COPING WITH DROUGHT AND WATER SCARCITY: LESSONS FOR THE AGRICULTURAL SECTOR

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October 2019

About Drought

The UK Droughts & Water Scarcity (D&WS) research programme was a five-year interdisciplinary, £12 million Natural Environment Research Council initiative in collaboration with other UK Research Councils (Economic and Social Research Council, Engineering and Physical Sciences Research Council, Biotechnology and Biological Sciences Research Council and Arts and Humanities Research Council). It was set up to support improved decision-making in relation to droughts and water scarcity by delivering research that identifies, predicts and responds to the inter-relationships between their multiple drivers and impacts.

Five projects were funded under the UK Droughts & Water Scarcity programme:

- Historic Droughts: Understanding past drought episodes to develop improved tools for the future
- IMPETUS: Improving predictions of drought to inform user decisions
- MaRIUS: Managing the risks, impacts and uncertainties of drought and water scarcity
- DRY (Drought Risk and You): Bringing together stories and science for better decision-making
- ENDOWS: Engaging diverse stakeholders and publics with outputs from the UK Drought and Water Scarcity programme

The programme's research was UK-focused, and contributed to NERC's natural hazards and climate system strategic science themes. This report summarises the key findings that emerged from the five projects to help the UK agriculture and horticultural sector to better understand, forecast, manage and respond to the challenges posed by droughts and water scarcity.

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Engineering and Physical Sciences Research Council
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Biotechnology and Biological Sciences Research Council

UK AGRICULTURE AND DROUGHT

Drought and water scarcity do not affect all sectors of agriculture equally. Understanding how different farm types are sensitive to drought and water scarcity is therefore essential for planning responses and increasing resilience.

Box 1: What is a drought?

A simple question, but surprisingly there is no internationally agreed answer, as drought can mean different things to different people! But for agriculture, there are commonly three types of drought:

- ***Meteorological drought***- a period with unusually low levels of rain
- ***Agricultural drought*** - a period with unusually low levels of rain (and often warm temperatures) leading to particularly dry soils and impacts on the growth of crops and grass
- ***Hydrological drought*** - a period with low levels of rain that leads to unusually low river flows and/or groundwater levels

Because of the UK's varied soils and geology, a 'meteorological drought' may not lead to similar agricultural or hydrological droughts in different areas.

The variability in the UK's climate, topography and soils leads to large regional differences in farming (Figure 1). In relation to drought (see Box 1), the UK's farming system can be broadly separated into farms where crops are dependent on rainfall, livestock grazing is dependent on rainfall and farms who supplement rainfall with irrigation (Table 1). The first two farm types are sensitive to periods of unusually low rainfall that lead to agricultural drought, whilst livestock farms may also be sensitive to hydrological drought if local water sources dry up, but both are not usually affected by water scarcity (see Box 2). Farms who use irrigation can be highly sensitive to restrictions on irrigation abstraction during hydrological droughts and to changes in abstraction licensing due to increasing water scarcity. It is therefore important to differentiate between the different types of drought, and water scarcity that can be exacerbated by drought events (see Box 1 and 2).

Figure 1 Illustrative distribution of farming types across the UK (from https://geography-revision.co.uk)

Box 2: Drought and water scarcity – are they the same thing?

No, although they are often confused. A drought is an event (weeks to years) caused by unusually low levels of rainfall; whereas water scarcity refers to the long term imbalance between the availability of water in rivers, reservoirs and aquifers and the demands for that water from all water users.

"On this sort of [*sandy*] soil, the word drought is not always used that much because we have to manage water so actively anyway" (HistoricDroughts farmer interview,)

Table 1 Sensitivity of farm types to different types of drought and water scarcity

	Sensitive to:			
Farm type	**Meteorological drought**	**Agricultural drought**	**Hydrological drought**	**Water scarcity**
Arable (rainfed)	✓ (when it leads to an agricultural drought)	✓	×	×
Arable and horticulture (irrigated)	×	✓ (if licenced volume is insufficient)	✓ (due to restrictions on direct abstraction, but can be reduced by on-farm reservoirs)	✓ (due to potential changes to abstraction licences)
Protected cropping	✓ (where rainwater harvesting is employed)	×	✓ (where reliant on direct abstraction or mains water)	✓ (due to potential changes to abstraction licences)
Dairy	✓ (when it leads to an agricultural drought)	✓	✓ (where reliant on springs and streams for stock watering; and abstractions for washing etc)	× (as use of water for washing/cooling is largely a non-consumptive use)
Hill farming (sheep and/or beef)	✓ (when it leads to an agricultural drought)	✓	✓ (due to reliance on springs and streams for stock watering)	×
Indoor livestock and poultry	× (but may be sensitive to high temperatures)	✓ (if leads to lack of fodder/bedding)	× (as animal welfare considerations likely to prevent restrictions)	× (due to animal welfare considerations)

HOW DROUGHT AFFECTS AGRICULTURE AND HORTICULTURE

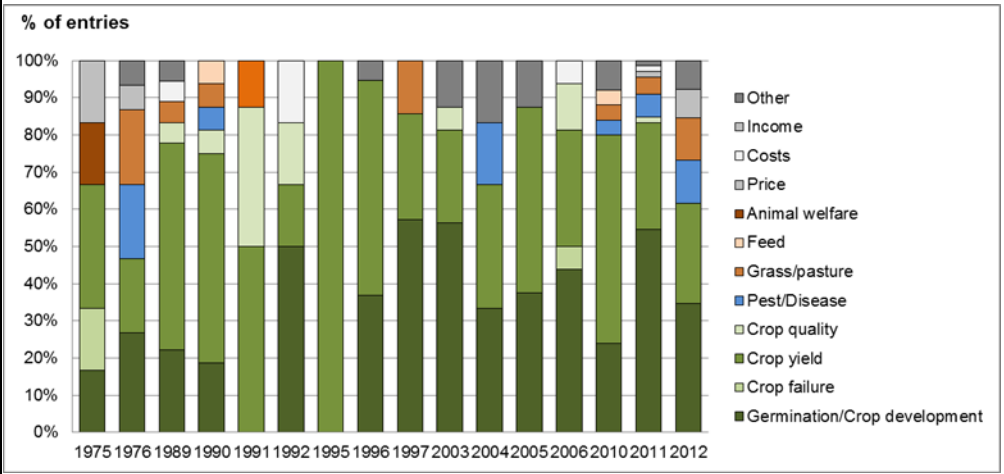
Droughts impact agriculture and horticulture in many different ways, whether that is by preventing farmers from achieving their expected levels and quality of production, increasing costs of production or increasing competition for water, which is often a limited resource. Each drought event is unique in its duration, severity and extent and so will lead to different impacts.

In the last 40 years, the UK has experienced a number of significant droughts, notably in 1975/76, 1989-92, 1995-97, 2004-06, 2010-12 and, most recently, 2018-19. The impacts from droughts on the UK's agricultural and horticultural sectors have varied considerably, due to differences in the geographical extent of each drought, its timing, severity and duration. Impacts can span a wide range of factors including crop yields and quality, animal productivity and welfare, availability and cost of livestock feed, farm economics, market confidence and farmer well-being (see Box 3). Droughts that extend beyond the growing season can also prevent recovery of water levels in soils, rivers, aquifers and reservoirs.

