Drought Risk and You

How will climate change affect permanent pastures?

Report on the DRY project rainfall manipulation experiment in the Frome catchment

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Summary

This report describes a field experiment set up in the catchment of the River Frome in South Gloucestershire, UK, to study the effect of reduced rainfall on the growth and biomass production of semi-natural grasslands. The experiment had four aims: better understanding of how drought might affect UK grasslands, engaging local people in drought science (volunteers/ citizen science), providing a focus for engagement activities and delivering detailed information that could contribute to future hydrological models.

A: Better understanding of how drought might affect UK grasslands

The experiment was set up on two contrasting areas of permanent grassland that were typical of the semi-natural pastures in the River Frome catchment. One site (Oldwood Pit, OWP) is a permanent pasture that has been managed with no inputs of fertilizer (apart from animal manure) or pesticide since at least the end of World War ll. OWP is managed either by sheep grazing or for a summer hay crop followed by autumn grazing. The other site (University of the West of England, UWE) is a former arable field that has been permanent pasture, with no artificial inputs, for at least thirty years. UWE was used for grazing sheep and cattle but for the three years preceding this work had not been grazed. It had been cut for hay in late September. The experiment ran from October 2015 to October 2018.

At each site, rainfall shelters were used to reduce incident rainfall by about 50%, on six 3 m x 3 m plots. These reduced rainfall (RR) plots were compared with six 3 m x 3 m Control plots. Automatic weather stations recorded environmental data, especially rainfall, from both RR and Control plots. The effect of reduced rainfall on above ground dry matter production (biomass or yield) was monitored by collecting and drying vegetation samples in late June/early July at OWP to mimic a summer hay cut, and in late September/early October to mimic autumn grazing at OWP and late hay cut at UWE. Vegetation growth was monitored by regular measurements of plant height. Regular surveys of the plant species present and the percentage of ground covered by each species were used to determine if reduced rainfall altered the plant species composition of the sward. During the summer months, flowers and pollinators were counted to assess the impact of drier conditions on floral resources and pollinators.

Over the three years of the experiment, there were only small differences in yield or plant height between the RR and Control plots at both sites. At OWP, regrowth of vegetation after the summer cut was less vigorous in the RR plots and this was reflected in the measurements of plant height and yield. In 2016/2017, the winter and early spring were drier than average and at both sites yield and plant height was reduced compared to 2015/2016 and 2017/2018. This difference was greater at UWE. When plant height or yield were plotted against rainfall, the data from RR and Control plots fell into separate groups. Within each group, there was a positive relationship with rainfall but the reduced rainfall in

the RR plots did not translate into reduced yield or plant height. We did not see any large differences between RR and Control plots in the numbers of flowers or pollinators.

The reduction in rainfall that we used in this work (50%) is more severe than the 20-28% reduction indicated for the R. Frome catchment, by the UK climate change predictions, but still fell within the 100 year extremes of reported rainfall for the R. Frome catchment. Our results suggest that well-established permanent pastures are likely to be resilient to reduced rainfall, at least in the short term, although farmers may need to be flexible in when they graze stock or cut hay.

B: Engage local people in drought science (volunteers/ citizen science)

Over the course of the experiment, more than 40 volunteers helped to collect data from the experiment. The volunteers included students, people wanting to learn new skills, environmental professionals wanting to update their field skills and people with an interest in climate change and natural history. The volunteers also took part in the narrative research part of the DRY project (https://dryutility.info/).

C: Provide a focus for engagement activities

Throughout the course of the experiment, the DRY project field experiment was used for many different types of public engagement activities to raise awareness of the importance of climate change. These included open days at the UWE field site as part of national and local events that aimed to raise awareness of environmental science, such as British Science Week and Bristol Festival of Nature. Twelve students (eight school year twelve, three undergraduate and one postgraduate) undertook research projects using the field site or data that had been collected during the experiment.

D: Deliver detailed information that could contribute to future hydrological models

All data collected from the field experiment have been stored on the UK Centre for Ecology and Hydrology database.

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Acknowledgements

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The experiment was designed by Dr Jill Thompson (UK Centre for Ecology & Hydrology, Edinburgh).

The experiment was managed and data collected by Dr S. Ayling. Dr P. Ramirez worked with the volunteers and assisted with data collection at UWE.

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All photographs S. Ayling.

Chapter 1 Background

1.1 The Drought Risk and You Project

The Drought Risk and You (DRY) project was a five year project funded through the RCUK Drought and Water Scarcity programme (Grant Number NE/LO1033X/1 awarded to Professor L. McEwen). The project started in April 2014, and aimed to develop an easy-to-use, evidence-based resource to support the decision-making process involved in drought risk management in the UK. The project drew together information from different disciplines and perspectives including hydrology, drought science, stakeholder engagement, citizen science and narrative storytelling to gain a better understanding of drought risks and how they are perceived than could be achieved through mathematical modelling alone. In the DRY project, 'data' included photographs and stories from a river catchment as well as numerical data from scientific experiments and hydrological modelling.

The project involved studies in seven river catchments within England, Wales and Scotland: R. Eden in Fife, R. Don in Yorkshire, R. Ebbw in S. Wales, R. Pang in Berkshire, Bevills Leam in East Anglia, R. Frome in S. Gloucester and R. Fowey in Cornwall. The catchments were chosen to provide North-to-South and East–to-West gradients across mainland UK. Details of the catchments can be found in Blake and Ragab (2014).

In three of these river catchments (Don, Eden and Frome, (Figure 1.1)), a field experiment was set up to study the effects of drought on semi-natural grasslands. The experiment involved the use of rainfall shelters to artificially alter the amount of rainfall received by the vegetation, and were a type of mesocosm[1] experiment. The field experiment was designed by Dr J. Thompson (UK Centre for Hydrology & Ecology, Edinburgh). This report describes the results of the field experiment set up in the catchment of the R. Frome in South Gloucestershire.

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[1]The term **mesocosm** originated in marine biology but is now used to describe an experimental system that is studied at a scale mid-way ('meso 'means middle or intermediate) between a micro study (laboratory or glasshouse) and a large (macro) field experiment. A mesocosm allows scientists to study a system under conditions that are close to natural, but with more control than is usually possible when working at field scale. The term mesocosm is believed to have been first used by the ecologist EP Odum in 1984.

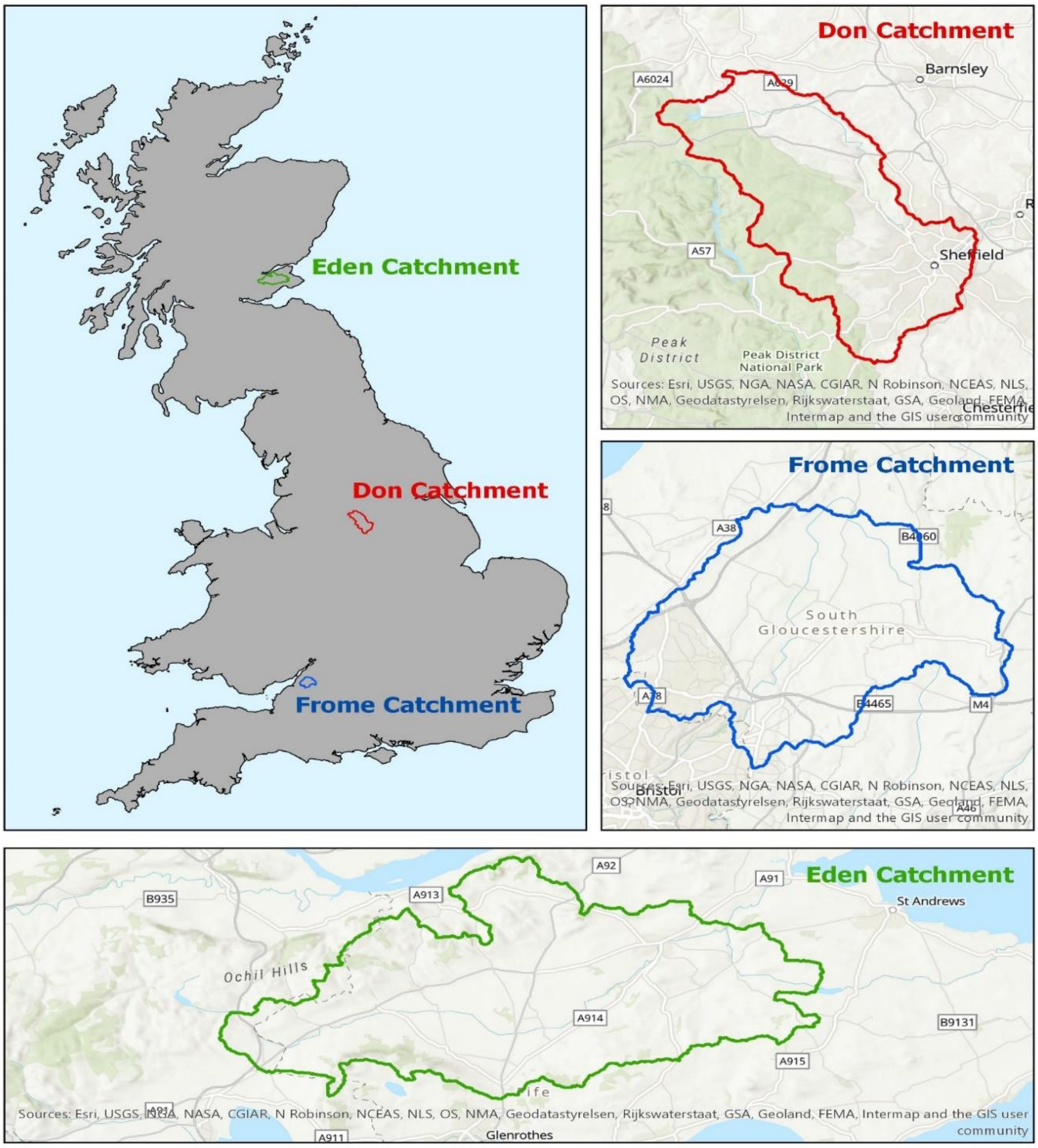

Figure 1.1. Location of DRY project catchments in which field experiments were set up (image curtesy H. West, UWE).

1.2 Grasslands

A grassland is any area where the vegetation is dominated by grasses (members of the plant family, Gramineae) but the vegetation may also contain large numbers of other species and types of plant. Many of our crops are members of the Gramineae, including wheat, maize, rice and sugar cane. The United Nations Food and Agriculture Organisation (FAO, 2005) considers grassland to mean grazing land that is dominated by grasses, and where trees and shrubs make up less than ten percent of the ground cover, while wooded grassland is grazing land where 10-40 percent of the ground cover is trees and shrubs (http://www.fao.org/3/y8344e/y8344e05.htm).

Grasslands are the most widespread type of vegetation on the Earth and include many iconic ecosystems such as the prairies of North America and the savannahs of East Africa. Grasslands cover 52.5 million km^2 of the World, approximately 40% of the land area, excluding areas such as Antarctica and Greenland that are too cold for plant growth (Figure 1.2). No grassland is entirely natural, and all show some degree of human influence whether through cultivation, grazing, burning or seeding. Many grasslands exist in areas that had previously had tree cover and now form a plagioclimax[2] vegetation.

