DROUGT IMPACTS ON AGRICULTURAL AND HORTICULTURAL CROPS

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About Drought

Headlines

- The effects of drought in UK agriculture is intrinsically linked to the duration and intensity of the drought and thus our ability to compensate or tolerate in the short or long term.

- The regional nature of past UK droughts complicate the prediction of their occurrence, intensity and overall UK impact and thus undermine long-term planning at both the farm and government level.

- Crop response to drought is always reduced production and quality but the potential to ameliorate these losses with irrigation is only feasible if water resources are both available and financially rewarding.

    - Irrigation of field vegetables and high value crops is implicit, economically viable and required to attain buyer specifications.

    - Broadacre crops would benefit from irrigation to protect yield and quality but it is seldom economic and often has no infrastructure in place.

    - Forage crop production would benefit from irrigation to protect both in-season and winter forage production, but it is never economic and not supported by the necessary infrastructure.

- The timing of drought will be critical for the yield penalties accrued by crops; drought initiating post April, and following an ‘average’ winter, will have significantly smaller effect on winter sown combinable crops than spring-sown, having passed critical growth stages.

    - Yield losses have been reported in wheat as c. 10 – 45%, which at current production would give losses of between 1.5 to 6.75mt valued currently at £255m – 1.147billion and leading to a home consumption deficit up to 43%.

    - OSR yield losses are reported between 15 – 85% when water stress occurs during flowering and pod-fill which equates to production losses of up to 1.76mt at a value of £644m. With UK production in 2017 of 91% of our use any yield loss would substantially increase our need to import.

    - Barley production appears to be significantly less affected by water-stress with only 12-18% reductions noted during the 1976 drought. Based on 2017 UK production a maximum yield loss of 1.3mt would occur with farm gate values of £134m. As 1.8mt of barley are used in the brewing/distillery industry the ultimate loss of value would be significantly greater.

- Spring planted root crops such as potatoes and sugar beet will be planted into drying soils which will reduce establishment and, where no or reduced irrigation is available, will senesce early and produce significantly lower yields.

  - The response of Sugar beet to early drought is suggested as 27.5% whereas only 12.5% to later drought. Yield loss at 2017 root production of 8.9mt the losses would be 1.11 to 2.45mt, equating to approximately 0.2 to 0.44mt sugar which would substantially increase our sugar import requirements.

  - Yield loss in main-crop potatoes during the 1976 drought was reported as c. 40% which at 2017 production equates to a loss of 2.48mt and farm gates losses at £359m. However, the UK potato industry is valued at £4.7bn in the UK economy and so the overall financial effect of crop loss could be significantly greater. The effect of the 2018 summer drought was reported to be up to 20% loss which equates to 1.24mt and £179m at the farm gate.

- Horticultural crops:
  - Key findings from the summer drought in Ireland were that significant horticultural crop failures occurred: broccoli and cauliflower showed poor growth with crops being rotavated in, broccoli also showed variable maturity and an estimated crop loss of 25%, cabbage production was reported to be reduced by 70%, irrigated onion sets showed reduced yield and size, salad onions had reduced germination and were patchy, irrigated iceberg lettuce grew well but hot temperatures caused head deterioration and further yield losses, non-irrigated swedes bolted and split along with boron deficiency which reduced saleable yield, carrot size and quality were reduced, parsnips had uneven germination and up to 30% of the crop was classed as poor, irrigated celery developed well but suffered blackheart due to heat stress, leek crops were backward even where irrigated with an estimated 15% crop loss which was also heat related. Yield loss in lettuce in rain-fed UK conditions would be expected to be up to 50% but the reality of not meeting buyer requirements by failure to irrigate would make this substantially higher. Overall the effects of a significant, even short, drought on fresh-produce production are substantial should irrigation not be available.

- Effect on established forage grass crops would be small initially but regrowth after grazing or cutting would be substantially lower throughout the remainder of the year, leading to use of stored winter forage to maintain productivity, inability to conserve forage for the coming winter and with significant impacts on both milk and beef production over the current season and following winter. Growth of alternative spring planted forage such as maize would also be substantially reduced leading to further loss of conserved forage for the following winter.

    - Yield losses reported for 2018 were 25% for silage which was limited initially by a very good first cut before the onset of the drought. For Hay a 40% reduction was reported as these crops are cut later, cut only once and taken during the developing drought in June. The production values were not given for the 1976 drought but grass growth was reported as negligible in the South of England, with many areas completely desiccated.

    - As milk and beef production is also linked to forage/fodder crop usage the quantification of the effects is complex as forage stocks and growing forage crops are used during droughts to supplement any shortfalls which postpone the impacts.

- Where drought is initiated pre-winter or continuing from a preceding summer-drought the effects will be additive and substantial for a wider range of crops. The establishment of winter sown cereals and other broadacre crops, e.g. oilseed rape and beans, will be problematic in dry seedbeds leading to use of higher seed rates and delayed sowing in an effort to compensate for poor seedbed conditions. The crops will then be subjected to significantly more negative soil moisture over all of the critical growth phases, leading to substantial yield reductions:

    - Yield loss in these crops would be additional to the losses reported for a summer-drought alone as already reported.

- The effect on the horticultural/vegetable crops would initially be seen from longer season crops such as carrots and onions where the extended drought would substantially reduce yields:

    - Water stress at any growth stage of onion growth reduces marketable yield and quality and with single stage water-stress reducing yield by >25% a longer term drought would substantially increase this loss.

    - Most carrot crops need 30-50mm of water per week, 450 - 600mm per season, and if irrigation cannot be applied when soil moisture has depleted by 40% the yield and quality of these crops would be expected to substantially reduce the production of 886,000t and value of £151m seen in 2017.

- Effects on top fruit production would equally vary with the duration and intensity of the drought but initial effects may be lessened where larger and more established root masses exist. Once soil moisture has been depleted to greater volumes and depths the losses would become more pronounced:

    - Yield loss in apples under developing early season drought, late-march to mid-June, reduces vegetative growth, leaf area and fruit set leading to substantial yield loss. Although a drought beginning only post summer would not significantly reduce yield, if the drought continues into the winter, as in 1976, significant impacts on the early growth of all orchard crops would lead to substantial reductions in fruit set, growth, yield and quality in the following year.

    - Soft fruit such as strawberries, raspberries, blueberries are all intensively irrigated and production would fall relative to restrictions of abstraction.

    - Yield loss in strawberries would be expected to be significant even when small water deficits occur, with class 1 losses reported of between 6 – 50% with limited stress from reduced irrigation. With output for soft fruit given as £541 million for 2017, a 50% reduction from moderate stress would cost the production industry £270m.

    - Raspberries had a crop value of £128m in 2017 and their shallow rooting behaviour requires a regular and uniform water supply from fruit set to harvest if yield loss is to be avoided. Although the plants have moderate tolerance of short water stress, longer periods affect phenological timing and also reduce yield by up to 38% in the following season.

    - Blueberries are highly sensitive to water-stress with rapid transpiration, stem diameter and shoot elongation reductions. In all water-stress conditions mean fruit weight and size decline and when stress occurs during flowering-induction in one year the number of flowers and thus the number of fruit and yields also decline in the following year.

    - Tomato production in the UK is worth £190m and their sensitivity to water-stress has been reported widely for many years. As with most crops the water-stress response will be associated to the timing and severity of the stress and the drought tolerance of the cultivar. Symptoms include physiological and morphological such as flower shedding reduced fruit size, increased fruit splitting, plus physiological disorders such as blossom end rot (BER). Water stress at 65 and 85% of available water significantly reduces yield and fruit size. Severe water-stress, applied when only 25% of ET was replaced during the reproductive stages showed yield reductions of between 40% with a drought tolerant cultivar compared to 90% in another cultivar.

- Hardy nursery stock and flower production are also intensively irrigated and the impacts on production would vary with plant species as some are more drought tolerant than others. With the industry production output for the plant and flower sector given as £1.35 billion and Hardy nursery stock accounting for £933 million. Yield and financial loss in these industries in the absence of adequate irrigation would be substantial.

- In addition to the summer drought impacts on all crop yields there is the added challenge of winter droughts whereby any abstraction restrictions which prevent re-filling of farm reservoirs would exacerbate the likely impacts of continuing droughts. With a subsequent spring drought further abstraction restrictions would continue to apply and crop failure in key producing areas such as Yorkshire and the Humber, the Midlands, South East, south west, and south of England would occur.

- One of the greatest problems for UK growers, unlike our Australian counterparts, is the excessively variable nature of our weather and the difficulty in providing longer term predictions to aid timely crop production decisions. Consequently with the approaching and longer term temperature rises and potential summer-drought increases the protection of production of the regional, often climatic, biased horticultural sectors requires that countrywide infrastructure is improved/created to move water from high rainfall to low rainfall areas. Many of the decisions for growers are made several months before planting as seed must be purchased, contracts agreed and land prepared. It is almost impossible to change cropping at anything less than four months prior notice before planting and impossible once planted.

Increased winter rainfall

Climate change for the UK has mainly been discussed in terms of increased temperatures, decreased summer rainfall and increased summer drought. However, the UK climate projections also highlight the increased winter rainfall which could play an crucial part in replenishing soil-moisture reserves and potential for substantial quantities of abstraction water for refilling farm-scale reservoirs. This overall effect therefore could be mixed with moderate yields for crops established pre-winter, moderate to severe yield losses for spring planted broadacre crops, variable yield and quality of irrigated cropping related to availability of summer abstraction, and difficult or late-planting of winter sown crops before soil moisture is replenished.

Response to elevated CO_2

Historically the atmospheric CO_2 concentration over the last 400,000 years has fluctuated between 200 to 280ppm. Recent records however show atmospheric CO_2 concentrations rising from *c.* 315ppm in 1960 to 409ppm currently (February 2019). The upward trend is linked to human activity and it was suggested that CO_2 concentrations could rise to between 500 – 1000 ppm by 2100 (IPCC, 2007).

- As part of essential plant functioning carbon dioxide, CO_2, is taken up into the plant from the atmosphere via stomata and is used in photosynthesis to produce chemical energy in the form of 3C or 4C sugars from C3 and C4 plants. As the rate of photosynthesis is CO_2 concentration dependent it is suggested that crop yields could increase by up to 30% at atmospheric CO_2 of up to 1500ppm.

- The C_3 plants include grasses, cereals, potatoes and the majority of horticultural plants in the UK and have a low response to elevated CO_2 concentration. Total grass biomass increases of 33% for C4 and 44% for C3 species at CO_2 concentrations at 550 – 750 µmol mol^{-1} have been reported whereas onion bulb dry weight increased from 35-45% when the air was enriched from 372 to 532 ppm. Similarly, spring wheat yield increased by 36% with enriched CO_2 but grain quality and protein decreased. However, although the response of crop, pasture and legume yields will increase by 10-20% for C3 plants in unstressed (non-droughted) conditions at 550 ppm CO_2 this would only occur if sufficient nitrogen and water were not limiting, i.e. not droughted. Using the current UK crop production figures as the benchmark response to current levels of CO_2 therefore it is likely that UK crop yields would increase in line with elevated CO_2 concentration but this would only occur where sufficient water and crop nutrition is not limiting the response.

- A useful benefit from increased CO2 however is that water loss by plants is intrinsically linked to stomatal opening and with elevated atmospheric CO_2 there will be reduced stomatal opening and a commensurate decrease in water use which could partially mitigate the impact of projected reduced rainfall.

Response to increased temperatures

The climate change projections from UKCP09 and UKCP18 include scenarios which suggest temperature increases between 0.1°C in the lowest projection and 6.1°C for the highest projection of increased CO_2 emissions. As the majority of crops in the UK are classified as C3 the optimum temperature range for photosynthesis and growth is given as 10 - 25°C which is substantially lower than for C4 plants at 30 - 45°C. Consequently any significant temperature increases above our current averages is likely to take us beyond the temperature optima for most of our crops and closer to the C4 requirement. Before average temperature increases become significant however, short summer temperature increases may substantially affect crop growth at key times by creating heat stress. Similar to water-stress, the effects of heat-stress are linked to both the timing and duration of the stress where the heat-killing effect of a stress temperature varies inversely in an exponential manner with time. In addition, the growth stage of the plant at the time of stress is also important when identifying the critical temperature or duration of heat and its ultimate effect on growth or yield. To complicate the issues it has also been shown that genotypic differences occur within species and that it is also necessary to separate the effects of drought and heat as they generally exist at the same time.

- In the longer term we may therefore require us to shift our cropping patterns in favour of C4 plants where applicable.

- The increase of daily or weekly temperatures may become be more of a concern during the higher temperatures in summer months. Some of these key effects have been identified and incorporated into the drought section of each crop to clarify potential problems.

Key areas of research or actions required

- Development of robust drought tolerance assays to enable drought tolerance to be investigated and reported in recommended variety lists of all key UK crop and varieties.

- Consolidation of information and further research on agronomic drought resilience measures, anti-transpirants, soil cultivation and soil-amendment practices including super-absorbent polymers.

- As the majority of our knowledge of crop responses to drought have been achieved with glasshouse or controlled environment experiments this information needs significant support from field based experiments in order to clarify responses.

- Unbiased consolidation of information pertaining to agricultural systems sustainability with respect to soil health, crop production, energy efficiency and financial credibility.

- Continued research required to further increase on irrigation use efficiency to make better use of the water resources.

- Improved UK water movement infrastructure to facilitate water availability and irrigation in key fresh-produce and fruit growing areas.

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1. Research context

The UK Drought and Water scarcity programme is a £12 million+ Natural Environment Research Council (NERC) programme, in collaboration with ESRC, EPSRC, BBSRC and AHRC. The rationale behind the program 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).

2. Introduction

The UK agricultural sector supports a labour force of some 466,000 people on commercial holdings and has a total income from farming (TIFF) of £3,610 million. The gross value added at basic price, thus representing contribution to GDP, was £8,196 million. The total numbers of pigs was 4.9 million, cattle and calves 10 million plus a dairy herd of 1.9 million, 33.9 million sheep and lambs, 173 million poultry, all of which relying on drinking water from rainfall or pumped mains supply. Unlike crops which can exist for weeks, if not months, utilising soil water reserves, animals need a regular daily supply of accessible drinking water to regulate body temperature and maintain organ functions such as digestion, waste removal and the absorption of nutrients (Ward & McHague, 2007). Some species have adapted mechanisms to cope with long periods without water but the majority need a constant daily intake. The value of some key outputs from the industry are given as; harvested wheat £1.6 billion, vegetable production of £1.5 billion, mutton and lamb £1.16 billion, milk and milk products £3.3 billion and eggs £603 million (Defra, 2017a). Overall therefore there is considerable requirement for an adequate clean/usable water supply for the agricultural industry crop and animal production.

The requirement within this task was to "consolidate knowledge on the impact of drought on crops grown in the UK and their response to different climate futures". Where helpful however, responses in non-UK crops will be utilised. The crops selected for review are based on those reported in the Defra Agricultural statistics (Defra, 2017) arable crops section: wheat, barley, oats, rye, triticale, Oilseed rape, Linseed, Potatoes, sugar beet (not fodder beet), peas, beans and forage maize, plus grassland as its impact on forage/fodder production, and key elements of the fresh produce, horticulture and orchard fruits sectors. In addition, as higher temperatures also occurs during drought this is included within crop responses. The crop responses to elevated CO_2 and climate change generally however has been included after the main cropping section as the work is either modelled or, in the case of CO_2, completed in 'managed' systems.

2.1 Drought and drought in the UK

“A drought impact is an observable loss or change at a specific time because of drought” (World Meteorological Organisation, 2016). In crop production drought is one of the most widespread causes of yield loss (Kumar *et al.,* 2017). Plants respond to reduced water availability/drought in varying ways and utilise several mechanisms to protect cellular functioning whilst under stress. However, the fundamental conundrum is balancing stomatal closure to restrict water-vapour loss whilst maintaining uptake of CO_2 for dry-matter production notwithstanding the necessity for the associated uptake of nutrients (Hu and Schmidhalter, 2005; He and Dijkstra, 2014) and plant metabolic processes. In addition, the significant effect of water-stress is often linked to key growth phases/periods during its development which produce reductions in the potential to produce not only a maximum or economic optimum yield but also a usable yield (Kumar *et al.,* 2017). These phases may be quite short or may extend for most of the growth of the plant as reported by Farooq (2009), Balla *et al*. (2011), Weerasinghe *et al*. (2016) and Faralli *et al.* (2017). The yield of potatoes can initially be affected by rate of emergence, the number of tubers set during tuber initiation, and once initiated, maximum yield can only be achieved by a regular supply of adequate water to maintain canopy growth and tuber bulking until harvest (Monneveux *et al.,* 2013; Obidegwu *et* al., 2015; Daryanto *et al*., 2016). Commercial transplanted lettuce crops need near field capacity soil moisture during the transplant, early growth and main growth periods (ADAS, 2007). All crops have a minimum standard that is required for their end market and drought during key growth phases may adversely affect the quality. Cereals are governed by mill intake to ensure minimum standards in respect of physical quality characteristics including grain size and grain fill as determined by hectolitre weight (NABIM, 2018). Unlike many cereal crops however, which are never seen by the end consumer, fresh produce is heavily influenced by visual aspects and buyer protocols which include size, shape and skin finish and blemishes in potatoes (Sterns *et al.*, 2001; Hingley *et al.*, 2006, OECD, 2018). Yield variability between years also makes estimating yield loss to drought problematic when separating natural variability from drought response, figure 2.1.

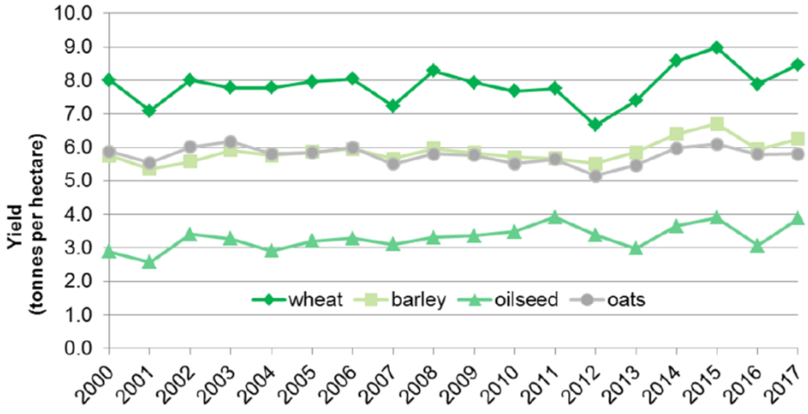
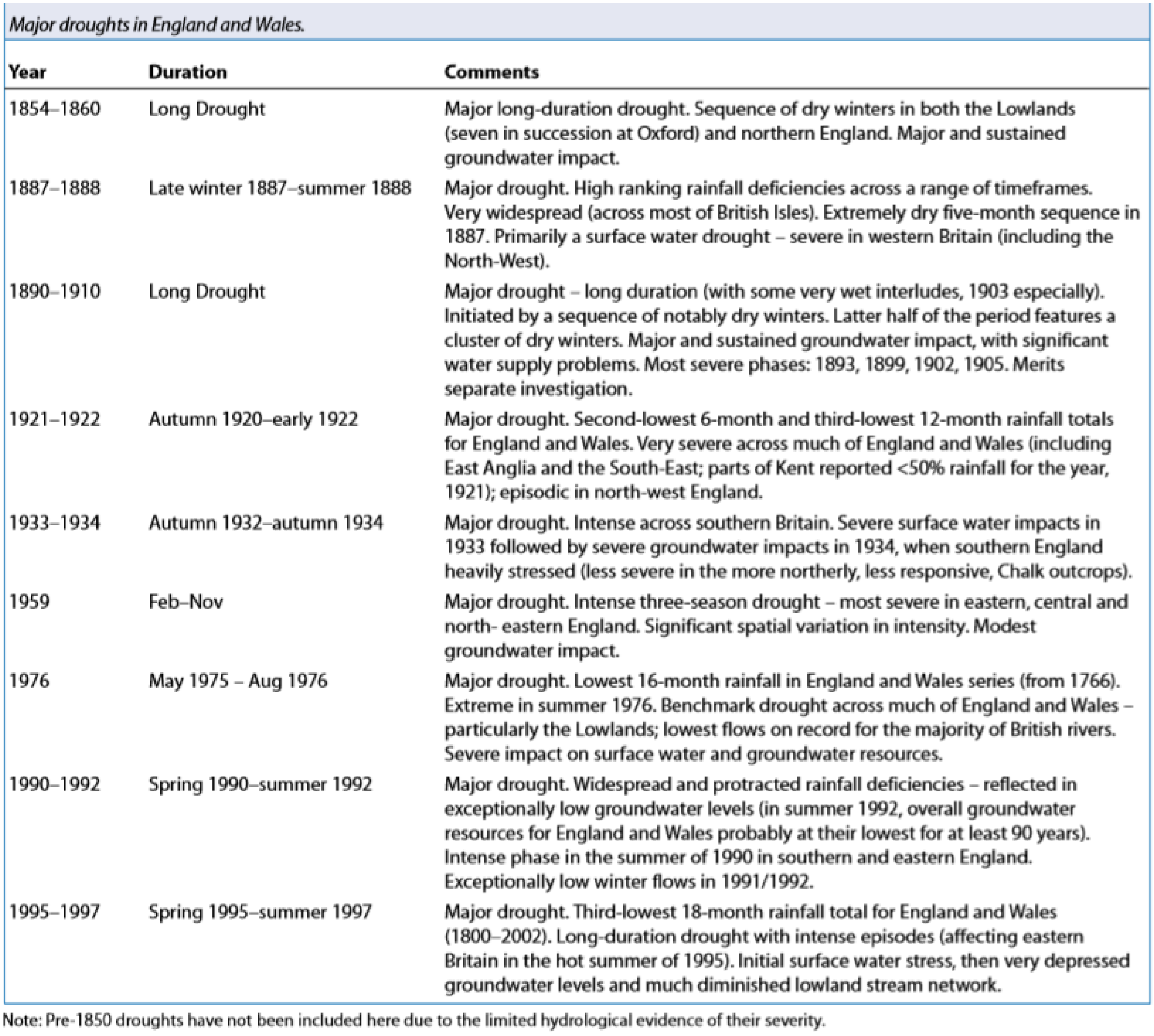


Figure 2.1. Variability of key UK crop yields (t/ha) 2000 – 2017 (Defra, 2017)

These observations are supported historically by MacKay *et al.* (2011) who reported the variability seen from 1948 - 2007 and Talbot (1984) who demonstrated normal yield variability of crop varieties in the same and different UK environments from 1968 – 1980, from over 1000 trials.

Historically. the most recent drought for which analysis has been reported, 2010 – 2012, estimated a 15% reduction of potato yield and overall farming losses of £400 million (Anglian Water and University of Cambridge, 2013). The most recent drought however occurred during the production of this work in the summer of 2018 and any estimations published have been recorded in appropriate cropping sections. Key drought events in the UK have been recorded, table 2.1, 2.2 and the 2018 situation across Europe, figure 2.2

Table 2.1. Major droughts in England and Wales 1800-2018
Adapted from Marsh *et al.,* 2007.



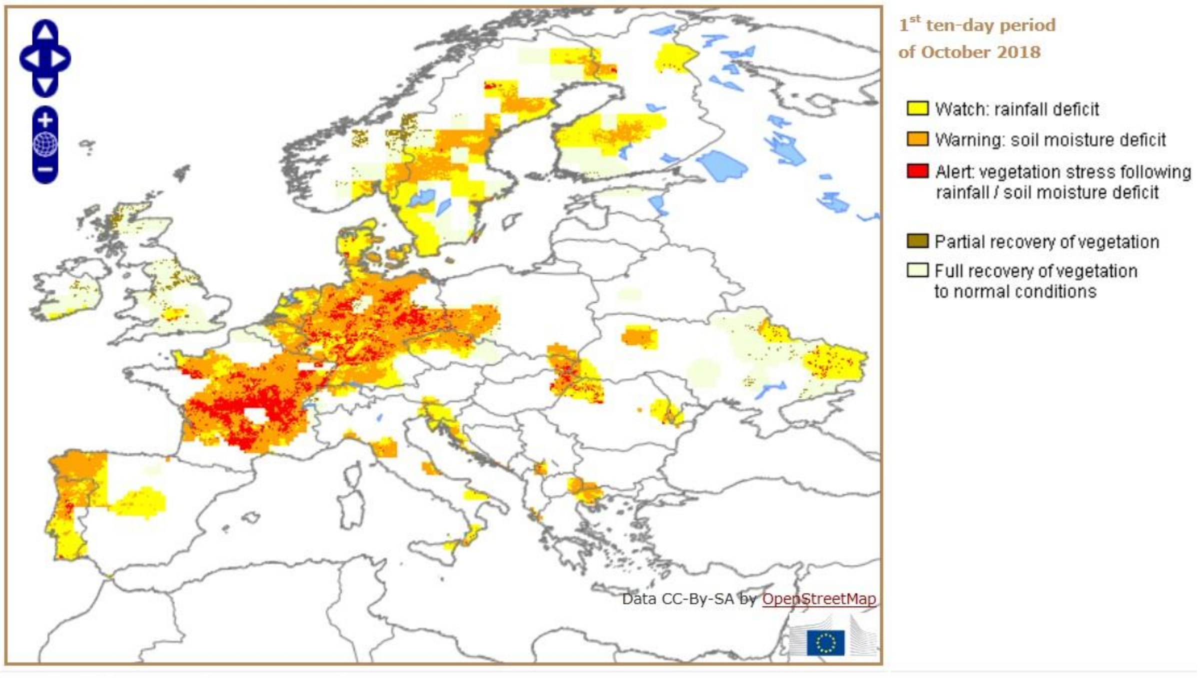
Major droughts in England and Wales.