The impacts of drought are somewhat different to those from flooding in two key respects. Firstly, the impacts of drought on agriculture can develop slowly and may persist long after rain has returned and (in the eyes of the media, public or policymakers) the drought has ended. These delayed impacts can be due, amongst other things, to reduced crop yields and/or quality at harvest, reduced livestock fertility, shortages of stored fodder and bedding for the coming winter, or a difficulty in filling on-farm reservoirs during expected periods of high flow. Because of these lags between the drought and some of the adverse consequences for farms and businesses, drought impacts may be ignored, or forgotten, in the wider community. Secondly, the impacts of drought in the UK may be at a greater spatial scale than flooding and may also be significantly affected by factors outside of the UK. For example, concurrent droughts in other countries can lead to crop shortages that increase market prices and may offset some of the adverse financial consequences of reduced crop yields in the UK. Such macro-scale price increases can also lead to increases in farm costs. This was seen with the shortages of silage and fodder in the UK, Ireland and parts of north-western Europe as a result of drought in the spring and summer of 2018.

"We had to ration water across all the irrigated crops. It was like being in a lifeboat and not knowing how many days you had to survive with a limited amount of water" (ENDOWS farmer interview)

Box 3: The nature of reported impacts in the farming press during drought events from 1976 to present.



The Farmers Weekly and Farmers Guardian have reported a broad range of impacts from droughts. These differ among drought events, but are dominated by concerns about crop development and yields. Reported impacts on livestock systems are less common, reflecting the geographical extent of some recent drought events.

Source: HistoricDroughts

HOW WATER SCARCITY AFFECTS AGRICULTURE

Water scarcity and drought are separate but inter-related concepts. Water scarcity occurs where there are insufficient water resources to satisfy long-term average requirements. It refers to long-term water imbalances, combining low water availability with a level of water demand exceeding the supply capacity of the natural system. High levels of water scarcity affects the probability of hydrological drought and is an issue for water resources management (e.g. who gets the water?), in which agriculture is always given lower priority than public water supply and the environment.

Water scarcity is a concern in some parts of the UK, especially in the south east and eastern England where many catchments are classified by the Environment Agency as being "Over licensed" or "Over abstracted". Consequently, many spray irrigation licences have so-called 'Hands Off Flow" conditions, which mean that abstraction has to stop when river flows drop below a pre-defined level. Groundwater abstraction licences can have similar rules based on water levels. In addition, drought management and water scarcity rules allow irrigation abstraction to be reduced or banned during severe drought events (through so-called 'Section 57' restrictions under the Water Resources Act 1991 in England and Wales; and CAR emergency provisions under the Water Environment (Controlled Activities) (Scotland) Regulations 2011 in Scotland). However, the farming community works closely with the national water regulators during periods of drought and often accepts voluntary restrictions to reduce the likelihood of total bans on abstraction.

The challenges of balancing the needs of different water users, whilst protecting the environment and public water supply, has led to ongoing efforts to reform the water abstraction system and to review irrigated agricultural users' need for water. This has led to

- some agricultural uses of water that were previously exempt from abstraction licensing, such as trickle (drip) irrigation, being brought into the licencing system;
- all new irrigation abstraction licences now being time-limited, and;
- a requirement to demonstrate the need for licence 'headroom' (or licensed water that is not used in normal or non-drought years, but which can be vital for irrigation in drought years).

"*The relationship [with the Environment Agency] is absolutely critical – they understand our business need and the challenges we face from a water resources perspective. It has highlighted how important trusted relationships are in this situation*" (ENDOWS farmer interview)

In 2018, many large on-farm irrigation reservoirs were emptied during the prolonged period of very dry and warm summer weather. Water scarcity will increase the need for on-farm reservoirs as water availability becomes more limited. However, it may also become more difficult to fill them in the winter (© Andrew Francis)

DROUGHT IMPACTS ON RAINFED AGRICULTURE

Livestock and arable cropping are the most extensive farming types in the UK and are typically rainfed; they can also be considered the most sensitive to meteorological and agricultural droughts. The impacts of any drought will depend on the water holding capacity of local soils; the types of crops and varieties being grown; the availability and price of fodder to supplement grass, and the reliance on springs, boreholes and streams for livestock watering. Future changes in climate may also increase the impacts of agricultural drought due to the expected increased likelihood of drier summers.

Rainfed farming systems are by far the most spatially extensive across the UK. Being "rainfed" might suggest that such farms are unaffected by hydrological droughts. Whilst this is true for arable farms, outdoor livestock farms can be highly reliant on boreholes, drainage channels, streams and springs to provide drinking water for cattle and sheep (particularly in the uplands) and to form 'wet fences' to control livestock movement. The drying up of such small water sources during droughts can lead to significant costs and effort in order to provide livestock with vital alternative water supplies.

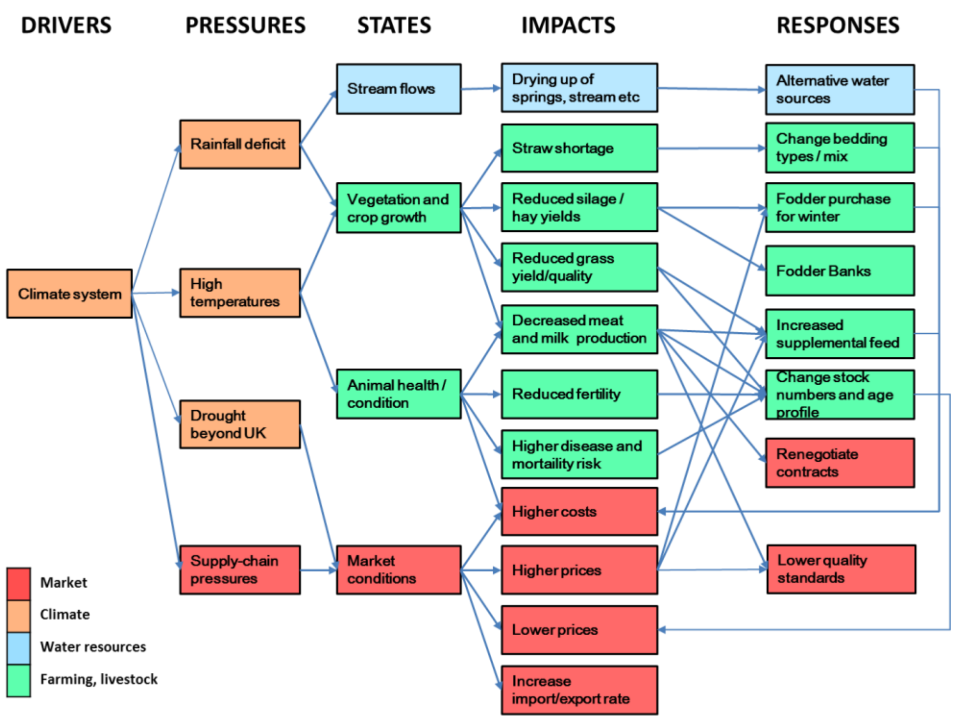
The effects of drought on UK agriculture is intrinsically linked to the timing, duration and intensity of the drought, but many of the impacts are inter-related (Figure 2). The DRY project carried out a comprehensive review of literature on the impacts of agricultural drought (Box 5). The timing of drought is critical for penalties to yields and quality (e.g. protein content of wheat; visual appearance of unirrigated fruit and vegetables). It is important to emphasise that short spells of drought at key growth stages can create major impacts, which cannot be recouped by later rainfall. Drought initiating after April, and following an 'average' winter, will have a significantly smaller effect on winter sown combinable crops (e.g. winter wheat) than spring-sown, as they will have passed critical growth stages. In such conditions, spring planted root crops such as potatoes and sugar beet will be planted into drying soils which will reduce establishment rates and, where unirrigated, will senesce earlier than usual, and thus produce significantly lower marketable yields.

