW, Daccache A and Weatherhead EK. 2015. The economics of irrigating wheat in a humid climate – A study in the East of England. *Agricultural Systems* **133**, 97-108.

Environment Agency. 2017. ENV15- Water abstraction tables for England. https://www.gov.uk/government/statistical-data-sets/env15-water-abstraction-tables

EUCMO. 2018. EU Crops Markets Observatory- Cereals: Cereals Dashboard: EU production area and yield: https://ec.europa.eu/agriculture/market-observatory/crops/cereals/statistics_en

Euronews. 2017. http://www.euronews.com/2017/09/04/the-devastating-and-surprising-effects-of-spain-s-drought

FAO. 1998. ETc under soil water stress conditions, Chapter 8. In: *Crop evapotranspiration - Guidelines for computing crop water requirements* - FAO Irrigation and drainage paper 56. FAO: Rome.

FAO. 2005. The importance of soil organic matter: Key to drought-resistant soil and sustained food production. FAO Soils bulletin 80. FAO: Rome

FAO. 2012. Crop yield response to water. Irrigation and drainage paper 66. FAO: Rome

FAO. 2012a. FAO penman-Monteith equation. Irrigation and drainage paper 66. FAO: Rome

FAO. 2018. FAOSTAT. Agricultural statistics: http://www.fao.org/faostat/en/#data

FAO. 2018a. AquaCrop Model. http://www.fao.org/aquacrop/en/

Faralli, M., Grove, I.G., Hare, M.C. and Kettlewell, P.S., 2017. In-field film antitranspirant application shows potential yield protection from flowering-stage drought periods in winter canola (Brassica napus). *Crop and pasture Science*, **68** (3), pp.243-253.

Faraji A., Lattifi N., Soltani A., Shirani-rad A.H. 2009. Seed yield and water use efficiency of canola (*Brassica napus* L.) as affected by high temperature stress and supplemental irrigation. *Agricultural. Water Management*. **96**:132-140

Farooq M, Wahid A, Kobayashi N, Fujita D and Basra SMA. 2009. Plant drought stress: Effects, mechanisms and management. In: Lichtfouse *et al.* (eds.) *Sustainable Agriculture*. DOI 10.1007/978-90—481-2666-8_12. Springer Science+Business Media B.V.-EDP Sciences. 153-188.

Fleming JE and Galwey NW. 1995. Quinoa (*Chenopodium quinoa*). In: Williams JT (Ed.) *Cereals and pseudocereals*. Chapman and Hall: London. Pp. 3 – 84.
Frame J, Charlton JFL and Laidlaw AS. 1998. Temperate forage legumes. CABI: UK. Pp 107 – 180.

French RJ and Schultz JE. 1984. Water use efficiency of wheat in a Mediterranean type climate: 1. The relationship between yield, water use and climate. *Australian Journal of Agricultural Research,* **35**, 743 – 764.

Gale, J., 1961. Studies on plant antitranspirants. *Physiologia Plantarum*, **14** (4), pp.777-786.

Gale J and Hagen RM. 1966. Plant Antitranspirants. *Annual review of Plant Physiology*, **17**. 269-282.

Gallardo M, Jackson LE and Thompson RB. 1996. Shoot and root physiological responses to localised zones of soil moisture in cultivated and wild lettuce (*Lactuca* spp.) *Plant, Cell and Environment* **19**, 1169-1178.

Genever L and McConnell D. 2014. Growing and feeding Lucerne. Beefandlamb.ahdb.org.uk

Giunta F, Motzo R and Diedda M. 1993. Effect of drought on yield of and yield components of durum wheat and triticale in a Mediterranean environment. *Field Crops research* **33** (4), 399-409.

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M. and Toulmin, C., 2010. Food security: the challenge of feeding 9 billion people. *Science*, *327*(5967), pp.812-818.

Grant W. 2017. Migrant labour and agriculture. The UK in a changing Europe, Kings College London. http://ukandeu.ac.uk/migrant-labour-and-agriculture/

HadUKP Data. 2018. Met Office Hadley Centre Observations Datasets: HadUKP: https://www.metoffice.gov.uk/hadobs/hadukp/

Hall DGM, Reeve MJ, Thomasson AJ and Wright VF. 1977. Water retention, porosity and density of field soils. *Soil Survey Technical Monograph No. 9*. Harpenden.

Haverkort AJ and Gourdiaan J. 1994. Perspectives of improved tolerance of drought in plants. *Aspects of Applied Biology* **18,** 1994*, Efficiency of water use in crop systems*. 79 – 92.