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.

Table 2.2 Additional droughts in England and Wales 2004 - 2018 (Adapted from Kendon *et al.* 2013; Met Office, 2018; Hanniford, 2018)

2004 -2006		Strong regional focus recognised resulting from a sustained exaggeration in the normal north-west–south-east rainfall gradient across the UK. Accordingly, drought severity in the summers of 2005 and 2006 was greatest in the English Lowlands, the South-East especially
2010-2012	Winter 2009/10 to March 2012	“The exceptionally dry spring of 2011 had adverse effects on agriculture and the environment, with eastern counties worst affected. Conditions were difficult for both livestock farmers and growers”. Many farm reservoirs were well below capacity. Eastern counties worst affected in spring 2011 with this area extending to west-midlands and
2018	April 2018 – Ongoing August 2018	Classified more as a summer drought due to the wet preceding spring



Combined Drought Indicator, based on SPI, soil moisture and fAPAR.

Figure 2.2 European Drought Observatory map of droughts October 2018 (source EDO, 2018)

The potential for UK crops to experience drought was also stated by Foulkes *et al*. (2001) that of the 1.9 million ha of land used for wheat in the UK at that time, 457,000 ha were on shallow or sandy soils which are easily droughted but the majority of all of the crops would encounter drought in drier years. Similarly Gale (1983) believed that clay soils would prove more problematic in dry years as although they held more total water a significant proportion was held at tensions outside of the easily available limit of 0.2 MPa making crops stressed even though soil moisture was present.

Daccache *et al.* (2015) also highlight the issues facing the UK growers in dry periods as irrigation requirements, seldom exceeding 1% of total freshwater withdrawals, increase during dry weather but abstraction can be prevented. However, when total on-farm abstraction is in excess of 300Mm^3 year and 60% is used for crop-irrigation (Knox, 2005), which returns little back to source, conflicts are inevitable. Unfortunately the water is always required for irrigation during the driest and hottest months and also in catchments already at or above their abstraction limits.

As droughts are generally part of a more complex environmental situation the direct yield effects of crop water-stress can become difficult to entangle. Figure 2.3 highlights the potential yield offset by increased solar radiation and thus Ps in the moist but drying soil in May and June, before soil moisture became limiting during the grain fill period.

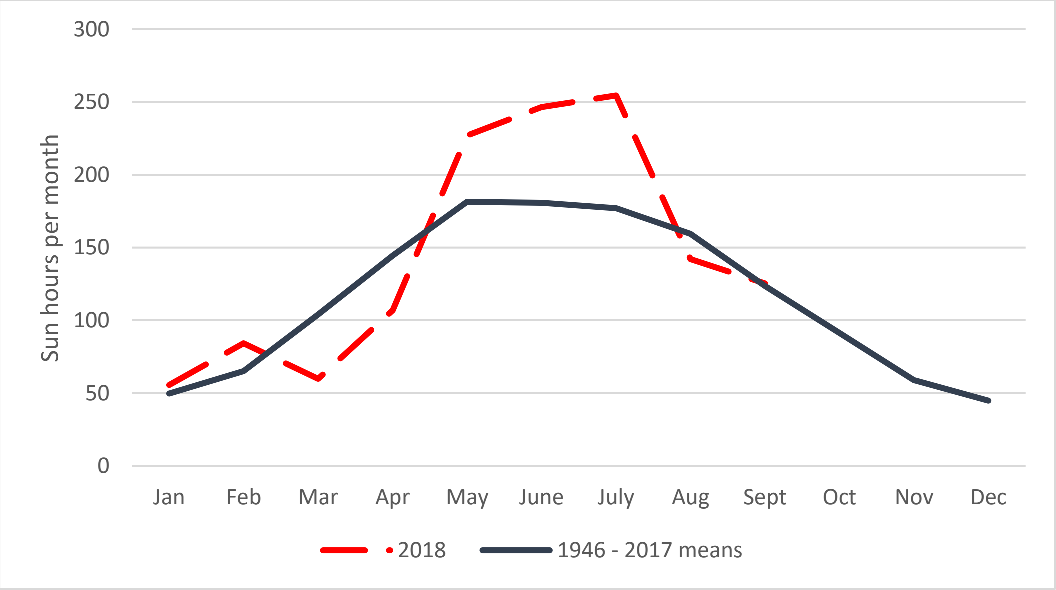


Figure 2.3 Sun hours per month recorded at Sutton Bonnington (CE) in the 'drought' year of 2018 compared to the means for 1946 – 2017. (Adapted from Met Office data 2018).

For the UK droughts however, consideration must also encompass the regional nature of past droughts, tables 2.1 and 2.2, and the regional nature of key agricultural production, table 2.3. The South west and North West have 62% of the dairy industry which relies heavily on good grassland production for forage. The East of England contributes 30% of field vegetables, 35% of the potatoes, 62% of sugar beet and 28% wheat, 23% barley and 24% of the OSR. Whereas the South East contributes 43% of both top and small fruits.

Table 2.3. Regional percentage areas of key agricultural enterprises relative to area of enterprises in England (Adapted from Defra, 2018d)

Region	Field Veg	Pots	Glass house	HNS	Sugar beet	Top fruit	Small fruit	Wheat	Barley	OSR	Dairy	Beef
North East	1	1						4	5	4	1	10
North West	5	7						2	5		24	12
Yorkshire Humber	15	17	13					14	15	14	7	12
East Midlands	30			24	23			20	14	26		
West Midlands		14				31	24	10	8		14	12
East of England	30	35			62			28	23	24	1	6
South East			25			43	43	13	13	13	6	10
South West				32		15		9	17	9	38	27

Notes: HNS Hardy nursery stock, Pots potatoes, OSR Oilseed rape)

Water needs of crops

Indicative values of water needs of crops and their sensitivity to drought are well documented, ranging from cereals at 450 – 650mm with low – medium sensitivity, to cabbage 350-500mm with medium to high sensitiy (Brouwer & Heibloem, 1986). Aldrich *et al.* (1975) also showed this diagrammatically as the quantity of water (kg or lbs) required to produce one kg (or lb) of dry matter, figure 2.4, which gives an broad indication of the water productivity of the crops. This report will therefore not include detailed discussions on this topic but focus on the response of the crop to drought, drying soil moisture and lack of rainfall or irrigation in protected crops.

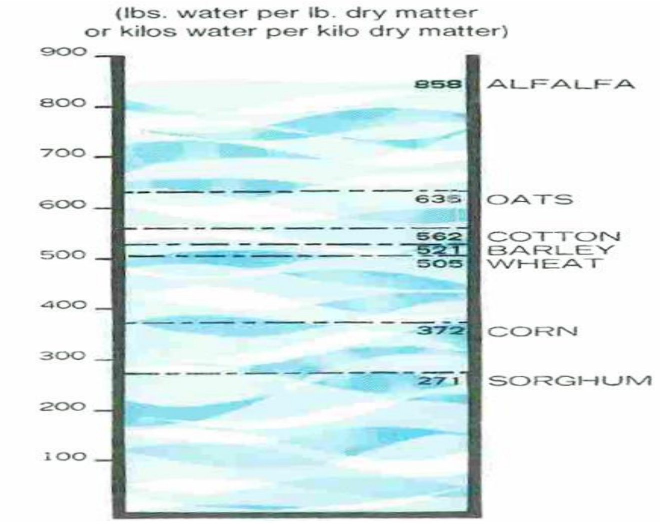


Figure 2.4 Water transpired by plants (kg or lbs) by several crops to produce one kg (lb) of dry matter in stems, leaves and seeds (Aldrich *et al.*, 1975).

2.2 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 is '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 4.77 million ha of arable and horticultural crops, of which 3.2 million ha were cereal crops, which includes 1.8 million ha of wheat and 1.2 million ha of barley, the dominant crops by volume and area in the UK (Defra, 2018), key crops are listed, table 2.4. Most of the UK cropping is classed as rain-fed with only 5% of crops in England and Wales irrigated (Knox, undated).

Table 2.4 Key crops grown in the UK by land area, production amount and use. (Source Defra, 2017a, 2017b, 2018)

Crop	**Area '000 ha**	**Production '000t**	**Irrigated in UK**	**Main uses**
Wheat	1, 823	14, 084	No	Bread, biscuits and animal feed
W. Barley S. Barley	394 762	2, 711 3, 895	No	Brewing and animal feed
Oats	174	857	No	Milling & animal feed
Minor cereals	51	194	No	Rye, triticale & mixed corn.
Oilseed rape	601	2,051	No	Cooking oil, lubricants & biodiesel
Linseed	27	48	No	Technical oils & animal feed
Sugar beet	116	5, 687	Yes	Sugar, animal feed & bioethanol
Field beans	177	649	No	Animal consumption (human consumption not included)
Potatoes	142	5, 373	Yes	All food uses (not stockfeed)
Fresh Veg	117 (a) 1 (b)		Yes Yes	Cabbages, carrots, cauliflower, calabrese, lettuce, mushrooms, onions & tomatoes.
Fresh fruit	24.2 (c) 10.8 (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.

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.

3. Arable Crops

3.1 Common wheat (*Triticum aestivum*)

UK production

Wheat is grown on 1.8 M ha in the UK and produced 14 Mt in 2016 (Defra, 2017) with an indicative water requirement of 450-650 and is suggested as having a low-medium sensitivity to drought (Brouwer C & Heibloem, 1986). Wheat or common wheat in the UK can be split into the broader categories of 'bread, biscuit or feed wheats' and to a significantly lesser extent pasta, durum, wheat. The crops can also be split into winter and spring varieties which can influence their susceptibility to timing and duration of drought.

The production of wheat across the UK however is not even which confounds the issues of climate/rainfall impacts/projections across the country. The greatest volume of production, 3,187,000t is in the Eastern region, whereas the lowest is in Northern Ireland (60,000t), Wales (176,000t) and the North west/Merseyside area (246,000t), figure 2.5.

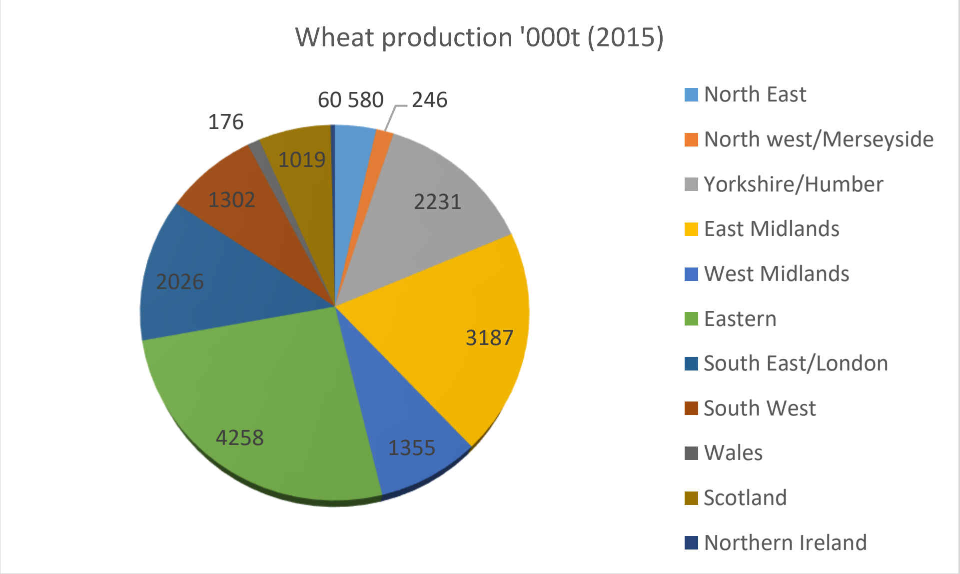


Figure 2.5 UK wheat production by region and volume ('000t). (Source Defra, 2016)

The greatest volume of production does not equate directly to greatest yield per ha, figure 2.6, as differences in rainfall, solar radiation, soil type and winter or spring cropping which all contribute to the complexity of the interpretation and effects. The droughts of 2004-2006 were very regional and did not affect the overall national yield based on an exaggeration of the normal North-West-South-East rainfall gradient (Marsh *et al*., 2007).

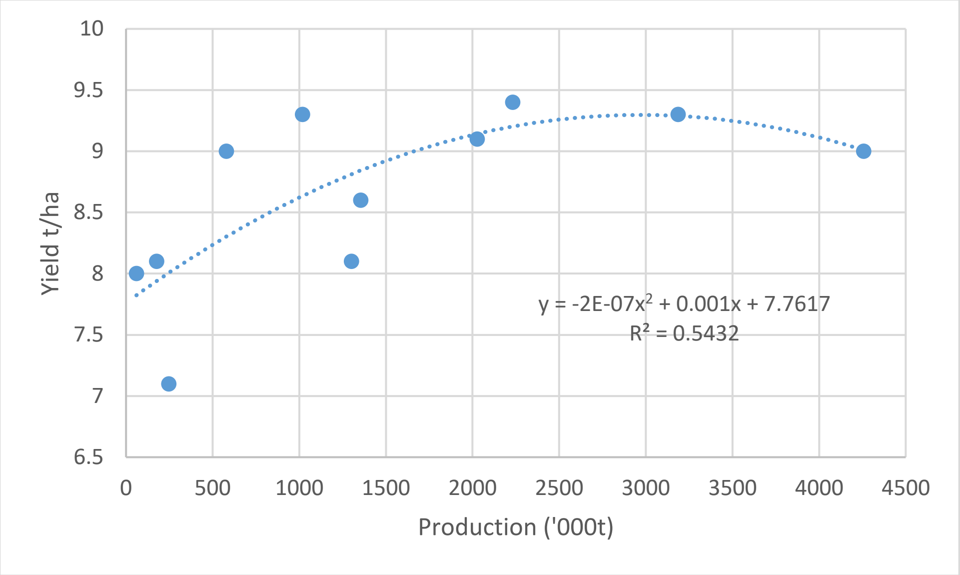


Figure 2.6 Polynomial regression of wheat yield t/ha as influenced by volume of production (‘000t). (Adapted from Defra, 2016)

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 respectively (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)

3.1.1 The impact of drought on wheat grown in the UK

The most recent farming press reported: “Average wheat yields in England and Wales dipped below 8t/ha for the first time in five years after a late spring and hot summer held crops back from achieving their potential. Figures from the NFU Harvest survey statistics reveal that the average wheat yield was 7.7t/ha for 2018, which is 6% lower than the five-year average of 8.2t/ha” (Farmers Weekly, 2018). Whereas Defra (2018) reported that prolonged hot dry weather late June/July hastened grain ripening and harvest began around two weeks earlier than 2016. Ilberry *et al.* (2013) also highlighted in a crop protection survey that one of the other key production concerns for growers was unpredictable weather.

For wheat the most recent work which investigated wheat response to drought in the UK was Clarke (2017) who used drought severity indices, DSI, to assess the effects of drought on wheat production near Cambridge (UK) using the Sirius crop model. The Sirius model was set-up to remove non drought-related yield losses and covered historical data from 1911 to 2015. The standard precipitation index (SPI), the Standardized Precipitation and Evapotranspiration Index (SPEI) and the Potential Soil Moisture Deficit (PSMD) gave the strongest correlations to wheat yields, r = 0.64 to 0.66. The model projected yield losses in key drought events from 15% in 1943 to 29% in 1976 and 38% in 1921. Yield loss was normally within the range of 1-2t/ha but severe droughts caused greater losses.

As a baseline it is possible to speculate that for any given percentage yield reduction the average 5 year production, i.e. most summers are non-limiting in that no drought was recorded, a commensurate loss of production would occur.

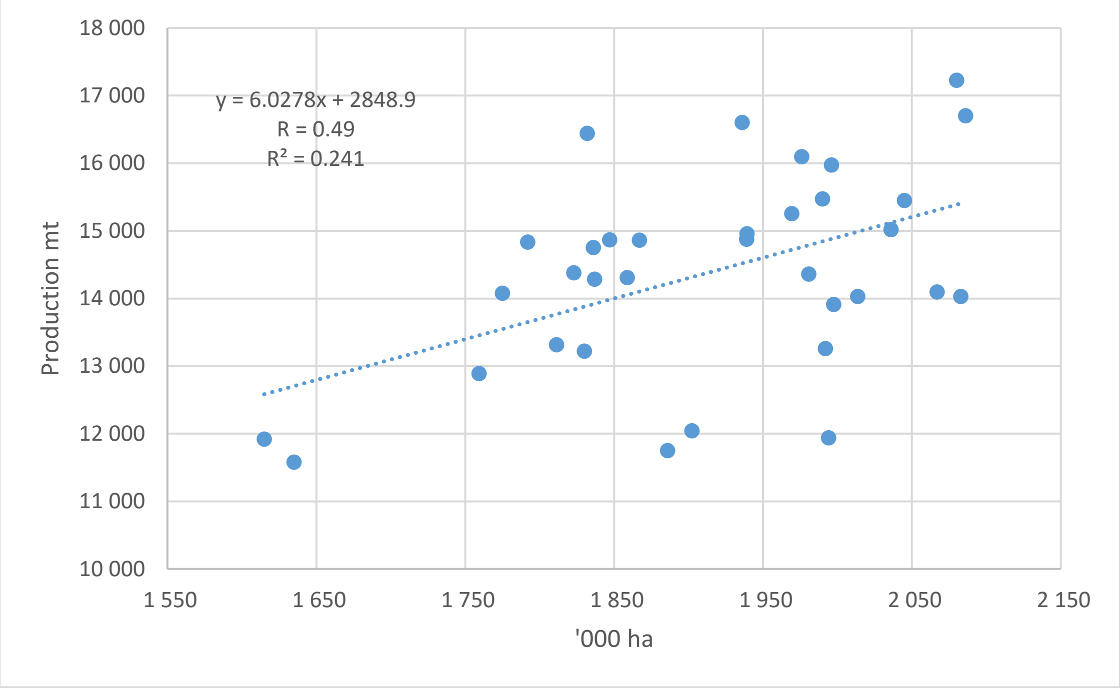


Figure 2.7 Wheat production in the UK, 1984 to 2017 (Adapted from Defra statistics, 2018)

The data displayed in figure 2.7 shows the relationship between the overall UK production in thousand tons relative to the area (ha) harvested. Overall there is average of 14,377,000t (range: 11,580,00 - 17,227,000t) grown on an average of 1,913,000 ha (Range: 1,615,000 – 2,018,600ha) giving 7.5 t/ha (range: 6 - 9t/ha). The relationship is only modest, r = 0.49, with only 24% of the variation in yield being associated with variation in land area harvested. This demonstrates that production is not simply related to area planted/harvested but also the influence of other factors, such as rainfall, solar radiation and temperature which affect the production. This is why correctly calibrated models are needed to make sensible projections for drought effects on yield/production loss.

As a crude estimate however, with an average yield of 7.5t/ha a 10% reduction in yield due to drought would reduce the UK production from 14,377,000t, to 13,055,900t, figure 2.7, a loss of 1,321,100t.

There is a strong relation between the total production and yield per ha, r = 0.8, but still only 64% of the variation in total production is due to the yield per ha. This is explained by the variable soil fertility, climates, varieties and crop management practices used in the industry.

In the UK Foulkes *et al.* (2007) suggested that yield losses from drought can range between 2 – 4.5t/ha and annual yield loss to drought is in the order of 15%. They also reported that 30% of UK wheat was grown on drought prone soils which lead to 10-20% production losses, equivalent to £72m. The stage or timing of drought is however very important studies often refer to crop establishment or early growth effects.

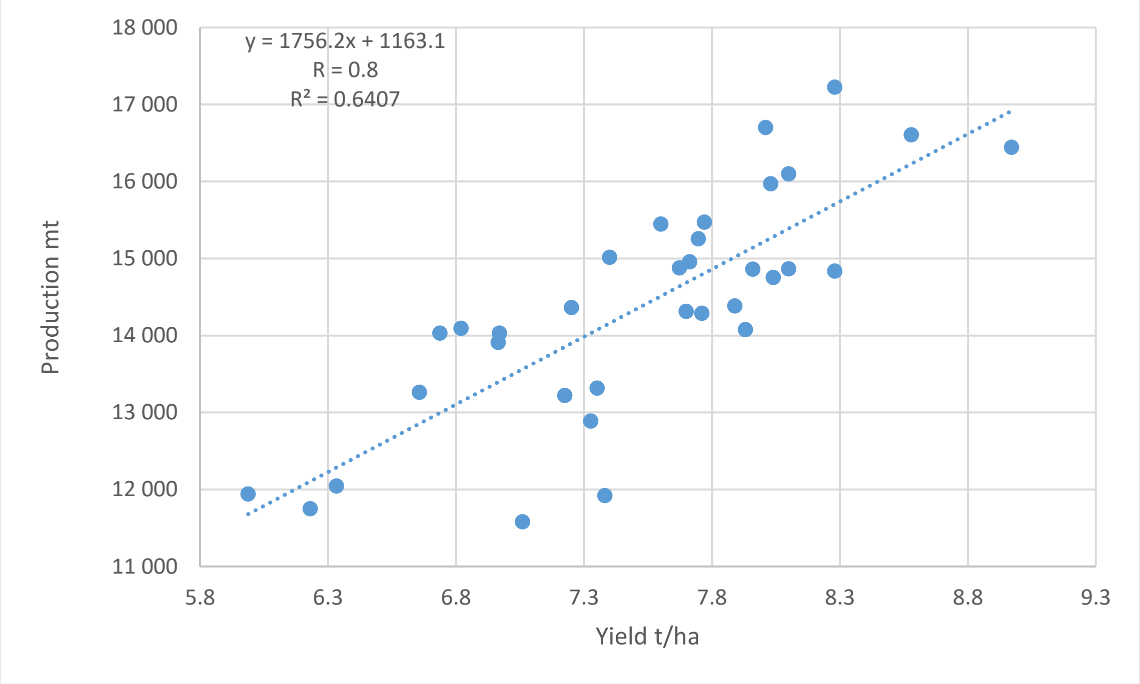


Figure 2.8	Total UK wheat production relative to the yield per ha (Adapted from Defra statistics, 2018)

The timing of drought is critical to yield reductions for most crops with the most drought sensitive stages for wheat suggested by Brouwer *et al.*(1989) as being flowering rather than yield formation and with little effect during ripening and harvest. This is in partial agreement with Sarto *et al.* (2017) who identifies that peak evapotranspiration occurs from the beginning of heading until the end of flowering but then identifies how drought affects various phases: plant density in the initial phase, tiller number in the tillering phase, plant height in stem elongation phase, fertilisation and grain fixation at flowering, thus affecting the number of viable seeds, and the ability of the source leaf to use and translocate assimilates to the grain, thus reducing grain weight. Drought or low water uptake during grain fill was shown by Balla *et al.* (2011) and Nuttall *et al.* (2017) to result in small/shrivelled grains and changes to protein and starch structure and content. In addition Weerasinghe *et al.* (2006) identified that drought stress during pollen mother cell meiosis at GS 41 can substantially reduce the number of grain sites formed. Sarto *et al.* (2017) also highlights not only the crop growth stage when drought occurs but also the duration and intensity which is in general agreement for most crops (Passioura, 1997; Farooq 2009). For a fuller explanation of the physical and physiological effects of drought the reader is referred to the review of Sarto *et al.* (2017) and Fisher (2007). However, any drought effects which reduce stem number, leaf size, leaf area, leaf area duration, ears m^2 (Day and Intalap, 1970; Choudhury and Kumar, 1979; Hassan *et al.*, 1987; Saini and Westgate, 2000; Gupta *et al.*, 2001, Beltrano *et al.*, 2006), grain set and grain fill will individually or in combination affect the components of yield, ‘the number of ears m^2 x number of grains per ear x individual grain weight’ (Hay & Porter, 2006).

In a large scale European study information was collected from 991 European cultivars grown between 1991-2014 from 636 trials sites across Finland, Denmark, Germany, Czech Republic, Slovakia, Belgium, France, Spain and Italy. One of the key findings was that there is still a paucity of information relating to the drought sensitivity of European cultivars (Mäkinen *et al.,* 2018) and so our ability to forecast the drought effects on wheat is still unsatisfactory. In the UK the Winter planted wheat is generally planted into wetting soils and therefore UK drought tolerance tends to focus on the later spring growth stages. However, planting seed into drying soil, as may occur when planting after a summer drought in the UK or for a spring planted crop after a dry winter, can lead to dehydration of seminal roots and coleoptiles (Guedira *et al.*, 1997) which reduces plant establishment. Drought stress during the tillering phase, GS20s, can impact tiller survival or performance (Stark and Longley, 1986) whereas drought during stem elongation and booting can also reduce grain number and grain yield considerably (Hassan *et al.*, 1987; Gupta *et al.*, 2001). Foulkes *et al* (2001, 2002) investigated the drought response of six mid-1990s commercial cultivars, Haven, Maris Huntsman, Mercia, Rialto, Riband and Soissons over the growing seasons 1993/94, 1994/95 and the drought period of 1995/96 (Marsh *et al.,* 2007). The experiments were located at ADAS Gleadthorpe, Nottinghamshire, England on a medium sand which would be expected to have plant available water contents of 13% in the topsoil and 7% in the subsoil (Hall *et al*., 1977) equating to approximately 133mm to 1.65m rooting depth. The work reported that Soil Moisture Deficits (SMDs) greater than 75mm did not occur in 1994 until early June, past GS39 and 10 days before flowering (GS 61) but then increased to 175 mm by late July, just before harvest. In 1995 and 1996, deficits of 84 and 103mm respectively were recorded by 1st June, beyond GS39, before progressing to 148 and 139mm by 15th July, well past GS61. The yields recorded give yield reductions from irrigated controls of 1.8t/ha (17.1%) from 10.5t/ha in 1994, 3.1t/ha

(34.1%) from 9.1t/ha in 1995 and 4.6t/ha (44.7%) from 10.3t/ha in 1996. It is clear that the earlier onset and continuation of greater SMDs seen in 1995 and 1996 restricted plant growth and yield formation with primary yield components affected more so than in 1994. Within the 'components of yield', mean values for all six varieties in 1994, 1995 and 1996 showed that ears m^2 were reduced by 2%, 7% and 15%, grains per ear were reduced by 5%, 8% and 22%, and weight per grain was reduced by 9%, 17% and 10%. With a later onset of severe drought in 1994 the ears m^2 are unlikely to have been affected as they would be well established before limiting deficits occurred. In 1995 and 1996 however the greater SMDs before GS39 suggest that although the formation of tillers would not have been affected the survival of those formed could have been compromised. In 1994 and 1995 the reduction of grains per ear were similarly low but in 1996 substantially reduced and can be linked to the greater SMD at this time in 1996. Pollen mother cell meiosis (GS41) is linked to pollen viability around GS33 (Weerasinghe *et* al., 2013) which is a critical time when drought can reduce the number of grains set. The final component, individual grain weight, was substantially reduced in all years but most affected in 1995 (-17%) which relates well to the greater SMD experienced in the grain filling period in 1995. Overall there were differences between cultivars suggesting that some were more drought tolerant than others by approximately 5%, equating to a 0.5t/ha less yield loss.