Established forage grass crops may initially be little affected by low rainfall, but regrowth after grazing or cutting can be substantially lower throughout the remainder of the year if drought persists (Box 6), leading to use of stored winter forage to maintain required levels of livestock productivity, and an inability to conserve forage for the coming winter. Growth of alternative spring-planted forage such as maize would also be substantially reduced by drought leading to further loss of conserved forage for the following winter. These would lead to significant impacts on both milk and beef production over the drought impacted season and following winter.

Where drought starts pre-winter or continues from a preceding summer drought, then the effects will be additive and substantial for a wider range of crops. The establishment of winter sown crops (e.g. cereals, oilseed rape, beans) will be problematic in dry seedbeds, leading to poor rates of germination. Later sowing and higher seeding rates would be needed to compensate for poor seedbed conditions. The crops will then be subjected to significantly lower levels of soil moisture during critical growth phases, leading to substantial yield reductions. Experimental research in DRY (Box 4) showed that spring-planted crops and forage crops were most sensitive to late spring/summer droughts, and that all rainfed crops were affected when dry weather starts pre-winter and continues into a spring/summer drought.

One of the greatest problems for UK growers is the highly variable nature of our summer weather and the difficulty in providing longer-term weather forecasts to aid timely crop management decisions. Many of the key decisions for growers are made several months before sowing, as planting programmes and rotations need to be fixed, seed must be ordered, contracts agreed and land prepared. It is challenging to change cropping with anything less than four months prior notice before planting and very costly once planted.

"*As the ground was so dry, we took the decision to bale the straw and capitalise on the strong demand for straw - this gave us an extra £75k of income*" (ENDOWS interview with arable farmer)



"I have never seen such a sustained period of dry weather...The fear is the shortage of grass - we are at least a month behind and the quality isn't there. The lambs aren't growing like they should be, and people have had to supplementary feed their stock at a huge cost" Report from the Western Isles (Farmers Weekly, July 2012)

"We had to default on our forward contracts for cereals [in 2012] and it was very costly to buy ourselves out because the market went against us." (HistoricDrought farmer interview, 2015)

Figure 2: Exemplar schematic showing how drought impacts and responses are connected to drought pressures from both inside and outside the UK

Box 4: Key insights from DRY agricultural mesocosm experiments

Agricultural mesocosm experiments (as shown in the photo below), at Harper Adams University, investigated the response of a range of cereal and forage crops to 38% lower spring and summer rainfall and 4% increased winter rainfall as projected under the 2050 high emissions climate scenario for the midlands region. The main findings were:

- Acceptable crop yields were achieved in wheat, barley and triticale whilst durum wheat, suited to a more Mediterranean climate, performed less well, and quinoa, reportedly a drought tolerant crop, performed inconsistently.
- For forage production, lucerne (alfalfa) outperformed perennial ryegrass demonstrating its greater suitability to drier and warmer climates.
- The return of the soil to field capacity from the increased winter rainfall within this climate change scenario is important. Replenishing the soil moisture, even at only a 4% precipitation increase, during the slow growing period between October and March ensures significant soil water recharge to support plants during the active cereal growing period from April to July.

From this study it can be inferred that critical drought issues for the UK are most likely to arise for spring-planted crops and forage crops in relation to late spring/summer droughts, or all rainfed crops when dry weather (drought) is initiated pre-winter with little soil-water recharge during the winter then followed by a spring/summer drought.

Box 5: Key insights from DRY evidence review on drought impacts on selected crops

Wheat: Yield losses in past UK droughts have been reported as c. 10 – 45%, which at current production would give losses of between 1.5 to 6.75Mt valued currently at £255m – 1.147billion, leading to a UK consumption deficit up to 43%.

Barley: Production appears to be less affected by water-stress than wheat with only 12-18% reductions during the 1976 drought. Based on UK production in 2017, a maximum yield loss of 1.3Mt would occur with a farm gate value of £134M. However, as 1.8Mt barley is used in the brewing/distillery industry the total loss of value would be substantially higher.

Oilseed rape: Yield losses have been reported to range between 15 – 85% in past droughts when water stress occured during flowering and pod-fill. This equates to production losses of up to 1.76Mt and a value of £644M. With most of the oilseed rape used in the UK (91% in 2017) being grown nationally, any yield losses substantially increase our dependence on imports.

Sugar beet: Early drought has been suggested to cause a sugar yield loss of around 27.5% whereas later droughts cause only 12.5% loss. Yield loss at 2017 root production of 8.9Mt would represent 1.11 to 2.45Mt, equating to approximately 0.2 to 0.44Mt sugar which would substantially increase our sugar import requirements.

Potatoes: Yield loss in maincrop potatoes during the 1976 drought was reported to be c. 40% which at 2017 levels of production would equate to a loss of 2.48Mt and farm gates losses of £359M. The effect of the 2018 summer drought was reported to be up to 20% yield loss which equated to 1.24Mt and £179M at the farm gate. However, the UK potato industry is valued at £4.7bn in the UK economy, so the overall financial effect would be much higher.

Horticultural crops: Significant horticultural crop failures occurred in the 2018 summer drought in Ireland. Broccoli and cauliflower showed poor growth with crops being ploughed-in rather than harvested; broccoli showed variable maturity with an estimated crop loss of 25%; cabbage yields were reported to be reduced by 70%; salad onions had reduced germination; non-irrigated swedes bolted and split; carrot size and quality were reduced; parsnips had uneven germination and up to 30% of the crop was classed as poor; growth of leeks was delayed with an estimated 15% crop loss which was also heat related. Yield losses in rainfed lettuce under UK conditions were estimated to be c. 50%.

Forage crops: 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 hay crops are generally cut later, cut only once and the 2018 harvest was taken during the developing drought in June.

Top fruit: Apples under early season drought show reduced vegetative growth and leaf area, and fruit set is low leading to substantial yield loss. Although a post summer drought would not significantly reduce yield in the drought year, if the drought continued into the winter, as in 1976, significant impacts would continue into the following year, and impacts on the early growth of all orchard crops would lead to substantial reductions in fruit set, growth, yield and quality.

Box 6: Key insights from DRY semi-natural grassland mesocosm experiments

Grassland is, by area, the most important UK crop, supporting around 10 million cattle and 34 million sheep. The DRY project used multiple 3m x 3m mesocosms (as shown in the photo below) to study the effects of an approximately 50% rainfall reduction in 2016-2018 on semi -natural grasslands in three catchments in England (Don and Frome) and Scotland (Eden).

In the Frome catchment, there were small non-significant differences in above ground biomass production (equivalent to yield) between the rainfall treatments. The dry autumn and winter of 2016 followed by the dry spring of 2017 led to a striking reduction in biomass collected in autumn 2017 in both the normal and reduced-rainfall mesocosms. In addition, the perennial grass Yorkshire Fog grew slightly taller in the reduced-rainfall treatment, perhaps because drier soil warmed more quickly in the spring.

The results showed that expected changes in future rainfall may lead to changes in the timing of hay and silage cutting, and require farmers, governmental policy and agri-environmental schemes to be more flexible in the face of changing climatic conditions.

DROUGHT AND WATER SCARCITY IMPACTS ON IRRIGATED AGRICULTURE

Supplementing rainfall with irrigation water taken from rivers, groundwater and on-farm reservoirs, particularly (but not exclusively) in the drier south and east of England, can be critical for meeting retailers' quality standards for many fruit and vegetables. Such supplementary irrigation is a high-value use of water that can, on certain crops, deliver economic benefits to the farmer of up to £50/m^3. However, irrigation restrictions due to drought or water scarcity can lead to significant financial losses. Proposed changes to the abstraction licensing regime, as water scarcity increases, means that irrigators may have access to less water in the future.