Hay RKM. 1995. Harvest index: A review of its use in plant breeding and crop physiology. *Annals of Applied Biology* **126**, 197-216

Hay R and Porter J. 2006. The physiology of crop yield (2nd ed). Blackwell Publishing: Oxford. Pp 21-22.

Hepworth C, Doheny-Adams T, Hunt L, Cameron D and and Gray J. 2015. Manipulating stomatal density enhances drought tolerance without deleterious effect on nutrient uptake. *New Phytol*. **208** (2), 336-341.

Hirota O, Oka M and Takeda T. 1990. Sink activity estimation by sink size and dry matter increase during the ripening stage of barley (Hordeum vulgare) and rice (Oryza sativa). *Annals of Botany* **65** (4), 349-353

Huang, G.T., Ma, S.L., Bai, L.P., Zhang, L., Ma, H., Jia, P., Liu, J., Zhong, M. and Guo, Z.F. 2012. Signal transduction during cold, salt, and drought stresses in plants. *Molecular biology reports*, **39** (2), pp.969-987.

IGC. 2018. International Grain Council Reports. https://www.igc.int/en/default.aspx

IPCC, 2007. The physical science basis. Contribution of working Group I to the fourth assessment report of the Intergovernmental Panel on Climate Change. *Climate change 2007*, pp.337-383.

Jacobsen SE, Mujica A and Jensen CR. 2003. The resistance of quinoa (*Chenopodium quinoa* Willd.) to adverse abiotic factors. *Food Reviews International* **19**, (1&2). 99-109.

Jensen M E. 1968. Water consumption by agricultural plants. Water deficits and plant growth, Chapter 1, volume 1. Academic Press: New York. pp. 1-22.

Julier B, Gasta F, Louarn G, Badenhausser I, Anicchiarico P, Crocq G, Le Chatelier D, Giollemot E and Emile JC. **2017**. Lucerne (Alfalfa) in European cropping systems, in: Murphy-Bokern D, Stoddard FL and Watson CA. *Legumes in cropping systems*. CABI: Oxfordshire. Pp.168-192.

Keogh RC, Robinson APW and Mullins IJ. 2018. Lucerne. Case study 16: Pollination aware – The real value of pollination in Australia. www.rirdc.gov.au

Jones HG. 2004. Irrigation scheduling: advantages and pitfalls of plant-based methods. *Journal of Experimental Botany* **55**, 2427-2436.

Jones HG. 2007. Monitoring plant and soil water status: established and novel methods revisited and their relevance to studies on drought tolerance. *Journal of Experimental Botany* **58,** 119-130.

Jones HG and Tardieu F. 1998. Modelling water relationships of horticultural crops: a review. *Scientia Horticulturae* **74**, 21-46

Kavar T, Mara M, Kidrič M, Šuštar-Vozlič J and Meglič V. 2008. Identification of genes involved in the response of leaves of *Phaseolus vulgaris* to drought stress. *Molecular Breeding* **21** (2), 159-172.

Kell DB. 2011. Breeding crop plants with deep roots: their role in sustainable carbon, nutrient and water sequestration. *Annals of Botany* **108**, 407-418.

Kettlewell, P.S., Heath, W.L. and Haigh, I.M., 2010. Yield enhancement of droughted wheat by film antitranspirant application: rationale and evidence. *Agricultural Sciences*, **1** (3), p.143.

Kettlewell PS. 2014. Waterproofing wheat–a re-evaluation of film antitranspirants in the context of reproductive drought physiology. *Outlook on Agriculture*, **43** (1), pp.25-29.

Khalel AM S. 2015. Effect of drip irrigation intervals and some antitranspirants on the water status, growth and yield of potato (*Solanum tuberosum* L). *Journal of Agricultural Science and technology B*, **5.** 15-23.

Kholova, J., Greg M, Vincent, V., Craufurd, P., and Hammer, G.L. 2013. Drought stress characterization of post rainy season (*rabi*) sorghum in India. *Field Crops Research*, **141**, pp. 38 – 46.

Knipfer, G. and Gjerstad, G., 1963. Plant Antitranspirants. *Quarterly Journal of Crude Drug Research*, ***3*** (4), pp.464-468.

Knox J W, Kay MG and Weatherhead EK. 2012. Water regulation, crop production, and agricultural water management Understanding farmer perspectives on irrigation efficiency. *Agricultural water Management* **108**, 3-8.