French and Legg (1979) reported that limiting SMD for both winter and spring wheats above which yield response to irrigation was recorded was 140mm on a flinty silty clay loam.

Work Carried out by Dickin and Wright (2008), using lysimeters, investigated the effects of drought and waterlogging on wheat varieties Claire, Xi-19 and Deben (not currently grown) in a clay loam soil. Yield was reduced by 53% in the variety Claire which was droughted from GS45 whereas the yields for Deben and Xi-19, droughted from GS61, were reduced by 24 and 17% respectively, which emphasises the relationship with drought timing and duration. In a similar lysimeter study Cannell *et al* (1984) allowed SMDs to develop to 150mm on a clay soil and 159mm on a sandy loam by harvest. For wheat the yield loss was reported as 17% on the clay soils.

In relation to current recommended list cultivars (AHDB, 2018) the effect of the reductions shown in (Dickin and Wright, 2008) i.e. 17.1% reduction in 1994, 34.1% reduction in 1995 and 44.7% reduction in 1996 the effects of similar droughts are proposed, table 3.1.

Table 3.1 Effect of drought on yields (t/ha) of 2018/19 recommended varieties of winter wheat (AHDB, 2018) based on 11t/ha UK mean control varieties and yield reductions reported by Foulkes *et al.*(2002) without accounting for any tolerance potential.

Group	Cultivar	Yield t/ha	Reduction of 17%	Reduction of 34%	Reduction of 44.7%
1	KWS Zyatt	11.2	9.3	7.4	6.2
1	Skyfall	11.0	9.1	7.3	6.1
1	Crusoe	10.7	8.9	7.1	5.9
2	KWS Siskin	11.3	9.4	7.5	6.2
2	KWS Lilli	11.2	9.3	7.4	6.2
2	Cordiale	10.6	8.8	7.0	5.9
3	Elicit	11.3	9.4	7.5	6.2
3	Spyder	11.0	9.1	7.3	6.1
3	Zulu	10.9	9.0	7.2	6.0
4	RGT Gravity	11.7	9.1	7.7	6.5
4	Graham	11.3	9.4	7.5	6.2
4	Grafton	10.9	9.0	7.2	6.0
	Means	11.1	9.2	7.3	6.1

Note: Group 1 Milling for bread, 2 Milling bread potential, 3 Biscuit wheat, 4 feed wheat

Further investigation of this idea was initiated to determine if recommended variety lists from drought and non-drought years could supply additional data. Unfortunately earlier recommended variety lists did not give actual yield values but were represented by upper and lower case letters to denote higher or lower yields (NIAB, 1999).

Roy *et* al. (1978) reported 22% decrease in wheat yield from 4.94 t/ha in 1974 to 3.85 t/ha in the 1976 drought year. Agricultural data and statistics are however available from Defra (2018a) and can be used to consider drought year impacts in comparison to wheat yield produced several years before and after a major drought. The noted drought year of 1976 produced a UK average yield of 3.9t/ha, in contrast to 4.94 t/ha for England and Wales as reported by Roy *et* al (1978), whereas the mean from 1970 - 1974 was 4.44t/ha and from 1977 – 1981 5.42 t/ha, table 3.2. The direct loss compared to 1970-1974 and 1977 – 1981 was therefore 12.2% and 28% respectively and a mean loss of 20%. This method does acknowledge some impact of changing varieties and management practices over the preceding and subsequent 5 years.

Table 3.2 Effect of 1976 drought on UK wheat yield compared to previous and subsequent 5 year averages. (Adapted from Defra, 2018a: historic cereal yields)

Wheat t/ha	**t/ha**	**Loss %**	**Loss%**
Mean of 1970-74	4.44	to 70-74	to 77-81
1976	3.9	**-12.2**	**-28.0**
Mean of 1977-1981	5.42		

Comparisons always need to be done with caution as if you only compare with previous years the management and varieties may be poorer than the following years and comparing with subsequent years only may be flawed as varieties and management improve.

Table 3.3 Effect of 2011 drought on UK wheat yield compared to previous and subsequent 5 year averages. (Adapted from Defra, 2018a: historic cereal yields)

Wheat t/ha	**t/ha**	**Loss %**	**Loss%**
Mean of 2006-2010	7.82	to 06-10	to 13-17
2011	7.70	**-1.5**	**-18.7**
Mean of 2013-2017	8.24		

Although the drought continued into 2012 by April 2012 rainfall began to alleviate the drought (Met office, 2018a) and 2012 crop yields were reduced, average 6.7 t/ha, due to inability to harvest effectively, figure 3.3.

The worldwide impact of drought on wheat production

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.

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.

Peltenon-Sainio *et al.* (2011) carried out comparisons using Finnish (MTT) variety trials and Finnish Meteorological Institute data to investigate the response of a range of crops to changing climates. They suggested that some of the responses of spring and winter wheats to increased temperatures were likely the result of 10mm reduced early summer precipitation decreasing yield by 45-75 kg/ha.

Wardlaw (2002) found that the effect of drought stress from anthesis on spring wheat was minimal at temperatures of 27/22°C (Day/Night) and was postulated to be drought escape related.

Jamieson et al. (1995), in new Zealand, investigated the drought response of field grown winter wheat under mobile rain-shelters in a deep Templeton sandy loam with AWC of 190mm/m. It was reported that the critical PSMD for winter wheat was 262mm before yield was depressed with lesser effects from late season drought. The grain yields were reduced from 9.78t/ha t/ha at 262mm PSMD to 3.59t/ha at 510mm PSMD. The actual SMDs recorded to 1.6m were 203mm for spring drought and 295mm for summer drought. Components of yield affected for wheat was mainly reduced grain number.

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 $\mathrm{WUE}_{\mathrm{Y/ET}}$ 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 $\mathrm{WUE}_{\mathrm{Y/ET}}$ 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).

Research needed

- Investigate the drought tolerance of all UK recommended and candidate varieties.

Temperature: Effects of temperature rise: Wheat has an optimum range of 18 -22°C for shoot growth but only 18 -20°C for root growth (Martin *et al*., 2006).
Asseng *et al.* (2015) used crop MME medians, e-median, from 30 models, and suggested that for every one degree (°C) temperature increase globally wheat yields will reduce by 6% due to faster growth rates and a reduced grain-fill period. Wheat has been reported by many researchers to be sensitive to heat stress at anthesis and grain-filling stages (Porter and Gawith, 1999; Peltonen-Sainio *et al.*, 2010) and confirmed by Vara Prasad and Djanaguiraman (2014) at temperatures >24 up to 35°C applied up to 8 days before anthesis. Wollenweber *et al.* (2003) also showed wheat sensitivity at 35°C at the double-ridge and anthesis stages, or at anthesis alone, where grain number declined by 41% and grain weight was reduced by 45%. *Barnabás et al.* (2008) demonstrated that a combination of drought and heat stress wheat productivity was lower more than for each stress alone.

4.1 Barley (*Hordeum Vulgare)*

UK Production: There were 1.2 million ha of barley producing 7.2 million t with a value of £893m in 2017. There was 4 m/t used for animal feed and 1.8 m/t used for brewing and distilling (Defra, 2018b). In 2017 Spring planting dominated at 754,000 ha compared to only 424,000 ha of winter cultivars (Defra, 2017). Water requirement of barley is given as 450-650mm with low-medium sensitivity to drought (Brouwer C & Heibloem, 1986).

The impact of drought on barley grown in the UK

Table 4.1 Effect of 1976 drought UK total barley yield compared to previous and subsequent 5 year averages. (Adapted from Defra, 2018a)

Barley t/ha	t/ha	Loss %	Loss%
Mean of 1970-74	3.84	to 70-74	to 77-81
1976	3.50	**-8.9**	**-18.6**
Mean of 1977-1981	4.30		

Table 4.2 Effect of 2011 drought on UK barley yield compared to previous and subsequent 5 year averages. (Adapted from Defra, 2018a)

Barley t/ha	t/ha	Loss %	Loss%
Mean of 2006-2010	5.82	to 06-10	to 13-17
2011	5.70	**-2.1**	**-7.8**
Mean of 2013-2017	6.18		

Barley yield loss is substantially less, figures 4.1 & 4.2, than those seen in tables 3.2 & 3.3, for wheat, which could be attributed to the greater drought tolerance of barley (Ahmed *et al*., 2016) though that is not undisputed (Samarah, 2005). Additionally, barley plantings are a 50/50 split between winter and spring and so encompass a greater area in Scotland which do not appear to have been as severely affected by the 2011 drought.

Roy *et al.* (1978) reported that the effect on average yield of barley for England and Wales during the 1976 drought was a reduction of 12%, from 3.95 t/ha in 1974 to 3.46 t/ha in 1976. They also reported a decline from 4.99 t/ha to 4.1 t/ha in Scotland over the same period, an 18% reduction. This greater effect in Scotland may partly be explained by the dominance of spring malting barley in Scotland which would be more severely affected than the dominant winter sown varieties in England and Wales but Roy *et al* (1978) suggested that it may have been significantly influenced by mildew infection over the growing season.

The worldwide impact of drought on barley

Worldwide production of barley, *Hordeum vulgare* was reported as 141 Mt and occupied 47 M ha 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 (FAO, 2018). 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).

Day *et al.* (1978) and Lawlor *et al*. (1978) reported different aspects of the same investigation of yield response of spring barley to various stages of drought in mobile rain-out shelters. Droughts were achieved by initiating irrigation at three periods through the life of the crops: period 1 28th April to 1st June, period 2 2nd to 22nd June, period 3 23rd June until the crop was almost ripe, achieving maximum SMDs of approximately 60mm, 100m and 160mm. Yield was depressed in a linear pattern linked to soil moisture deficit but with no critical point of initiation however, a prolonged early drought significantly depressed yield. Early drought reduced LAI from 4 to 2 Drought periods which affected the components of yield were: number of grains per ear were most affected from drought at tillering and ear formation, ears per m^2 stem extension, grain weight at grain filling.

In field experiments using rain-out shelters Legg *et al*. (1979) demonstrated that spring barley grain yield was reduced on a silty clay loam by up to 50% when the crop was stressed from emergence to harvest and up to 40% when stressed from mid-May to harvest. The yield reductions occurred mainly from reduced solar radiation interception arising from substantially smaller leaf area index and also to drought induced stomatal closure.

Cannell *et al.* (1984a,1984b) investigated the growth of winter barley in clay soil within lysimeters. Drought was imposed from 1st April until harvest and reached an SMD of 150mm, reported as equivalent to a 1 in 10 dry year in the driest area of England. Irrigated lysimeters for comparison reached a maximum SMD of 84mm. The drought did not significantly reduce the grain yield but did depress straw production by 12%.

Jamieson et al. (1995), in new Zealand, investigated the drought response of field grown winter wheat, spring barley and Maize under mobile rain-shelters in a deep Templeton sandy loam with AWC of 190mm/m. It was reported that the critical PSMD for spring barley was only 75mm before yield was depressed and this was independent of drought timing and was lower than for wheat, 262mm. The barley yields were reduced from 9.6t/ha at 75mm PSMD to 3.4t/ha at 250-300mm PSMD which is in agreement with the UK findings of French and Legg (1979). The actual SMDs recorded to a depth of 1 m were 144 mm (early drought),183 mm (middle drought), and 194 mm (late drought). Critical PSMD differences between barley and wheat were attributed to the substantially smaller rooting depth for the spring sown barley of only 0.9m compared to the 1.6m recorded for the winter sown wheat. Components of yield affected for barley was reduced grain number and size when drought was early as opposed to reduced grain number under late drought which are generally in agreement with Day *et al.* (1978).

Barley yield reduction with drought was associated with reduced grain size and number when drought was early, but mostly with reduction in grain number and screening loss when drought was late. Wheat yield reduction was associated mainly with reduced grain number, and maize yield reductions mostly with reduced grain size.

Temperature: barley has an optimum range of 15 -20°C for shoot growth but only 13 -16°C for root growth (Martin *et al*., 2006). Work by Cao and Moss (1989) showed how rate of leaf appearance, phyllocron, averaged only 57 degree-days at *c.*7.5°C but up to *c.*116 degrees days at 25°C thus demonstrating how simple increases of non-extreme temperatures would impact on expected growth patterns of both wheat and barley. Schelling *et al*. (2003) reported that the optimum temperature range for grain filling of barley was 14 - 18°C and that yield was reduced by 4.1-5.7% for every 1°C increase above that. Savin and Nicolas (1996) investigated the effects of the short term high temperatures after anthesis of 40°C for 6h/d over 5 – 10 days and they demonstrated that it reduced the rate and duration of grain growth in the absence of drought but was exacerbated in the presence of drought.

Research needed

- Investigate drought tolerance within all current UK barley cultivars

5.1 Oats (*Avena Sativa)*

The production of oats in the UK was 875,000t, with a farm-gate value of £100m, produced from 161,000ha at an average of only 5.4 t/ha in 2017, down from a 3-year average of 6t/ha (Defra, 2018). Oats can be split into winter and spring varieties with 85% winter varieties in England and Wales but proportionally more spring varieties in the North and Scotland due to the lack of frost tolerance. Oats are an important world crop with production at 22 Mt in 2016 (FAOSTAT, 2018) but are considered as one of the least productive cereals per unit of water transpired as highlighted by the harvest indices of 0.14 – 0.3 reported by Sánchez-Martín *et al.* (2014).

The impact of drought on oats grown in the UK

The indicative water requirement of oats is given as 450-650 for the full growth period and it is suggested as being low-medium sensitivity to drought (Brouwer C & Heibloem, 1986). Roy *et al.* (1978) reported the agricultural effects of the 1975-76 drought and noted that the yield reduction in oats was only 12% in both 1975 (3.45 t/ha) and 1976 (3.42 t/ha) compared to the 1974 average of 3.88 t/ha. This does of course presume that the 1974 yield is representative of a 'normal' year. Unfortunately there are no historic UK yields listed for Oats earlier than 1980 making it difficult to gauge the robustness of the comparison. It is however fair to say that the yields of both wheat and barley from 1970 – 1973 were lower than the 1974 comparison. In contrast, the yield in the drought year of 2012 fell from an average 5.6 t/ha (2007-2011) to 5.1 t/ha in 2012, before achieving an average of 5.9 t/ha in 2013-2015 (Defra, 2018a).

Salter & Goode (1967) reviewed the knowledge accumulated up to that time, from the late 1800's on, and concluded that drought just before and during heading was most damaging to yield due to the effects on pollen viability and fertilisation. This is then supported by Sandhu and Horton (1977) who stressed oat plants by drought imposed for 9-11 days at (a) late boot stage or (b) anthesis and early grain filling or (c) at both stages. All stresses appeared to increase root growth but reduced grain yield by 20, 58 and 67% respectively and highlighted that plants were more prone to drought stress at anthesis and early grain filling. In recent work by Mahadevan *et al.*(2016) the critical stress period for oats was defined as from stem elongation at GS31 to about 10 days post anthesis, with reduced grain number being the key issue. They also noted that even with a limited comparison the varietal differences were important. Barr (1988) however reported work which also identifies drought effects on germination and early tillering in that environment. This may be particularly important under climate change for temperate regions such as the UK as currently planting times for UK cereals tend to coincide with wetter periods whereby drought during these growth phases are seldom a concern. Rabiei *et al.* (2009) also demonstrated that the seed produced from droughted plants had significantly lower seed vigour and germination percentage, making it a serious concern for use of this seed for planting.

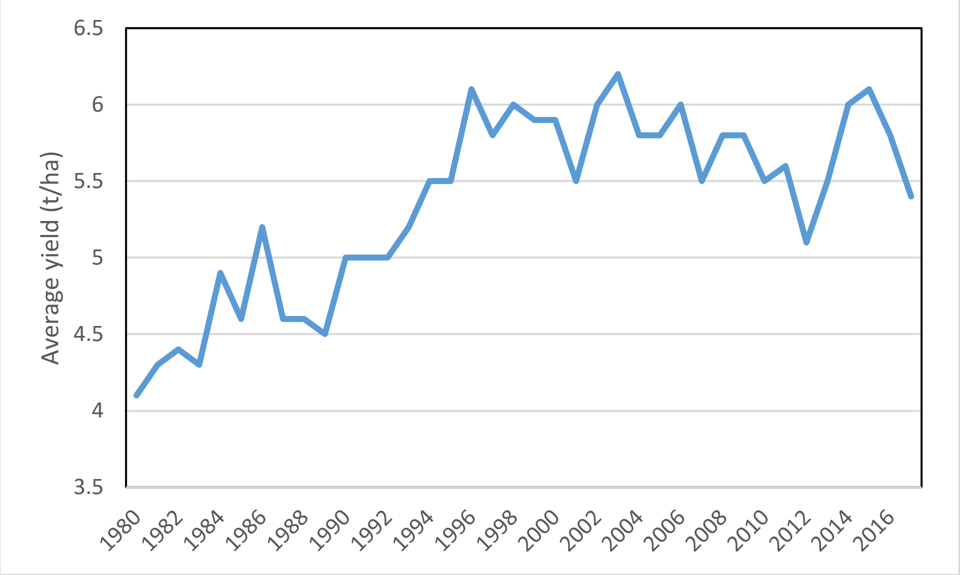


Figure 5.1 Average yield (t/ha) of Oats (Avena sativa) in the UK 1980 – 2017 (Source Defra, 2018a)

Mahadevan *et al.* (2016), working in southern Australia and southern Chile, investigated the stress response of several varieties of oats where they identified the critical stress period as similar to that found in common wheat, from GS31 to 10 days after anthesis. This agrees with Sadras *et al.* (2017) who noted that the peak water demand arose between 500 °Cd before to 500 °Cd after anthesis. Mahadevan *et al.* (2016) identified that reduced grain number per panicle was a key determinant of reduced yield and also proposed that genotype-dependent responses to time of stress was important.

Larsson and Górny (1988) investigated the drought response/tolerance of old cultivars of black and white oats, new cultivars of white oats and new oat breeding lines over two years on clay and sand soils using field rain-out shelters in Sweden. The drought, dry conditions, and control were created by irrigating all plants initially to establish plants evenly, continuing irrigation for the controls but applying no irrigation for 60 days for dry plants. Rain shelters were then removed and all plots received natural rainfall until harvest. The effect of this dry period was a 40% reduction in grain yield on the sands and 30% on the clays, with substantial grain weight reductions on both soils. As no rainfall appears to have been recorded the total amount of water received by the crops cannot be judged and no indication of soil moisture deficit or real stress can be gauged. Similarly as no growth stages or harvest dates are given it is impossible to determine the point and growth stage at which the drought was terminated. However the early growth, tillering, stem extension and probably up to anthesis may have been covered.

Temperature: Oats have an optimum range of 15 -25°C for shoot growth but only 15 -20°C for root growth (Martin *et al*., 2006). A reduction in grain-weight under high temperatures was reported by Eagles *et al.* (1978) with a temperature regime of 20°C day and 15°C night applied from coleoptile emergence. This would be greater temperature than would be experienced in the UK during early growth but not during later growth stages. The temperature range for most cereals is *c.* 5 - 30°C with optimum Ps between 15 - 20°C (Farnworth, 1997).

Research Needed

- Varietal tolerance

6.1 Rye (*Secale Cereale)*

The area of Rye production in the UK was suggested as 51,000t from 36,000 ha in 2017 (Eurostats, 2018), which would equate to only 1.4 t/ha. As the majority of rye production in the UK is for wholecrop however these values are probably not representative of grain yield. Unfortunately there are no values given for rye alone in the Defra statistical publications, e.g. ‘Agriculture in the UK 2017’ (Defra, 2018b and also no historic yields listed earlier than 1980 (Defra, 2018a). Currently the data lists rye areas grown, production and yields along with triticale and mixed corn making it impossible to provide useful current vales.

The impact of drought on rye grown in the UK

Using the data from 2002 to 2014 the average yield was 5.7 t/ha which includes an average of 5.3 t/ha in the dry years of 2011 and 2012 (Defra, 2018a) a 7% yield reduction. Yield during other notable droughts of 1990-1992, 1995-1997 and 2004-2006 were 4.6, 5.6 and 6.1 t/ha respectively which are close to normal values of that time. Rye is reported as the most drought tolerant of the cereals, using 20-30% less water per unit dry matter, and has very good water uptake due mainly to its large and well branched root system (Starzycki, 1976).

Kottmann (2015) and Kottmann *et al.* (2016) reported from field experiments in 2011-2013 in Germany that severe or mild drought which was imposed pre and post-anthesis, produced grain yield reductions from 14 - 57%. The pre-anthesis drought reduced spikes m^2 and grains per spike whereas drought post-anthesis reduced 1000 grain weight. Hüber *et al.* (2013) also demonstrated average yield losses to drought of 23.8% in large scale rainfed/irrigation field experiments when investigating 220 lines of two population crosses in six environments within Europe. The crop was also shown to be least sensitive crop to drought in multi-location trials in the Czech republic (Hlavinka, 2009). The severe drought in Germany in 2007 was also reported to have reduced rye yields by 16% compared to the average yields (Kottmann, 2015).

Research needed

Rye is a crop with limited use for grain in the UK but is a useful whole-cop forage especially on marginal land. It may be pertinent therefore to investigate the drought tolerance of this crop in the UK as a useful annual forage crop.

7.1 **Triticale (*Triticosecale*)**

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. 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). 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). According to Basu *et al.* (2011) triticale often out-yields wheat in both favourable and unfavourable environments.

The impact of drought on triticale grown in the UK

Unfortunately there are no historic UK production listed for Triticale earlier than 1987 and therefore impact of the 1976 drought cannot be judged. However, with an average yield of 4.9 t/ha since 1987 the average yield for the dry/drought year of 2012 was only 3.5 t/ha (Defra, 2018a), a reduction of 29%.

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.

Research Needed

- Revisit and explore the potential for tritcale to replace the less drought tolerant common wheat used for animal feed and currently grown in the UK.

8.1 Oilseed rape (*Brassica napus* L.)

Oilseed rape is grown on 579,000ha in the UK and produced 1.8 Mt (Defra, 2017). *Brassica napus* L. is the primary oil crop grown in the UK and Europe (Snowdon *et al.*, 2007) and it favors heavy water retentive but drained land. The water requirements of OSR are not readily specified but is suggested to be in the range of 310mm in the UK (Berry and Spink, 2006) approximately 270mm for spring canola in Canada (Aiken *et al.* 2011).

The impact of drought on oilseed rape grown in the UK

Unfortunately there are no historic yields listed for OSR earlier than 1984 (Defra, 2018a)

Table 8.1 Effect of 2012 drought UK total OSR yield compared to previous and subsequent 5 year averages. (Adapted from Defra, 2018a)

OSR t/ha	t/ha	Loss %	Loss%
Mean of 2006-2010	3.32	to 06-10	to 13-17
2011	3.40	**2.4**	**-2.9**
Mean of 2013-2017	3.50		

The increase over the preceding 5 years, 2006-2010, highlights one of the issues with OSR, the variability from year to year.

Oilseed rape has been shown to be very sensitive to drought during the reproductive stages of development when reduced water uptake can cause up to 40% yield loss (Richards & Thurling, 1978). This early work however is one of the few reports of oilseed rape response to drought which are available. Hess *et al*. (2015) highlight that our knowledge of water relations for the oilseeds is poor in comparison to other species and Spink *et al.* (2009) whilst reviewing the potential to increase productivity of wheat and oilseed rape, identified poor water and nutrient acquisition by the roots as yield constraints in both well-watered and droughted crops. In order to redress this lack of knowledge Hess *et al*. (2015) carried out investigations using lysimeters and reported that above ground biomass of spring OSR at harvest was reduced by 52% when soil was allowed to reach PWP which was substantially more than for the spring wheat grown in the same experiment which reduced by only 21% biomass. They also noted that transpiration rates reduced at less negative soil potential and was more sensitive to restricted water than wheat. In addition although it was felt that OSR was as efficient as wheat at extracting water from soil they believed that OSR was not reaching its yield potential, especially during droughts, because of inferior root length density (RLD: root length per unit volume of soil) which for wheat is in the range of 1 - 2cm/cm^3 soil (Passioura, 1983; Gregory and Brown, 1989; King *et al*., 2003; Blake and Spink 2005) and for which 1cm/cm^3 is a critical minimum. OSR is reported to have significantly reduced RLD below 40-45cm (Barraclough, 1989) with root length correlating well to seed yield (Koscielny and Gulden,2012) which could therefore be responsible for yield losses of 1.2 t ha^{-1} under water-limited conditions (White *et al*., 2015). This is supported by Blake and Spink (2005) who demonstrated in the field that after a moderately dry June, 50% of LTA rainfall, the yield of OSR was increased by 0.5t/ha when RLD was increased by only 20% below 40cm depth.