Although most irrigation occurs in arid and semi-arid areas of the world where there is insufficient rainfall to support crop growth, supplementary irrigation can also be important in humid countries such as the UK, where it buffers the effects of summer rainfall variability on soil moisture, crop development and quality. Given an increasing emphasis on quality standards within the fresh produce supply chain, supplementary irrigation is increasingly becoming essential to ensure the viability and profitability of particular crops in some regions.

In order to protect public water supplies, wetlands and river ecology in the UK under drought conditions, abstraction of water from rivers (and groundwater) for agricultural irrigation has the lowest priority for water allocation. This partly reflects a historical perception that the financial value of water use in agriculture is low compared to other sectors, such as public water supply, and that during drought conditions there is scope to increase the 'efficiency of use' of agricultural irrigation.

Supplementary irrigation can improve both crop yield and quality although the financial benefits associated with irrigation vary greatly among crops (Figure 3). Irrigation of soft fruit produces the highest average benefits in a dry year because of the major reduction in price associated with lower fruit quality. In contrast, irrigation of sugar beet will produce a negligible benefit in crop quality but might offer some financial reward from increased yields.

Research within the Drought and Water Scarcity Programme has quantified the financial losses that would be incurred in a dry year if abstractions were banned (see Box 7). The estimated losses for England and Wales were c. £665 million, with the largest irrigation benefits being attributed to soft fruit, orchard fruit and potatoes. The irrigation applied to high-value crops, primarily for maintaining quality, results in very high financial benefits, and hence the potential financial impacts of abstraction restrictions will be substantial. These estimates exclude the major 'added value' on these crops post farm-gate.

"Drip [irrigation] is an expensive insurance option that retail and supply chain not willing to pay for through raised farm gate prices." [ENDOWS farmer interview]

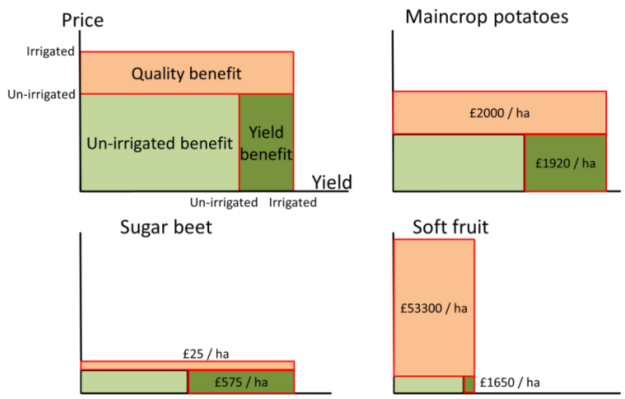


Figure 3: Illustrative average combined crop quality and yield benefits attributable to supplemental irrigation in a dry year for three key crops (Source: HistoricDroughts and MaRIUS)

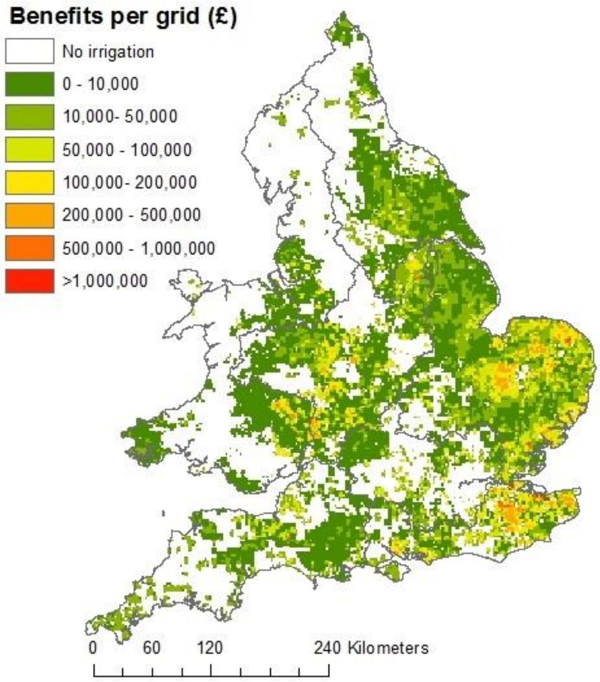
"Being risk averse in water means pulling back on production to be sure we have sufficient headroom to cope with the very worst of conditions. Commercially this is very difficult for us, we can't afford it. So we have to accept a higher level of risk that we feel comfortable with" [HistoricDrought farmer interview]

Box 7: The economic value of irrigation water to agriculture

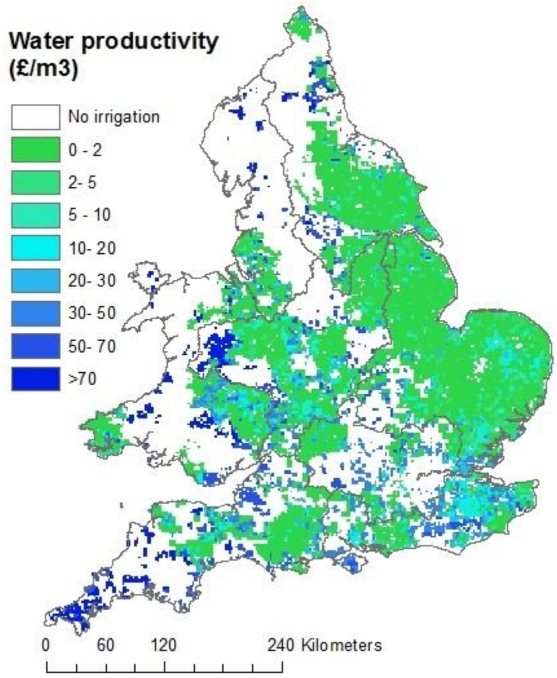
Research within the HistoricDroughts and MaRIUS projects provided the first national-scale estimate of the total financial benefit of outdoor irrigated production in England and Wales assuming no constraints in water resource availability and optimal irrigation practices.

The analysis suggests that the financial net-benefits of irrigation that would be lost in a 'design' dry year if irrigation were banned, are around £665 million, based on average national crop prices (£/tonne, adjusted for inflation using the Agricultural Price Index for the UK). The estimated average financial benefits per unit volume of water abstracted is in excess of £3.30 per m^3, with soft fruit and early potatoes producing the highest average water productivity (around £50 and £2 per m^3, respectively), demonstrating the high financial value of irrigation.

Estimated irrigation benefits (£ per 2km x 2km grid cell)



Water productivity (£/m^3)



Abstraction of water for irrigation can be subject to voluntary or mandatory restrictions during drought events in order to protect public water supplies, wetland habitats and river ecology. These restrictions are triggered by exceptionally low river flows. Our research has sought to understand the current and changing future risks of such restrictions and the resultant distribution of financial losses (see Box 8).