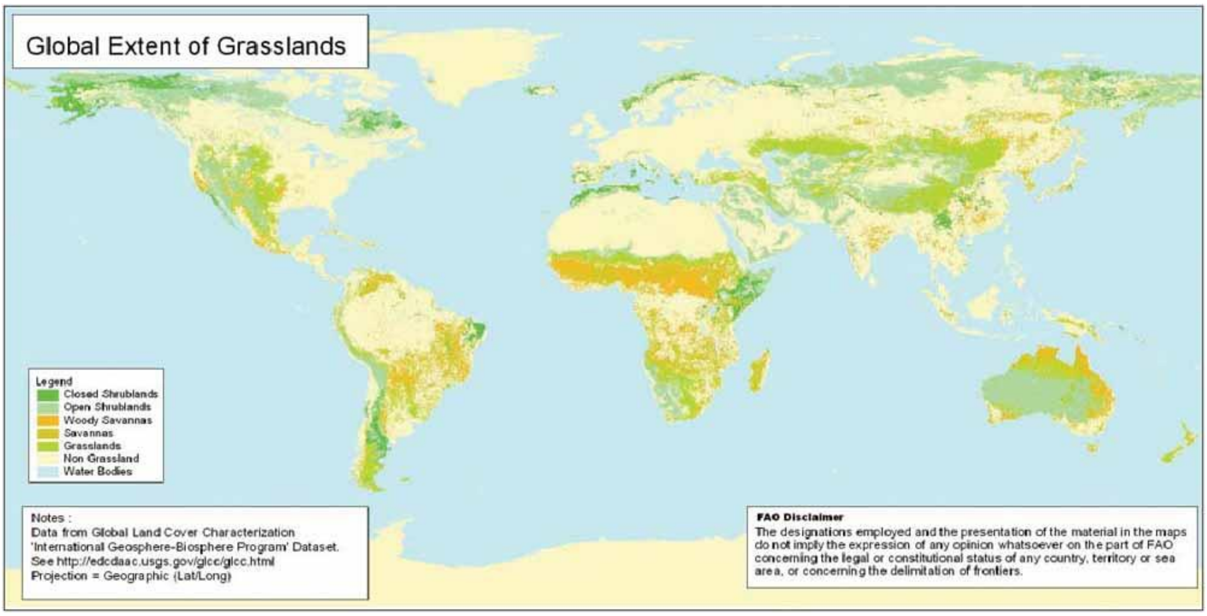

Figure 1.2. The global extent of Grasslands (taken from FAO (2005) Grasslands of the World. http://www.fao.org/3/y8344e/y8344e05.htm)

In the UK, most land, except the mountain tops, was originally covered by woodland, but human activities from around 5000 B.P. (Neolithic period) led to woodland gradually being replaced by grasslands except on very steep or wet sites (Pennington, 1974). Grasslands are the major form of vegetation in UK, forming a plagioclimax that dominates our landscapes. This can be seen in the UK land cover map (Figure 1.3); all of the green and olive green areas are types of grassland.

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[2] **Plagioclimax** vegetation is a type of vegetation that may have been present for many hundreds of years but which cannot survive without human intervention. The climax vegetation of an area is the vegetation that would be there if natural processes were allowed to progress without interruption. Grassland is the dominant vegetation type in UK but without human activities it would gradually revert to scrub followed by woodland.

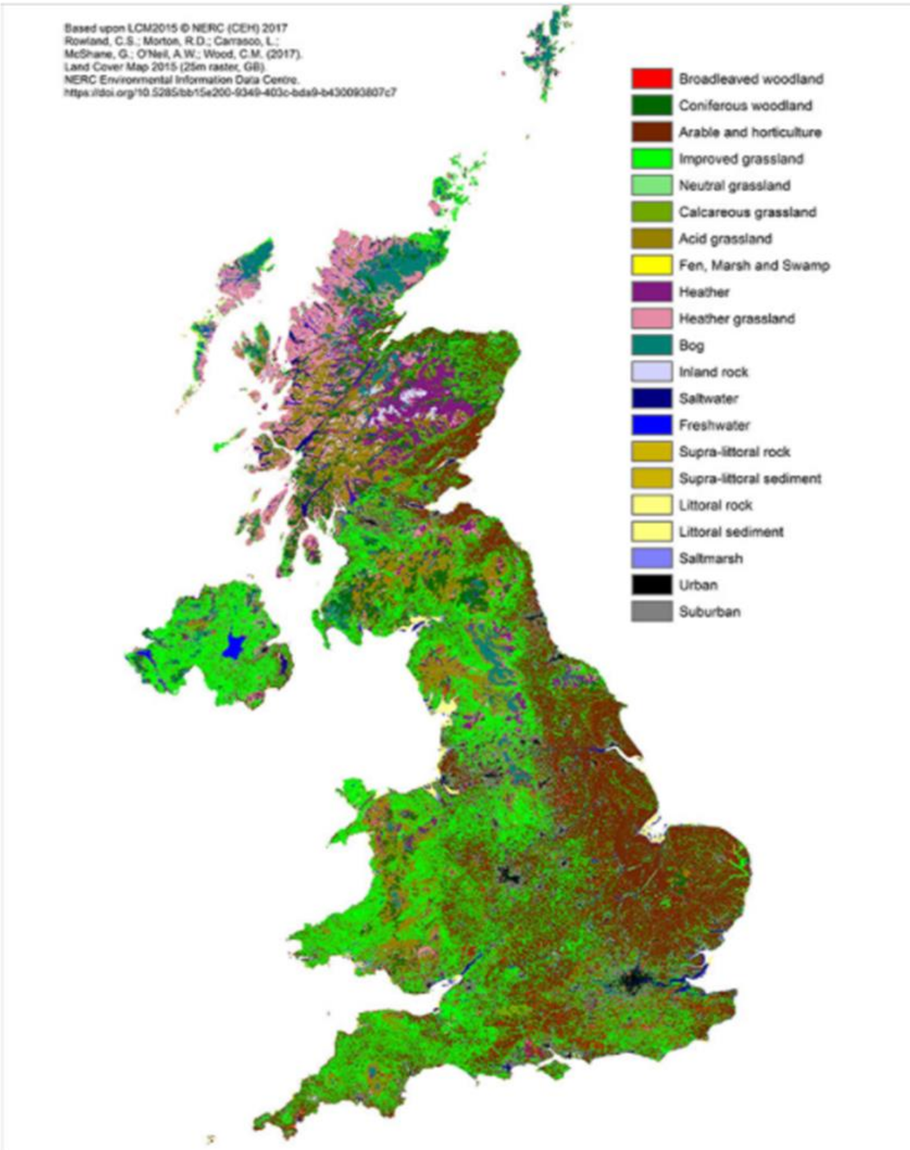


Figure 1.3. UK land cover 2015 (http://www.ukso.org/static-maps/land-cover-map.html)

In the UK, more than 40% of the land area (15 million hectares) is agricultural grassland. Grassland is, by area, the most important crop in the UK. 89% of total agricultural lands are agricultural grasslands, including cereals, (Table 1). This proportion has changed little over the last 60 years; in 1961, around 90% of farmland was under grass of some sort (Moore, 1966). These grasslands support around 10 million cattle and calves and 34 million sheep and lambs. In 2013/14, forage crops contributed £265 million to farm income and the livestock industry £8,889 million (Defra and Office of National Statistics, 2014 and 2017). In addition, there are about 490 thousand hectares of golf courses (2% of UK area) and 1525 thousand hectares of urban green space (parks and sports fields make up 54 % of the urbanised area). Sport England estimates that in 2010 outdoor sporting activities contributed about £20 billion directly to the economy and an additional £11 billion through benefits on health and wellbeing. Lawns, a type of grassland, are an important feature of the UK's 508 thousand hectares of gardens (Defra, Office of National Statistics, 2017).

Table 1.1. Agricultural land use in UK in 2017 in thousands of hectares

Utilised agricultural area (UAA)	17, 476
UAA as a proportion of total UK area	72%
Total agricultural area	18, 835
Common rough grazing	1, 198
Total croppable area	6,131
Total crops	4, 745
Arable crops	4, 577
Cereals	3, 181
Oilseeds (includes linseed and borage)	590
Potatoes	145
Other crops	661
Horticultural crops	168
Uncropped arable land	241
Temporary grass under 5 years old	1, 144
Total permanent grassland	10, 138
Grass over 5 years old	6, 135
Sole right rough grazing	4, 003
Other land on agricultural holdings	1, 368
Woodland	1, 037
Land used for outdoor pigs	10
All other non-agricultural land	321
https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/741062/AUK-2017-18sep18.pdf	

British grasslands are very diverse. They can be very broadly divided into three groups: natural, semi-natural and managed. There are very few or no natural grasslands in the UK. Semi-natural grasslands are those (mostly agricultural) that have been grassland for many years, are not usually given heavy doses of fertilizer, and although they may occasionally be reseeded or over seeded, are not regularly reseeded. These semi-natural grasslands include meadows and permanent pastures. Managed grasslands are those that are regularly cut, or rolled; management may include application of fertiliser to increase the growth rate and productivity and herbicide to control which plant species are present. Managed grasslands include leys that are usually reseeded every 2 to 3 years to maintain productivity. Lawns, sports fields and golf courses represent extreme types of managed grassland.

Permanent pastures are agricultural grasslands that have not been ploughed for at least five years (ONS, 2020). These pastures may support a wide range of plant and animals species (Natural England, 2001). Permanent pastures often have much higher water infiltration rates (up to 60 mm water per hour) than arable crops (10 mm per hour) (Holtan and Fitzpatrick, 1950; Goudie, 2001), thus making them particularly important during heavy rainfall to ensure that water infiltrates the pasture and moves into groundwater, rather than running off to cause flooding. In England, grasslands with a high diversity of different species may store more than 500 % of the carbon stored by grassland monocultures (Alonso et al., 2012).

The importance of permanent grasslands is recognised within the UK Government Basic Payment Scheme for farmers. Farmers may not plough grassland that has been established for more than 15 years without an inspection and approval from Natural England. If the area of permanent pasture as a proportion of agricultural land falls by more than 5%, farmers may be required to reinstate permanent grass (Rural Payments Agency, 2020).

The Countryside Vegetation System (Bunce et al., 1999) recognises at least 57 distinct types of grassland in the UK reflecting local variations in soil, topography, climate and management. They range from lowland pastures, to upland rough grazing where heathers and rushes may be almost as abundant as grass species (Figure 1.4). The different types of grassland contain a very large number of plant species ranging from spectacular orchids to easily overlooked, but equally beautiful, ferns and mosses. They also provide homes for many animals and birds, and millions of invertebrates and fungi. There may be more than 2000 cm^{-2} predatory invertebrates. It is estimated that 0.4 hectare (1 acre) of established meadow may contain 2.25 million spiders (these will eat at least 108 million insects in six months) and the soil can contain 400 million insects and 600 million mites (http://www.countrysideinfo.co.uk/meadows/animals.htm).

	
Lowland pasture, South Gloucestershire	Rough moorland grazing, University of Sheffield Field Station, Yorkshire

Figure 1.4. UK grasslands are very diverse. Photos S. Ayling

Grass and grasslands are strongly linked to human cultural identity. In the UK, lawns are an important part of most gardens. Grasslands (gardens, sports fields and parks) make up about 50% of the urbanised area. As well as popular sayings, such as 'make hay while the sun shines', there are thousands of songs and poems about grass or grasslands, and some of the most famous and popular paintings are of grass and grasslands. Commercially, the importance of grasslands to our sense of identity and wellbeing is reflected in the use of images of grasslands in advertisements for products ranging from cars to shampoo.