Using anti-transpirants to protect key growth stages of OSR development Faralli *et al.* (2016, 2017) applied ATs at the flower bud stage and demonstrated increased yields of droughted rapeseed by 22%.

Worldwide oilseed production (Mainly *Brassica napus* L., *Brassica campestris* L. and *Brassica juncea* L. and *Brassica tournefortii* Gouan species) in 2016 was 68.8 Mt with Canada and China the largest producers, 18 & 15 Mt respectively (FAOSTAT, 2018). Average yields however were only 2.3 and 2.0t/ha as compared to 3t/ha in the UK and 3.5t/ha in Germany. The crops are reported to be most sensitive to water stress during the flowering and pod development stage (Gan *et al*., 2004; Sinaka *et al*., 2007) centered around 300 °CD at GS BBCH60 using 0°C base and defined as the sum of the daily temperature minus the base (Kirkegaard *et al.*, 2018). Drought reduced yields in key production areas such as Canada (Wan *et al.*, 2009) and Australia (Kirkegaard *et al.*, 2018). OSR was suggested by Jensen *et al.* (1996) to appear to have a low tolerance to drought which could be attributed to a drought 'avoidance' strategy whereby water loss is restricted due to a sensitive stomatal response to drought and fast abscission of leaves.

Andersen *et al.* (1996) reported drought effects on field grown winter OSR on a coarse sandy soil, 65mm AWC to 60cm depth, in Southern Jutland, Denmark, for 1991-1993 where drought severity was managed by irrigation application. Potential evapotranspiration (PET) never exceeded rainfall in 1991 and maximum SMD reached only 35mm which still produced a 16% yield reduction. In 1992 where PET greatly exceeded rainfall in early June, the yield reduction was 53% when drought was allowed to develop during flowering, 49mm SMD, and 40% with drought at pod-fill, 55mm SMD. In 1993 PET greatly exceeded rainfall in May and continued beyond July giving yield reductions of 67% when droughted during flowering and 85% when droughted during pod fill. The pod number and seeds/pod were also substantially reduced by drought but the seed weight was increased after drought during flowering in 1991, 1992, 1993 and also after pod-fill in 1993.

Champolivier and Merrien (1996) showed in pot experiments that a 63% reduction of the water requirement reduced winter OSR yield, and thus the yield components, by 48% when the water shortage occurred from flowering to the end of seed setting. There was also a substantial reduction in oil concentration and a 60% increase in glucosinolate content when drought occurred from anthesis to maturity.

Műller *et al*. (2010) established plants in a field situation before transplanting them to containers and subjecting them to 13 days unclarified drought stress during the ‘shooting’ (GS13-14) stage. They reported that the onset of flowering was not affected but the period of flowering was prolonged and that pod and shoot dry weight were reduced by 29 & 19% respectively. There were not actual seed yield results.

Gan *et al*., (2004) carried out growth chamber studies and reported significant whole plant and branch stem yield reductions to drought, 50% of AWC, during the bud, flower and pod stages. The drought period covered 10 days and was set to 50% of available water on a Swinton silt loam soil which has approximately 12% AWC (Ayres *et al*., 1985) and which may not therefore have been enough to stress the crop to any severe degree based on Cutforth *et al*. (1991). Of particular interest for climate change scenarios however is that they found no yield reductions at the higher temperature regime of 35/18° compared to 28/18°.

Papantoniou *et al*. (2013) suggested that the hot and dry conditions in Northern Greece reduced net assimilation rates and translocation of pre-anthesis assimilates of three hybrids (Royal, Exact, Excalibur) and an inbred line (Fortis) leading to variable OSR yields.

Rad *et al*. (2012) investigated the drought response of 34 rapeseed cultivars over two years in the semi-arid region of Iran by utilising either irrigation throughout the season or stopping irrigation post-flowering (partial irrigated). The overall effects were significant grain and oil yield reductions. Cultivar responses were notably different with the Sunday cultivar decreasing grain yield from 4.9t/ha (irrigated) to 2t/ha (partial irrigated) in contrast to cultivar ORW20 2.8t/ha (irrigated) and 2.5t/ha (partial irrigated), figure 8.1.

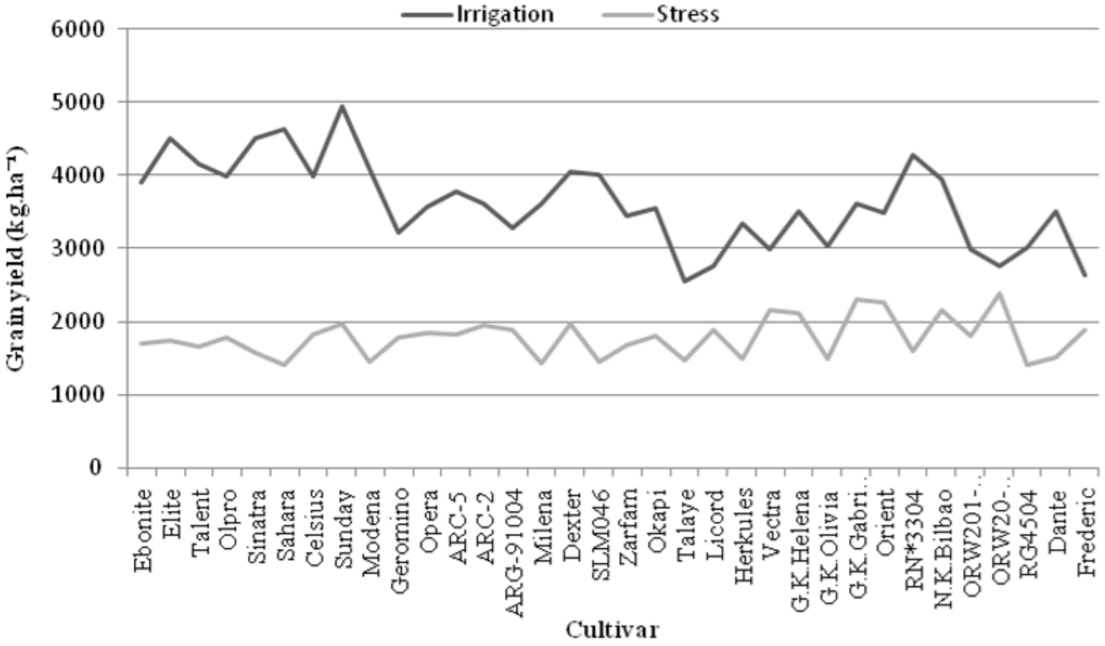


Figure 8.1 Effect of irrigation post-flowering on 34 cultivars of OSR in Iran (Rad *et al*., 2012)

Overall OSR yield is significantly affected by drought from early flowering to pod fill. As flowering of winter OSR in the UK occurs around April the previous winter rainfall and thus the post-winter soil moisture deficit, would be very important for the extent to which drought will affect this crop. Although the grain yield is always the greatest concern, the effects on oil and glucosinalate content may also be important.

Research Required

- Determine the baseline water requirement for winter and spring cultivars.
- Investigate drought tolerance and the rooting abilities of current and candidate recommended varieties of both Winter and spring OSR
- Develop fast screening techniques which can identify genetic rooting traits
- Identify agronomic practices which encourage rooting.

9.1 Linseed (*Linum usitatissimum* L.)

Linseed or flax are names that are used for the same plant, *Linum usitatissimum* L., with the different being the type/variety and its end use. Linseed is a shorter type which gives good seed yield whereas flax is a taller plant which produces less seed but more fibre due to its stem height. For the benefit of this work the drought effects will be considered as they are reported. Linseed is a predominantly spring planted rain-fed break crop in the UK and is classed as minor crop with planted areas ranging from 48,572ha in 2005 to 12,736ha in 2002, currently 26,000ha in 2017 which produced 46,000t seed (Defra, 2009, 2018). The crop produces on average 1.5-2.5 t/ha and provides oil for industrial use (paints, varnishes and linoleum), human and animal consumption, and the straw has been used within biomass energy burners. Linseed is suggested as a shallow rooting crop which requires good soil moisture in upper soil layers (Wood, 1997). Water requirements are as 150 – 200mm over the three growing months, mid-May to Mid-August (Turner, 1987).

There is relatively little published work on drought effects of linseed or flax but Rashwan *et al.* (2016) reported yield responses to irrigation every 35 days in field experiments with three flax cultivars in Egypt which is in agreement with Lisson and Mendhan (2000) who reported increased yields from irrigation in Tasmania. Chorumale *et al.* (2001) and Yenpreddiwar (2007) also suggest that irrigation significantly improves yields by irrigation at flowering and capsule filling. Unfortunately, none of these reports provide information on soil moisture deficits at any time during the growth period and therefore it is difficult to judge the critical soil moisture deficits which trigger growth reductions.

Kariuki *et al.* (2016) investigated the response of three linseed cultivars to incremental drought at 90, 70, 60, 50, 40 % of field capacities using 2 years of glasshouse experiments in Kenya. Leaf number and dry-weight declined when 30–80 % of available soil water had been used up. Nematallahi and Saeidi (2011) investigated the drought tolerance of 10 breeding lines and five landraces in field experiments in Iran. They found significant genotype drought response differences with some genotypes showing little yield loss under 70mm irrigation, as opposed to 140mm, whilst yield of other genotypes was substantially reduced.

Heller and Byczyńska (2015) investigated the response of 51 flax genotypes to reduced soil humidity, 62.5% of optimal, and reported fiber yield reductions of 39.7 – 49.3% and significant quality reductions. There was genotypic differences with some varieties being more drought tolerant than others.

Mostafi (2011) who also identified that very little work had been reported at that time on drought effects or drought tolerance on Linseed (Flax). An in-vitro experiment therefore investigated the germination response of four cultivars to three drought stresses of zero, -6 and -12 bar using polyethylene glycol (PEG). Germination of the cultivars ranged from 25 – 53% at zero bar, significantly reduced in all cultivars at -6 bar and no germination at -12 bar. It was concluded that two of the cultivars were more drought tolerant at these early growth stages which may be important if planting into very dry seedbeds.

Temperature: Effects of temperature rise: Linseed has an optimum range of 10 - 30°C but is suggested to perform better at 8 - 21°C as higher temperatures can inhibit seed fill (Turner, 1987).

Research required

- In the absence of any definitive data on critical growth stages or limiting soil moisture deficits this must form the basis of any basic research program for this crop.
- Additional research is needed to determine effective rooting depths, benefits or drawbacks of winter and spring planted crops and the cultivar responses to drought overall.

10.1 Potatoes (*Solanum tuberosum. Ssp. Tuberosum)*

Potatoes are reported as the fourth most important food crop in the world which is cultivated on 19.2 million ha and produced a total of 376 million tons in 2016 (FAO, 2018). According to Renault and Wallender (2000) potatoes produce more kcalories of dietary energy per m^3 applied water (5600) than maize (3860), wheat (2300) and rice (2000), making it a very important nutritional crop. The water requirements of potatoes is between 400-750mm dependent on climate and season length (FAO, 2018a) and also maturity class in the UK, i.e. earlies, 2^{nd} earlies or maincrop. UK production in 2017 was 74% of demand at 6.218 Mt from 145,000ha at a farm-gate value of £897 million (Defra, 2018).

The impact of drought on potatoes grown in the UK

The production in the UK is variable, figure 10.1, with climatic effects of both drought and flooding adding to the overall variability in 2012. It is not possible to generalise about drought effects on UK production from historic figures as at least 50% of the crop is supplemented with irrigation.

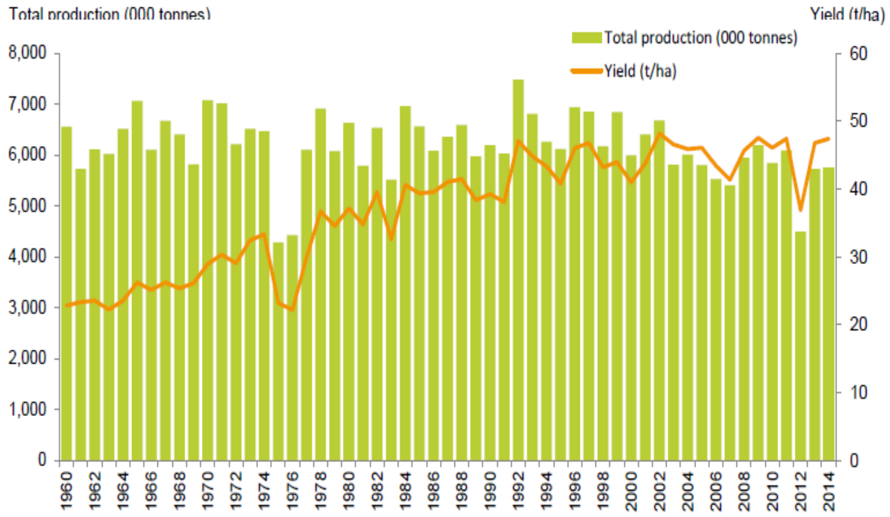


Figure 10.1 Potato production in the UK 1960-2014 (AHDB, 2015)

However, Roy *et al.* (1978) reported that average effect on yield of main-crop potatoes for England and Wales during the 1976 drought was a reduction of 40%, from 33.9 t/ha in 1974 to 20.4 t/ha in 1976. They also reported a 15% reduction from 30.9 t/ha to 26.2 t/ha in Scotland over the same period. A note of caution is perhaps also required with this information as they also reported that harvest was very difficult due to a change to very wet conditions around harvest time which could have reduced the amount of crop which was harvested.

In press:

Allison (2018) reported a 20% reduction of crop yield across the northern European area, where the Netherlands, Belgium, Germany, France and the UK would be 8% their 5 year average following the spring/summer drought of 2018. It was also highlighted that only 48% had the potential for irrigation as compared to 80% in 2006 due to abstraction restrictions imposed to protect water supplies.

Scientific research

Potatoes are most often perceived as a drought sensitive crop (van Loon, 1981, Weisz *et al*, 1994) which can be affected by shortage of water during all of its growth phases (Obidegwu *et al.*, 2015) with yield losses resulting from as small as 10% reduction from optimum water requirement (King and Stark, 1997). The sensitivity is suggested as partly attributable to a shallow rooting system (van Loon, 1981; Curwen, 1993; Weisz *et al*, 1994; Muthoni and Kabira, 2016) which is supported by Lahlou and ledent (2005) and King and Stark (1997) who suggest 60cm as maximum rooting depth at 100 DAP. However, the limited root growth is also classed as ‘relatively’ weak rooting which is normally prevented from accessing deep soil layers due to cultivation pans or other restrictive layers. The work by Stalham and Allen (2001) agrees generally with these statements but demonstrates that although rooting is often restricted by poor soil conditions the actual rooting potential is variety dependent, can reach up to 140cm with total root lengths (TRL) of 16.9km m^2 and root length densities (RLD) of 5.5cm cm^3. The difference between varieties is clearly shown as TRL for cv. Bintje is reported at 4 - 7.1, to 70cm (Vos and Groenwold (1986) and for cv. Record from 7.8 - 20.9, to 100cm (Parker *et al.*, 1989). Weisz *et al.* (1994) highlighted the connection between transpiration and the fraction of transpirable soil water (FTSW) and reported that transpiration was unaffected by water stress until 64 – 80% of extractable water had been used. In contrast the potato leaf growth declined when only 40% of FTSW was used which then reduces canopy size and solar radiation interception. For irrigation purposes in the UK it is suggested that maximum rooting depths should be considered as 70cm and AWC should not be allowed to exceed 50% or significant yield penalties will occur (AHDB, 2015) which is in line with Steduto *et al.* (2012). In the UK irrigation is a key component of the management of the crop with yield and quality paramount for viability of the enterprise and requirements of the market (Knox *et al.,* 2012). This is demonstrated by the survey of outdoor irrigated cropping by Weatherhead (2006) where 27% and 35% of the maincrop area and 53% & 53% of ‘earlies‘ areas were irrigated in 1990 and 2005 respectively.

Several researchers have investigated the potential to reduce water application during different growth phases however, drought effects are cumulative. Reduced irrigation during early canopy development reduces solar radiation interception and can affect tuber initiation whereas during mid-season the tuber bulking period is retarded. Overall, Frederick and Bethke (2018) summarised the relationship of relative water availability to relative tuber yield, figure 10.2.

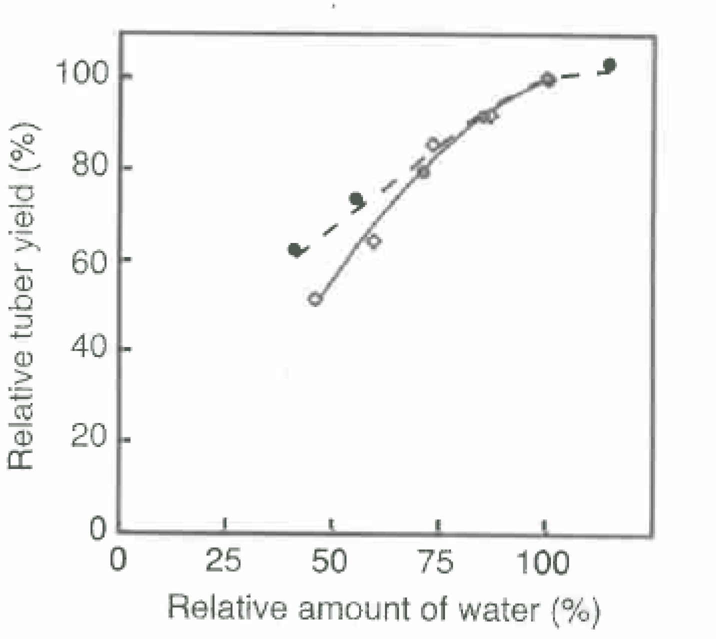


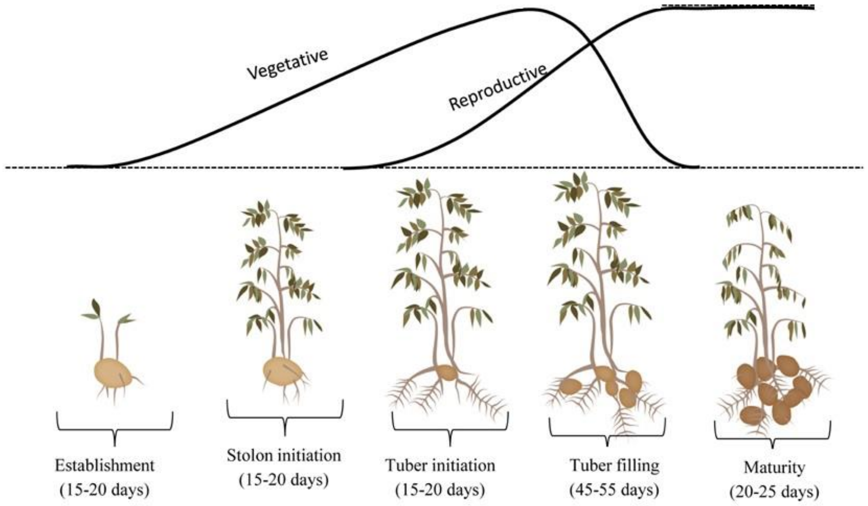
Figure 10.2 Relative yield responses of potato to relative water availability (Source: Frederick and Bethke, 2018. Data from King *et al*, 2011 and Yuan *et al*, 2003)

The most recent drought for which analysis has been done, 2010 – 2012, as opposed to the most recent in 2018, reported an estimated 15% reduction of potato yield (Anglian Water and University of Cambridge, 2013).

Work at Rothamsted on irrigation from 1964 – 1976, reported by French and Legg (1979), suggested that the limiting deficits for potatoes was only 84mm and that a maximum response to irrigation was in the order of 0.19t/ha/mm. This would equate to a theoretical yield of 38 and 66 t/ha for seasonal rainfall events of 200mm, as usual in the Cambridge area, and 350 mm, as usual in Shropshire. Jefferies and MacKerron (1987) demonstrated that drought to >100mm SMD reduced total dry matter production and tuber yields but saw an increase of tuber dry matter and varietal differences of tuber yield was linked to solar radiation interception, LAI. Tuber number were substantially reduced by drought in all varieties and both field experiments. It was further noted that there was a substantial lack of knowledge regarding cultivar differences. Parker *et al*. (1989) reported that water uptake from 0.3 – 0.4m below the rooting depth, capillary rise, appeared to contribute up to 13% of the total water uptake.

International scientific research

Muthoni and Kabira (2016) identified the importance of potatoes in food production and their ability to be grown at altitudes from sea level up to 3700m. They reiterated the issues with drought susceptibility and identified that water stress during plant emergence and tuberisation had the greatest effect on yield. Obidiegwu *et al.* (2015) reviewed the response of potatoes to drought stress and highlighted the effects at all stages of growth from emergence through to harvest, figure 10.3.



Impact of water deficit	Delayed emergence Restrict root establishment Restrict plant development Presence of fewer stalks/stem	Restrict plant development Limited stolon initiation Limited number of stolon Restrict root growth Restricts uptake and response to nutrients	Limited foliage and plant development Limited tuber initiation Limited number of tubers	Limited plant and tuber development Restricts tuber size Promotes distorted tuber shape Faster senescence	Limited relative tuber density Limited tuber size

Figure 10.3. Effect of water stress on different stages of potato (Obidegwu *et al*., 2015)

Water deficits reduce internal turgor pressure leading to reduced leaf expansion (Jefferies, 1993), LAI and stem growth leading to reduced solar radiation interception and concomitant total dry matter production (Van Loon, 1981; King and Stark, 1997; Chang *et al.*, 2018). Minhas and Bansal (1991) and King and Stark (1997) agree that that tuber initiation was the most sensitive as it can reduce the number of tubers per plant and that water stress during bulking reduces tuber growth and hastens leaf senescence in agreement with van Loon (1981). This however is not supported by Chang *et al.* (2018) who found no effect of drought on tuberisation on early and medium maturity cultivars and the effect on late maturing cultivar tuberisation was dependent on the duration of the drought. Also, in complete contrast to Minhas and Bansal (1991) and King and Stark (1997) stolon number was increased by drought in three out of four cultivars (Lahlou and Ledent, 2005) but the ultimate tuber yield was reduced in all cultivars. King and Stark (1997) also note that low soil moisture at harvest can produce greater levels of blackspot bruising due to low tuber hydration. Not all potato genotypes/cultivars are equally as drought sensitive however with the well-known USA cultivar Russett Burbank reported as drought resistant by Banik et al. (2016). In addition to the drought stress effects on potato yield and tuber dry matter, Iriatani (1981) highlight that drought stress during early growth can also cause tuber misshapes, high reducing sugar content, growth cracks and hollow heart, all making tubers unsuitable for their intended market.

Kumar *et al.* (2007) reported findings from field work in the Punjab over the two seasons of 2002/2003 and 2003/2004. Water was applied by irrigation to match 0.6 to 1.2 Epan and a very good relationship, $r^2 = 0.976$, was shown between yield and water applied. As the water application reduced there was commensurate decreases of tuber yield, tuber size and tuber size distribution, plant height, branches per plant, above ground biomass, dry matter/specific gravity and starch percentage. Water use efficiency was however greatest at Epan 0.8. The approach used in this work would have created season long effects for the treatments as water declined on a continuous basis and would therefore have become progressively more severe as the season progressed. This would simulate drought that progresses in the UK from either a dry winter or dry spring followed by reduced rainfall, dry weather, as the season progresses.

In three seasons of field work in Hokkaido, Japan, Kawakami *et al*. (2006) investigated the growth and yield of irrigated and droughted potatoes grown from micro-tubers and conventional seed. Plants were allowed to emerge before rain-out shelters covered the plots and then either irrigated or allowed to dry for the remainder of the season, *c.*100 days. Although there were reductions of leaf area and plant growth by mid-flowering, root depth, up to 1.5m, and root length density, c. 4.1 cm cm^3, did not differ greatly between irrigated and droughted. Tuber yields were reported as 18% lower in droughted plots. However, it should be noted that the soil water potential in the droughted plots did not exceed -60 kpa at any point in the season which, although below the stress point for potatoes at -25 kpa (Epstein and Grant, 1973; MacKerron and Jeffries, 1986), would not be considered a severe or extreme stress at an equivalent to 25 – 30mm SMD.

Trejebo and Midmore (1990) investigated the effects of reduced water on potato cultivars grown in Lima, Peru, in a cool (18.8°C/12.3°C) and hot seasons (28.7°C/16.8°C). Control applications were 312mm in the cool season and 584mm in the hotter season. Reduced irrigation started 16-18 days after planting (DAP) in the dry treatments as -20% (170mm) in the cool season and -35% (380mm) in the hotter season. The yields were reduced by 20% in the cooler season and 52% in the hotter season. Reduced irrigation depressed dry matter production as early as

28 DAP and delayed tuber initiation by one week. At 62 DAP stressed plants were shorter, produced 41% less leaf area and solar radiation interception was reduced by c.30%, with fewer stems, branches and leaves. As reduced irrigation was initiated after crop emergence the effect on this growth stage could not be judged.

Banik *et al.* (2016) investigated drought mechanisms of several cultivars including the drought resistant Russet Burbank. It was suggested that cultivars with the greater stem water reserves were able to act as useful sources of water for leaves and maintained greater leaf water contents under stress. They also reported that the use of drought acclimation prior to drought helped to reduce wilting, induced a thicker cuticular layer and more open stomata under stress.