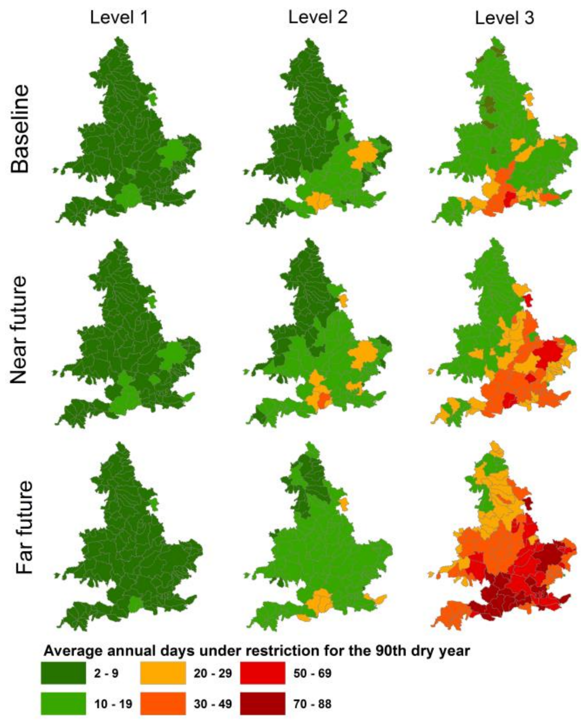
The results show that irrigation abstraction restrictions will become more widespread and severe, more frequent and longer lasting in the future, as climate change increasingly affects rainfall, evapotranspiration rates and river flows. Assuming current irrigated areas and the proportion of surface water abstracted directly for irrigation, then the highest financial losses will occur where drought-sensitive crops with a high financial value in the fresh produce supply change are located in water stressed catchments.

"What we have to be very careful of is to be consistent as producers because if you start to become inconsistent you will start to loose contracted volume into your customer, they'll see you as an unreliable supplier. And that is the problem with water availability and drought management, is that anything that affects our consistency of supply goes against us commercially not just from a single year yield point of view but in terms of medium and long-term plans where we sit in our customers food supply chain" (HistoricDrought interview)

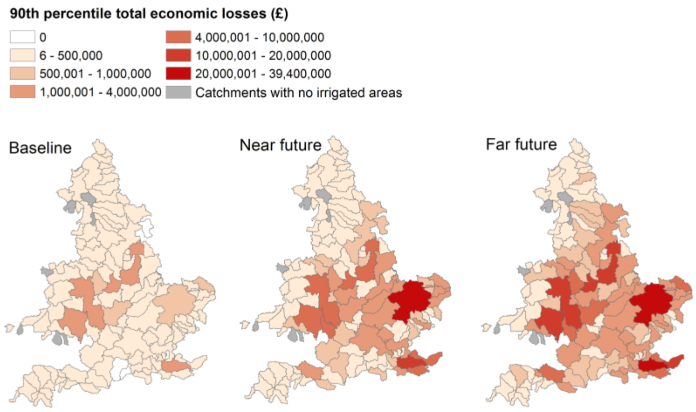
Box 8: Understanding the risk and economic consequences of irrigation abstraction restrictions during drought

The MaRIUS project explored the current and future risk of drought management restrictions on direct surface-water abstraction for irrigation and the consequential economic damages. A state-of-the-art numerical weather model was used to simulate many years of daily weather which 'could' happen in our current climate and under future climate change. These weather data were then used in a national-scale hydrological model to simulate river flows in catchments across England and Wales, to which typical drought management rules were applied. Based on the areas and types of irrigated crops grown in each catchment and the crops' sensitivity to differing levels and timing of irrigation restriction, the economic damages were estimated.

Changing average number of days under some level of mandatory abstraction restriction in a 1 in 10 year dry year



Changing economic losses due to mandatory surface water abstraction restrictions in a 1 in 10 year dry year



Not being able to irrigate optimally to deliver high-quality potatoes leads to skin blemishes and a lower value product

"*Financially [cutting the irrigated area] will cost £70,000 to £80,000 in lost profits, but we can only work with the water we've got…We're cutting production so we have water security to enable enough crop to reach harvest*" (Farmers Weekly, March 2012)

The peak water requirements for potatoes and onions normally occur at different times, but in 2018 they perfectly overlapped so we had seed planted onions doing nothing because we were on full irrigation on the potatoes for scab control. As a consequence onions were seriously under-irrigated" (ENDOWS farmer interview)

Catherine Little (NFU, Whittlesey Branch) tells her family story about farming in the Fens during 'The Reasons' event in Peterborough (©DRY project)

CAN WE FORECAST DROUGHTS AND THEIR IMPACTS?

As extreme and relatively rare events, droughts are difficult to predict. However, advances in our understanding of what causes meteorological droughts are enabling improved seasonal forecasts to be made. Combined with improved availability of drought status information, tools from the Drought and Water Scarcity programme may be used to inform the likelihood of future abstraction restrictions and crop varietal choice.

Monitoring and early warning systems are a key part of drought preparedness. They provide accessible information on the current drought state (e.g. rainfall, soil moisture, river flows, groundwater levels) and their likely future evolution over the coming weeks, to months and seasons ahead, to drought and water resource managers and farmers. The Drought and Water Scarcity programme engaged a wide range of stakeholders including farmers, allotment holders, horticulturalists and agricultural organisations, to appraise their key needs and existing monitoring and early warning tools. This identified the need for local, high resolution information; improved data on emergent soil moisture conditions; and more robust, more long-term and more timely forecasts ("for farmers and growers, droughts can become a problem overnight…").

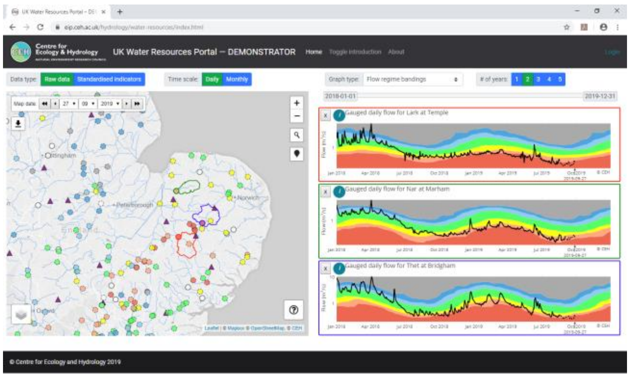
The Drought and Water Scarcity programme has developed new tools (see Further Information for links) for monitoring, early warning and risk assessment that respond to some of these needs:

- The UK Drought Portal was launched in 2017, to showcase a more interactive environment for monitoring, providing dynamic mapping of rainfall deficits at a 5km scale.
- The UK Water Resources Portal launched in 2019 provides daily real-time river flows for over 500 UK gauging stations, and COSMOS-UK soil moisture monitoring sites, as well as recent catchment rainfall information (Box 9).
- The UK Hydrological Outlook has integrated two new agriculturally-relevant products (Box 10): monthly Dryness Maps which provide a 1km^2 map of subsurface dryness for the UK; and % rainfall deficit maps which provide information on the rainfall needed to overcome the subsurface storage deficit, and the likelihood of this occurring over the coming months.
- The online D-Risk webtool (www.d-risk.eu) to help farming enterprises rapidly understand their business drought and abstraction risks has new a reservoir-costing module (Box 11).

These new products will provide an invaluable new source of information and near real time data to support improved decision-making for the agricultural sector.

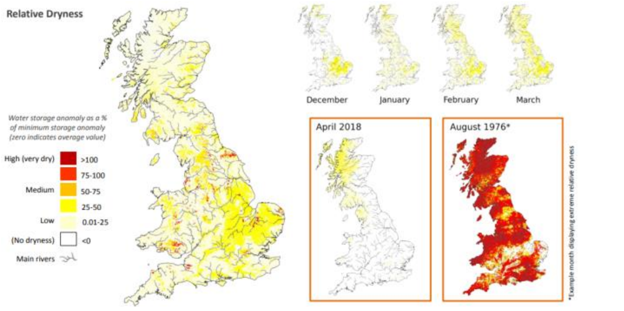
Box 9 UK Water Resources Portal demonstrator

The map in the screenshot below gives real-time river flows coloured according to flow conditions, showing exceptionally low flows in late April 2019 in East Anglia. The graphs show these time series for a selection of catchments. The local scale and timeliness (i.e. daily updates of river flows and soil moisture) of the Portal should be valuable for farmers. Interactive visualisations respond to user needs e.g. comparing where flows are at the current time with any given past drought year – "where are we now compared to 1995 or 1976?".