In the UK, grasslands are an important part of the landscape, are economically important, contribute to the biodiversity of our environment, and are part of the country's cultural identity. Anything that affects grasslands will have important implications for the economic and cultural wealth of the nation. Further background information about grasslands is available on the DRY project website (https://dryutility.info/grasslands/).

1.3 The River Frome catchment

The River Frome catchment is in South Gloucestershire, UK and covers an area of 149 km^2 above the flow gauging station at Frenchay. The catchment is between 20 m and 194 m above ordnance datum (AOD). Data about rainfall and river flows, from 1961 to present, are available from the National River Flow archive (https://nrfa.ceh.ac.uk/). Grasslands cover about 48% of the catchment with arable farming and horticulture covering a further 22 %. The catchment has experienced a number of drought periods, including: 1976, 1990, 1995, 2005 and 2011 (Blake and Ragab, 2014).

The catchment lies to the Northeast of Bristol, and includes the town of Yate; both Bristol and Yate are expanding rapidly. There is a high demand for land for development, which is likely to increase demand for water (and other services) and reduce the amount of undeveloped land, and this may influence hydrology and ground water supplies within the catchment.

Further information about the physical characteristics and hydrology of the R. Frome catchment is given in Blake and Ragab (2014), Afzal and Ragab (2019) and the Dry Utility (https://dryutility.info/).

1.4 Climate change in the UK and likely hydrological impacts in the Bristol region

Between 1961 and 2015, average air temperatures in Great Britain have risen by 0.20 ± 0.13 °C $decade^{-1}$ and evapotranspiration by 0.87 ± 0.55 mm yr^{-1} yr^{-1} (Blyth et al., 2019). The Climate Predictions for the UK (UKCP09 and UKCP18, Met Office (2018)) suggest that within the next twenty to thirty years, in the UK, average temperatures and winter rainfall are likely to increase, while rainfall in the summer is likely to decrease. Associated with these changes, extreme events, such as episodes of heavy rainfall, are likely to become more frequent.

The UK climate change predictions (UKCP09) suggest that, in the R. Frome catchment by the 2050s, average temperatures may be 1.9 ˚C higher in winter and 2.4 ˚C higher in summer; summer rainfall is predicted to decrease by 14% compared to the 1961 - 1990 average (Table 1.2, Afzal and Ragab, 2019). Higher summer temperatures will increase the amount of water lost by evapotranspiration and this combined with any reduction in summer rainfall, will increase the demand placed on water supplies. Detailed hydrological modelling, using the Distributed Catchment Scale Model (DiCaSM), of the likely effects of future changes in land use combined with climate change indicated that reducing the area under grass in the Frome catchment could reduce ground water recharge (Afzal and Ragab, 2019), and thus affect water supplies.

Table 1.2. Likely changes in winter and summer rainfall and temperature in the Bristol region, compared with the 1961 – 1990 average, based on the UKCP09 climate change scenarios. Low emissions: a decrease in the rate of greenhouse gas emissions. Medium emissions: the same rate of emission of greenhouse gases as at present. High emissions: four times increase over the current rate of greenhouse gas emissions. Data taken from Afzal and Ragab (2019).

	Time period	Low emissions		Medium emissions		High emissions	
		Winter	Summer	Winter	Summer	Winter	Summer
Change in precipitation (%)	2020s	4.7	-6.7	5.7	-7.52	6.1	-8.16
	2050s	10.3	-9.5	17.24	-14	15.7	-20
	2080s	17.3	-15.7	22.1	-20	23	-28
Change in temperature (°C)	2020s	1.1	1.61	1.27	1.72	1.3	1.5
	2050s	1.7	2.32	1.89	2.4	1.9	3
	2080s	2.1	3.08	2.6	3.6	3	4.5

1.5 Field Experiment

A field experiment was set up at two sites in each of three river catchments (R. Frome, R. Don and R. Eden). Rainfall shelters (mesocosms) were used to reduce incident rainfall by around 50%. This figure was chosen to simulate the reduction in summer rainfall predicted for Central England in the 2050s if global emissions of greenhouses gases rise to four-times 2009 levels (UKCP09, Met Office 2018, https://catalogue.ceda.ac.uk/uuid/077fd790439c44b99962552af8d37a22) and to reflect the conditions that were used in a parallel mesocosm study of arable crops conducted at Harper Adams University (Grove and Monaghan, 2019). In the study at Harper Adams University, summer rainfall (received by plots within a polytunnel) was reduced by 38%. The grassland field experiment used open-sided shelters located in fields; therefore to allow for some rainfall entering the plots from the side, we reduced incident rainfall by 50%.

The experiment incorporated a study, into the effect of the rainfall shelter itself on the microclimate and growth of the pasture. This study, of the impact of the rainfall shelter on microclimate, was carried out across all three catchments (Don, Eden and Frome) by Dr J. Thompson (UK CEH Edinburgh) and will be reported separately.

The experiment had four aims:

A: Better understanding of how drought might affect UK grasslands

B: Engage local people in drought science (volunteers/ citizen science)

C: Provide a focus for engagement activities

D: Deliver detailed information that could contribute to future hydrological models

Part A Better understanding of how drought might affect UK grasslands

Chapter 2 Methods

2.1 Site selection

We selected two sites in the R. Frome catchment, University of the West of England (UWE) and Oldwood Pit (OWP) (Figure 2.1). The two sites were selected to represent the typical permanent pastures of the region. The sites chosen had to be accessible so that we could make regular visits, but safe from vandals.

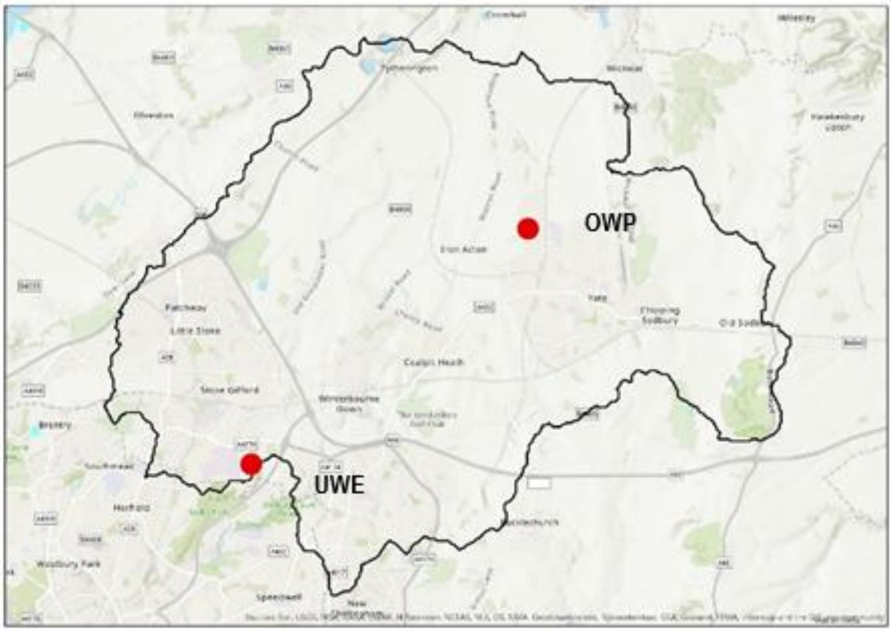


Figure 2.1. Location of DRY project field sites in the R. Frome catchment. Image curtesy H. West (UWE).

2.1.1 *University of the West of England (UWE)*

The UWE site is located between the University of West of England Frenchay campus and the M32 motorway (Grid ref ST629778) in the south of the catchment, close to the Frenchay gauging station. The site is about 135 m AOD and slopes gently towards the northeast and the R. Frome. The soil is a Worcester series gleyed brown earth (Chromic vertic luvisol) (Cranfield University, 2021) developed over Mercia mudstone (Findlay, 1976). The field lies within UK soil scape 8 (Cranfield University, 2021) and is in an area of grade 1 and 2 soils. The field, at one time, was used for arable crops but has been grassland, grazed by sheep or cattle, with minimal artificial inputs for at least thirty years; in the four years preceding the start of this work the field had been cut for hay in late September.

The vegetation at UWE (Figure 2.2) is dominated by *Arrhenatherum elatius* (L.) (False oat grass), *Holcus lanatus* (L.) (Yorkshire fog) and *Dactylis glomerata* (L.) (Cocksfoot) with *Cirsium arvense* (L.) (Creeping thistle) and *Heracleum sphondylium* (L.) (Hogweed), *Leucanthemum vulgare* (Ox-eye daisy) *and Rumex* (L.) *spp.* (Docks). There are also less common species such as *Lathyrus nissolia* (L.) (Grass vetchling), and the orchids (*Dactylorhiza fuchsii* ((Druce) Vermeul.), *Dactylorhiza praetermissa* ((Druce) Vermeul.), and *Ophrys apifera* (Huds.)). Plant nomenclature follows Stace (2014).

2.1.2 *Oldwood Pit (OWP)*

The OWP site is a few miles outside Yate (Grid ref ST699853), in the north of the catchment, close to the headwaters of the R. Frome. The site is at 65 m AOD and more or less level. The site lies within the North Bristol coalfield geological area. The soil is a Dale series surface water gley (Findlay, 1976), (Clayic eutric stagnosol (Cranfield University, 2021)), within UK soil scape 17 (Cranfield University, 2021). The site is species-rich permanent pasture that is managed either by grazing during spring and summer with sheep, or for a hay cut in early July, followed by late summer/autumn sheep grazing. The site has received no fertilizer or herbicide since at least 1960 and probably not since before the Second World War.

The pasture (Figure 2.2) contains *Holcus lanatus* (L.) (Yorkshire fog), *Agrostis capillaris* (common bent), *Festuca rubra* (L.) (Red fescue) and *Lolium perenne* (L.) (Rye), as well as numerous nitrogen fixing species such as *Trifolium repens* (L.) and *T. pratense* (L.) (Clover) and *Lotus corniculatus* (L.) (Birdsfoot trefoil). The site has some uncommon plant species, including *Ophioglossum vulgatum* (L.) (Adder's tongue fern) and *Dactylorhiza fuchsii* ((Druce) Vermeul.) (Common spotted orchid).

	
UWE with *Arrhenatherum elatius* in foreground	OWP with *Ranunculus acris and R. repens*

Figure 2.2. Vegetation at the two field sites in the R. Frome catchment.

2.2 Vegetation management

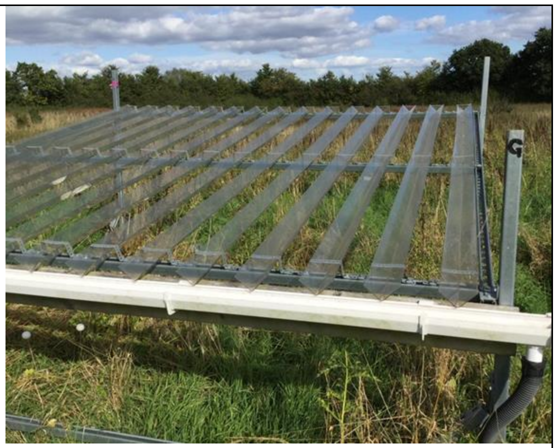
We needed to be confident that any changes that we observed were due to the imposed rainfall reduction treatment, and not to changes in management as a result of the experimental set up. Within the experimental plots at each site, we approximated the existing vegetation management regime by cutting the vegetation, with hand shears, to 1-2 cm above ground level and removing the arisings (Figure 2.3). In October 2015, when the experiment started, all plots were cut to ensure that samples collected in subsequent years only represented the current year of growth. At UWE, plots were cut each year in late September/ early October to simulate autumn mowing. At OWP, plots were cut each year in late June/ early July to simulate a hay cut, and again in late September/early October to simulate early autumn grazing. Plots were cut block by block (see Experimental design) to ensure any differences due to date of cutting were distributed across all treatments.