Kochler M, Kage H and Stutzel H. 2007. Modelling the effects of soil water limitations on transpiration and stomatal regulation of cauliflower. *European Journal of Agronomy* **26**, 375-383.

Körner C, Scheel JA, Bauer H, 1979. Maximum leaf diffusive conductance in vascular plants. *Photosynthetica* **13**, 45-82.

Kumar J and Abbo S. 2001. Genetics of flowering time in chickpea and its bearing on productivity in semi-arid environments. *Advances in Agronomy* **72.** 107-138.

Lanceras, J.C., Pantuwan, G., Jongdee, B. and Toojinda, T. 2004. Quantitative trait loci associated with drought tolerance at reproductive stage in rice. *Plant Physiology*, **135** (1), pp.384-399.

Li FM, Liu XL and Li SQ. 2001. Effects of early soil water distribution on the dry matter partition between roots and shoots of winter wheat. *Agricultural Water Management* **49** (3). 163-171

Liu F, Jensen CR, Shahanzara A, Anderson MN and Jobobsen S. 2005. ABA regulated stomatal control and photosynthetic water use efficiency of potato (Solanum tuberosum L) during progressive soil drying. *Plant Science* **168**, 831-936.

Lopez G, Behboudian M H, Girona J and Marsal J. 2012. Drought in deciduous fruit tress: Implications for yield and fruit quality. In: Aroca R (eds), *Plant responses to drought stress. From morphological to molecular features*. Springer: London. Pp441-460.

Lucas ME, Hoad SP, Russell G and Bingham I J 2000. Management of cereal root systems. Research Review 43. Project no. 1725. HGCA: London

Machibya M, Mdemu M and Lankford B. 2004. Draft irrigation efficiency and productivity manual. DFID Knowledge and Research. KAR 8064. file:///C:/Users/00480971/NERC%20DRY%20laptop/R8064-Irrigation_Efficiency_Productivity_Manual-1.pdf

Mafakheri A, Siosemardeh A, Bahramnejad B, Struik PC and Sohrabi Y. 2010. Effect of drought stress on yield, proline and chlorophyll contents in three chickpea cultivars. Australian Journal Crop Science **4** (8):580-585

Maggio A, Miyazaki S, Veronese P, Fujita T, Ibeas JI, Damsz B, Narasimhan ML, Hasegawa PM, Joly RJ, Bressan RA. 2002. Does proline accumulation play an active role in stress-induced growth reduction. *Plant J* **31**: 699–712

Manivannan P, Abdul Jaleel C, Sankar B, Kishorekumar A, Somasundaram R, Lakshmanan GMA, Panneerselvam R. 2007. Growth, biochemical modifications and proline metabolism in Helianthus annuus L. as induced by drought stress. *Colloids and Surfaces B*: Biointerfaces **59**: 141–149.

Marsh T, Cole G and Wilby R. 2007. Major droughts in England and Wales, 1800-2006. *Weather*, **62** (4)**,** April 2007. Royal Meteorological Society, 2007 doi: 10.1002/wea.67

Medrano H, Escalona JM, Bota J, Gulias J and Flexas J. 2002. Regulation of photosynthesis of C_3 plants in response to progressive drought: stomatal conductance as a reference parameter. *Annals of Botany* **89**, 895-905

Medrano H, M Tomás, Martorell S, Flexas J, Hernández E, Rosselló J, Pou A, Escalona J and Bota J. 2015. From leaf to whole plant water use efficiency (WUE) in complex canopies: Limitations of leaf WUE as a selection target. *The Crop Journal*, **3** (3), 220-228.

Met Office 2018: https://www.metoffice.gov.uk/climate/uk/interesting/2012-drought

Met Office. 2018a: Regional climates: Eastern England. https://www.metoffice.gov.uk/climate/uk/regional-climates/ee#rainfall Accessed: 27th January 2018.

Met Office. 2018b. https://www.metoffice.gov.uk/public/weather/climate/ Accessed 5th May 2108.

Met Office. 2018c. UK Climate projections: http://ukclimateprojections.metoffice.gov.uk/

Moftah, A.E. and Al-Humaid, A.R.I., 2005. Effects of antitranspirants on water relations and photosynthetic rate of cultivated tropical plant (*Polianthes tuberosa* L.). *Polish journal of ecology*, **53** (2), pp.165-175.

Murray-Cawte KL. 2013. Dry matter production and water use of lucerne and perennial ryegrass under dryland and irrigated conditions. Thesis submitted to Lincoln University, New Zealand.