Box 10 New Dryness Maps within the UK Hydrological Outlook

Dryness maps showing 1km^2 subsurface anomalies for the UK compared to recent months and historical precedents



The Drought and Water Scarcity programme has also made significant advances in hydrological forecasting. A new, 'ensemble-based' forecasting system was developed within IMPETUS and operationalised for 300 catchments (Figure 4). While there is inevitable uncertainty in long-term forecasts, in many catchments in southeast England the method provides useable information on potential river flow status at long lead times (e.g. up to 6 months ahead),. Results on a catchment-by-catchment basis were disseminated every month during the 2018 and 2019 drought to a range of stakeholders. Both regulators and farmers have indicated this provided useful context, over and above the more static, regional-scale information currently available.

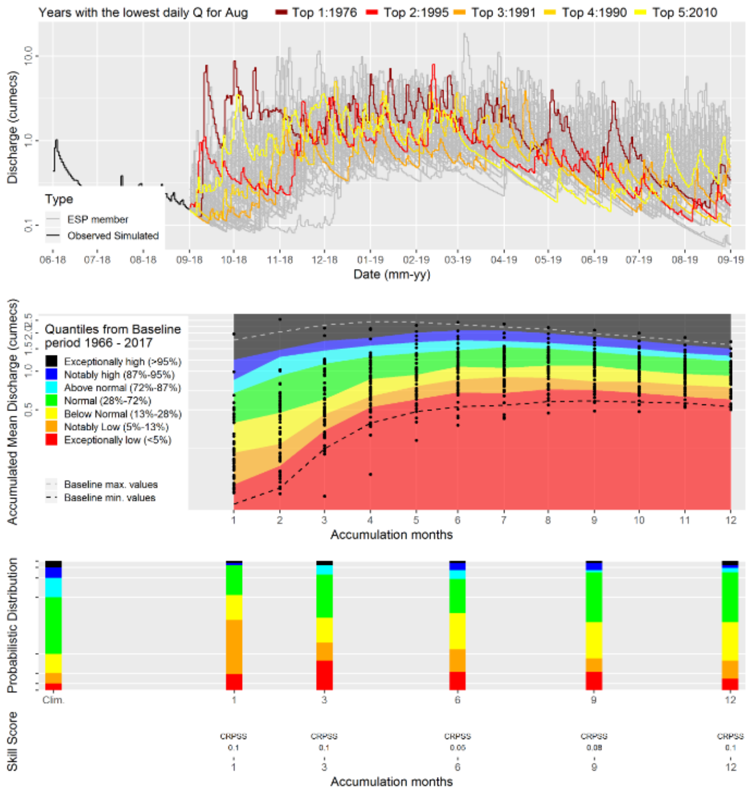
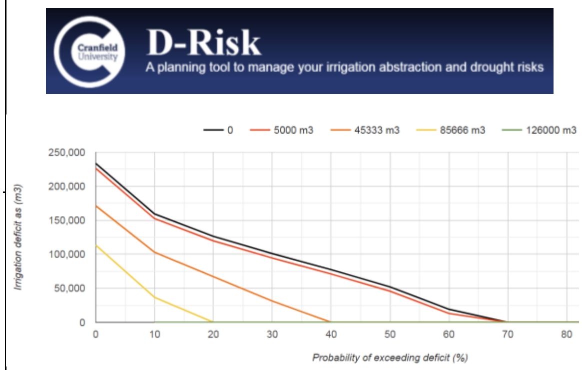


Figure 4: Catchment-based ensemble forecasts being provided to users in the ENDOWS project, showing (top) a range of possible streamflow forecasts informed by the historical record, highlighting notable drought years, (middle) the range of ensemble spread for 1 – 12 months into the future against various flow regime categories and (bottom) the likelihood of flows being in these categories at 1, 3, 6 and 12 months.

Box 11 New reservoir sizing and costing module in D-Risk

A reservoir costing and sizing module has been added to the D-Risk webtool (www.d-risk.eu) to allow users to explore how different sized on-farm reservoirs and storage licences can reduce the risk of being unable to meet crop irrigation need. The module was developed with industry specialists to ensure that the indicative cost estimates (for civil engineering works, earthworks and lining costs, only) for clay-lined and (plastic- or HDPE-) lined designs are realistic. D-Risk reservoir can provide rapid indicative guidance to help determine whether the likely investment in reservoir construction for a given level of annual drought risk reduction merits investigation.



Example D-Risk output showing how increasing reservoir volume reduces the annual probability of exceeding a given level of irrigation deficit

"The EA [Environment Agency] … they gave us a lot of forward notification. They were forecasting about if we have average rainfall we will need to have this level of restriction…And that was extremely helpful. It gave us the ability to plan our risk…" (HistoricDroughts interview)

The [ENDOWS} drought forecasting and advances in how Standard Precipitation Index information has been used was useful for explaining current situations, helping our audiences to understand it visually and combining it with work the Environment Agency was producing. We are now developing communications based on the outlooks and the maps are a really good tool for engaging with farmers as well as colleagues, it really helps everyone to understand the situation" (Nicola Dunn, AHDB)

HOW CAN DROUGHT AND WATER SCARCITY IMPACTS ON AGRICULTURE BE REDUCED?

Reducing the impacts of drought and water scarcity on agriculture requires actions from farmers, retailers, Government and the public. These actions can range from investment in on-farm reservoirs, changing crop and grass varieties, changing the balance between forward and open contracts with retailers; influencing consumer behaviour, facilitating more efficient water trading; and improving communication with the regulators.

Effective drought management that improves farm resilience and balances the needs of agriculture and the environment requires actions across all levels, from the Government and retailers to individual farmers; it also requires much stronger vertical integration within the so-called drought management pyramid (Figure 5). Discussions with farmers within the DRY project highlighted the broad diversity of perspectives on drought and drought management (see Box 12).

Other sectors, such as public water supply and energy generation, are legally required to plan and address future water demand-supply imbalances, yet agriculture has no equivalent. A strategy is urgently needed: in catchments where irrigation is concentrated and resources are over-abstracted; regions where irrigated production may need to expand; or where rainfed cropping may be vulnerable. The protected cropping and horticultural sectors are also at risk. Consequently, through working with key informants within the agricultural, horticultural and protected cropping sector, the Drought and Water Scarcity programme has developed a Water Strategy, containing a set of actions needed to support sector growth, and employment (see Box 13).