Figure 2.3. A partly cut Control plot at OWP. Note rain gauge in bottom right-hand corner, blue circle is an Adcon (used to measure soil moisture content), coloured markers indicate where samples have been taken.

2.3 Experimental design

At each site, fifteen 3 m x 3 m plots, arranged in three replicate blocks were set out. Within each block there were two reduced rainfall (RR) plots, consisting of metal frames (3 m x 3 m square, 1 m from the ground at the front and 1.5 m from the ground at the back). These supported V-shaped transparent gutters that intercepted approximately 50% of the rainfall (Figure 2.4 A and B). One plot in each block had a similar frame and roof, but the gutters were inverted to allow rainfall to pass through. This roof control (RC) plot was part of a study of the effect of the frame and roof on microclimate and plant growth (unpublished data). Two plots in each block were Control plots with ambient conditions, no metal frame or roof. Intercepted rainfall flowed into PVC house roof gutters and plastic pipes carried intercepted rainfall away from the plots. The rainfall shelter design was a variation of Yahdjian and Sala (2002). The gutters were made from PEGT. PEGT is Polyethylene Terephthalate (PET) with the addition of ethylene glycol. PEGT is transparent, flexible and can easily be moulded into V-shapes that are less likely to fracture than V-shapes made from acrylic. The plots and frames were at least three meters apart. Figure 2.4 C shows an aerial view of the UWE field site.

A Metal frames at UWE before roofs fitted



B Reduced Rainfall Plot at UWE showing metal frame and ‘V’-shaped gutters

C Aerial view of UWE field site (copyright Google maps)

Figure 2.4. Views of the rainfall shelters used in the DRY project field experiment. A UWE frame before roof fitted. B UWE, frame with ‘V’-shaped gutters. C aerial view of UWE site.

The frames were put in place during April of 2015 and the roofs installed on 19/20 October 2015 at OWP and 21/22 October 2015 at UWE. The experiment ran until October 2018; thus, we had three full growing seasons and three hydrological years (2015/2016, 2016/2017 and 2017/2018).

Within each (3 m x 3 m) plot, a 2 m x 2 m plot was marked out. A 0.5 m buffer strip surrounded this plot. The 2 m x 2 m plot was divided into four 1 m x 1 m subplots (Figure 2.5). One 1 m x 1 m subplot in each plot was randomly assigned for biomass sampling, one for soil sampling, one for measurement of plant species presence and vegetation cover and another was used to locate the rain gauge and for access to the other subplots.

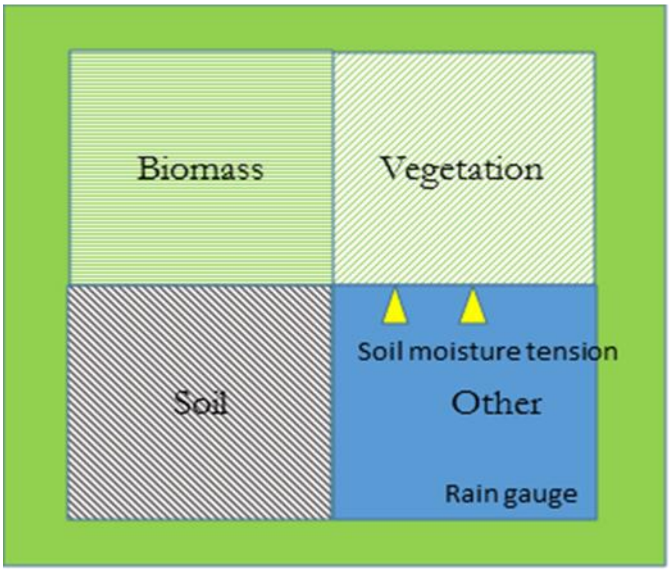


Figure 2.5. Division of each plot into sub-plots

The plots were not hydrologically isolated; lateral movement of water within the soil would have been possible. Experimental plots can be isolated, from the surrounding soil, by trenching but this can cause damage to the adjoining vegetation and influence hydrology within the trenched area (Beier et al., 2012). We needed to return the fields to the landowners in the same or better condition after the experiment had finished. This precluded use of trenching.

2.4 Environmental monitoring

2.4.1 *Data loggers*

At both sites, automatic weather stations, connected to data loggers (Campbell Scientific, Loughborough, UK; Table 2.1) with mobile telephone data uplift, recorded environmental conditions. There were three data loggers at each site, one for each experimental block. The weather stations recorded data every 30 minutes. Data were sent automatically to UK Centre for Ecology & Hydrology (UK CEH), Wallingford; and stored on a database. If the mobile telephone signal was interrupted, data could be manually downloaded from the data loggers. The data loggers were powered by batteries that were charged by solar panels.

2.4.2 *Rainfall*

There were eight rain gauges (Table 2.1) at UWE and eight at OWP. At each site, there was one rain gauge in each of three of the six Control plots, one in three of the six RR plots, and one in two of the three RC plots. At OWP, one rain gauge in a Control plot failed to record. Replicate rain gauges allowed us to calculate average rainfall at each site, and gave us within site quality control. The under-roof rain gauges allowed an estimate of the rainfall reduction by the roofs.

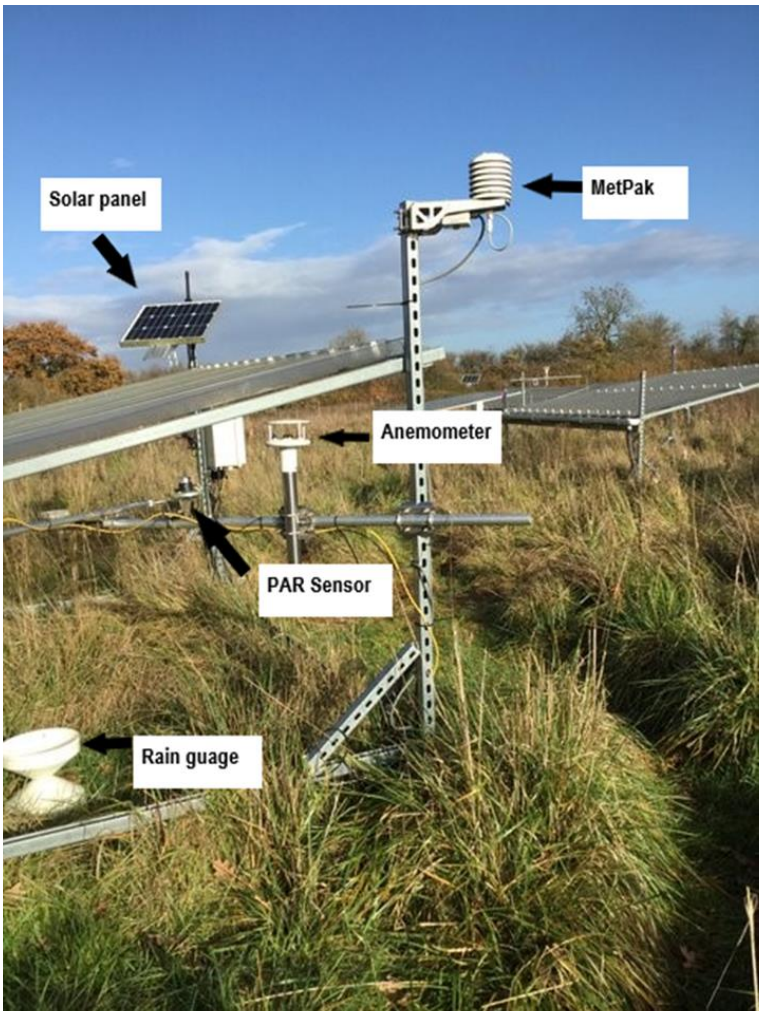


Figure 2.6. View of rainfall shelter at UWE showing environmental monitoring equipment.

2.4.3 *Soil moisture and soil temperature*.

Soil moisture tension and soil temperature were measured using Decagon MP6 ceramic sensors (Table 2.1) installed horizontally, at 5 cm and 10 cm depth, near the centre of the 2 m x 2 m plots, with the sensor head towards the 1 m x 1 m vegetation monitoring sub-plot. Soil moisture content (%) was measured, at 10 cm intervals, between 10 cm and 90 cm depth using Adcon SM1 Soil Moisture Sensors (Table 2.1) installed close to the centre of the 2 m x 2 m vegetation plots. Data about soil moisture and soil temperature were recorded from three Control plots, six RR plots and three RC plots at each site.

2.4.4 *Radiation.*

Photosynthetically active radiation (PAR) was measured using Licor PAR sensors (Table 2.1, Figure 2.6). At UWE, one sensor was mounted above and one sensor was mounted underneath the roof on one RR shelter and one RC shelter. At OWP, one sensor was mounted above and one sensor was mounted underneath the roof on two RR shelters. Net radiation was measured using NR Lite2 Net Radiometers (Table 2.1). At both sites, one Net

Radiometer was mounted underneath the roof of one RR shelter and one was mounted outside.

2.4.5. *Air temperature, relative humidity, wind speed and wind.*

Air temperature, relative humidity, wind speed and wind direction were recorded using a MetPak base station (Table 2.1, Figure 2.6) attached to the shelter frame. There were two MetPak base stations at each site, each in a different block. We wanted to compare environmental conditions outside the rainfall shelters, under the roof of the reduced rainfall (RR) shelters and under the roof of the RC (gutters inverted to allow rain to pass through) shelters. At UWE, air temperature and relative humidly were recorded outside one RR shelter and under one RC shelter; wind speed and direction were recorded under one RR shelter and outside one RC shelter. At OWP, measurements were made under the roof or outside each of two RR shelters.

2.4.6. *i-buttons.*

In March 2016, i-buttons mounted on wooden posts were placed, at about 50 cm above ground, in each plot. These recorded air temperature and relative humidity once each hour. Data from these instruments were collated and sent to UK CEH Edinburgh for analysis.

Table 2.1. Details of environmental monitoring instruments at the Frome field sites.

Environmental monitoring equipment at DRY project field sites			
Environmental parameter	**Instrument**	**Manufacturer**	**Manufacturer location**
Precipitation	ARG100 aerodynamic precipitation sensor (tipping bucket rain gauge)	Campbell Scientific	Loughborough, UK
Net radiation	NR Lite2 Net Radiometer	Kipp and Zonen Ltd	Delft, The Netherlands
Photosynthetically active radiation	Li Cor Quantum Sensor	LI-COR Biosciences	Lincoln, USA
Relative humidity	MetPak Base Station Rotronic Hygroclip HC2-S3 temperature/humidity probe	Gill Instruments Limited	Lymington, UK
Air temperature			
Wind speed and direction	Gill WindSonic		
Soil moisture tension	MPS-6 Calibrated water potential sensor	Decagon Devices, Inc	Pullman, USA
Soil moisture content	ADCON SM1 Soil Moisture Sensor	OTT Hydrometry	Sheffield, UK
Data logger	CR-1000 or CR-500	Campbell Scientific	Loughborough, UK
Air temperature and relative humidity	i-buttons	Thermochron Ltd	Baulkham Hills, NSW 2153, Australia

2.5 Biomass sampling

Above-ground dry matter production was assessed by biomass sampling. A randomly selected strip of vegetation (50 cm x 10 cm) was cut, as close to the ground surface as possible, within the subplot that had been assigned for biomass sampling. On each occasion, one sample was taken from each biomass sample subplot. The samples were collected block by block, to ensure any differences due to day of sampling were distributed across all treatments. Cut vegetation was immediately placed in a large plastic bag in a cool box. Samples were stored in a refrigerator at 4°C for not more than two days before processing. The cut vegetation was sorted into all dead plant material, and live vegetation of different functional types including graminoid (grasses, rushes and sedges), broadleaved plants, pteridophytes, bryophytes and woody material. After sorting, the different types of vegetation were dried at 60-80 °C for at least 4 days and then again for 24 hours before weighing.