Temperature: Potatoes are generally classed as a ‘cool season’ crop with tuber growth reduced below 10°C and above 30°C and optimum yields achieved at a mean of 18-20°C (Ewing, 1981; FAO, 2008). Rykaczewska (2015) however identifies optimum haulm growth occurring at 20 - 25°C and optimum tuber growth 15 - 20°C. Stol *et al.* (1991) however define optimum growth as a daily minimum temperature of > 5°C and a maximum of <28°C. air temperatures above 30°C create moderate heat stress which can reduce tuber yields by increasing carbon partitioning to the roots, reducing Ps and the partitioning of assimilates to the tubers (Ewing, 1981; Prange *et al,* 1990). Similarly tuber temperatures >30°C will reduce or inhibit tuber growth and bulking (Struik *et al.*, 1989) and will cause greater yield reduction during the early phases of tuber bulking.

Rykaczewska (2017) investigated the effect of high temperature, day/night 38°C/25°C, and drought on tuber yield and quality. Heat effects on droughted plants were investigated at four periods: 33-46 DAP whilst buds were forming, 46-61 DAP during flowering, 61-75 DAP during fruit development, 75-89 DAP at the beginning of maturity. Plants were grown in pots outside until the application of heat/drought regimes for each 14 day period in controlled environments and then returned to the outside where normal temperatures and a full watering regime was used. Drought was imposed/created by cessation of watering when transferred to controlled environments, but the extent to which ‘drought’ was achieved was not discussed. The averaged effects for the heat/drought at all timings were reductions in plant height, Ps, tuber yield and tuber size, but there were increases in number of deformed and immature tubers and increased LAI. Results from imposition of heat/drought on individual growth phases, from stage 1 to stage 4, indicated progressive reductions on plant height, Ps, LAI, and the number of physiological defects and immature tubers. The size of tubers and yields were however affected most when heat/drought was applied at phases 2 & 3. The overall conclusion was that although the physical/physiological impact of the heat/drought stress was dependent on the growth phase of imposition, when it was applied at early growth phase 1 the yield included a significant proportion with physiological defects and immature tubers. In reality, although this work is useful, short term temperature increases of this magnitude, from 21°C/13°C rising to 38°C/25°C within days or weeks are unlikely in the UK currently and so work on longer term incremental rises is required. Unfortunately the drought event was always accompanied by temperature increases and so it is not possible to determine the effect of the drought alone in each phase.

Modeling and prediction

Haro-Monteagudo *et al*. (2017) investigated the potential of using drought indices to predict potato production based on long term weather records, Hindcast 1851-2014, and CEH-GEAR 1890-2014, aggregated to 1900-2014 for an Eastern England catchment. Although they identified that the 'Standardised Precipitation Evaporation Index (SPEI) gave a good correlation for potato response to drought and confirmed that the weather/rainfall in late spring and early summer were key components for yield potential, they noted that using these indices to prepare for drought gave too little time for drought mitigation measures to be implemented.

Research needed for potatoes

- As with most other UK crops there is a dearth of information relating to the drought tolerance of the commercially available potatoes and this is therefore a cornerstone requirement.
- Relationship between drought tolerance and quality aspects including cooking characteristics.
- One of the key areas where research is still required for potatoes in the UK however is methods to prevent compaction developing during the cultivation and bed preparation which leads to restricted root proliferation to depth.

11.1 Sugar beet (*Beta Vulgaris*)

The impact of drought on sugar beet grown in the UK

The water requirements of sugar beet are between 550-750mm dependent on climate and season length with emergence and early growth the most affected by water deficits (FAO, 2018a). The crop can be grown either as rainfed or irrigated in the UK but the best yields are achieved with irrigation. In the UK planting in mid-March and harvesting at the maximum yield point in Mid-November would equate to *c.*245 days. Although sugar beet is classed as moderately drought sensitive Jaggard *et al.* (1998) and Pidgeon *et al.* (2001) report that it is a major cause of sugar beet yield loss in the UK at approximately 25% (Sparkes, 2016). This is demonstrated by a farming press (Farmers Guardian) report that the 2018 summer drought reduced production by 30% on expected yields (Blenkiron, 2019). Sugar beet growth is localized to the East of the UK in relatively close proximity to the four sugar beet processing facilities: Newark (Nottingham), Wissington (Norfolk), Bury St Edmunds (Suffolk) and Cantley (Norwich). In this area, East of England, the average June to September rainfall is given as 150mm in stark contrast to the requirement of 350mm used by the crops as ET and consequently yield losses to drought are reported to rise from 10% in ‘average’ years to 30% in dry years (Jaggard *et al.,* 1998). In the 2005 survey of outdoor irrigated crops (Weatherhead, 2006) sugar beet was only irrigated on 27,710ha of the 194,000ha planted in 1990 (*c.* 14%) and only 8487ha of the 130,136ha planted in 2005 (*c.* 6.5%) showing that the majority of crop was not irrigated at that time. BBRO (2018) have reported that the new Xbeet Enrich^{100} seed treatment is being promoted to give protection against abiotic stresses such as drought.

Roy *et al.* (1978) reported that growth of sugar beet was slow during mid-June to the end of July, with considerable mid-day wilting.

Table 11.1 Indicative drought response of sugar beet.

	Response	**Source**
Early drought	27.5% sugar yield loss	Brown *et al.* 1987
Late drought	12.5% sugar yield loss	Brown *et al.* 1987
No irrigation/rainfall	17.5% sugar yield loss	Brown *et al.* 1987

Table 11.2 UK sugar beet production (Defra, 2018) and effect of early and late drought reductions

	UK Production	Early drought reduction 12.5 %	Late drought reduction 27.5%
Sugar beet root 2016	5.687 (Mt)	0.71 (Mt)	1.56 (Mt)
Sugar 2016 (17.3%)	0.984 (Mt)	0.12 (Mt)	0.27 (Mt)
Sugar beet root 2017	8.918 (Mt)	1.11 (Mt)	2.45 (Mt)
Sugar 2017 (17.81%)	1.59 (Mt)	0.20 (Mt)	0.44 (Mt)

UK Sugar production 64% of requirements in 2017, *c.* 2.15 Mt (Defra, 2018)

Figure 11.1 shows a very strong correlation (r = 0.79) between production (Mt) and land area used for that production but only 62% of the variation in production arising from variations in that area. The other factors causing variation in production will be due to factors such as dry springs reducing establishment and preventing attainment of good leaf area index over peak solar radiation, dry summers, poor harvesting conditions and the effects of pest and disease.

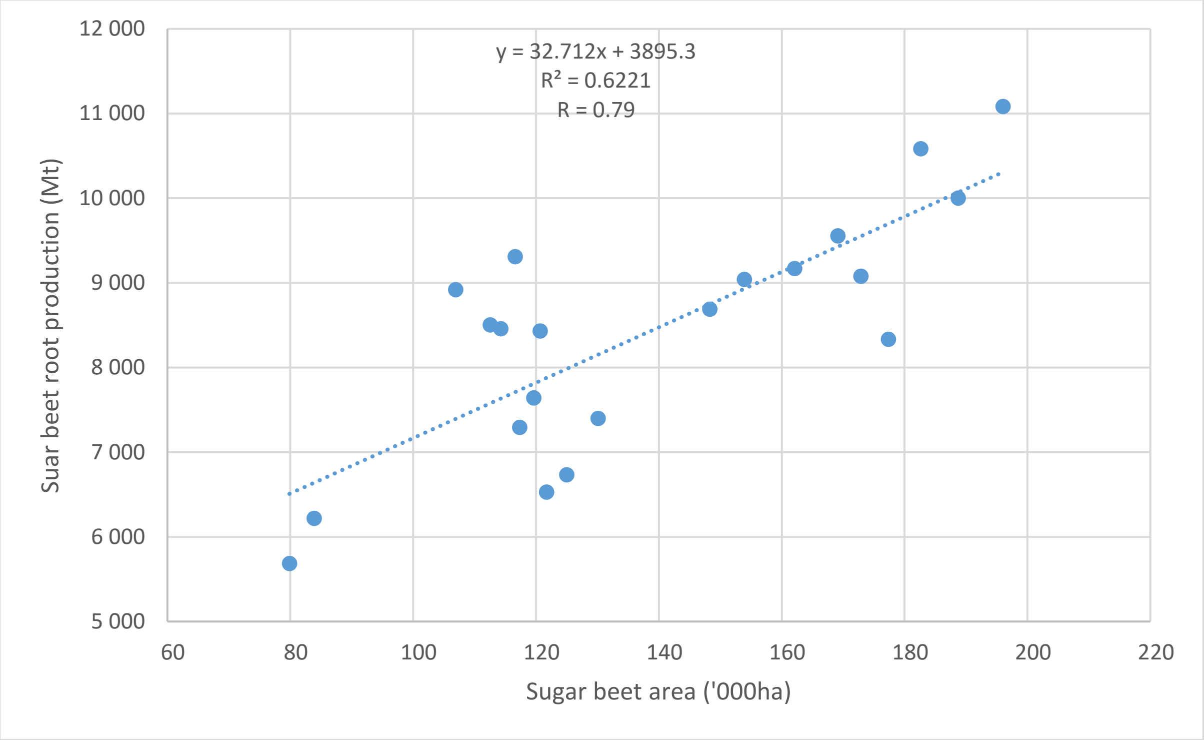


Figure 11.1 UK sugar beet area (‘000ha) and root production (Mt) from 1997 – 2017 (Source Defra, 2018)

Brown *et al.* (1987) investigated the effect of early and late drought on field grown sugar beet on a Barrow series sandy loam soil at Brooms barn experimental station, UK. Total yield was substantially reduced in both the early and late drought treatments, 52.8 t/ha and 56.3t/ha respectively, compared to the irrigated control of 69.4t/ha. Interestingly the unirrigated control also achieved 56.1 t/ha without any rainfall or irrigation. Sugar yield followed a similar pattern with early and late drought treatments, 8.7 t/ha and 10.5t/ha respectively, compared to the irrigated control of 12.0t/ha and the unirrigated control achieving 9.9 t/ha. The early drought equates to a 24% root yield loss and a 27.5% sugar loss whereas the late drought equates to a 19% root loss but only a 12.5% sugar loss. The unirrigated/non-rainfall sugar yield loss equates to only 17.5%. In relation to drought impacts therefore a late spring/early summer drought, as occurred in 2012, could have a greater potential impact than a summer drought where roots to depth are well developed and have greater access to water at depth. The early drought plots were covered by rain shelters for 8 weeks (6 June to 1 August) and reached a maximum SMD of 150mm. The late drought plots were irrigated until 1st August, at which point the SMD was *c.* 70mm, when they were then covered and droughted until 26th September, reaching a SMD of >200mm. A covered none irrigated control attained a maximum SMD of only *c.*175mm. Drought substantially reduced solar radiation interception due to reduced leaf area in early drought under maximum daylight hours but did recover after re-instigation of irrigation. Root growth was significantly reduced by the early drought whereas late drought allowed the development of a more robust fibrous root system before moisture became limiting. This concurs with work in a range of crops of the importance of root growth for drought resistance (Dardenelli *et al.,* 1997; Schenk & Jackson, 2002; Kell, 2011; Wasson *et al.,* 2012, Bao *et al.*, 2014; Chaiwanon and Wang, 2015; White *et al.*, 2015; Basu *et al*., 2016).

Drought tolerance of 30 European *Beta* genotypes with some UK cultivars available in 1999, were investigated by Ober & Luterbacher (2002). The field experiment in a sandy loam soil in Sufflok, UK, found significant variation and interactions with drought treatment between genotypes. A Drought Severity Index (SI) demonstrated that some genotypes were substantially more drought sensitive, or tolerant, than others. The UK cultivars Oberon, Nicola and Roberta produced similar middle ranked SI but some of the Syngenta and KWS genotypes demonstrated much better drought tolerance. This type of variation between genotypes is supported and demonstrated by work in the semi-arid Iran where Sadeghian e*t al.* (2000) reported 30-40% root yield and 33 – 40% sugar yield losses due to severe drought in Iran. Jones *et al.* (2003) utilising Brooms Barn simulation model and the General Circulation model data for 2021-2050, reported that although climate change would increase sugar yields by c. 1 t/ha the yield losses to drought could be expected to double from 7% to 18% in areas with existing problems. Whilst it was also reported that whilst the yield response to increased CO_2 in the atmosphere was an overall yield increase it was suggested that breeding for drought tolerance was important.

Research needed

- Identification and classification of drought tolerance in Sugar beet
- Enhancing the soil environment for improved soil water retention
- Investigation of the long-term viability of water absorbing polymers

12.1 Field Beans (*Vicia faba) and* Peas (*Pisum sativum* L.*)*

Field beans are one of the most important global but drought sensitive grain legumes (Alghamdi *et al*., 2015). Production for 2016 was 1.6 Mt Mainland China, 0.9 Mt Ethiopia and 0.3 Mt for the UK, which includes both *V. faba* vars. major and minor (FAO, 2018). Peas are grown in the UK for dry or processing markets. Dry combined peas occupied 40,000ha in 2017 (Defra, 2017) The UK is 85% self-sufficient and is the largest producer of vining peas with over 34,000ha, producing *c.* 135,000t for freezing and 3,000t for canning (British Growers, 2018). *Vicia faba* var. *major* (broad beans) produce large seeds (650-850 g/1000 seeds) and is cultivated mainly for human consumption, though culled broad beans can be fed to livestock. Whereas *Vicia faba* var. *minor* (horse beans or field beans) produce smaller seeds (250-350 g/1000 seeds) and are used mainly for livestock feeding.

They are a useful stock-feed and break crop in the UK, especially useful for their nitrogen fixing capability, but are sensitive to drought stress throughout the season but in particular during pod-set, especially the spring bean varieties (Knott *et al.*, 1994).

Effects of the 2018 summer drought on pea production was reported via the BBC by Marston (2018) as “UK pea growers are warning of shortages in supplies following the recent hot weather.   Growers say the heat and lack of rain means peas are struggling to form in their pods and that crops will be 20-30% below normal levels”.

Scientific reports for field beans (*Vicia faba* L.)

Work by Loss and Siddique (1997) demonstrated significant yield reductions, c. 50%, in a drier year as the result of reduced seed weight and number of pods whilst Xia (1994) reported 45% yield loss.   The reduction in yield due to drought or high soil moisture deficits have been recorded in several areas around the world and spanning many years (Greenwood, 1955; El Nadi, 1970; Keatinge and Shaykewich, 1977; Krogman *et al*., 1980; Sprent *et al*., 1977; Hebblethwaite, 1982; Pilbeam *et al.*, 1990, Xia,1994; Wu and Wang, 2000; Khan *et al.*, 2007, Khan *et al.* 2010, Ammar *et al.*, 2014, Hegab *et al*., 2014, Abid *et al.*, 2017)

Within these reports Keatinge and Shaykewich (1977), in Manitoba, suggested that reduced yields arose from high soil moisture stress during early phases of reproductive development. Sprent *et al.* (1977) showed that water supply following pod-set was probably more important to yield than solar radiation or plant competition in agreement with Xia (1994).   Krogman *et al.* (1980), in Alberta Canada, using irrigated and non-irrigated crops suggested that the soil moisture must always be maintained above the 50% AWC for full yield potential to be achieved.   Elston *et al.* (1976) showed that water stress decreased the absolute growth rate but did not affect the duration of growth to any great extent and also initiates earlier senescence (Finch-Savage and Elston, 1976; Karamanos, 1978). French and Legg (1979) suggest that the limiting soil moisture deficits for spring-sown field beans as 80mm and the grain dry-matter response to water was 0.006t/ha/mm. These reports are generally supported by Hussain *et al.* (1990) in New Zealand, who used irrigated and non-irrigated field crops and demonstrated reduced plant height, rate of leaf expansion and specific leaf area but increased root growth and leaf senescence. However, their conclusions were that unlike other authors who suggested drought sensitivity mainly at flowering and pod-fill, they believed that beans were drought sensitive at all developmental stages. Khan suggested that drought resistance mechanisms seen in *faba* beans arise with varieties with deeper roots whilst Ricciardi (1989a, 1989b) suggested that varieties with low stomatal density were associated with better stress adaption but osmotic adjustment does not appear important in beans (Amede and Schubert, 2003). Amede and Schubert (2003), also reported yield reductions of 36% moderate soil water potentials of -0.64 MPa and suggested that no differences occurred in water use efficiency between field beans and peas (*Pisum sativum*). Encouraging rapid growth before the onset of summer drought in the UK, drought escape, is not really an option at the present time as the planting dates and growing conditions are not favourable for this approach. However, increased temperatures due to climate change may change this situation

Scientific reports for peas (*Pisum sativum* L.)

In New Zealand Martin and Jamieson (1996) investigated the effect of both timing and intensity of drought in field grown peas covered by rain-shelters. They reported a linear reduction to yield to increasing soil moisture deficits with the greatest effect seen from severe drought during early growth pre-flowering. The yield loss over the potential soil moisture deficits of 49 - 323mm was characterized as 9kg/ha seed yield loss per 1mm additional deficit. It was suggested that although the number of pods were reduced by water-stress the number of peas per pod was not affected and that some of the yield loss was recouped from fewer pod numbers by increased weight per pea. They also concluded that the vegetative growth phases were more sensitive to drought than the reproductive phase. Similarly Andersen and Aremu (1991) identified that drought sensitivity was greatest during the flowering stage and yield loss was connected to reduced pod numbers.

Research needed

- Cultivar and determinacy tolerance required.

13.1 Forage Maize (*Zea Mays* L.)

Across the world maize has been grown extensively for many years but for many areas such as the USA it is grown more as a grain crop (Campos *et al.*, 2004) and is referred to as ‘corn’. In the UK there is very little maize grown for the grain itself as the primary use is as a forage crop and only a small area grown as sweetcorn. Consequently the effects of drought on production must acknowledge the aspect of growth/yield which is most important to the researcher, grower or market. Maize requires between 500- 800mm water and is suggested to have medium-high sensitivity to drought (Brouwer & Heibloem, 1986). In comparision to other crops the efficiency of water use by Maize is substantially better than most other crops at 271kg water transpired for every Kg of above ground biomass produced whereas wheat needs 505kg water per kg above ground biomass (Aldrich *et al*., 1975). In Northern Europe water requirements are greatest during July and August when both maximum growth rates and maximum evapotranspiration occur and is suggested for Southern England as 300-400mm from May to October (Bunting, 1978). It is also suggested that root growth can be from 0.75m to 2.5m dependent on soil conditions but was recorded at 1.3m at Rothamsted in the UK (French and Legg, 1977).

The impact of drought on forage maize grown in the UK

Drought stress is a major concern for maize production (Chapman and Edmeades, 1999; Eadmeades *et al.*, 1999). For corn production it appears to be most significant between tasselling to the dough stage (Aldrich *et al*., 1975) which is very similar to other suggestions such as at flowering, during which silk-growth, pollination and kernel set occur (Shaw 1977 as cited by Campos *et al.*, 2004).

Jamieson et al. (1995), in new Zealand, investigated the drought response of field grown Maize under mobile rain-shelters in a deep Templeton sandy loam with AWC of 190mm/m. It was reported that the critical PSMD for maize was 275mm before yield was depressed where they reduced from 12.02 t/ha to 9.66t/ha at 510mm PSMD with yield reductions mostly arising from reduced grain size. Maximum actual soil moisture deficits at 1.6 m were recorded as 79, 205, and 141 mm for early, mid and late drought. There were no differences in the components of grain yield.

Klocke *et al.* (2007) investigated the effect of irrigation and dryland production of field grown corn in a silt loam soil in the semi-arid state of Nebraska, USA, over the period 1986 to 1998. Grain yield was reduced by an average of 44% in the dryland crop (442mm rainfall) as compared to the fully irrigated crops (672mm combined rainfall/irrigation), at 7.8 and 11.8 t/ha respectively. Partially irrigated crops received 549mm (rainfall/irrigation) and achieved an average of 10.6 t/ha, 10% yield reduction. There were no other growth parameters published in the paper. Continuing the work Klocke *et al.* (2014) reported a more comprehensive 8 year study, 2005-2012, in Garden City, Kansas, USA. The soil type was a Ulysses silt loam (fine-silty, mixed, mesic Aridic Haplustoll) with AWC of 18%. Leaf area index was approximately 0.5 for no irrigation and increased to 5.5 as irrigation frequency increased were commensurate with grain yields, especially in the dry years.

In early work Carr and Hough (1978) it was highlighted that the timing and duration of the drought was especially important in relation the end use of the crop, i.e. for grain or forage maize. For grain maize the critical period was given as around the appearance of leaf 10 up to silk sensecing, whilst for forage maize drought at any stage which restricts growth and dry matter production can be important. They then identified effects at key growth stages for maize grown in Northern Europe as: limited effect on growth and leaf development during the establishment phase unless the drought was severe and resulted from a dry previous winter leading into a dry spring; reduced cell and leaf expansion during vegetative growth, from six leaves to tasselling, leading to reduced leaf area, solar radiation interception and ultimately yield. From the 14th leaf until flowering when another 4 – 6 leaves are produced is aslo suggested as being especially sensitive to heat and drought (Ciampitti, 2013). Downey (1971) also highlighted that drought stress during male meiosis reduced growth, tassel development chlorophyll content and light absorption but said it was not detrimental to grain yield, but identified that drought stress during the grain filling period reduced grain yield by 50%, dry matter yield by 29% and also reduced grain weight. Water stress during late stem extension delayed tasselling and silking reducing grain yield by 12-15% in 1966 but 53% when stressed during silking and an overall 30% yield reduction in 1966 and 1967(Claasen and Shaw, 1970a, 1970b). Grain yield is also substantially reduced by 22 – 50% if droughted during the pollination phase (Reinhardt, 1971).

Temperature: Maize has an optimum range of 25 -30°C for both shoot and root growth (Martin *et al*., 2006).

Research needed

- Varietal tolerance

14.1 Ryegrasses: Perennial Ryegrass (*Lolium perenne)*

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.

The impact of drought on forage grass grown in the UK

One of the impacts of the summer 2018 agricultural drought was as a case study where silage production was reduced by 25% and hay production was reduced by 40% on a Peak district farm (NFU, 2019). Roy *et al.* (1978) reported that grass growth during the 1976 drought was negligible in the south of England with many areas completely desiccated and animals needing supplementary feeding. 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 dry weather in 2018 reduced grass growth substantially in England from June through to late-August, figue 14.1, producing an average 1 t/ha DM less than the 13.3t/ha DM in 2017, equating to a 7.5% DM loss. During the same period however

Northern England and Scotland had near ideal growing conditions showing the climatic variability across the UK (AHDB FNN, 2018)

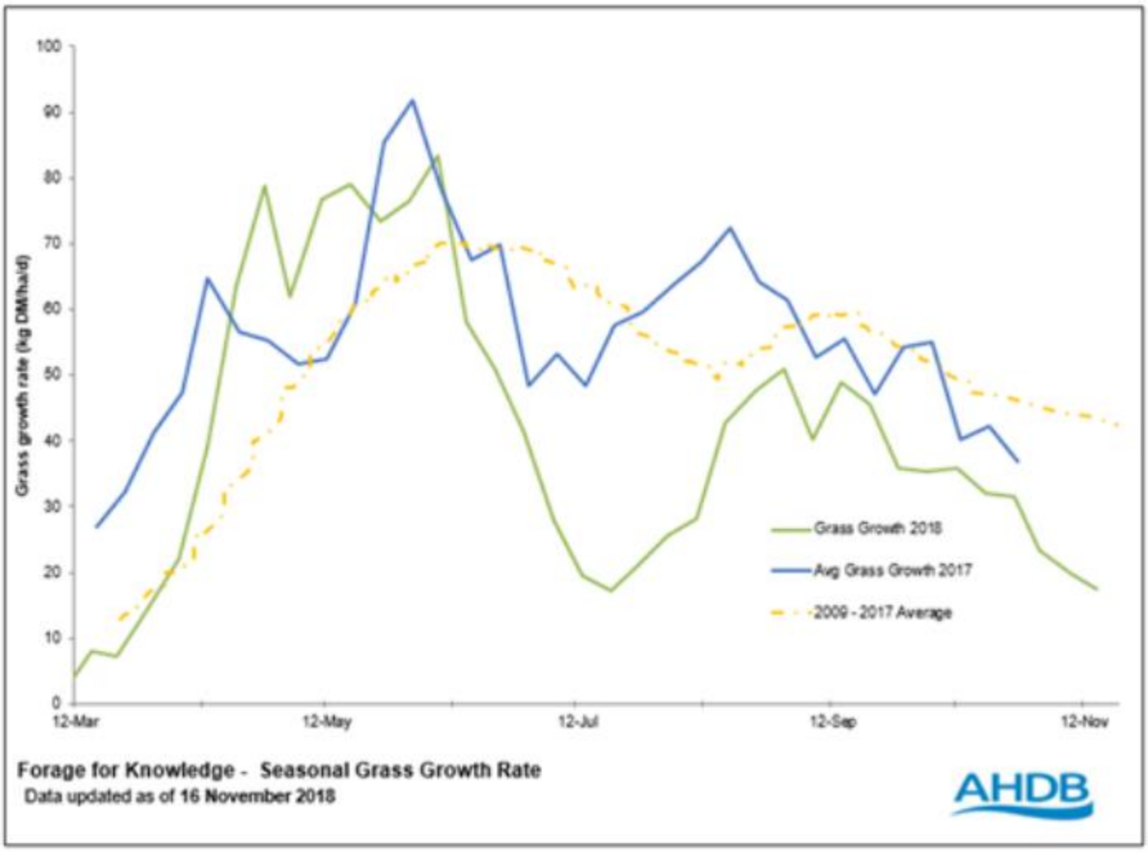


Figure 14.1 Seasonal grass growth in 2017 and 2018 compared to the 2009 -2017 average (AHDB Forage for knowledge: AHDB FFN, 2018)

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.