"Many businesses have been compromising on irrigation investment – but not anymore. We hadn't moved on, but now we are looking long and hard at the resilience of our business planting programmes and water resources needed to meet contracts in a drought year. 2018 was a wake-up call" [ENDOWS farmer interview]

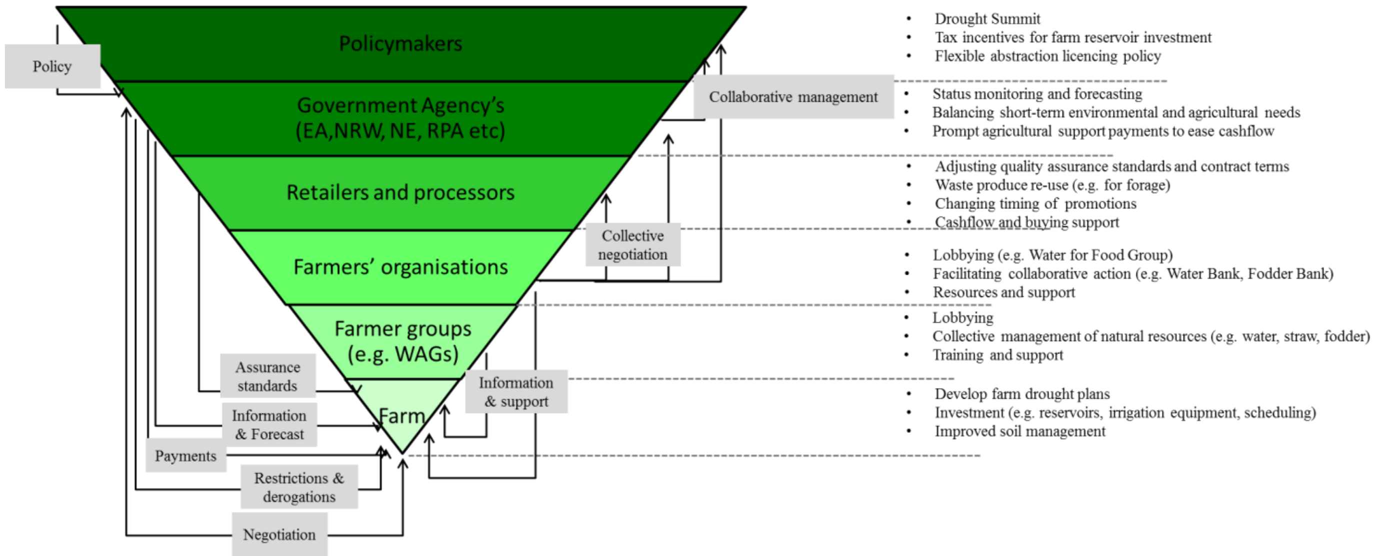


Figure 5: The drought management pyramid

"A reservoir is effectively a very very expensive insurance policy. So you have to ask yourself, is it worth doing? What is the risk?" (East Anglian farmer, 2017)

"It is a refreshing change that our retail customers have across the board lowered their specifications allowing more "wonky" fruit than normal" (Farmers Weekly, October 2012)

Box 12: Talking agriculture, drought and adaptation – insights from stories garnered in the DRY (Drought Risk and You) project.

The DRY project brought together science and stories about past, present and future, involving drought experiences and ways of coping and adapting, as a new evidence base to support decision-making in UK drought risk management. DRY had conversations with farmers, and organisations that work with farmers, about building resilience to drought, in seven catchments in England, Wales and Scotland. DRY gathered stories of drought and behaviours involved in wider water activities across six sectors (agriculture, environment, built environment, business, health and wellbeing, and people in their communities).

UK farming is diverse. We found farmers' voices - their experiences and perceptions of drought - were varied, depending on wide-ranging factors, including the nature of the farm, soil type and its variability, their water source(s), whether or not they could irrigate, their location in the UK and national governance requirements, and the crops they choose. We heard contrasting accounts of whether 'drought is bad' or 'drought is good'. Stories of hardship, of making money, of collaborations and of tensions. So memories of the 1976 drought combined those stories of making 'quick money', where potatoes that could be irrigated increased in price, but with potatoes never regaining the same market share.

> *"It's kind of legendary now. Especially 1976. Potato prices were extremely high that year and it was basically because there was a shortage and there wasn't that many people that had the capability to irrigate."* (Potato farmer, Fife Eden catchment)

At the same time, others remember the hard life of livestock farmers when there was competition for water supply or where water supply was private. The same contrast applies more recently; for some farmers, 'drought' in summer 2018 was 'good' because they were growing the right crops, at the right time on the right soil. For livestock farmers, it was clearly very different as the grass did not grow and they struggled to find enough hay for feed under the dry conditions.

So drought and its impact on agriculture can be experienced in many ways, with implications for coping strategies and adaptation. The types of knowledge that farmers collect and use in their decision-making could embrace both local knowledge gained from their experience, and technical knowledge (e.g. around how to judge when to irrigate based on soil characteristics). We were told stories of useful management strategies to gather data for their very specific farm.

> *"Ok, normally in the past I always had a weather station to keep local information. Because what happens on this farm will be quite different to the farm across the valley. The averaging information you can get from other sources on the internet and etc. I've always felt it was never quite accurate enough to understand what's happening on my soil, so I've always had my own weather station."* (Organic farmer, Pang catchment)

We also heard of traditional coping strategies (knowing how to deal with dry seasonal 'droughty weather' or dust clouds); of creative adaptation and resilient thinking (e.g. about soil resilience and agricultural practices that maintain soil structure like Minimum-Tillage or the value of herbal leys):

> *"I mean there's all sorts of other benefits to these herbal lays. They're great for improving soil structure. They've got medicinal qualities and all sorts."* (Farming advisor, Frome catchment)

Some accounts were of higher-cost technical solutions, such as building a reservoir for water storage, and pumps to extract water from rivers. We also heard stories of farmer's wider engagements with uncertainty and climate change, and of seeking out knowledge from often droughted countries overseas, such as Israel and those in Southern Europe.

Critical actions, tensions and opportunities for adaptation were perceived to lie not just within agriculture, but also at the interfaces between government policy, water resource managers, agriculture and the market. We heard stories of the need for shops and the public to be more accepting of 'wonky vegetables'; of shifting public perceptions of farming and farmers; of tensions between rainwater recycling for washing vegetables and human health and safety; of relationships between future drought, agriculture and food (new crops, or new watering regimes for old crops – with implications for the British diet); of how increased water storage (in the Fenlands) might ultimately help both environment and agriculture; and of how the impetus for natural flood management might also have drought resilience benefits.

Farmers' stories of their experiences, both of living through droughts and their longer-term adaptations, have significant value and should be captured as a living evidence bank. We found great potential and utility in capturing farmer's insights and sharing their stories, creative thinking and adaptive behaviours among catchments and agricultural sectors, and that 'evidence' for decision-making was not necessarily about a deficit of science. Farmer's sensitivity to, and their recognition of, early drought stages also suggests value in sharing their drought stories and observations with different publics, in the same way as growers and allotment holders can be considered 'harbingers' of drought in local communities.

> *"It's time to change the way we do things. We need to incentivise the water companies, EA [Environment Agency] and farmers to work together"* [ENDOWS farmer interview]

Box 13: Increasing the agri-food industry's resilience to drought and water scarcity risks – a water strategy for UK agriculture and horticulture

The Drought and Water Scarcity programme engaged a wide range of stakeholders and worked collaboratively with key informants to develop a draft long-term water strategy for agriculture and horticulture. ***But why is this needed?***

The agri-food industry is the UK's largest manufacturing sector- it is worth £110 billion to the national economy (7% of total), employs 3.8 million people (14% of total) and accounts for 19% of the UK's total manufacturing turnover. It buys two-thirds of the UK's agricultural and horticultural produce, including substantial quantities of high-quality potatoes, fruit and vegetables. **Water is essential for the industry's future sustainable development**, and is at the heart of farming and agri-businesses, particularly in the west midlands, eastern and south-east England, the driest and most water-stressed areas in the UK. Without water, most agri-businesses would simply not survive.

The agri-food industry adds £4 in food processing, wholesale, and logistics and a further £5 in food and retail catering for every £1 of Gross Value Added (GVA) of primary production. Supplemental irrigation is not a low value, marginal use of water, but a critically important component of high-value production used to secure high yielding produce that also meets the stringent quality assurance requirements for retailers. However, increasing regulation, droughts and a changing climate all threaten the sustainability of this industry and the livelihoods it supports.