Biomass samples were collected just before vegetation in the plots was cut. The sampling regime reflected the management regime in place at each site. At UWE, biomass samples were collected in autumn (late September/ early October) of 2015, 2016, 2017 and 2018 and in summer (early July) 2018. At OWP, biomass samples were collected in autumn (late September/early October) of 2015, 2016, 2017, and 2018 and summer (late June/early July) of 2016, 2017 and 2018. Table 2.2 gives full details of site management and biomass sampling dates.

Table 2.2. Dates of biomass sampling and vegetation cutting at DRY project field sites OWP (Oldwood Pits) and UWE (University of the West of England). All activities were carried out by hand and whilst kneeling on wooden boards placed either outside the plot or (when entry to the plot was unavoidable) in the 'other' sub-plot to avoid crushing the vegetation or compacting the soil. On each occasion, complete blocks were sampled or cut to ensure that equal numbers of plots from each treatment were cut on each occasion.

Site	**OWP**		**UWE**	
Activity	**Biomass sampling**	**Vegetation cutting**	**Biomass sampling**	**Vegetation cutting**
Calendar Year				
2015	21 and 28 September	16/17 November	4 and 6 October	21 October
2016	5 and 11 July	13/14 July		
	4 and 10 October	7 and 14 November	26 September and 2 October	17 October
2017	3 and 5 July	10/11/12 July		
	9 and 11 October	18 October	2 and 4 October	16 October
2018	2/3 July	10 and 12 July	25/26 June	
	8 October		1/2/October	

2.6 Plant species composition

Within each 1 m x 1 m sub-plot designated for vegetation monitoring, the plant species present, and the amount of ground surface covered by each species (estimated to the nearest 5%), were recorded at regular intervals throughout the experimental period. These data were augmented by detailed observations made within a 0.5 m x 0.5 m quadrat (sub-divided into 25 10 cm x 10 cm squares) placed at the innermost (central) corner of the sub-plot. At UWE, the vegetation was very tall (above 1.5 m in places) and this precluded using the 0.5 m x 0.5 m quadrat except in early spring when the vegetation was short. Table 2.3 gives details of the dates and types of recording made.

Table 2.3. Dates and procedure followed to assess plant species composition

Calendar Year	Site	Date	Type of survey
2015	University of the West of England (UWE)	June 2015	1 m x 1 m as 100 squares Plant species ID and % cover
		July 2015	Columns Plant species ID and % cover
		September 2015	0.5 m x 0.5 m quadrat as 25 squares Plant species ID and % cover
	Oldwood Pits (OWP)	July 2015	Columns Plant species ID and % cover
		September 2015	0.5 m x 0.5 m quadrat as 25 squares Plant species ID and % cover
2016	UWE	February 2016	0.5 m x 0.5m quadrat as 25 squares Bryophyte species ID and % cover
		May 2016	1 m x 1 m Plant species ID and % cover
		June 2016	1 m x 1 m Plant species ID and % cover
		September 2016	1m x 1 m Plant species ID and % cover
	OWP	February 2016	0.5 m x 0.5 m quadrat as 25 squares Bryophytes species ID and % cover
		May 2016	1 m x 1 m Plant species ID and % cover
		June 2016	0.5 m x 0.5 m quadrat as 25 squares Plant species ID and % cover
		September 2016	1 m x 1 m Plant species ID and % cover
2017	UWE	February 2017	0.5 m x 0.5 m quadrat as 25 squares Bryophyte species ID and % cover
		May 2017	Veg survey practice
		June 2017	1 m x 1 m

			Plant species ID and % cover
		September 2017	1 m x 1 m Plant species ID and % cover
	OWP	March 2017	0.5 m x 0.5 m quadrat as 25 squares Bryophyte species ID and % cover
		May 2017	1 m x 1 m Plant species ID and % cover
		June 2017	1 m x 1 m Plant species ID and % cover
		September 2017	1 m x 1 m Plant species ID and % cover
		September 2017	0.5 m x 0.5 m quadrat as 25 squares Plant species ID and % cover
2018	UWE	March 2018	0.5 m x 0.5 m quadrat as 25 squares Bryophyte species ID and % cover
		May 2018	0.5 m x 0.5 m quadrat as 25 squares Plant species ID and % cover
		June 2018	1 m x 1 m Plant species ID and % cover
		June 2018	1 m x 1 m Grass species ID and % cover
		September 2018	1 m x 1 m Plant species ID and % cover
	OWP	March 2018	0.5 m x 0.5 m quadrat as 25 squares Bryophyte species ID and % cover
		June 2018	1 m x 1 m Plant species ID and % cover
		June 2018	0.5 m x 0.5 m quadrat as 25 squares Plant species ID and % cover
		June 2018	1 m x 1 m Grass species ID and % cover
		September 2018	1 m x 1 m Plant species ID and % cover
		September / October 2018	0.5 m x 0.5 m quadrat as 25 squares Plant species ID and % cover

2.7 Measurement of plant height

Plant height can be strongly affected by water shortages because the rate of cell expansion depends on an adequate supply of water not just to maintain the turgor of the plant cells but also to ensure that biochemical processes within the plant cells take place at maximum rates. It is relatively straight forward to identify the tallest plant in a small area. The average vegetation height can, however, be difficult to measure; particularly if the vegetation is composed of several different species or if, as in this case, it is not possible to mark individual plants because the vegetation will be cut and removed. If measurements need to be made repeatedly over long periods, to avoid damage caused during the measurement process influencing subsequent measurements, it may only be possible to measure maximum heights.

Three types of measurement were made: the maximum effective height of selected species, the maximum height at pre-selected random points and the tallest individual plant. These measurements were made on vegetation in the soil sub-plot, to avoid damage to the biomass and vegetation monitoring sub-plots.

2.7.1 *Maximum effective height of selected plant species*

The maximum effective height of selected species was measured, using a steel tape measure, in a strip about 25 cm wide around the outside two edges of the soil sub-plot (Figure 2.7). The strips were located 10 cm in from the outside edge of the subplot. The maximum effective height is the maximum height above ground level of the plants without straightening the plant. Climbing or sprawling plants such as *Convolvulus arvensis* (field bindweed) or *Vicia tetrasperma* and *V. hirsuta* (tares) may have stems several meters long but their effective height will be limited by the height of the surrounding vegetation. Species were selected from those identified in the vegetation composition surveys from 2015 on the basis of frequency of occurrence and ease of identification, and included plants from different functional groups. Different plant species were selected at each of the two sites, but particular attention was given to *Holcus lanatus* (L.) (Yorkshire fog) because it was frequent at both UWE and OWP, and also occurred at the DRY project field sites in the Don and Eden catchments.

At UWE, volunteers/citizen scientists helped to develop the protocol for these measurements, and helped with the data collection. At UWE, initially only five species were monitored for plant height but after October/ November 2017 additional species were introduced. This was in response to observations that some abundant species were not included, and a desire on the part of the volunteers working on the experiment to extend their plant identification skills.

The plant species measured at UWE are listed in Table 2.4 and those measured at OWP in Table 2.5.

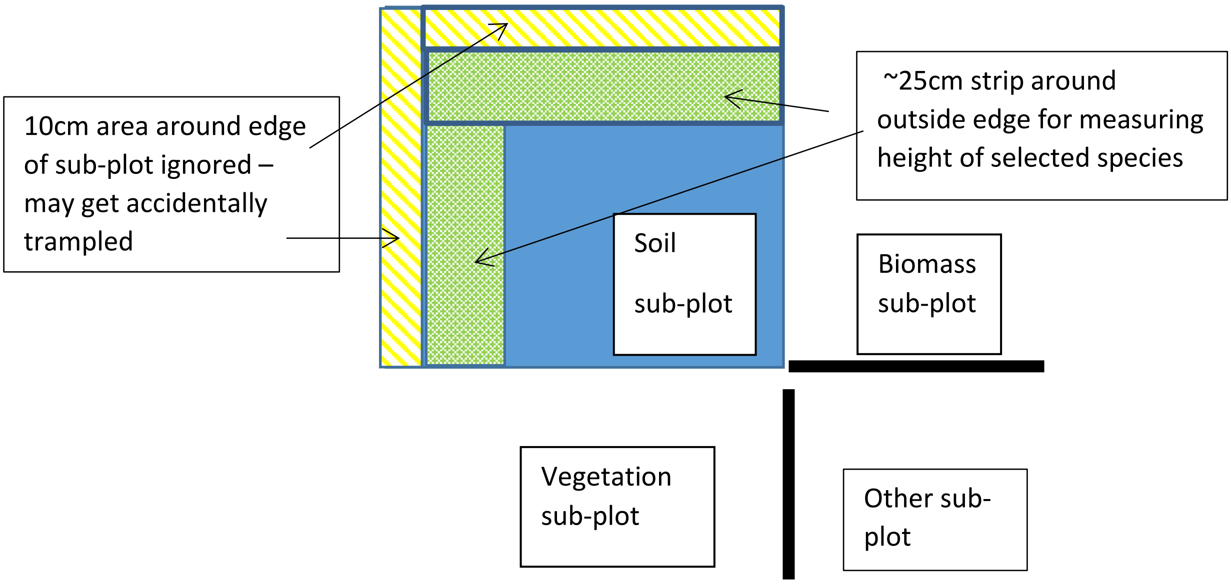


Figure 2.7. Selection of area from which to measure maximum effective plant height

Table 2.4. Plant species and type of plant whose maximum effective height was recorded at UWE.

Plant Species	**Plant common name**	**Type-of plant (functional group)**	**Notes**
Holcus lanatus	Yorkshire fog	grass	From March 2016 to November 2018
Vicia tetrasperma, V. hirsuta,	Tares	Legume, annual	
Equisetum arvensis	Field horsetail	pteridophyte	
Rumex acetosa	Common sorrel	Tap-rooted perennial	
Ranunculus repens	Creeping buttercup	Adventitious rooted perennial	
Festuca arundinacea	Tall fescue	Tall grass	From Oct 2017 to November 2018
Dactylis glomerata	Cocksfoot	Tussock forming grass	
Cirsium arvense	Creeping thistle	Adventitious rooted flowering plant	
Festuca rubra	Red fescue	Short fine-leaved grass	From Nov 2017 to November 2018
Rumex spp	Other docks	Tap-rooted perennial	
Heracleum spondylium	Hogweed	Tap rooted biennial	
Cerastium fontanum	Common mouse-ear	annual	
Epilobium spp	Willowherbs	annual	
Leucanthemum vulgare	Ox-eye daisy	biennial	
Geranium spp.	Geranium species	annual	
Taraxacum agg	Dandelion	Tap rooted perennial	
Convolvulus arvensis	Field bindweed	climber	

Table 2.5. Plant species and type of plant whose maximum effective height was recorded at OWP.