NABIM. 2017. National Drought Mitigation Center. 2013. Status of State Drought Planning. ⟨http://drought.unl.edu/portals/0/docs/10StepProcess.pdf⟩

NABIM. 2018. Wheat and flour testing. NABIM: London: http://www.nabim.org.uk/wheat-testing-at-mill-intake

Nardini A and Salleo S. 2000. Limitation of stomatal conductance by hydraulic traits: sensing or preventing xylem cavitation? *Trees*, **15**. (1) 14-24

NERC. 2018. UK Droughts and water scarcity. Available from: http://www.nerc.ac.uk/research/funded/programmes/droughts/#xcollapse1 Accessed on 27th January 2018.

NFU. 2016. Farming in East Anglia. https://www.nfuonline.com/about-us/our-offices/east-anglia/east-anglia-key-content/farming-in-east-anglia/

Novak V and Havrila J. 2006. Method to estimate the critical soil water content of limited availability for plants. *Biologia,* Bratislava, **61**/Suppl. 19: S289—S293, 2006 Section Botany DOI: 10.2478/s11756-006-0175-9.

Nyachiro JM, Briggs KG, Hoddinott J, Johnson-Flanagan AM. 2001. Chlorophyll content, chlorophyll fluorescence and water deficit in spring wheat, *Cereal Res. Commun*. **29**: 135– 142.

Ogbaga, C. C. and Johnson, G. N. 2014. Characterization of the responses of sorghum and maize to progressive drought; In *Regulation of photosynthesis in sorghum in response to drought,* pp.48 – 75.

Ouerghi, F., Ben-Hammouda, M., Teixeira Da Silva, J.A., Albouchi, A., Bouzaien, G., Aloui, S., Cheikh-M'hamed, H. and Nasraoui, B., 2015. The effects of vapor gard on some physiological traits of durum wheat and barley leaves under water stress. *Agriculturae Conspectus Scientificus (ACS)* **79** (4), pp.261-267.

Ouyang W, Struik PC, Yin X and Yang J. 2017. Stomatal conductance, mesophyll conductance, and transpiration efficiency in relation to leaf anatomy in rice and wheat genotypes under drought. *Journal of Experimental Botany*, **68** (18). 5191-5205.

Palosuo[a]Kurt T, Kersebaum C, Angulo C, Hlavinka P, Moriondo M, Olesen[f]Ravi, J Patil H, Ruget F, Rumbaur C, Takáč J, Trnka M, Bindi M, Çaldağ[j] B, Ewert F, Ferrise R, Mirschel W, Şaylan L, [j]Šiška B and Rötter R. 2011. Simulation of winter wheat yield and its variability in different climates of Europe: A comparison of eight crop growth models. *European Journal of Agronomy* **35** (3), 103-114.

Pask, AJD., Pietragalla, J., Mullan, DM. and Reynolds, MP. (Eds.). 2012. Physiological Breeding II: A Field Guide to Wheat Phenotyping. Mexico, D.F.: CIMMYT.

Passioura JB. 1997. Drought and drought tolerance. In: Belhassen E, Eds: *Drought Tolerance in higher plants, Genetical, Physiological and molecular biological analysis.* Springer Science. Pp 1-6

Peterson PR, Sheafer CC and Halla MH. 1992. Drought effects on perennial forage legume yield and quality. *Agronomy Journal* **84**, 774-779.

PROTA. 2006. Cereals and Pulses: *Volume 1 of Plant resources of tropical Africa*: ISBN 9057821702

Ragab R. Undated. A note on water use efficiency and water productivity: http://www.water4crops.org/wp-content/uploads/2014/08/RR_Water-use-efficiency-and-water-productivity.pdf

Ragab R. 2002. A holistic generic integrated approach for irrigation, crop and field management: the SALTMED model. *Environmental Modelling & Software* **17**, 345–361

Reddy, B. V., Ramesh, S., Reddy, P. S. and Kumar, A. A. 2009. 3 genetic enhancement for drought tolerance in sorghum. *Plant Breeding Reviews,* **31**. 189 – 222.

Richards RA, Rawson HM and Johnson DA. 1986. Glaucousness in Wheat: Its Development and Effect on Water-use Efficiency, Gas Exchange and Photosynthetic Tissue Temperatures. *Australian Journal of Plant Physiology* **13**(4) 465 - 473

Risi J and Galwey NW. 1991a. Genotype x environment interactions in the Andean grain crop quinoa in temperate environments. *Plant Breeding* **107,** 141-147.