Other grasses and considerations

It is not possible in this review to cover all of the grasses used in the UK and although there contributions to the overall feed-stocks are important further research would be required to explore the potential of each in relation to climate change. However, in addition to the mainstay perennial ryegrasses there are also Italian ryegrass (*Lolium multiflorum*) with low tolerance of drought, Hybrid ryegrasses (*Lolium x boucheanum*) which has greater drought tolerance than IRG, Timothy (*Phleum pratense*) a cool humid climate haymaking grass intolerant of drought or prolonged high temperature, Cocksfoot (*Dactylis glomerata*) a meadow and haymaking grass, not a productive as the ryegrasses, but drought tolerant. All of these provide valuable contributions to livestock forage and overall feed-stocks, especially in less intensive and organic systems.

Unlike most other annual or perennial crops poor grass growth due to drought impacts significantly on contractors who are used for silage production as reduced growth of grass means less cuts 9harvests) per year. For instance in 2018 there was a good 1st cut, a few small second cuts but significantly less 3rd cut, if any.

There is also the effect on livestock farmers having to buffer feed during dry summer spells using forage designated for winter feeding, reduced potential to procure the forage for winter to replace it, lower quality, higher costs of subsequent winter feeds and bedding.

Research needed

- Drought tolerance of individual cultivars of PRG, IRG and hybrid RG
- Comparative work of cocksfoot and RG in single or mixed community grasslands
- Water productivity of grass species and communities under drought and higher temperature regimes.

15.1 **Lucerne (Alfalfa: *Medicago sativa*)**

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.

Temperature: Effects of temperature rise: Alfalfa haa an optimum range of 20 -30°C for shoot growth and 20 -28°C for root growth (Martin *et al*., 2006).

Research required

- Lucerne can be difficult to establish in the UK and therefore varietal traits which ensure good establishment and production on a range of soil types and environments found in the UK is paramount.

16.0 Horticultural, vegetable and fruit crops

Defra (2018c) reported the following areas and values for horticultural crops in 2017:

Roots and onions: 27,931ha with a value of £370m (parsnips, turnips and swedes, Dry bulb and spring onions and carrots which covered the greatest area of 11, 933ha).

Brassicas: 27,308ha with a value of £265m (Brussel sprouts, Spring/summer/Autumn and winter cabbage, and cauliflower and broccoli which together covered 16,500ha)

Legumes: 37,958ha with a value of £72m (beans and fresh, dry peas and processing peas which accounted for 34,614ha). Note that these crops are seldom irrigated.

Others: 20,286ha with a value of £394m (asparagus, celery, courgettes, leeks, baby leaf, rhubarb, water cress and others, and lettuce covering 4,391ha).

Orchard fruit: 24,449ha (Dessert apples, canary apples, pears, cider apple and perry pears, plums and cherries) and soft fruit: 10,747ha (excluding glasshouse) and 217ha (Glasshouse) (Strawberries, raspberries, blackcurrants). The total fruit value was provisionally given as £764.8m.

These crops are grown predominantly in specific areas within England normally due to soil or climatic preferences, table 8.*

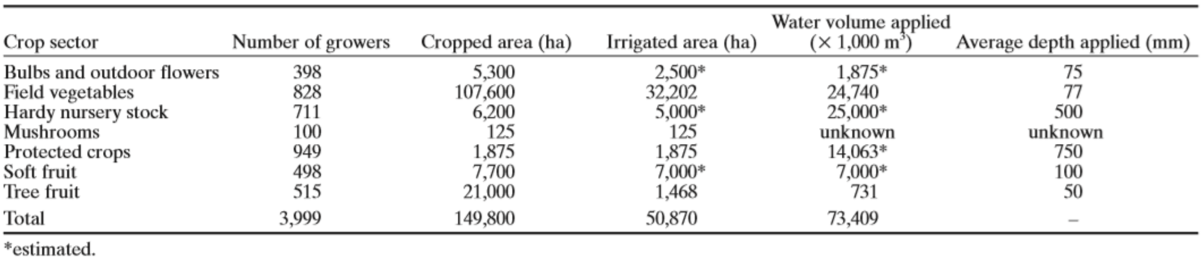
Table 16.1 Regional percentage areas of key horticultural enterprises relative to area of enterprises in England (Adapted from Defra, 2018d)

Region	Field Veg	Potatoes	Glasshouse	HNS	Sugar beet	Top fruit	Small fruit
North East	1	1					
North West	5	7					
Yorkshire/Humber	15	17	13				
East Midlands	30			24	23		
West Midlands		14				31	24
East of England	30	35			62		
South East			25			43	43
South West				32		15	

Notes: HNS Hardy nursery stock

It was reported by Hess and Sutcliffe (2018) that the production of fresh fruit and vegetables requires a substantial quantity of water for both growing and processing the crops. The work also reports that where our imported produce from water stressed areas such as Spain, Egypt, South Africa, Chile, Morocco, Israel and Peru this supply chain is becoming more exposed to changes in physical, regulatory and reputational water risks. For the UK industry therefore it is essential that we understand the water requirements and drought risks associated with our own production. There are seven key sectors recognised by the Horticultural Development Council (HDC): field vegetables, bulbs and outdoor flowers, hardy nursery stock (HNS), mushrooms, protected crops, soft fruit and tree fruit with a significant proportion of horticulture irrigated driven partly by supermarket demands for quality, consistency and continuity of supply (Knox *et al.*, 2010; Kumar *et al.*, 2017). The direct effect of drought therefore is inextricably linked to the availability of abstracted water for many of these sectors.

Table 16.2 Irrigated area (ha), volume of irrigation water (m^3) abstracted,, and average depths of water applied (mm) for each horticultural crop sector in England and Wales in 2005 (Knox *et al.*, 2010)



Crop sector	Number of growers	Cropped area (ha)	Irrigated area (ha)	Water volume applied ($\times$ 1,000 m^3)	Average depth applied (mm)
Bulbs and outdoor flowers	398	5,300	2,500*	1,875*	75
Field vegetables	828	107,600	32,202	24,740	77
Hardy nursery stock	711	6,200	5,000*	25,000*	500
Mushrooms	100	125	125	unknown	unknown
Protected crops	949	1,875	1,875	14,063*	750
Soft fruit	498	7,700	7,000*	7,000*	100
Tree fruit	515	21,000	1,468	731	50
Total	3,999	149,800	50,870	73,409	–

*estimated.

From the 2005 survey, table 16.2, Protected crops are 100% irrigated with an average application of 750mm irrigation ha and soft fruit 91% irrigated.

The overall production area of fresh vegetables, plants and flowers, and fresh fruit for 2017 as reported by Defra (2018b) is substantially less than the area used for the broadacre cropping of cereals, 3.18 m/ha: fresh vegetables 117,000 ha grown in the open and 1,000 ha protected; plants and flowers 13,000 ha; fresh fruit 24,000 ha orchard fruit and 11,000 ha soft fruit. The value of the products is however significantly greater value than cereals, £2.99m: fresh vegetables £1,000m grown in the open and £356m protected; plants and flowers £1,351m; fresh fruit £224m orchard fruit and £541m soft fruit. As with all crops the reduced growth and production associated with drought will impact on volume of production and also on the financial output from the enterprises. However, as will be seen from the research in this area, the saleability of the majority of these crops is such that irrigation is a pre-requisite and that even a moderate reduction of plant available water can lead to failure to attain the quality criteria (Jones and Tardieu, 1998; Stagnari *et al.,* 2016) especially in relation to that required by the large-scale buyer. For the fruit and vegetable sector there is also the requirement for substantial amounts of water for washing and processing the produce before being packaged and thus may become a limiting factor when severe drought restricts mains water use.

Irrigation requirements for a range of horticultural crops

A recent potato and horticultural irrigation survey commissioned by the AHDB (AHDB SD, 2017) identified a mean output value from the sector of *c.* £15,500 ha with a range from £4,400 (for a range of deep-rooted field vegetables) to over £460k ha for some high-value glasshouse salad crops. The survey respondents covered a cropped area of 64,000 hectares with over 40,000 hectares irrigated, 63% (AHDB SD, 2017). Defra (2017a) report that crop values for 2016 were £1.3 billion for home produced vegetables, which contribute 54% for all vegetables but with carrots and cabbages contributing 90% of total UK supply, £670 million for fruit, 17% of total UK fruit although UK apples represent 42% of UK supply, and 1.2 billion for UK ornamentals making this section of the industry of significant importance. In relation to drought impacts it is worthy of note that the UK imports 33% of its fresh vegetables, mainly tomatoes, lettuce and cauliflower and 21% of our fruit from Spain whose production may be similarly at risk due to climate change.

Knox *et al.* (2000) identified that a good robust supply of abstraction water for irrigation was critical for profitable field vegetable production. Unfortunately, Knox and Hess (2014), in a HDC report, highlighted that 35% of all HDC holdings were within catchments with ‘no water available’ and a further 19% were in catchments that were ‘over abstracted’, which could then lead to significant water deficits in low rainfall or drought years. The HDC holdings included top and soft fruit, protected cropping, mushrooms, hardy nursery stock, field vegetables and bulbs and flowers. Standard irrigation requirements for selected field crops are shown, table *.*, which highlights the key response periods and soil moisture deficits trigger values which prevent yield and quality losses.

Table 16.3 Typical irrigation requirements for selected field crops to maintain yield and quality in the UK.

Crop	**Pre-sowing or planting irrigation**	**Response periods**	**SMD trigger (mm) Low - High AWC soil**
Cabbage	April to July	May - September	20 - 50
Carrots	April to June	Throughout	25 - 50
Cauliflower	Throughout	Throughout	20 - 25
Celery	June	Throughout	20 - 25
Courgettes	April - May	Throughout	20 - 25
Lettuce (Summer)	April to August	Throughout	20 - 50
Salad onions	April - September	Throughout	25
Radish	April - August	Throughout	25
Spinach	April - July	Throughout to August	25
Swedes	May - June	June – July	25 - 75

Note: Adapted from ‘A water management toolkit for field crops growers. Defra 2007.

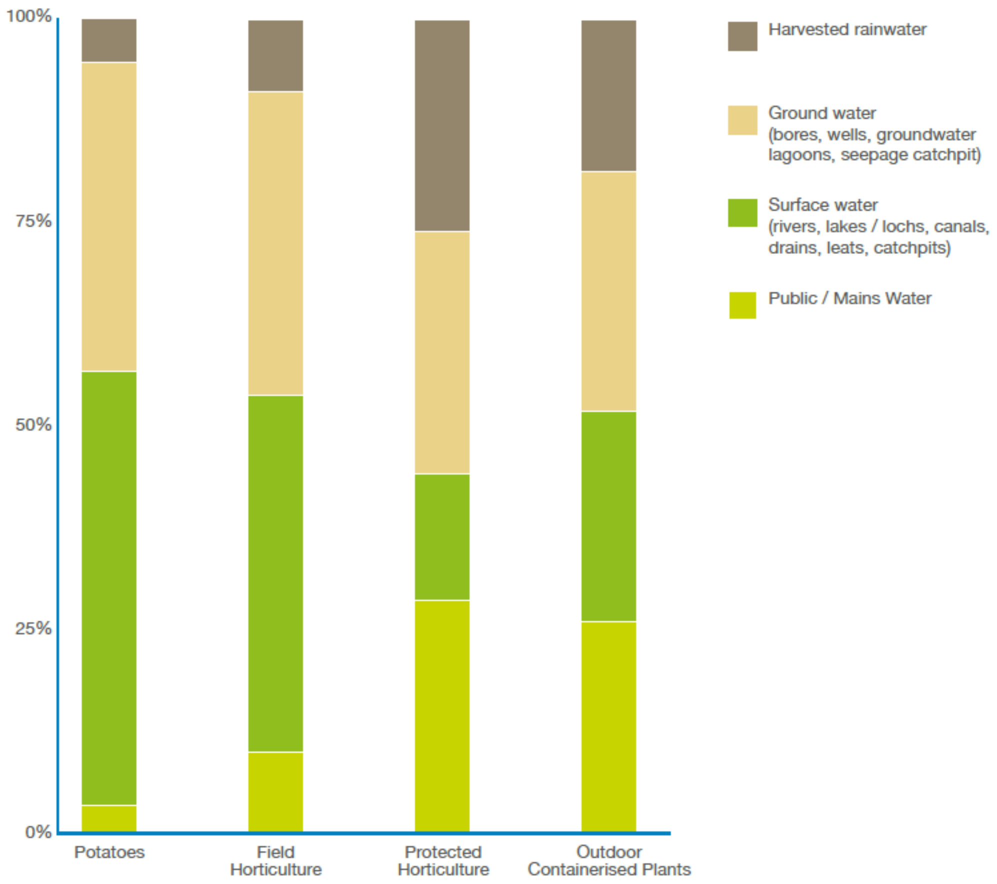


Figure 16.1 Water sources used for agriculture (AHDB SD, 2017)

Drought

The drought of 2018 had significant implications for the Irish horticultural sector where rainfall recorded at Dublin airport for May and June was less than 19% of the LTA and soil moisture deficits ranged from 70-95mm (Whelton and Alexander, 2018). It was suggested as the worst drought to affect the Irish vegetable industry in living memory. For the majority of crops the very wet spring led to delayed planting and poor establishment which was then aggravated by the succeeding drought conditions. There were some significant crop failures where no irrigation was available and other individual crop effects: broccoli and cauliflower showed poor growth with crops being rotavated in, broccoli also showed variable maturity and an estimated crop loss of 25%, cabbage production was reported to be reduced by 70%, irrigated onion sets showed reduced yield and size, salad onions had reduced germination and were patchy, irrigated iceberg lettuce grew well but hot temperatures caused head deterioration and further yield losses, non-irrigated swedes bolted and split along with boron deficiency which reduced saleable yield, carrot size and quality were reduced, parsnips had uneven germination and up to 30% of the crop was classed as poor, irrigated celery developed well but suffered blackheart due to heat stress, leek crops were backward even where irrigated with an estimated 15% crop loss which was also heat related, spinach crops had bolted due to long periods of sunshine even where irrigated, whilst courgettes and pumpkins were reported not to be affected by the drought at that time (Whelton and Alexander, 2018). Netafim (2018) reported the effects of two years of drought in the Cape region of South Africa where not only current yield losses but also future production will be affected. The report highlights that drought stress during flowering can reduce the number, size and shape of the apples formed and suggest that the trees need 'plenty of water' during the last two months before harvest.

16.1 Cauliflower:

The production and value of UK cauliflower production in 2017 was 90,000t worth £42 million utilising approximately 9,255ha (Defra, 2018b, 2018c). According to ADAS (1982) Yields of early and late summer cauliflowers benefit from irrigation whenever SMDs reach 25mm on low/medium AWC soils whereas for soils of high water retention 50mm should be applied 20 days prior to cutting. Kage *et al.* (2004) reported that drought and limited water supply down to 80cm depth, after establishment, reduced the sink strength of the cauliflower curd and curd growth and dry matter production were substantially and progressively reduced relative to reduction in water availability. Field experiments achieved almost total depletion of soil moisture and there was evidence that drought stress increased the rooting depth during the later stages of the growth period. Doerge *et al.* (undated) and Thompson *et al.* (2000) reported that optimum marketable yield and head quality of cauliflower was achieved when soil water tension was maintained above 10 – 13 cbar (close to FC) for the whole season in field experiments during 1995-96. These are also supported by Bozkurt *et al.* (2011) who demonstrate that maximum yield can only be achieved by maintaining soil moisture at FC. Wiebe (1981) found that the greatest yield was obtained when soil was maintained at a potential of 0.06bar, close to FC, during the 'head growth' phase, during the period of greatest water use, and significant losses were seen at soil water potentials of -1.0 bar. Low soil moisture during leaf initiation phase retarded head growth but did not substantially reduced marketable head size.

Drought sensitivity for cauliflower would therefore appear to be important over most growth phases but significantly so over the 'head growth' period.

16.2 Lettuce (*Latuca sativa* L.)

The production and value of UK lettuce production in 2017 was 99,000t worth £167 million utilising approximately 4,391ha (Defra, 2018b, 2018c). Production can be split into seeded or transplanted and the main horticultural types of Crisphead (Iceberg), Butterhead, Cos (Romain) and leaf. Lettuce is classed as a cool-season crop growing well at temperatures of 18 - 25°C daytime and 10 - 15°C night-time. Lettuce is classified as having a shallow tap root system (Maynard and Hochmuth, 1997) growing to a soil depth of only 0.6m when grown from seed (Sale, 1966; Gallardo *et al*., 1996a) and with significant shallow lateral root growth from which significant quantities of water and nutrients are taken (Jackson, 1995). The crop requires a substantial amount of water for good growth from either rainfall or irrigation (Ryder, 1999; Wellbaum, 2015) with the number of applications varying dependent on soil texture, environmental conditions length of the crop cycle. In addition where transplants are used, although the season is 3-4 weeks shorter, the transplant growth period also requires water for growth.

Response to drought and irrigation: Kerbiriou *et al.* (2013) demonstrated that early drought, applied between 320 – 432 °Cd, significantly reduced total root length and root length density in all soil layers and subsequent fresh-weight yield by 40%. Late drought imposed between 432 – 544 °Cd however slightly increased root development in the top 10cm but reduced root growth in deeper soil layers, and led to dryweight reductions of approximately 25%. Rowse (1974) protected lettuce crops from rainfall and reported 75% reductions in root growth, less shallow roots but greater root growth at depth in 1971-1972. Yield loss was 54% in 1971 but only 5% in 1972, the difference for 1972 was reported as due to the soil being returned to FC after thinning in contrast to 1971. Unfortunately no actual rainfall or water quantities were reported and Central England records (Alexander and Jones (2001) show that June 1971 was significantly wetter, 71.5mm, than June 1972, 50.3mm, leading only to the conclusion that the irrigation itself compromised the 1972 work. Loss of yield to small soil water deficits has been widely reported (Sammis *et al*., 1988; Sutton and Merit, 1993; Thompson and Doerge*,* 1996; Aggelides *et al.,* 1999; Sanchez, 2000; Acar *et al*., 2008; Bozkurt *et al.,* 2009; Tsabedze and Wahome, 2010; Kizil *et al.*, 2012; Vickers *et al.*, 2015) and has a linear relationship whereby marketable yield decreases at a faster rate than total yield (Bar-Yosef and Sagiv, 1982). Irrigation is normally applied to replace water lost to ET in order to protect both yield and quality as demonstrated by Defra (2007) guidelines where trigger SMDs are set at just 20mm on light soils. Sammis *et al*. (1988) demonstrated a linear increase in marketable yield from 6 field experiments in response to water application (irrigation/rainfall) of between 150 – 190mm, average season length of 65 days from transplant to harvest. Seasonal evapotranspiration was calculated as 205mm and yield reduction was between 34 – 47% in the rain-fed only treatments. When measured in soil water tension a similar reliance on high soil water content is demonstrated whereby optimum yields are attained when soil water potential is less negative than -6 to -7kPa at a 0.3m (Thompson and Doerge, 1996) or -30kpa (Aggelides *et al.,* 1999). Karam *et al*. (2002) reported that irrigation at 80% and 60% of the ETc reduced lettuce leaf number, leaf area index (LAI), total dry matter also reduced final fresh weight by 20% to 30% compared to the 100% ETc irrigated control.

Acar *et al.* (2008) demonstrated that quality as, measured by Brix, was significantly reduced when irrigation fell from 100 to 80 and 60% of class A pan evaporation and Vickers *et al* (2015) reported increased post-harvest pinking in treatments with increased irrigation. Overall therefore the majority of research on lettuce identifies that to maintain yield and quality for this crop the soil-water must be kept close to FC but not exceed it.

Temperature: lettuce shows little growth below 7.2°C, optimum temperatures are between 18.3 - 21°C whereas temperatures above 30°C stunt growth, increase bolting, produce bitterness and poor quality. Romaine and leaf lettuce are suggested to be more tolerant of high temperatures than iceberg and butterhead types (Turini *et al.*, 2011)

16.3 Cabbage (*Brassica Oleracea* capitata*)*

The production and value of UK cabbage production in 2017 was 224,000t worth £104 million utilising approximately 7,404ha (Defra, 2018b, 2018c). Cabbage is classed as a leafy vegetable with intermediate susceptibility to water stress (Kage *et al.,* 2004; Xu and Leskover, 2014) with the head formation stage most sensitive (Smittle *et al*., 1994). The most critical periods for water stress are suggested as 3 to 4 weeks prior to harvest but the greatest yields are seen when soil moisture is maintained <25KPa, which is close to FC. Ramadan and Omar (2017) reported fresh-weight and head-weight loss of *c.* 17 and 40% and yield loss was 12 and 33% when ET was only replaced by irrigation at 80 and 60% respectively compared to the 100% irrigation control, giving some indication of response to water scarcity. WUE was also shown be substantially reduced by 12 and 33% from an average of 12.32 kg m^3 to 8.29 kg m^3. In addition to yield reduction however drought stress increases the thickness of cell walls, relative dry weight, lignin content, suberin and cellulose which create a fibrous and woody texture disliked by consumers and also increased physiological disorders and diseases such as ‘brown head’ (Dixon, 2007).

16.4 Broccoli (*Brassica oleracea* Italica)

The production and value of UK broccoli production in 2017 was 73,000t worth £62 million utilising approximately 7,236ha (Defra, 2018b, 2018c).

Water stress: Doerge *et al.* (undated) reported that optimum marketable yield and head quality of broccoli was achieved when soil water tension was maintained above 10 – 13 cbar (close to FC) for the whole season in field experiments during 1995-96. Khan *et al* (2011a, 2011b) showed significant fresh-weight reductions when drought was imposed 14 days after planting and also leads to increased aliphatic glucosinolate and flavonoid levels (Fortier *et al*, 2010). Wurr *et al* (2002) reported that head weight and diameter and stem turgor are all reduced by water stress (-0.6MPa) and that the timing of water stress produced variation in shelf life of the produce. Whereas Cogo *et al.* (2011) demonstrated that water stress during growth followed by cold storage gave the best preservation of colour, antioxidant activity and L-ascorbic acid and 5-methyl-tetrahydrofolate contents, but did not report any yield effects.

Temperatures above 30°C during inflorescence production or floral initiation causes unevenly-sized flower buds on broccoli inflorescences, abnormal and uneven head development and reduced marketability. Higher temperatures can prevent vernalisation, producing leafy heads and flower death (Björkman and Pearson, 1998).

16.5 Onions (*Allium cepa* L.*)*

Onions are grown for a range of markets which affect their overall water requirement and critical growth periods. Markets include green salad onions or bulb onions for consumption uncooked, consumption cooked, pickling, factory made food, dehydration, sets and seed production (Brewster, 2008). The production and value of UK onion production in 2017 was 380,000t worth £134 million for dry bulb and 15,000t worth £25million for spring onions, utilising approximately 10,200ha (Defra, 2018b, 2018c). The main growing regions are Lincolnshire, East & West Anglia, Bedfordshire and Kent. The depth of rooting in onion is suggested as mainly in the range 20 - 40 (Allen *et al*.,1998; Welbaum, 2015; Khokhar, 2018). This lack of rooting depth therefore significantly reduces the plant ability to access soil moisture and makes them particularly susceptible to low soil moisture availability especially under high ET demands (Brewster, 2008).

Water stress: Water is suggested as the main limiting factor for low bulb yield in onion (Khokhar, 2018). Water stress is reported to occur at only 30% of the readily available soil moisture and frequent supplemental irrigation is required. An early report by Singh and Alderfer (1966) suggested that water stress at any growth stage of onion growth reduced marketable yield but water stress during bulb formation and enlargement than during the vegetative stage. Agreeing with this Pelter *et al.* (2004) reported that when soil moisture was allowed to depreciate to 50% AWC, when stress was imposed at either the 3, 5, 7 and 9 leaf stages, total yield was reduced. However the greatest yield reduction for single stage stress was seen at the 5 or 7 stage but yield loss increased to 26% if the stress was applied at both the 3 and 7 leaf stages. Similarly, Dragland (1974) reported that yield loss from a 3-week early season stress was greater than a 3-week stress later in the season as did and Van Eeden and Myburgh (1971). In addition only the no-stress control and stress at the 9 leaf stage achieved greater than the industry standards of > 70% single-centre bulbs, an important quality criteria, whereas water stress at the 3 and 7 leaf produced only 35% single-centres and at the 3 leaf stage only 45% single centres. Stress at the 3 and 7 leaf stage also significantly reduced average bulb weight. Overall it can be seen that avoiding water stress during the early growth stages and bulb formation and enlargement is paramount for good yield and quality.

16.6 Carrots (*Daucus carota* L. ssp. *Sativus*)

The production and value of UK carrot production in 2017 was 866,000t worth £151 million utilising approximately 11,933ha (Defra, 2018b, 2018c). There is little European research available on water stress of carrots but Defra (2007) suggest that it is necessary to irrigate carrots throughout their production when soil moisture deficits reach as little as 25mm on light soils and only 50mm for water retentive soils. This is supported by Rubatzsky and Yamaguchi (1997) who state that most carrot crops need 30-50mm of water per week, 450 - 600mm per season, and should be irrigated when soil moisture has depleted by 40%, in agreement with Martin *et al.* (2014), as low soil moisture causes slow growth, thickened woody cells, reduced sugar content and a bitter taste. Whilst there is evidence of genotypic variation in drought tolerance in Canadian cultivars (Lada *et al.,* 2004) there is little information on this trait in UK cultivars. Reid and Gillespie (2017) in Australia, Quezada *et al.* (2011) in Chile and Carvalho *et al.* (2018) in Brazil, all demonstrated linear reductions of root yield with increasing moisture deficit and all concluded that minimising water deficits was essential for crop yield and quality.