Plant Species	**Plant common name**	**Type-of plant (functional group)**	**Notes**
Holcus lanatus	Yorkshire fog	Perennial grass	From January 2017 to November 2018
Lolium perenne	Rye grass	Perennial grass	
Dactylis glomerata	Cocksfoot	Tussock forming grass	
Festuca rubra	Red fescue	Short fine-leaved grass	
Rumex acetosa	Common sorrel	Tap-rooted perennial	
Ranunculus repens	Creeping buttercup	Adventitious rooted perennial	
Ranunculus acris	Meadow buttercup	Erect perennial	
Luzula campestris	Field woodrush		
Cirsium arvense	Creeping thistle	Creeping perennial	
Cirsium palustre	Marsh thistle	Erect biennial	
Cirsium vulgare	Spear thistle	Erect biennial	
Potentilla anserina	Silverweed	Creeping perennial	
Trifolium pratense	Red clover	Hairy perennial, nitrogen fixing	
Trifolium repens	White clover	Creeping rooting perennial, nitrogen fixing	
Lotus corniculatus	Birdsfoot trefoil	Low creeping perennial, nitrogen fixing	

2.7.2 *Height and plant identity at pre-determined random points*

Five points, within the soil sub-plot, were selected randomly. At each of these points, the height and identity of the tallest plant was recorded. These measurements gave an indication of the average maximum height of the vegetation.

2.7.3 *Height of tallest individual plant*

The maximum height and identity of the tallest individual in the plot was recorded. The plants were held upright, to ensure that we recorded the maximum height measured using a steel rule held vertically. This allowed us to have a record of the tallest species within our sward. In many instances, these plants were species of grass that are more difficult to identify in their vegetative state than those selected for regular measurement. At OWP, because a larger number of different species were being monitored for maximum effective height than at UWE, these measurements were only made in 2018.

Measurement of plant height started at UWE in spring 2016 and at OWP in spring 2017. At both sites, measurements were made fortnightly except when weather conditions or other field tasks did not permit. At UWE, we had assistance from volunteer citizen scientists and have more records from this site. If time was short, or in bad weather, priority was given to measurement of the maximum effective height of selected species.

2.8 Numbers of flowers and pollinators

In each of the plots, within the vegetation sub-plot, the number of flowers of each species were recorded. A plant was said to be in flower if the anthers were visible. For species that have flowers in small groups, such as *Vicia* spp., each group was counted as one flower, for umbellifers each umbel was counted, for *Compositae*, each flowering head was counted as one flower, and for species such as *Rumex* spp. that have an inflorescence made up of several branches, each branch that had open flowers was counted. If the plant species could not be identified in the field, it was photographed and identified later, and a brief description written on the data sheet. If flowers were present, the sub-plot was observed for 5 minutes and the numbers of pollinators visiting each type of flower recorded. The pollinators were divided into bumble bees, honeybees and solitary bees, hoverflies and other flies, beetles, butterflies and moths, wasps, and other (spiders, crickets etc.). This method was chosen because it was one that had been published by the charity Buglife. Buglife published an easy to use identification guide (Figure 2.8) and we were able to contribute data to their national survey. An example data recording sheet is shown below (Table 2.4).

Table 2.4. Example recording sheet for flowers and pollinators.

Count the number of flowers of each type

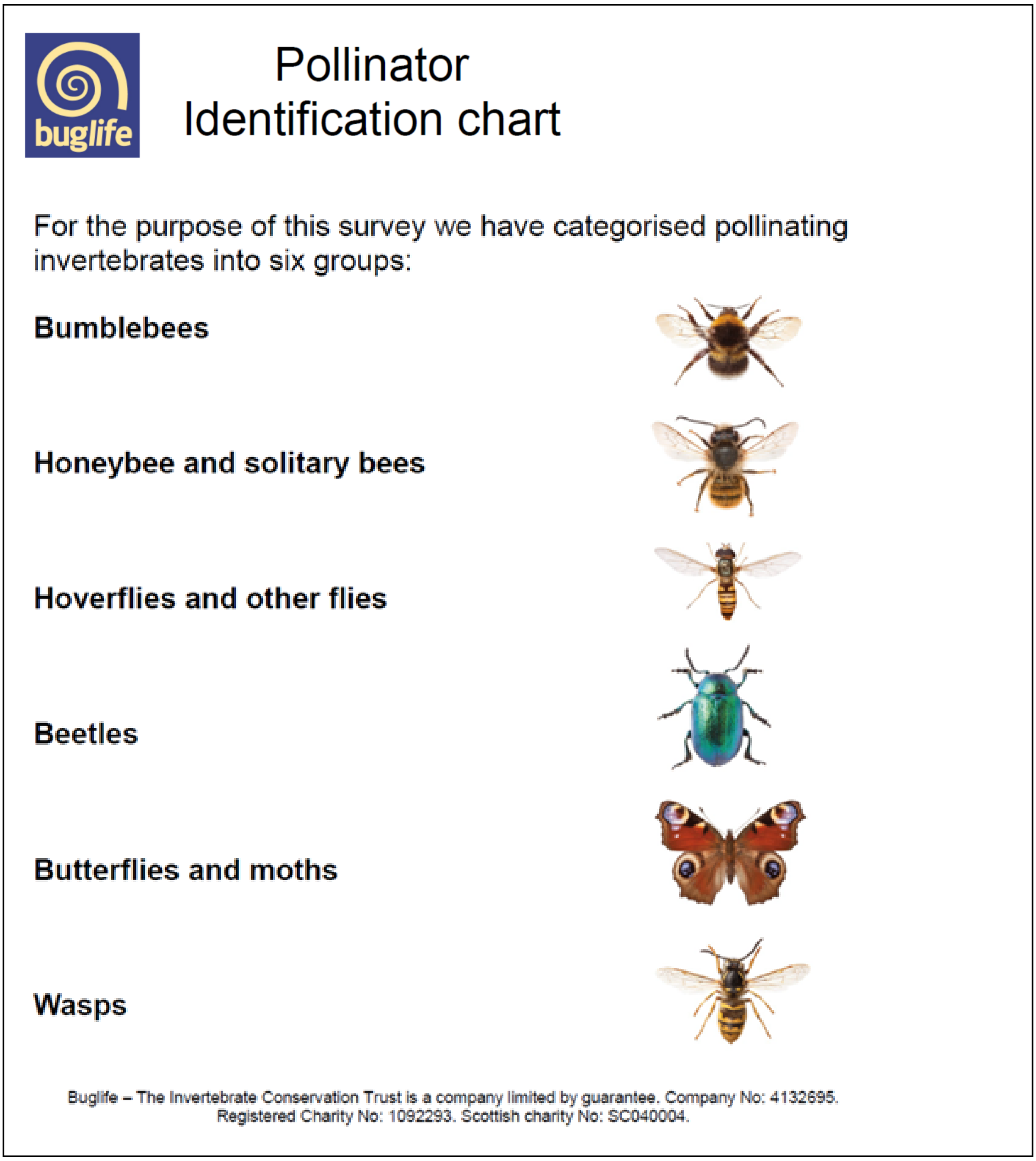
Assign the pollinators to one of the six groups on your chart, record as other if it does not fit any of these groups.

Record the type of flower that the pollinator visits.

Please use 5-bar gates to tally the observations.

Site Plot Date Time Weather Recorder

Flowers		Pollinators							
Type	No.	Bumblebees	Honey and solitary	Flies and hoverflies	beetles	Butterflies and moths	wasps	other	Total
Yellow daisy *Senecio jacobaea*	5	III	I	~~IIII~~		I	I		10
Mauve pea *Vicia sativa*	2	I	III	I	I			I	7
Grass *Holcus lanatus*	25		II	IIII	~~IIII~~				10
Small white *Cerastium fontanum*	3	III				II			5
Totals	35	7	6	9	5	3	1	1	32


buglife

Pollinator
Identification chart

For the purpose of this survey we have categorised pollinating invertebrates into six groups:

Bumblebees

Honeybee and solitary bees

Hoverflies and other flies

Beetles

Butterflies and moths

Wasps

Buglife – The Invertebrate Conservation Trust is a company limited by guarantee. Company No: 4132695.
Registered Charity No: 1092293. Scottish charity No: SC040004.

Figure 2.8. Front page of the Buglife pollinator identification guide.

2.9 Soil

2.9.1 *Soil Series identification*

At each site, soil cores were taken to 1 meter depth or bedrock. The cores were photographed before being taken back to the laboratory where they were compared with the descriptions given in the Soil Survey Monographs, for the locality, for the series shown on the soils map of the UK as likely to be present. After identification, the cores were chilled and sent to UK CEH Edinburgh for storage.

2.9.2 *Soil Properties*

Soil samples were collected from each plot at the start and finish of the experiment. Three samples were taken, using a 30 mm diameter soil corer, at randomly selected locations within the 1 m x 1 m sub-plot designated for soil sampling. Care was taken to ensure that samples were taken more than 12.5 cm away from the top of the Adcon, to avoid sampling affecting the measurement of soil moisture content. The samples were divided into soil 0 - 100 mm deep and soil 100 - 150 mm deep; for each depth, the three samples were combined. The samples were chilled in a fridge and then sent to UK CEH Edinburgh where they were frozen until they could be analysed.

2.10 Data preparation and statistical analysis

Data on environmental variables, biomass, plant species composition, plant height and numbers of flowers and pollinators from each field site (UWE and OWP) in the Frome catchment were analysed separately, because the vegetation management and sampling regime at the two sites was different.

2.10.1 *Environmental data*

Environmental data (rainfall, soil moisture (tension and content), air temperature, soil temperature and photosynthetically active radiation) were collated and summarised using Excel 2016 (Microsoft Corp., Redmond, USA). Data for days with incomplete records, resulting from equipment failure, were excluded.

Rainfall

At each site (OWP and UWE), the rain gauges recorded incident rainfall from July 2015 to October 2015. The average rainfall for each day during this period was calculated, for each site (OWP and UWE), and the rainfall recorded by each individual rain gauge was compared to the average to check the calibration and function of the rain gauges. The slope of the fitted line between daily rainfall recorded by each individual rain gauge and average daily rainfall was between 0.96 and 1.04 with a correlation (R^2) of 0.99. This meant that if, for technical reasons, one rain gauge was not working we could extrapolate, with confidence, from the neighbouring gauge to fill in the missing data. Values of daily rainfall were calculated, for Control, RR and RC plots at each site, by averaging the amount of rainfall recorded, each day, by each rain gauge across each treatment.

Soil Moisture

Soil moisture tension gives an indication of the amount of work that a plant needs to do to acquire water. Water in a soil can be freely available, available, slightly available or unavailable to plants; these amounts are different for every soil and depend on the water holding properties (texture and structure) of the soil. Freely available water can be defined as that when the soil moisture tension is less (more positive) than -59 kPa (Berglund, 2020). We calculated, for each plot, the number of days per month when average soil moisture tension was between 0 and -59 kPa (Ayling et al., 2021), and soil water was freely available for uptake by plants. We used these numbers to calculate an average across Control or RR plots.