Risi J and Galwey NW. 1991b. Effects of sowing date and sowing rate on plant development and grain yield of quinoa (Chenopodium quinoa) in a temperate environment. *Journal of Agricultural Science* **117** (3), 325-332.
Ritchie, J.T. 1981. Soil water availability. *Plant Soil* **58**, 327. https://doi.org/10.1007/BF02180061

Rodriguez D and Sadras V. 2008. Farming systems design and water use efficiency (WUE), challenging the French and Schultz WUE model. Grains Research and Development Corperation Update papers. Australian Government.

Roques SE, Kindred DR and Clarke S. 2017. Triticale outperforms wheat on a range of UK soils with a similar nitrogen requirement. *Journal of Agricultural Science* **55** (2), 261-281.

Sade N, Gebremedhin A and Moshelion M. 2012. Risk-taking plants: Anisohydric behaviour as a stress-resistance trait. *Plant signalling and behaviour* **7:7**, 767-770.

Sadras V O and Angus J F. 2006. Benchmarking water-use efficiency of rainfed wheat in dry environments. *Australian Journal of Agricultural Research*, **57**, 847–856.

Sage RF and Kubien DS. 2007. The temperature response of C3 and C4 photosynthesis. *Plant, Cell and Environment* **30**. 1086 – 1106.

Saini, H.S. and Aspinall, D. 1981. Effect of water deficit on sporogenesis in wheat (*Triticum aestivum* L.). *Annals of Botany*, **48** (5), pp.623-633.

Saini, H.S. and Westgate, M.E., 1999. Reproductive development in grain crops during drought. *Advances in agronomy*, **68.** 59-96.

Sanders G.J., Arndt S.K. 2012. Osmotic Adjustment Under Drought Conditions. In: Aroca R. (eds) *Plant Responses to Drought Stress*. Springer, Berlin, Heidelberg. 199-229.

Serraj R and Sinclair TR. 2002. Osmolyte accumulation: can it really help increase crop yield under drought conditions? *Plant, Cell and Environment* **25,** 333-341.

Sharma B, Molden D and Cook S. 2015. Water use efficiency in agriculture: Measurement, current situation and trends, In: *Managing Water and Fertilizer for Sustainable Agricultural Intensification:* International Fertilizer Industry Association (IFA), International Water Management Institute (IWMI), International Plant Nutrition Institute (IPNI), and International Potash Institute (IPI).

Sinaki M., Heravan E., Shirani Rad H., Noormohammadi G., Zarei G.H. 2007. The effects of water deficit during growth stages of canola (*Brassica napus* L.). *Am.-Euras. J. Agr. Environ. Sci.* **2**: 417-422

Sinclair T.R. & Ludlow M.M. 1986. Influence of soil water supply on the plant water balance of four tropical grain legumes. *Australian Journal of Plant Physiology* **13** (3), 329–341.

SLU. 2017. Fast growing durum wheat for hot climate receives innovation prize. https://www.slu.se/en/ew-news/2017/11/fast-growing-durum-wheat-for-hot-climate-receives-innovation-prize/

Smith R. 2012. Perennial ryegrass growing in Tasmania. Wealth from Water factsheet.

Sobeih WY, Dodd IC, Bacon MA, Grierson D and Davies WJ. 2004. Long distance signals regulating stomatal conductance and leaf growth in tomato (*Lycopersicon esculentum*) plants subjected to partial rootzone drying. *Journal of Experimental Botany* **55**, 2353-2363.

Stagnari, Fabio & Galieni, Angelica & Pisante, Michele. 2016. Drought stress effects on crop quality. 375-392. 10.1002/9781119054450.ch23

Stanhill G. 1986. Water use efficiency. *Advances in Agronomy* **39**, 53-85.

Steduto P. 1996. Water Use Efficiency. In: Pereira L.S., Feddes R.A., Gilley J.R., Lesaffre B. (eds) *Sustainability of Irrigated Agriculture*. NATO ASI Series (Series E: Applied Sciences), **312**. Springer, Dordrecht

Stewart R, Dossena M, Bohan D, Jeppesen E, Kordas R, Ledger M, Meerhoff M, Moss B, Mulder C, Shurin J, Suttle B, Thompson R, Trimmer M and Woodward G. 2013. Mesocosm Experiments as a Tool for Ecological Climate-Change Research. *Advances in Ecological Research*, **48**; 78 – 181.