Temperature: the majority of carrot production occurs in temperate climates as root and foliage growth are optimum between 16 - 21°C. Greater than 21°C leads to short stubby roots and above 30°C foliage growth and root quality reduces (Rubatzsky and Yamaguchi, 1997).

16.7 Leeks (*Allium ampeloprasum* var. *porrum* (L.) J. Gay)

The production and value of UK leek production in 2017 was 33,000t worth £27 million utilising approximately 1,595ha (Defra, 2018b, 2018c). Drought stress significantly reduces plant production and nitrogen uptake (Sørensen, 1996). Jezdinský *et al.* (2012) compared the effects of irrigation initiated at <65 or <45% AWC and showed that the latter decreased the photosynthetic and transpiration rate from 5.04–5.37 to 3.33–3.43 µmol CO_2.m^{-2}. s^{-1} and from 1.78–1.91 to 0.99–1.03 mmol H_2O. m^{-2}. s^{-1} on average, the weight total fresh weight of plants from 355–453 g to 152–255 g, and also reduced the leaf area, the length and diameter of pseudostem. Sørensen *et al*. (1995) demonstrated a 30% yield increase when irrigation was initiated at just -20kPa and reduced yield at less frequent irrigation, at soil water potential of 0.09Mpa. It was also reported that less frequent irrigation also increased in dietary fibre, vitamin C, protein, Ca, Mg and Mn content.

17.0 Orchard and soft fruit

The main top fruit, apples, is grown solely over the west midlands and into southern England with no significant production at higher latitudes. Total orchard fruit area was 24,000ha and the value of orchard fruit production, including pears, was given as £224 million with dessert and culinary apples accounting for £141 million in 2017 (Defra, 2018b). The total soft fruit area was 11,000ha, including wine grapes, with the value of soft fruit production given as £541 million for 2017, with strawberries accounting for £328 million (Defra, 2018b). The soft fruit industry overall includes strawberries, raspberries, blackcurrants, grapes, gooseberries, blueberries. In 2016, 50% of the area of soft fruit grown was grown under temporary tunnel with strawberries, raspberries and blackberries greater than 80% under temporary tunnel. Irrigation to prevent water-stress and ensure that quality matches retailer requirement at harvest is essential (Thompson *et al.* (2007). The key growing areas are predominantly the Midlands and lower latitudes plus Scotland, with little grown in Wales or Northern England.

17.1 Apples (*Malus domestica)*

A review of literature by Lakso (2003) suggested that the quantity of water required by apple trees will be influenced by factors including climate, tree characteristics and environment and suggested that most useful expression to quantify water use is the water rate per unit leaf area in mid-summer. Based on a range of material it was concluded that water rates of 1 – 1.7 litres per day per m^2 leaf area in mid-summer was a good approximation. During early growth and later growth, with reduced leaf area, this rate will be smaller. Under developing early season drought, late-march to mid-June, vegetative growth, leaf area and fruit set will all be reduced (Ferree and Schmidt, 1990), as these are principally cell division processes (Hsaio,1973), as seen in Cox's Orange Pippin (Powell, 1974). Whereas there was little effect when droughted from mid-June until harvest (Powell, 1976). Lakso (2003) suggests that water stress which develops in mid-Summer will have less effect as vegetative expansion, canopy formation and fruit set is mainly completed by this time. This is supported by Mills *et* al. (1996) who found leaf area, shoot length and crop weight on 3 year old Braeburn were reduced by deficit irrigation imposed from 55 days after full bloom (DAFB) until harvest but not when deficit irrigation was imposed from 105 DAFB. It was also concluded that fruit water relations and sugar concentration are modified by early season water deficit but less so by later season deficit in agreement with (Mills *et al.*, 1994; Kilili *et al.*, 1996). Catzeflis (1979), growing Golden Delicious, however, found little effect from early drought, no effect from late-Summer but substantial effects from mid-Summer drought. Naor *et al*. (2008) working in semi-arid Israel however demonstrated that even when trees of cv. Golden delicious were well watered until the post-cell division phase, reducing irrigation substantially reduced crop yield and mean fruit mass but not the number of apples produced. overall Atkinson *et al.* (1999) however, also demonstrated that the effect of drought will also be influenced by the rootstocks themselves. A key consideration for the effect of drought on apple growth will be the timing of the drought. In the UK winter rainfall often returns soils back to FC and early season drought is less likely. In the major droughts such as 1976 however a dry preceding winter is likely to significantly impact on the early growth of orchard crops which is then likely to lead to significant reduction in fruit set and growth. Unlike annual crops trees generally possess roots which extend significantly deeper and thus give access to greater volumes of soil water.

Irrigation for the prevention or reduction of drought is preferable to maintain fruit size and yield (Atkinson *et al.*, 1998; Higgs and Jones, 1991) but is not always possible either economically or practically (Atkinson *et al.*, 1999). In a survey of irrigated outdoor crops in 2005 it was reported that only 1,468ha of orchard fruit were irrigated from a total of 21,000ha of tree fruit (Weatherhead, 2006; Knox *et al*, 2010). The requirement is also affected by end use whereby cider apples not requiring blemish free skin would generally not be irrigated. Newer orchards are more likely to have drip or trickle systems installed when used for fresh fruit production. When irrigation is used the trigger deficit would be set to approximately 35% of total available water capacity of the soil in the USA because at 30% total available water (TAW) leaf senescence occurs and fruit production declines (Ebel et al, 2001). Although the effects of water deficit appear to be negative several studies have investigated the use of partial rootzone drying (PRD) and deficit irrigation which has substantially reduced water use. In multi-year semi-arid environment Einhorn and Caspari (2004) demonstrated that fruit growth rate, final fruit size, and fruit quality of Gala apples at harvest, and after cold storage, did not differ between treatments. Whereas Talluto *et al.* (2008) demonstrated that using PRD in ‘Pink Lady’ production, reducing water application by 50%, produced some reduction in fruit number there was no change in yields and fruit quality compared with conventional irrigation. This suggests that although apple can be sensitive to drought or reduced water there are irrigation techniques which reduce the effects if practiced correctly.

Temperature: Apples are suggested as a temperate deciduous species requiring a cold winter period to break dormancy but which can be grown across latitudes from 25 - 52° and suitable areas outside of this. They can withstand temperatures as low as -40°C, when the rootstock is killed (Palmer *et al.,* 2003). Early season temperature is critical for good pollination with significantly slower pollen tube growth below 13 - 15°C and less pollinator movement. Daytime temperatures exceeding 25 - 27°C reduce flower formation (Jonkers, 1980) whilst ambient temperatures exceeding 36°C can cause sunburn of the skin as actual skin temperatures are closer to 50°C (Bergh *et al*. (1980). This is in line with the 13 - 14°C rise suggested between ambient and skin temperature (Thorpe, 1974). Root growth also appears to be substantially reduced at soil temperatures exceeding 30°C but with serious damage to the leaves when root temperatures increased at 35°C and greater (Gur *et al.*, 1972). Using growing degree days (GDD^{-1}), above 4°C, Johnson and Lakso (1985) demonstrated a linear relationship for shoot growth even between cultivars and rootstocks but although a similar relationship existed for leaf area it was not consistent between cultivars.

17.2 Strawberries and other soft fruit

These are produced using several systems, protected or un-protected with a value given as £283m in 2017. Table-top substrate production, which is protected, utilises significant irrigation with advice being suggested to irrigate to achieve 10-20% run-off to prevent dry spots within the growth medium but also to prevent the build-up of salts (Else, 2013). Unfortunately the practice led to excessive vegetative growth, increased disease, fruit with reduced shelf-life and reduced eating quality. Investigating irrigation efficiency in field-grown (protected) strawberry shoot growth and cropping potential was shown to be reduced by even small soil moisture deficits, with yields of class 1 fruit reducing from 26.7 in the fully irrigated control to 13.5 t/ha in some treatments. Overall however, by applying various reduced irrigation strategies such as regulated deficit irrigation (RDI) or partial root-zone drying (PRD) it was reported that the quality parameters were generally improved and yields were statistically similar. In further grower trials the soil moisture tension irrigation trigger, to avoid water-stress, was set between -75 or -80 to -100kPa and total class one yields were 18% or between 6 – 15% than in the fully irrigated control (HDC, 2012). Allowing the soil/medium to dry out below these small deficits would probably not be advisable due to yield and quality losses.

Raspberry production in the UK was valued at £128m in 2017 (Defra, 2018). They are reported to be shallow rooting and require a regular and uniform water supply from fruit set to harvest (Crandall, 1995). The plant responses to water stress are similar to those experienced in most plants i.e. reduced production and yield (Morales, *et al*, 2013) arising from reduced leaf growth, stomatal conductance and transpiration, reduced photosynthesis and carbohydrate accumulation, modified/reduced cell size and early plant senescence (Crandall, 1995; Pecival *et al.,* 1998, Privé and Janes, 2003). In addition although the plants have moderate tolerance of short water stress, longer periods of water-stress, up to 28 days before re-watering, also affected phenological timing and reduced yield by up to 38% in the following season (Morales *et al.*, 2013). Much of the work reported here has however only been with the Heritage variety (remontant type).

Blueberries (highbush) production has been increasing in the UK. Currently the crop is grown in large outdoor containers which probably further restrict the natural shallow rooting nature of the crop. Blueberry is reported to be highly sensitive to water-stress (Améglio *et al.* 2000; Bryla, 2011). Work by Mingeau *et al.* (2001) demonstrated that in response to water-stress there was a rapid transpiration reduction coupled no stem diameter or shoot-elongation growth in highbush blueberries. In addition, under all water stress conditions mean fruit weight and size declined. When stress occurred during flowering-induction in one year the number of flowers and thus the number of fruits also declined in the following year (Bryla, 2011; Mingeau *et al.*, 2001).

Tomatoes (*Lycopersicon esculentum*): There is currently 92,000t of British tomato production p.a, with a value of £190m, almost entirely grown in glasshouses which can also utilise captured CO_2 to enrich the growing environments (British Tomato Growers, 2019). The systems use drip irrigation or the Nutrient Film Technique where both water and nutrients are re-used and re-circulated. The sensitivity of tomatoes to water-stress has been reported over many years (Salter, 1954; Waister and Hudson, 1970; Rao *et al.,* 2000). The response of tomatoes to the water-stress will be associated to the timing and severity of the stress and the drought tolerance of the cultivar. Typical symptoms include reduced photosynthesis and respiration rate, reduced overall growth and leaf area, flower shedding, alteration of the root/shoot ratio, reduced mineral absorption, reduced fruit size and increased fruit splitting, plus physiological disorders such as blossom end rot (BER) (Kumar et al. 2012; Jangid and Dwivedi, 2016). Nuruddin *et al.* (2003), imposed different stress at 65 and 85% of available water and included different timings and durations of the stress. It was demonstrated that although water stress applied throughout the season significantly reduced yield and fruit size, plants stressed only during flowering reduced fruit number but increased individual fruit size. However, although when water-stress was only applied at flowering it produced both better yields and quality than when stress was applied at other specific times, the yield was still reduced from that seen in the un-stressed plants. Severe water-stress, applied when only 25% of ET was replaced during the reproductive stages showed yield reductions of between 40% with a drought tolerant cultivar compared to 90% in another cultivar (Wudiri and Henderson, 1985).

17.3 Hardy Nursery Stock

Defra statistics for 2017 (Defra, 2018b) give the value of the plant and flower sector as £1.35 billion with a total area of 13,000ha. Hardy nursery stock accounted for £933 million. Outdoor HNS is often grown with tickle irrigation or as capillary on a sand-bed system. It can be seen from the irrigation survey 2005 that 81% of the HNS growers used irrigation, with an average depth of 500mm (Knox *et al.*, 2010), making generalised effects of drought difficult to quantify. Knox *et al.* (2010) highlighted the drought sensitivity of soft-fruit, hardy nursery stock and protected cropping and emphasised how they all relied heavily on irrigation. This is supported by irrigation research done on behalf on the Horticultural Development Council (HDC, 2010) where the water requirement of HNS was shown to be high with irrigation applications normally on a little and often basis for plants on capillary matting, small pots or cells or in larger quantities applied every 1 – 4 days for larger pots and containers. The range of plants grown in this sector is extremely wide and although they will have different growth patterns, different critical growth stages and different cultivars within the same species, as suggested by Larcher (2003), they are often grown together in the same location where the underlying drought sensitivity stems from the generally small soil volume available for water storage in the containers (Lea-Cox *et al*., 2001; Grant, 2013), figure 17.1. The majority of work in these crops tends towards the saving of irrigation water and the avoidance of stress (Costa *et* al, 2007) with plants exhibiting a range of responses to water stress such as leaf senescence and abscision shown in *Cytisus x praecox*, leading to complete loss for the season (HDC, 2010). Work in the USA investigated the necessity for irrigation to replace ET on a selected range of herbaceous annual ornamentals; *Impatiens walleriana* Hook. fil. `Tempo White' only grew well when water was replaced at 100% ETo whereas *Begonia carrieri* Hort. `Vodka', *Lobelia erinus* L. `Cobalt Blue', and *Viola × wittrockiana* Gams. `Crown Gold' grew only grew well when 50% or more ETo was replaced. *Antirrhinum majus* L. `Sonnet Yellow', *Dianthus L.* `First Love', *Lobularia maritima* (L.) Desv. `Carpet White', and *Pelargonium ×hortorum* L.H. Bailey all grew well even when only 25% to 50% ETo was replaced. However, the species *Catharanthus roseus* (L.) G. Don `Peppermint Cooler', *Rudbeckia hirta* L. `Indian Summer', *Senecio cineraria* D.C. `Silver Dust', *Tagetes erecta* L. `Inca Yellow' and *T. patula* L. `Bonanza Gold', *Zinnia angustifolia* Kunth., and *Salvia farinacea* Benth. `Rhea Blue', all grew well with either no additional water or water applied up to 25% of ETo, as did the heat and drought tolerant *Petunia ×hybrida* hort. ex. E. Vilm. `Merlin White' and *Glandularia* J.F. Gmel. `Imagination', and it was concluded that these were well suited for low-water conditions (Henson *et al*., 2006). This work suggests that there is indeed a range of responses to water deficits for herbaceous annuals and that there is probably considerable scope for further research in this area.

The key effect of drought in this industry in the UK is the potential for loss of abstraction for irrigation which would significantly impact on the saleability of the produce with substantial losses occurring within a short time frame for many crops.

A discussion with Martin Emmett at AHDB (Chair of AHDB HNS Panel) confirmed one of the key issues was due the production in pots which have a much smaller soil volume from which to survive if not irrigated for any period of time. He also highlighted the problem with water for parkland and landscaped gardens and trees, which need to be protected due to the significant cost when buying and installing the material. As a water source Mr Emmett suggested that the majority of growers use groundwater rather than river abstraction and also recapture water, which is supported by the AHBD SD (2017) survey, figure 16.1.

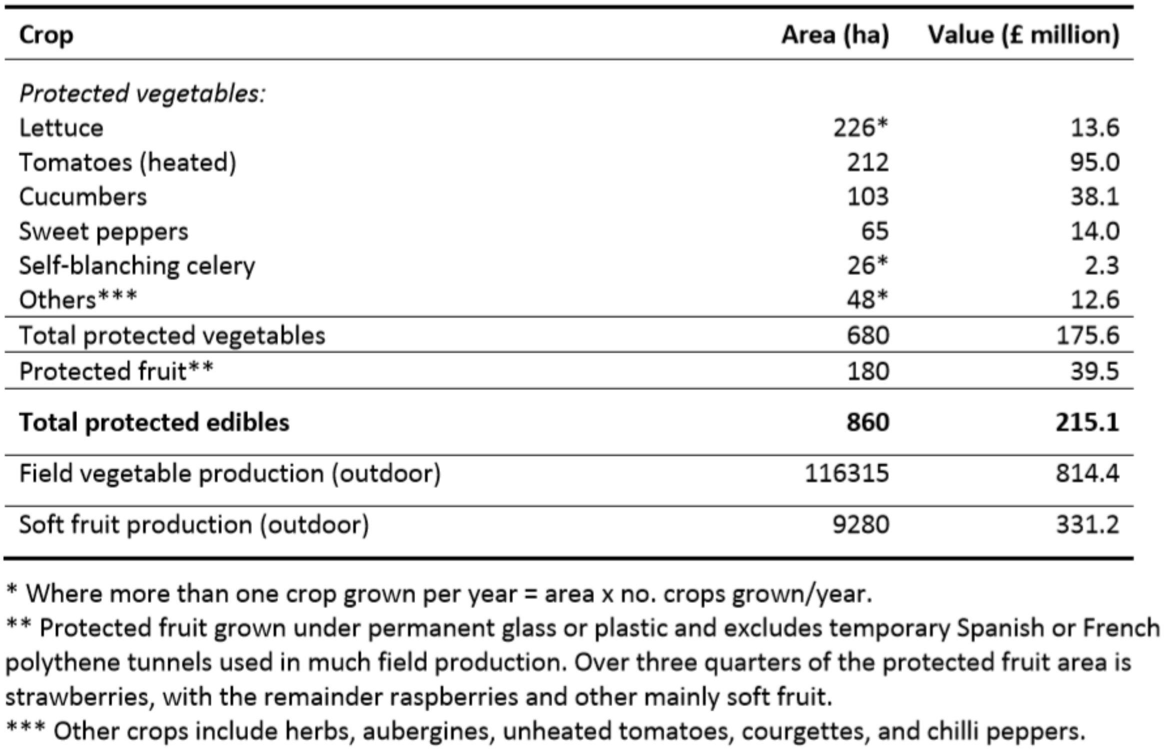
Figure 17.1 *Heuchera* plants grown in protected environment (left) with a thermopile scan (right) showing dryer/warmer plants (yellow/orange) at the top and wetter cooler plants (green/blue) lower down (HDC, 2010)

17.4 Protected cropping

Protected cropping can include both edible and non-edible produce and relates to crops which are grown under polythene or glass.

17.4.1 Protected edibles

As part of Defra project (WU 0123) Burgess (Undated) reviewed the water/irrigation requirements for the ‘protected edibles sector, figure 17.2.



Crop	Area (ha)	Value (£ million)
Protected vegetables:		
Lettuce	226*	13.6
Tomatoes (heated)	212	95.0
Cucumbers	103	38.1
Sweet peppers	65	14.0
Self-blanching celery	26*	2.3
Others***	48*	12.6
Total protected vegetables	680	175.6
Protected fruit**	180	39.5
Total protected edibles	**860**	**215.1**
Field vegetable production (outdoor)	116315	814.4
Soft fruit production (outdoor)	9280	331.2

* Where more than one crop grown per year = area x no. crops grown/year.
** Protected fruit grown under permanent glass or plastic and excludes temporary Spanish or French polythene tunnels used in much field production. Over three quarters of the protected fruit area is strawberries, with the remainder raspberries and other mainly soft fruit.
*** Other crops include herbs, aubergines, unheated tomatoes, courgettes, and chilli peppers.

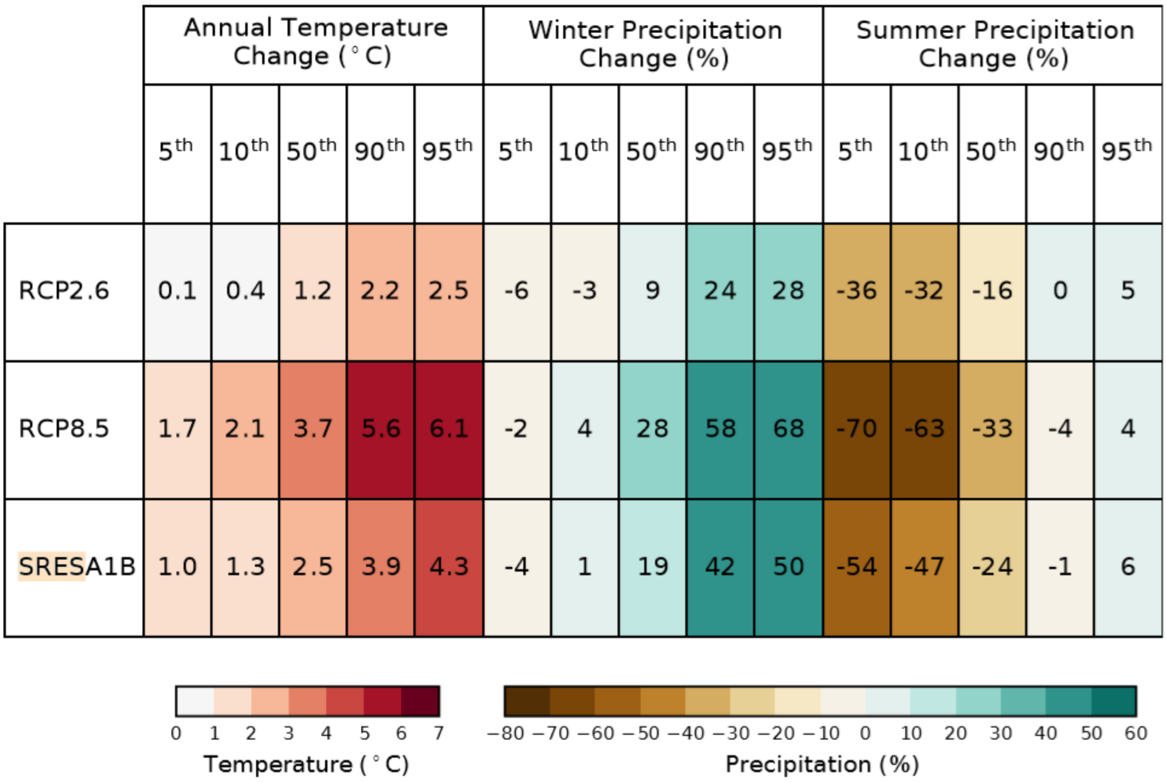
Figure 17.2 Estimated cropped areas and farm gate values for UK protected edible production (excluding mushrooms) as based on data from 2008 (Burgess, undated)

Burgess (undated) suggests that the majority of protected edibles are grown hydroponically using artificial substrates or the nutrient film technique. In this respect the normal direct effects of drought, increasing soil moisture deficits, is irrelevant as the crops are not grown in the soil or dependent on soil moisture for their water supply. The indirect effects of drought however, on yield and quality, exist if abstraction from water sources is curtailed or reduced by the water authorities. The direct effects for cropping in this case is simply as termination of production as crops cannot exist in these environments without a steady and constat supply of water.

18.0 Climate change and crop response

In common terms when we discuss climate we are discussing the long term weather pattern, 30+ years, of a region, i.e. temperature, humidity, precipitation, barometric pressure and wind velocity. Climate is distinct from weather which only reflects these variables over short time frames. For crop production the climate model outputs most discussed are increased temperature, reduced precipitation and occurrence of drought, for which the preceding chapters have outlined the crop responses.

Climate projections are run on models to create simulations and multiple simulations can be used to produce an ensemble of simulations. When many models are used individually and compared the results are often quite variable, but when used to produce a multi-model ensemble (MME) the results as means, e-mean, or medians, e-median, produce predictions which appear to predict quite well (Wallach *et al*., 2018). Investigating MMEs for prediction of crop-environment-management interactions Wallach *et al.* (2018) highlight the advantages of ensemble predictors for that role but also show their limitations. As an example UKCP09 utilises MMEs that use 12 climate models (UKCP, 2018).



	Annual Temperature Change (°C)					Winter Precipitation Change (%)					Summer Precipitation Change (%)				
	5th	10th	50th	90th	95th	5th	10th	50th	90th	95th	5th	10th	50th	90th	95th
RCP2.6	0.1	0.4	1.2	2.2	2.5	-6	-3	9	24	28	-36	-32	-16	0	5
RCP8.5	1.7	2.1	3.7	5.6	6.1	-2	4	28	58	68	-70	-63	-33	-4	4
SRESA1B	1.0	1.3	2.5	3.9	4.3	-4	1	19	42	50	-54	-47	-24	-1	6

Figure 18.1 Projected change in temperature and precipitations for the UK regions from 1981-2000 to 2080-2099 using the probabilistic projections (Met Office, 2018).

The output of the models use probabilistic projections and incorporate alternative CO_2 emissions scenarios which affect the outcomes, RCP 2.6, 4.5, 6.0 and 8.5, though figure 18.1 displays 2.6. 8.5 and SRESA1B. The use of probabilistic projections were explained as indicating responses that were “very likely to be less than or very unlikely to be greater than to describe projections with a cumulative probability of 90%” or “very likely to be greater than or very unlikely to be less than for a cumulative probability of 10%”. “Central estimate describe the projections having 50% cumulative probability (properly known as the median of the distribution).

The key changes were encapsulated from figure 18.1

"In UKCP18, the probabilistic projections provide local low, central and high changes across the UK, corresponding to 10%, 50% and 90% probability levels. These local values can be averaged over the UK to give a range of average warming between the 10% and 90% probability levels. By 2070, in the high emission scenario, this range amounts to 0.7°C to 4.2°C in winter, and 0.9°C to 5.4°C, in summer. For precipitation, corresponding ranges of UK average changes are -1% to +35% for winter, and -47% to +2% for summer, where positive values indicate more precipitation and negative values indicate reduced precipitation" (Met Office, 2018).

The long-term changes demonstrated in figure 18.1, 2080-2099, would suggest annual mean temperature increments from the 1980-2000 mean with a maximum of 5.4°C in the summer. How this compares to the optimum plant ranges will depend on the initial location and thus the average mean in that area. Simplistically, using Met office data (Met Office, 2019), figure 18.3, mean summer temperatures recorded in the Midlands range from 11.4 to 17.2°C. With a maximum uplift of 5.4°C therefore the summer means for the Midlands would rise to 15.8 – 22.6°C.