Soil moisture content (%) (Adcon SM1 Soil Moisture Sensors) recorded by each sensor was averaged for each day. These daily average values were used to estimate monthly average soil moisture content for Control and RR plots at each site and for within site data quality control. Data about soil moisture content at 10 cm, 50 cm and 90 cm are presented here.

Air and Soil temperature

Daily average air temperature was calculated from the daily maximum and daily minimum air temperature (Kendon et al., 2019). Daily average soil temperature at 10 cm was calculated from the daily maximum and daily minimum soil temperature recorded by the MP6 Decagon sensors. These daily values were used to calculate monthly averages.

Photosynthetically active radiation (PAR)

PAR changes throughout the day and is lower in winter when, in UK, daylight hours are shorter and the angle of the sun's rays lower. We calculated the average midday PAR value, between 11:00 and 13:30 for each day.

2.10.2 *Vegetation biomass data*

Vegetation biomass data were analysed using univariate general linear models in the statistical package SPSS26 (IBM, Armonk, USA): treatment and time of year were fixed factors, year was a random factor.

2.10.3 *Plant species composition and % cover*

Data about plant species composition and % cover were analysed using Canonical Correspondence Analyses at an individual site level. (These analyses were done by Dr Alan Gray at UK CEH Edinburgh).

2.10.4 *Plant height and Numbers of flowers and pollinators*

Data collected about plant height, numbers of flowers and numbers of pollinators were collated and summarised using Excel 2016 (Microsoft Corp., Redmond, USA). Data about maximum effective height, for each species, were used to calculate the median value for each treatment (across all plots), for each date when plants were measured. Data about the height of plants at random points, from all plots within each treatment, were combined for each occasion and used to calculate the average maximum height.

Chapter 3 Results and Discussion

3.1 Environmental Data

3.1.1 Rainfall

At UWE, total rainfall for the year (1 October to 30 September), in Control plots, in 2015/16 was 979.1 mm, in 2016/17 749.0 mm and in 2017/18 782.4 mm (Figure 3.1). At OWP, equivalent totals were 990.5 mm, 756.6 mm and 771.2 mm (Figure 3.2). The 1961 to 2017 average for the Frome catchment, for year 1 October to 30 September, is 816 mm (National River Flow Archive). There was no statistically significant difference between monthly total rainfall recorded, in Control plots, at UWE and at OWP (P=0.95, t-test). Total rainfall recorded in Control plots between November 2015 and October 2018 was 2508 mm at UWE and 2506 mm at OWP. Over the three years of this study, rainfall recorded in the RR plots at UWE was 52% of that in the Control plots and at OWP, 48% (Figures 3.1 and 3.2). When compared to the long-term average for 1961-2017, rainfall recorded ranged from 44 % in the OWP RR treatment in 2016/17 to 120% for the UWE Control plots in 2015/2016 (Table 3.1).

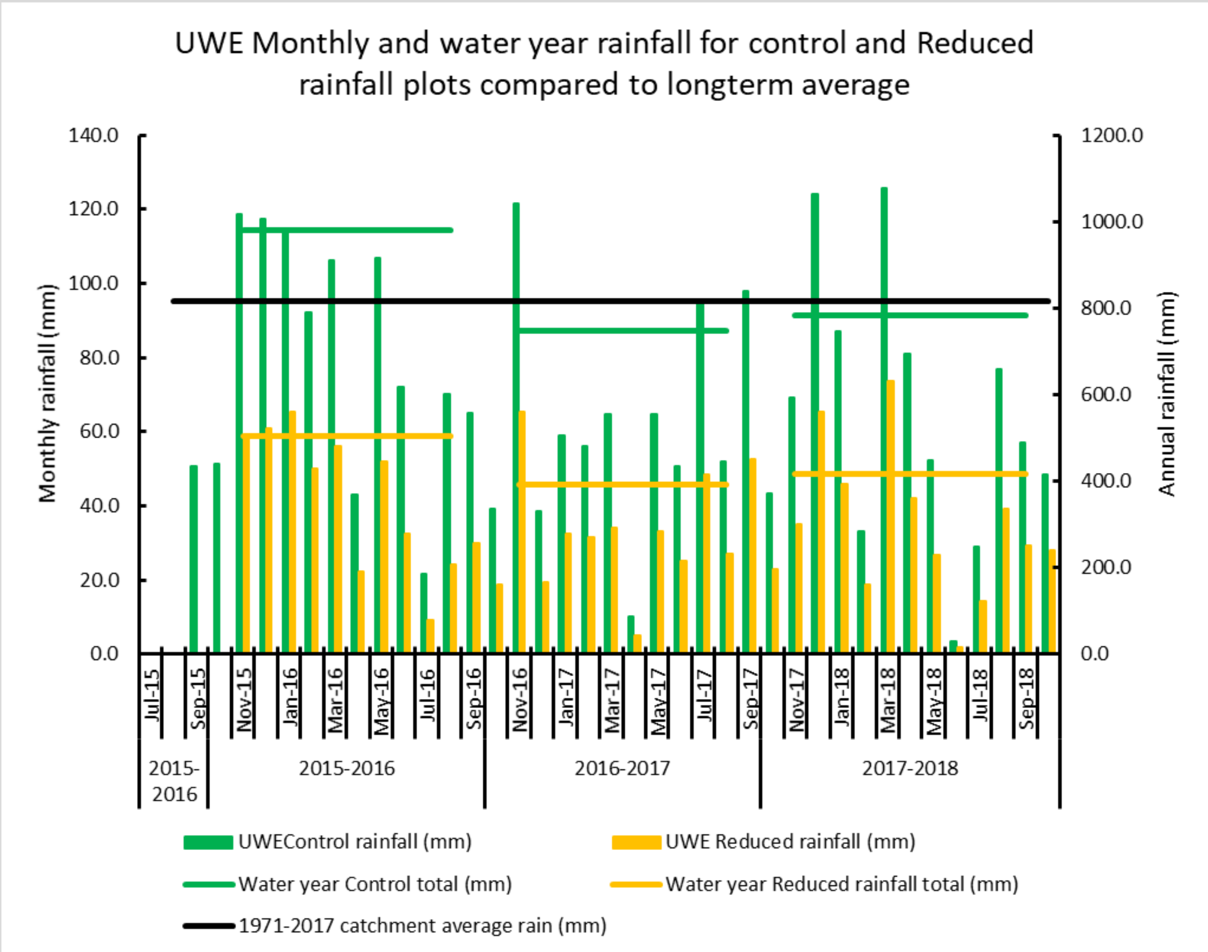


Figure 3.1. Monthly, water year and long-term catchment average rainfall for Control and reduced rainfall plots at UWE.

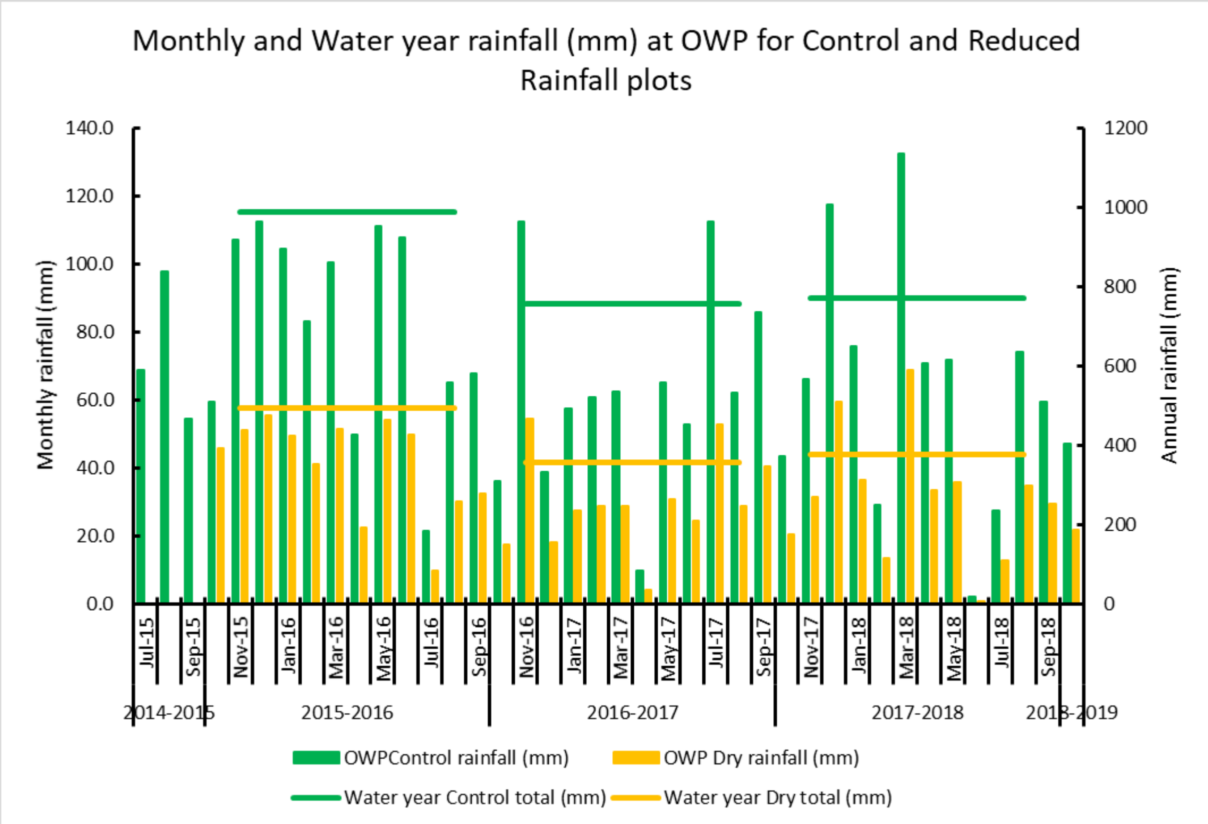


Figure 3.2. Monthly and water year rainfall for Control and reduced rainfall plots at OWP.

Table 3.1. Rainfall in each year (1 October to 30 September) for Control and RR treatment at UWE and OWP as percentage of catchment 1961- 2017 average.

Rainfall Year	Control rainfall OWP %	Control rainfall UWE %	Reduced rainfall OWP %	Reduced rainfall UWE %
2015-2016	121	120	61	62
2016-2017	93	92	44	48
2017-2018	95	96	46	51

There was considerable year-to-year variation in the total annual rainfall recorded at OWP and UWE. 2015/16 was much wetter than the 1961-2017 average (Figure 3.1 and 3.2, Table 3.1), and 2016/17 and 2017/18 were drier. There were also large year-to-year seasonal variations in rainfall. 2015/16 was the wettest year during the experiment, but the summer (July, August and September) was the driest with only 157 mm of rain falling at UWE and 154 mm at OWP (Figure 3.1 and 3.2). 2016/17 was the driest year, but the summer (July, August and September) was the wettest during this study, with 244 mm rain at UWE and 260 mm at OWP (Figure 3.1 and 3.2). This type of year-to-year and season-to-season variation is a normal part of the UK climate (Kendon et al., 2019) but the variability in rainfall patterns is predicted to become greater over the next twenty to thirty years (UKCP2018, Met Office. 2018). Compared with the annual rainfall for England (Kendon et al., 2017, 2018 and 2019), the Frome catchment was wetter in 2016, drier in 2017 and similar in 2018. This is likely a reflection of location in the western part of the UK. Over the course of the experiment, the amount of rainfall recorded in the Frome catchment was more variable than the English seasonal averages (Kendon et al., 2017, 2018 and 2019), with wet seasons being wetter and dry seasons drier. Total rainfall recorded from Control plots at OWP and UWE was similar even though UWE is 70 m higher than OWP. There are some month-to-month differences between the two sites (Figure 3.1 and 3.2); rainfall in November and December was greater at UWE than at OWP. This is probably due to a combination of direction of prevailing winds and local orographic effects.