Takahashi F, Suzuki T, Osakabe Y, Betsuyaku S, Kondo Y, Dohmae N, Fukuda H, Yamaguchi-Shinozaki K, and Shinozaki K. 2018. A small peptide modulates stomatal control via abscisic acid in long-distance signalling. *Nature*; DOI: 10.1038/s41586-018-0009-2

Tardieu F and Simmonneau T. 1998. Variability among species of stomatal control under fluctuating soil water status and evaporative demand: modelling isohydric and anisohydric behaviours. *Journal of Experimental Botany* **49,** 419-432.

Tezara W, Mitchell VJ, Driscoll SD and Lawlor DW. 1999. Water stress inhibits plant photosynthesis by decreasing coupling factor and ATP. *Nature,* **401**. 914-917.

Thrapa S, Reddy SK, Fuentealba MP, Xue Q, Rudd JC, Jessop KC, Devkota RN and Lui S. 2018. Physiological responses to water stress and yield of winter wheat cultivars differing in drought tolerance. *Journal of Agronomy and Crop Science* **20** (4). 347-358.

Turner, N.C., 2004a. Sustainable production of crops and pastures under drought in a Mediterranean environment. *Annals of Applied Biology*, **144**(2), pp.139-147.

Turner, N.C., 2004b. Agronomic options for improving rainfall-use efficiency of crops in dryland farming systems. *Journal of Experimental Botany*, **55** (407), pp.2413-2425.

UKIA. 2018. UKIA news bulletin July 2018. UK Irrigation Association. Bedford: Cranfield University. www.ukia.org/contact

Vilagrosa A., Chirino E., Peguero-Pina J., Barigah T., Cochard H., Gil-Pelegrín E. 2012. Xylem Cavitation and Embolism in Plants Living in Water-Limited Ecosystems. In: Aroca R. (eds) *Plant Responses to Drought Stress*. Springer, Berlin, Heidelberg

Vincente A. 2017. Spain, Portugal struggle with extreme droughts: https://phys.org/news/2017-11-spain-portugal-struggle-extreme-drought.html

Wakrim R, Wahbi S, Tahi H, Aganchich B and Serraj R. 2005. Comparitive effects of partiual rootzone drying (PRD) and regulated deficit irrigation (RDI) on water relations and water use efficiency in common bean (*Phaseolus vulgaris* L.). *Agriculture, ecosystems and environment* **106**, 275-287

Wasson AP, Richards RA, Chatrath R, Misra SC, Sai Prassad SV, Rebetzke GJ, Kirkegaard JA, Christopher J and Watt M. 2012. Traits and selection strategies to improve root systems and water uptake in water-limited wheat crops. *Journal of Experimental Botany* **63** (9): 3485-3498.

Weber, L.E. (ed.) 1990. Amaranth grain production guide. Rodale Press, Emmaus, PA.

Weerasinghe, M.M., Kettlewell, P.S., Grove, I.G. and Hare, M.C., 2016. Evidence for improved pollen viability as the mechanism for film antitranspirant mitigation of drought damage to wheat yield. *Crop and Pasture Science*, **67** (2), pp.137-146.

Williams JT and Brenner D. 1995. Grain amaranth (*Amaranthus* species) in: Williams JT (ed) *Cereals and pseudocereals*. London: Chapman and Hall. Pp. 129 – 186.

Xu Z and Zhou G. 2008. Responses of leaf stomatal density to water status and its relationship with photosynthesis in grass. *Journal of Experimental Botany* **59** (12). 3317-3325.

Yamamoto Y. 1990. Studies on transplanting injury in rice plants. VII. Effects of antitranspirant and irrigation water depth on the transplanting injury, rooting and early growth. *Research Reports of the Kochi University, Agricultural Science* **39**, 35-47

Zadoks, J.C., Chang, T.T. and Konzak, C.F., 1974. A decimal code for the growth stages of cereals. *Weed Research*, **14** (6), pp.415-421.

Zhang J, Nguyen HT and Blum A. 1999. Genetic analysis of osmotic adjustment in crop plants. *Journal of Experimental Botany*, **50** (332). 291–302,

Zhang J, Wensuo J, Jianchang Y and Aldelbagi M. 2006. Role of ABA in integrating plant responses to drought and salt stresses. *Field Crops Research* **97**, (1). 111 - 119

Figure A 1.1 Growth differences between Lucerne and PRG in the HAU mesocosm experiments in September 2017

Figure A 1.2. Excessive growth seen for quinoa growing in the HAU mesocosms at HAU during September 2015