High level vision The water strategy identifies the emerging water-related risks, the economic importance of securing a 'fair share of water', and the priorities for action. It defines a number of shared ambitions:

- To secure a fair share of water and recognise that agriculture is an 'essential use'
- To protect licensed 'headroom' in future water allocations for drought insurance
- To foster multi-sector collaboration with public water supply, energy and environment
- To share risks and benefits in future water supply investments
- To increase water productivity (t of produce / m^3 water used) and water value (£/m^3)
- To support knowledge translation to increase resilience to drought / water scarcity risks
- To drive innovation in precision water management and technology uptake

Water companies are legally required to produce Water Resource Management Plans (WRMPs) every 5 years that identify the water-related risks facing public water supplies, setting out their strategic investment plans to cope with population growth, socio-economic development and climate change. Agriculture needs to adopt a similar approach to forward planning.

So how will these be achieved? Three strategic 'themes' have been defined:

Theme 1 Managing current abstraction 'hotspots' and forecasting future demand

Theme 2 Addressing environmental and environmental challenges linked to a changing climate

Theme 3 Supporting collaboration and building resilience to climate and water risks

Finally, for each theme, the existing knowledge gaps and a set of key priorities for action have been developed.

The 2018 drought highlighted the importance of water for agriculture and the fragility of the fresh produce supply chain in the face of water-related risks. Without a strategy, the consequences of inaction in preparing for droughts and during future drought are substantial. Inaction could result in an increasingly fragmented and vulnerable agrifood sector, water 'traded' out of agriculture and business contraction/stagnation, with impacts on GVA, and employment.

It is over 40 years since the "Strutt Report" ("Water for Agriculture: future needs") set out a long-term plan. Our new strategy is therefore timely and will provide essential direction for policy makers, the agri-food industry and researchers to address the serious drought and water scarcity issues facing the sector, and to support the future sustainable growth of the nationally-important agri-food industry.

Whilst most individual farmers use irrigation water efficiently, there is still substantial potential to increase the overall effectiveness of use of licensed irrigation water through water trading, as many licence holders have unused licensed water in most years. Water trading has been seen as a way of increasing access to this water, but it is a time-consuming processes and a lack of understanding of the system has limited uptake. The proposed water abstraction reform in England aims to encourage water trading. The agricultural drought of 2018 resulted in a situation where groundwater and river flows remained largely 'normal' through the irrigation season but licence holders began to run out of water because they had reached (or were in danger of reaching) their annual licensed volumes. During this period the EA allowed rapid decisions to be taken on applications for short term and emergency trades which proved highly valuable in terms of reducing crop yield and quality losses. This was supported by initiatives such as the NFU's WaterBank and the EA's licence GIS system[1]. Experiences from 2018 (and 2012) showed the potential for water trading to support irrigated agriculture, but the focus on emergency trading through 'primary' markets was reliant on the rapid actions of Agency staff. The D&WS programme has investigated the potential for more sophisticated secondary market products to potentially offer greater flexibility and risk-reduction benefits to agriculture (see Box 14).

Dr Antonia Liguori (DRY Project team) interviewing Richard Morris, farm manager at Sheepdrove Organic Farm, Lambourn, Hungerford (© DRY project)

"Relations with the Agency have improved immeasurably over the last 15-20 years. They are much more ready to talk to abstractors, to discuss the problems, to try to reach solutions that enable them to fulfil the regulatory rules plus give as much flexibility to the abstractors as possible" (HistoricDroughts interview, 2015)

Connecting the public with farming (© DRY project)

"Many businesses have been compromising on irrigation investment – but not anymore. We hadn't moved on, but now we are looking long and hard at the resilience of our business planting programmes and water resources needed to meet contracts in a drought year. 2018 was a wake-up call" (ENDOWS farmer interview).

Box 14: Assessing opportunities for secondary markets for water in response to proposed abstraction reforms

Cranfield University and the NFU looked at the potential for secondary market products to potentially offer greater flexibility and risk-reduction benefits to agriculture in the context of the abstraction reform[2]. International experience has shown that they can reduce risk management costs, enable water users to better match water access to their requirements, and encourage more efficient utilisation of water rights. Key types of secondary market products are:

Forward and futures contracts represent an agreement to buy/sell a certain volume of water in the future for a specified price.

Option contracts give the holder the right (but not the obligation) to buy or sell a water volume on a given date for a given price, allowing the holder to delay water purchase decisions until more information is available, and offer protection against price volatility.

Secondary markets enable advance pre-approval of trades, overcoming a key shortcoming of the current system. However, the implications of 'hands off flow' conditions and 'Section 57' restrictions for pre-approved trades will need to be carefully assessed before secondary markets can deliver their promise

Despite much ongoing effort, collective actions with other stakeholders and significant investment by agri-businesses and the farming community, the risks of drought and water scarcity will continue to pose serious challenges to the agricultural sector. Future climate and agro-economic change will exacerbate the situation and amplify the risks. .

It is strategically important to recognise that ongoing efforts will be needed, at all levels from policy formulation, across all sub-sectors of the industry and on-farm to ensure that a thriving agricultural and environmentally sustainable sector continues to provide high quality food to UK society.

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1 https://www.arcgis.com/apps/webappviewer/index.html?id=c9176c299b734cff9a6deffcf7f40a4e

2 https://www.nfuonline.com/nfu-online/science-and-environment/irrigation-and-abstraction/cranfield-nfu-report-secondary-markets-oct-18/

FURTHER INFORMATION

Further useful information and data can be found at the following web addresses.

Project websites:

- Historic Droughts: https://historicdroughts.ceh.ac.uk/
- MaRIUS: http://www.mariusdroughtproject.org/
- DRY: http://dryproject.co.uk/
- ENDOWS: http://aboutdrought.info/

Publications

- Drought planning in England: a primer - http://www.mariusdroughtproject.org/wp-content/uploads/2017/09/MaRIUS_Drought_Primer_Online.pdf
- Irrigation Brief: http://aboutdrought.info/drought-research/publications/briefing-notes/
- List of D&WS Programme project publications: http://aboutdrought.info/drought-research/publications/

Tools

- UK Water Resources Portal: https://eip.ceh.ac.uk/hydrology/water-resources/
- DRY Utility: https://dryutility.info/ This initiative is developing a searchable Story Bank of 300+ water/drought narratives (past, present and future), and a series of Story Maps that can be explored by sector and by DRY's seven case-study catchments.
- Historic Drought Inventory Explorer: https://eip.ceh.ac.uk/hydrology/drought-inventory/
- UK Hydrological Drought Explorer: https://shiny-apps.ceh.ac.uk/hydro_drought_explorer/
- UK Drought portal: https://eip.ceh.ac.uk/apps/droughts/
- DRisk: www.d-risk.eu

Data

- Meteorological, hydrological, groundwater, modelling datasets generated within the Drought and Water Scarcity programme can be accessed from http://aboutdrought.info/drought-research/data-and-information/
- Historic droughts inventory of references from agricultural media 1975-2012: http://reshare.ukdataservice.ac.uk/853167/

ACKNOWLEDGEMENTS

We greatly appreciate the many individuals within the agricultural sector and the wider agri-food industry who have freely given of their time during the Drought and Water Scarcity programme. We cannot name everyone who has contributed, but would particularly like to thank Paul Hammett (National Farmers Union), Melvyn Kay (UK Irrigation Association), Mike Storey and Nicola Dunn (Agriculture and Horticulture Development Board) and John Adlam (Dove Associates) for their support.

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