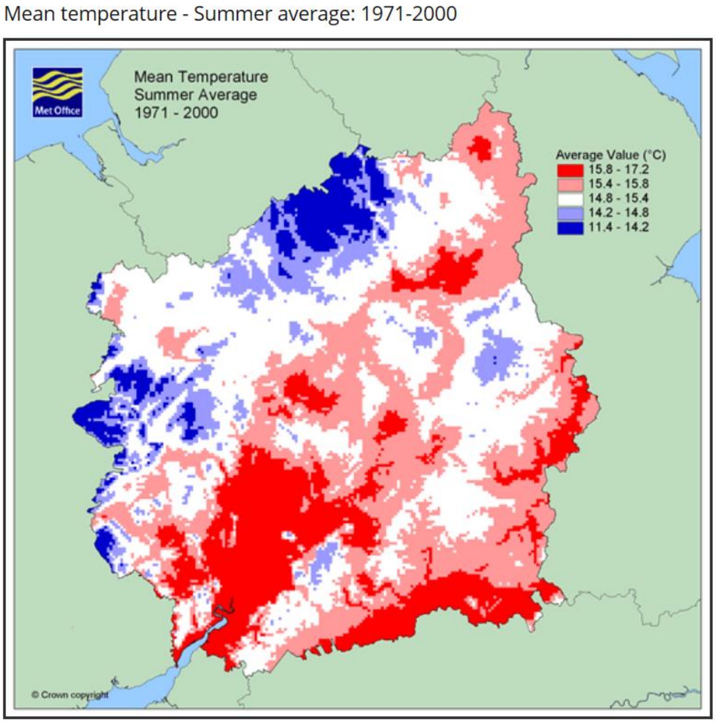


Figure 18.2 Mean Summer temperatures 1971 – 2000 for the Midlands region (Met Office 2019)

None of these temperatures exceed the optima for C3 plants (Eastin and Sullivan, 1984), of which the UK cropping mainly consists, and so the initial thoughts may be that cropping should not be affected under the worst case scenario. However, one of the key considerations is not the mean annual or seasonal temperatures but the maximum temperatures and the duration, intensity and the timing of those temperatures in relation to critical growth phases within the plants.

1) Optimum temperature for photosynthesis of C3 plants 15 - 30°C
2) Optimum temperature for photosynthesis of C4 plants 35 - 45°C
3) Optimum temperature for growth of C3 plants 10 - 30°C
4) Optimum temperature for growth of C4 plants 30 - 40°C

(adapted from Eastin and Sullivan, 1984)

Some of these key temperature effects have been reported in the individual crop sections covered earlier in the work and so will not be reiterated here. Adding the suggested temperature increases to the recorded maximum temperatures, again in the Midland region, figure 18.3, suggests an uplift from the range of 15.5 - 22°C to 20.9 – 27.4°C, which although still within the temperature optima for C3 plants, the average values do not reflect actual values that would occur in the Midlands.

Mean daily maximum temperature - Summer average: 1971-2000

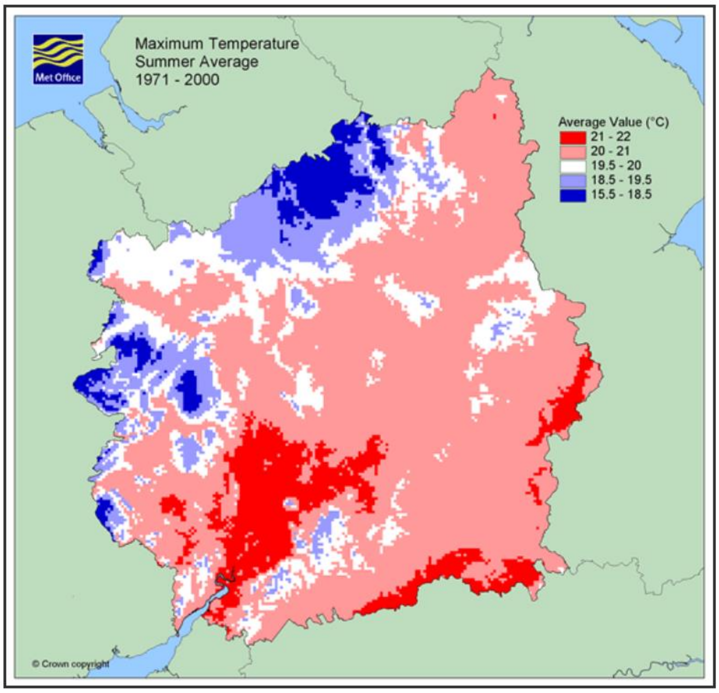
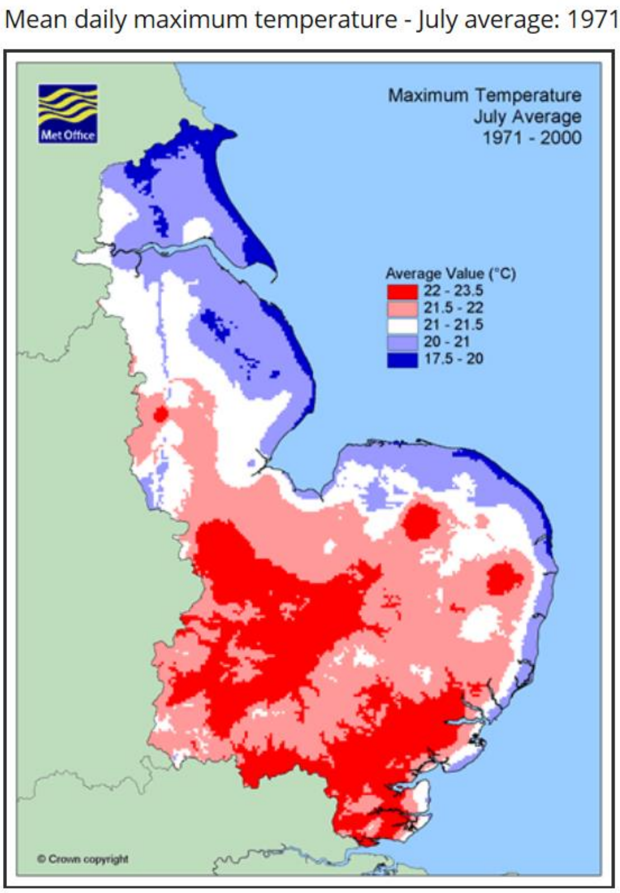


Figure 18.3 Maximum Summer temperatures 1971 – 2000 for the Midlands region (Met Office 2019)

Similarly, if the July temperatures in one of the major fresh-produce areas in the UK would also to experience a similar uplift of 5.4°C from the 1971-2000 average, figure 18.4, then temperatures would be approaching the maximum optima for both growth and photosynthesis of C3 plants, range 22.9 – 28.9°C.



Mean daily maximum temperature - July average: 1971-2000

Figure 18.4 Maximum July temperatures 1971 – 2000 for the Eastern region (Met Office 2019)

One of the key aspects reported from climate models for crops are the suggested effects of temperature on the phenology of the crops. Asseng *et al.* (2015) suggested that crop yields would reduce across temperate Europe due the increased temperatures with accelerated crop development and shorter crop growth periods. Iglesias (1995) suggested that maize yields would reduce in Spain due to shortened periods between growth stages, a reduced grain-filling period and not net gain from increased CO_2 as maize is a C4 plant, but wheat yields would increase in response to the elevated CO_2 and reduced cold periods. Harrison *et al*. (1995) also suggested reduced yields in wheat, onion and sunflower due to increased development rates, shorter growing periods including grain-fill periods, reduced accumulation of dry-matter but, also suggested compensatory effects from elevated CO_2. However, (Rezaei *et al.* (2018) reported results from phenological studies from 1952 – 2013, in Western Germany, which investigated the time taken from wheat emergence to flowering for a range of wheat cultivars. They concluded that when models use a single cultivar concept it produces overestimations of the sensitivity of winter wheat to increasing temperatures and that the phenology of newly developed cultivars are not generally included within the models leading to uncharacteristic results. Hìlden

(2005) reported that the length of the growing season for wheat in Finland had been extended by 10 days due to cultivar improvements and Grogan *et al.* (200%) in the USA, reported how the vernalisation requirement and photoperiod sensitivity of new cultivars of winter wheat were significantly smaller than those of old cultivars.

Maracchi *et al.* (2005) suggested that agriculture should generally be positively affected by climate change in Northern Europe due to introduction of more productive species and varieties and thus greater crop production. It was also suggested that there could however be a greater requirement for crop protection products, greater risk of nutrient leaching and accelerated organic matter loss.

Investigating the modelled response of Broccoli and Cauliflower in the UK, Olesen and Grevsen (1995) reported that increased temperatures would shorten the growing period and elevated CO_2 would increase dry matter contents and prevent curds/florets becoming loose. There was concerns however that the higher mid-summer temperatures could lead to greater crop failure due to bracting.
Balkovic *et al*. (2018) suggested that should the rise in global temperature not exceed +2∘C the effects on global agriculture would be pronounced and largely beneficial. Using the 'Environmental Policy Integrated Climate (EPIC) model together with regional climate projections from the European branch of the Coordinated Regional Downscaling Experiment(EURO-CORDEX)' a positive calorie yield change was projected for most of the Northern EU. The average improvement due to increased CO_2 and higher temperature were increases from 10 Gcal ha^{-1} in Southern Europe to 30 Gcal ha^{-1} in Northern Europe, notwithstanding any other impacts direct heat or soil degradation impacts. Harrison *et al*. (1995) reported that modelled water–limited wheat yield would increase under most scenarios but yield of sunflower and onion were variable dependent on the scenarios with the yields increasing transient scenarios and declining in equilibrium scenarios.
The IPCC (2018) guide for policymakers give high confidence that the temperature extremes are also projected to warm more than the global mean and that the number of hot days is projected to increase. In addition there was medium confidence of increased risk of drought and precipitation deficit coupled with heavy precipitation events.

18.1 Crop response models and drought indices

Predicting or modelling crop yield response to drought, or reduced water availability, is a difficult and complex task for many reasons. Initially there are the intrinsic variations between crop species such that their morphological, physiological and biochemical responses alone can be significantly different, i.e. some plants are very drought tolerant to mild drought but intolerant to severe drought. Whereas other plants are very intolerant to all types of drought. Crop plants are seldom species which are adapted to severe and long term drought as the mechanisms within these plants are adapted for survival and not therefore not normally used for crop production. Plant characteristics such as root growth intensity and rooting depth not only vary between species (Dardanelli *et al.*, 1997; Smit and Groenwold, 2005; Fan *et al.*, 2016) but also within cultivars of the same species, although little data is available to support this varietal difference for most crops. However, crop simulation models (CSM) can be used to investigate the crop responses to a range of climatic/environmental factors including irrigation, nutrient management and climate change. Examples include: SaltMed (***), FAO- Cropwat (****), Aquacrop (Steduto *et al.,* 2009), Cropsyst (Stockle *et al.*, 2003) DSSAT Ceres-wheat (Jones *et al.*, 2003), and Sirius 2005 (Lawless *et al.*, 2005). whereas Drought stress indices (DSI) such as the Palmer drought severity index (PDSI), the standard precipitation index (SPI), the Standardized Precipitation and Evapotranspiration Index (SPEI) and the Potential Soil Moisture Deficit (PSMD) Hydrothermal coefficient)

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 1 (FAO, 2012):

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

Equation 1: 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.

Potential Soil Moisture Deficit (PSMD): PSMD can be used as an Aridity Indicator as it can be used to identify the dryness or wetness of a specific location and can therefore be used to quantify irrigation needs (Rey *et al.,* 2016). According to Bashir *et al.* (2016) PSMD can be used to determine water deficit effects on the growth and development of crops whereby when the PSMD is greater than the water deficit which limits yield it would compromise crop productivity.

18.2 Response to elevated CO_2 concentration in the atmosphere

Historically the atmospheric CO_2 concentration over the last 400,000 years has fluctuated between 200 to 280ppm. Recent records however show atmospheric CO_2 concentrations from *c.* 315ppm in 1960 rising to 409ppm currently (February 2019), figure 18.5. The upward trend is linked to human activity including the burning of fossil fuels (ECST, 2019) and it was suggested that CO_2 concentrations could rise to between 500 – 1000 ppm by 2100 (IPCC, 2007).

As part of essential plant functioning carbon dioxide, CO_2, is taken up into the plant from the atmosphere via stomata where it reacts with water in photosynthesis, in the Calvin cycle, from which both chemical energy and carbon are used within plant processes. The chemical energy can be produced in the form of 3C sugars when produced in C3 pathway plants or 4C sugars when produced in C4 pathway plants. It is well recognised that the C4 system, and plants which use it such as sugarcane, corn (maize) and sorghum, are more productive than C3 types. However, as the rate of photosynthesis is CO_2 concentration dependent it is suggested that crop yields could increase by up to 30% at atmospheric CO_2 of up to 1500ppm. The C_3 plants include grasses, cereals, potatoes and the majority of horticultural plants in the UK and have a low response to CO_2 concentration in contrast to the C4 plants such as maize (Fageria, 1992; Fageria *et al.* 1997). Consequently any increased CO_2 concentration is likely to be more beneficial to the C4 plants

Nuttall *et al,* (2017) suggested that under elevated CO_2 wheat yield could increase by up to 36% but grain quality, protein, would decrease. It was also suggested that grain-set, grain size and milling yield would decline under high temperature.

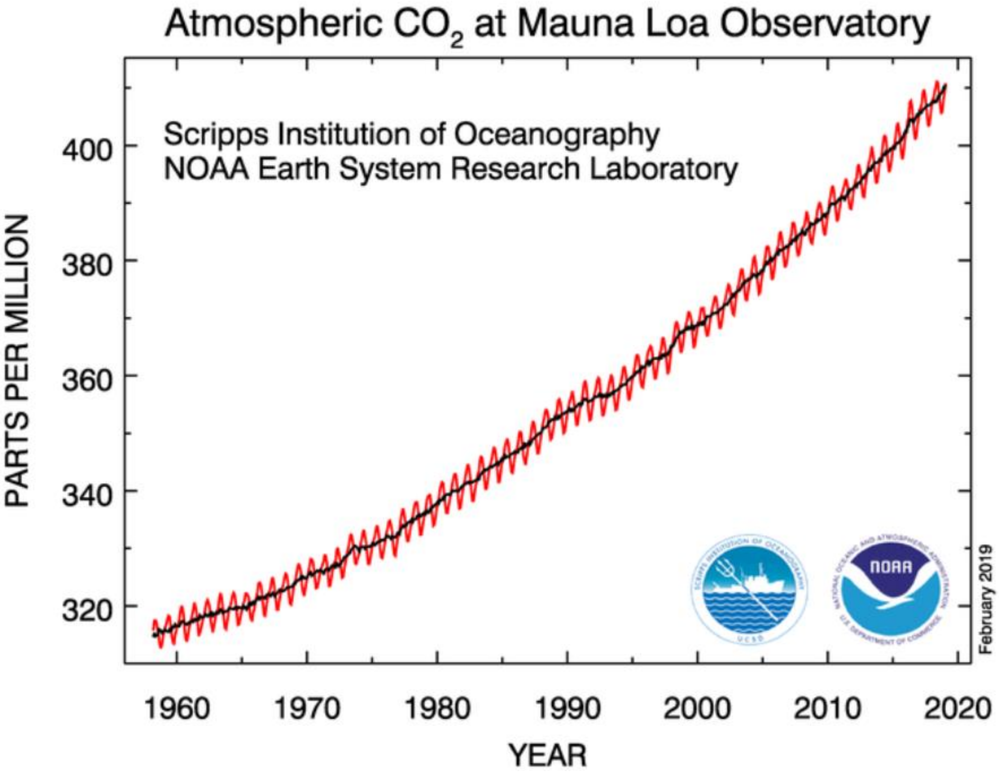


Figure 18.5 NOAA full CO_2 record 1960 - current (ESRL, 2018)

In a meta-analytic study covering publications from 1980 to 1997 on the responses of both C3 and C4 wild grass species to elevated atmospheric CO_2 Wand *et al.* (1999) reported overall total biomass increases of 33% for C4 and 44% for C3 where concentrations were increased from 300-400 µmol mol^{-1} to between 550 – 750 µmol mol^{-1}. The actual responses seen were; C3 grasses increased tillering whereas C4 increased leaf area; stomatal closure and increased leaf WUE were seen in both types; higher carbon assimilation occurred in both but as 33% increase for C3 and 25% for C4. It was concluded that these responses were not as expected based on photosynthetic theory and re-evaluation of the assumptions was therefore required.

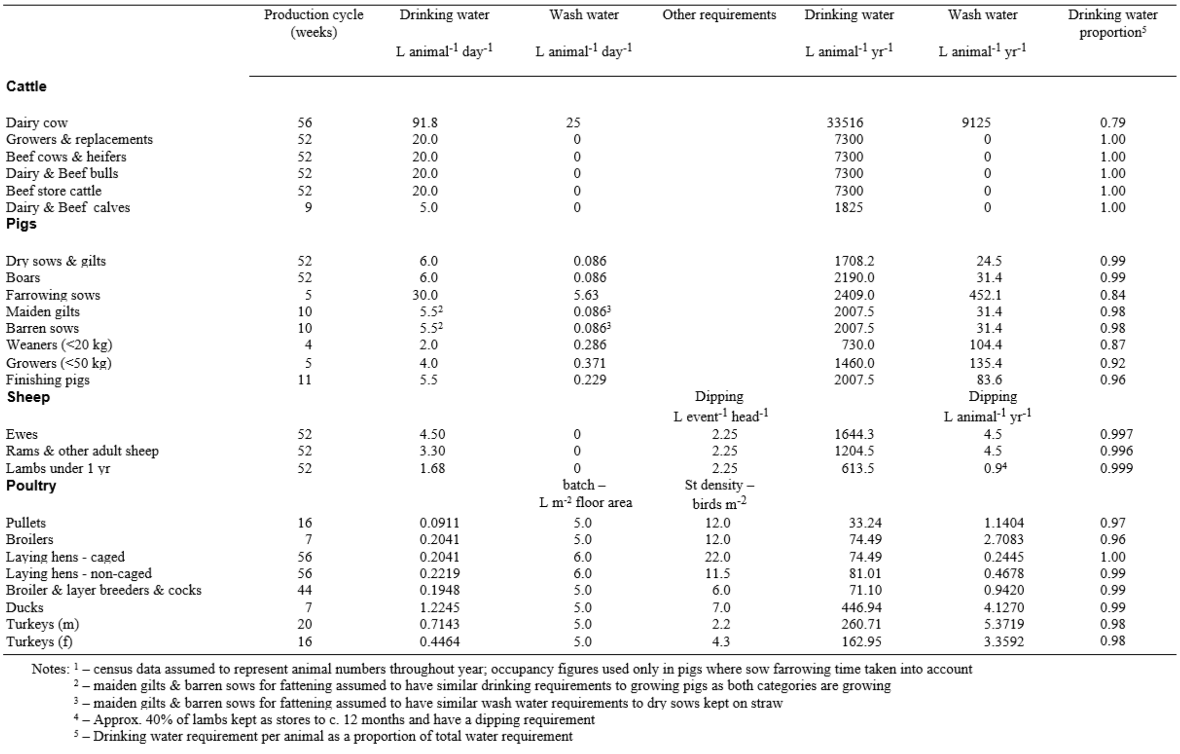
In Free Air CO_2 Enriched (FACE) experiments UK grown C3 plants such as wheat, PRG, white clover and potatoes showed increased Ps, biomass and yield significantly, decreased stomatal conductance and increased water use efficiency, phenology accelerated (which will affect planting to harvest lengths) (Kimball *et al.* 2002). Similarly, O'Leary *et* al. (2004) also demonstrated increased yield and improved water use efficiency in the semi-arid regions of Australia. Wheeler *et al*. (1995) demonstrated bulb dry weight increases in onion in field tunnels of between 35 – 45% when the air was enriched from 372 to 532 ppm, Wolf (1995) showed substantial yield increases of spring wheat when CO_2 was increased from 315 – 695 ppm whilst Deng and Donnelly (1993) reported yield enhancement in raspberry transplants subjected to CO2 increase from 320 to 1500ppm. However, a review of 16 FACE experiments by Nowak *et al*. (2004) does not support the original hypothesis that all plant responses would be positive and notes that for drier ecosystems and drier years the species response and resource availability, e.g. nitrogen, will be key in the actual responses. This is in agreement with normal concepts of limiting factors which would only allow continued response should water and nutrition were not limiting. Tubiello *et al.* (2007) reviewed the response of crops to climate change and provided evidence to suggest that both crop, pasture and legume yields will increase by 10-20% for C3 plants in unstressed (non-droughted) conditions at 550 ppm CO_2 as long as sufficient nitrogen is also available.

An additional benefit of elevated CO_2 concentration is the relationship of CO_2 uptake and water loss through stomata. Johansson *et al.* (2005) confirm the partial closure of stomata in response to elevated CO2 concentration but indicate that the actual extent of this response varies widely among species but can lead to decreased stomatal conductance and reduce their water consumption and thus water productivity. Hamin (2005) investigated the response of C3 (wheat and kale) and C4 wild grass (*Echinochloa crus-galli*) and Amaranthus (*A. caudatus*) to 350 and 700ppm in controlled chambers and reported reduced stomatal conductance in well-watered conditions at the elevated levels and thus transpired less water. The photosynthetic rate of the C3 increased at elevated CO_2 but this was not seen in the C4. Currently plant stomata stay open to allow diffusion of CO_2 onto the stomatal cavity and close in response to water stress from drying soils. At greater concentrations of atmospheric CO_2 however, the stomata may only need to be partially open to achieve the necessary uptake, thus reducing evaporative demand and total plant water requirement, in agreement with Maracchi *et al*. (2005) and ultimately therefore more yield per kg water.

CO_2 enrichment in glasshouses has also created several fold increases in the production of tomatoes (*Lycopersicum esculentum* L.), Lettuce (*Latuca sativa* L.) and cucumber (*Cucumis sativis* L.) (Moss, 1984)

19.0 Livestock farming

Water is one of the ‘five freedoms’ for animals and as such there is no potential for reducing water requirements of livestock *per se*. Access to a clean plentiful supply of water is a paramount requirement for animal welfare. (ASPCA, undated). Thompson *et al*. (2007) reported the drinking and wash water requirements for an extensive range of agricultural livestock, figure 19.1. However, during drought or dry weather conditions the effect on metabolism will be significant should these requirements not be met. For a very detailed account of the requirements in livestock production the reader is guided to Thompson *et al*. (2007) and Defra project WU0132 (ADAS, 2012). Where drought affects the production of forage for either daily intake or for winter fodder the combined effects could significantly impact on both animal welfare and profitability of the farmer and industry.



	Production cycle (weeks)	Drinking water L animal^{-1} day^{-1}	Wash water L animal^{-1} day^{-1}	Other requirements	Drinking water L animal^{-1} yr^{-1}	Wash water L animal^{-1} yr^{-1}	Drinking water proportion[5]
Cattle							
Dairy cow	56	91.8	25		33516	9125	0.79
Growers & replacements	52	20.0	0		7300	0	1.00
Beef cows & heifers	52	20.0	0		7300	0	1.00
Dairy & Beef bulls	52	20.0	0		7300	0	1.00
Beef store cattle	52	20.0	0		7300	0	1.00
Dairy & Beef calves	9	5.0	0		1825	0	1.00
Pigs							
Dry sows & gilts	52	6.0	0.086		1708.2	24.5	0.99
Boars	52	6.0	0.086		2190.0	31.4	0.99
Farrowing sows	5	30.0	5.63		2409.0	452.1	0.84
Maiden gilts	10	5.5[2]	0.086[3]		2007.5	31.4	0.98
Barren sows	10	5.5[2]	0.086[3]		2007.5	31.4	0.98
Weaners (<20 kg)	4	2.0	0.286		730.0	104.4	0.87
Growers (<50 kg)	5	4.0	0.371		1460.0	135.4	0.92
Finishing pigs	11	5.5	0.229		2007.5	83.6	0.96
Sheep				Dipping L event^{-1} head^{-1}		Dipping L animal^{-1} yr^{-1}	
Ewes	52	4.50	0	2.25	1644.3	4.5	0.997
Rams & other adult sheep	52	3.30	0	2.25	1204.5	4.5	0.996
Lambs under 1 yr	52	1.68	0	2.25	613.5	0.9[4]	0.999
Poultry			batch – L m^{-2} floor area	St density – birds m^{-2}			
Pullets	16	0.0911	5.0	12.0	33.24	1.1404	0.97
Broilers	7	0.2041	5.0	12.0	74.49	2.7083	0.96
Laying hens - caged	56	0.2041	6.0	22.0	74.49	0.2445	1.00
Laying hens - non-caged	56	0.2219	6.0	11.5	81.01	0.4678	0.99
Broiler & layer breeders & cocks	44	0.1948	5.0	6.0	71.10	0.9420	0.99
Ducks	7	1.2245	5.0	7.0	446.94	4.1270	0.99
Turkeys (m)	20	0.7143	5.0	2.2	260.71	5.3719	0.98
Turkeys (f)	16	0.4464	5.0	4.3	162.95	3.3592	0.98

Notes: [1] – census data assumed to represent animal numbers throughout year; occupancy figures used only in pigs where sow farrowing time taken into account

[2] – maiden gilts & barren sows for fattening assumed to have similar drinking requirements to growing pigs as both categories are growing

[3] – maiden gilts & barren sows for fattening assumed to have similar wash water requirements to dry sows kept on straw

[4] – Approx. 40% of lambs kept as stores to c. 12 months and have a dipping requirement

[5] – Drinking water requirement per animal as a proportion of total water requirement

Figure 19.1 Summary of drinking and wash water requirements of livestock (Thompson *et al,* 2007)

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