The Reduced Rainfall (RR) treatment was successful in reducing rainfall within the plots by about 50% (Figure 3.1 and 3.2 and Table 3.1). Monthly rainfall in the RR plots was within the lower quartile of values for each month recorded in the last one hundred years for the Frome catchment (National River Flow Archive, https://nrfa.ceh.ac.uk), but never fell below the one hundred year minimum monthly rainfall. This shows that the rainfall reduction created by the RR treatment is realistic for this catchment. The rainfall reduction achieved by the RR treatment is greater than the 28 % reduction in summer rainfall indicated by the UK Climate Change predictions (UKCP09) for the Frome catchment by 2080, assuming that greenhouse gas emissions increase to four times 2009 level (Afzal and Ragab, 2019). Thus the applied treatment is a good test of the resilience of the two grasslands.

3.1.2 *Soil Moisture*

At both UWE and OWP, the soil moisture tension (Decagon MP6 instrument) in all plots was between 0 and -59KPa (soil water deemed freely available to plants (Berglund, 2020)) on every day of the month between December and March of each year (Figure 3.3 and 3.4). Soil moisture tension in the RR plots, at both sites, in each year (2015/16, 2016/17 and 2017/18) was between 0 and -59 KPa for fewer days of each month than in Control plots (Figure 3.3 and 3.4) during the peak growing season (April to September).

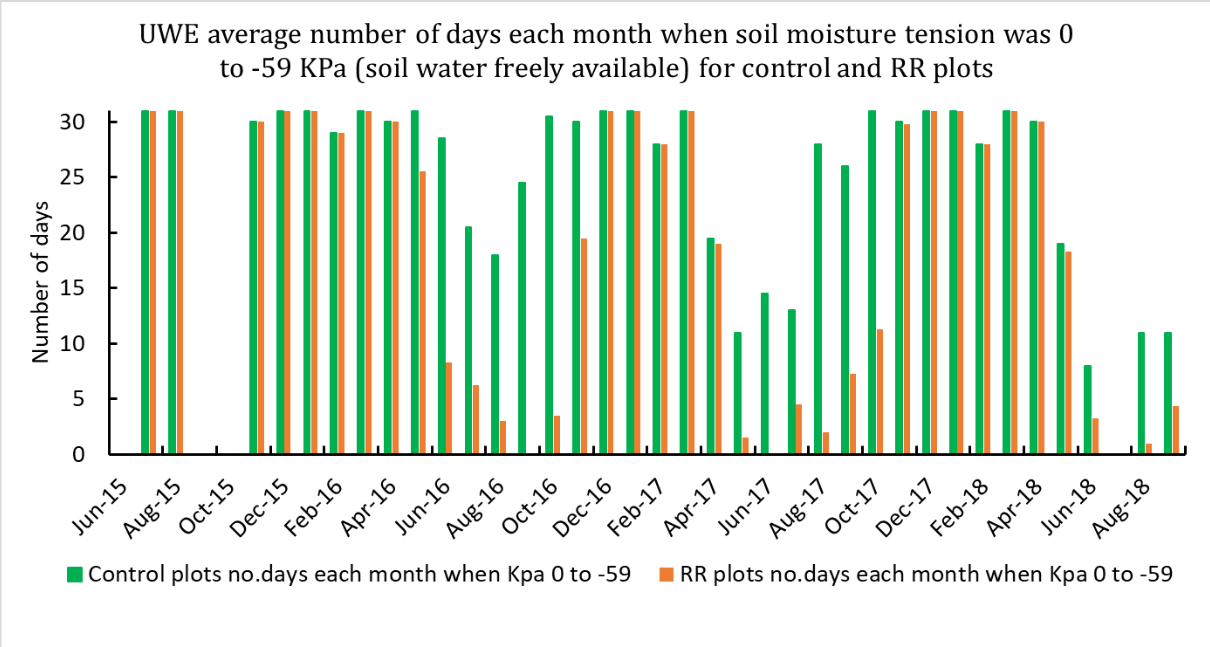


Figure 3.3. UWE Average number of days each month when soil moisture tension was between 0 and -59 KPa (soil moisture freely available) for Control and RR plots.

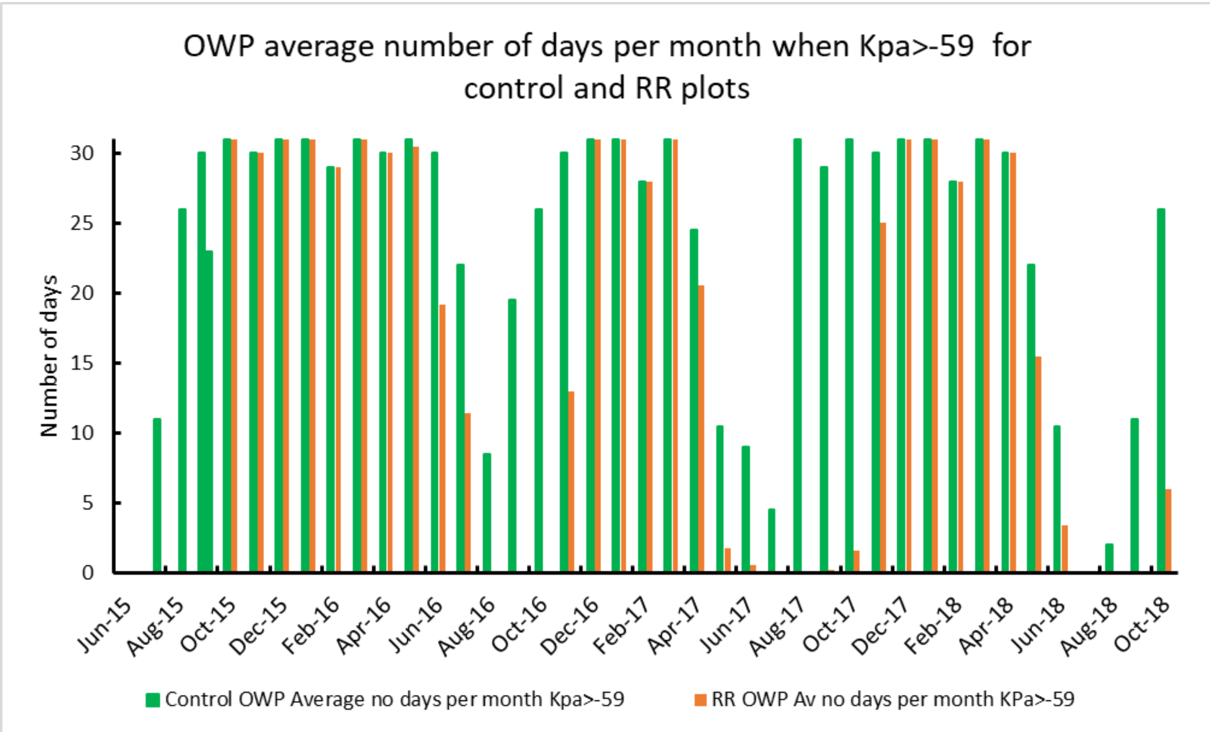


Figure 3.4. OWP Average number of days each month when soil moisture tension was between 0 and -59 KPa (soil moisture freely available) for Control and RR plots.

Soil moisture content (%) (Adcon sensors) at 10 cm showed large season variations. At UWE, this was from as little as 37% to around 60%, and at OWP from below 30% to around 60% (Figure 3.5, 3.6 and 3.7). Changes in soil moisture content at 50 cm and 90 cm were smaller, for example at UWE, soil moisture content at 50 cm ranged from 54- 58%, and at 90 cm from 58-60-%. Any changes in soil moisture content at 50 cm and 90 cm lagged, in time, behind the changes at 10 cm, as shown in this example set of data for Control plots at UWE (Figure 3.5).

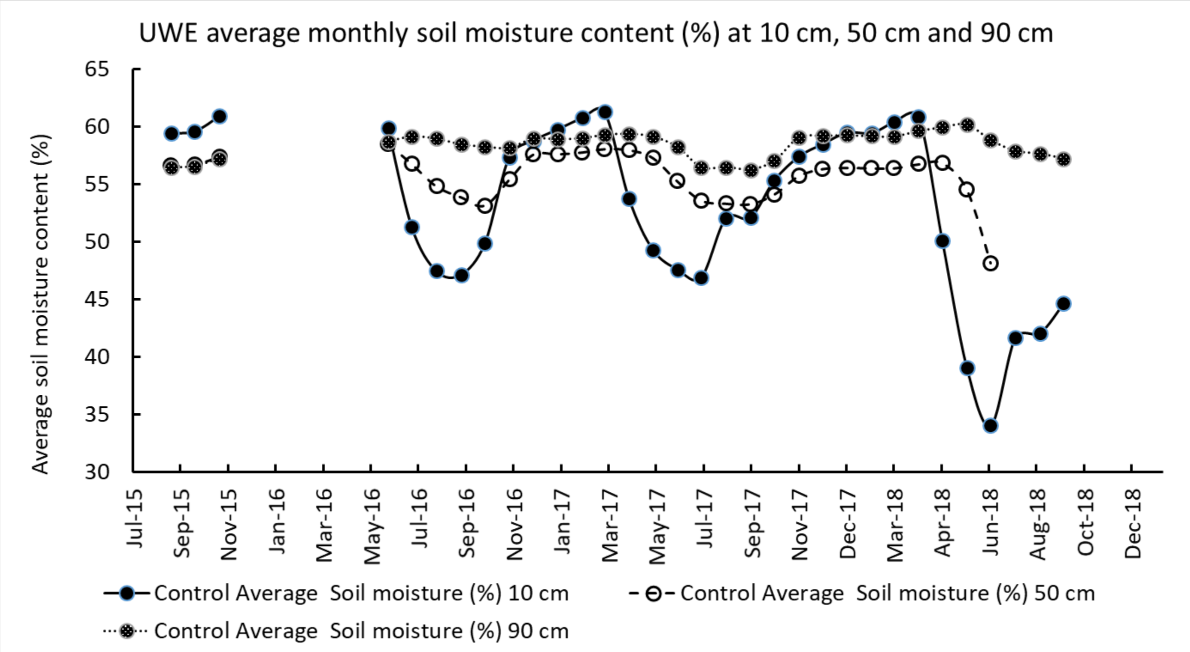


Figure 3.5. Soil moisture cotent (%) at 10 cm, 50 cm and 90 cm for Control plots at UWE.

At both UWE and OWP, average soil moisture content at 10 cm was usually higher in Control plots than in RR plots (Figure 3.6 and 3.7). The soil in Control plots returned to field capacity (maximum water content after any excess water has drained away under the influence of gravity) more quickly than the soil in the RR plots (Figure 3.6 and 3.7). At OWP, soil moisture content (%) at 50 cm and 90 cm during the 2016/2017 growing season was lower in the RR plots than in the Control plots, and this was different to UWE where soil moisture content (%) at 50 cm and 90 cm was only slightly lower in RR plots than in the Control plots (Figure 3.6 and 3.7).

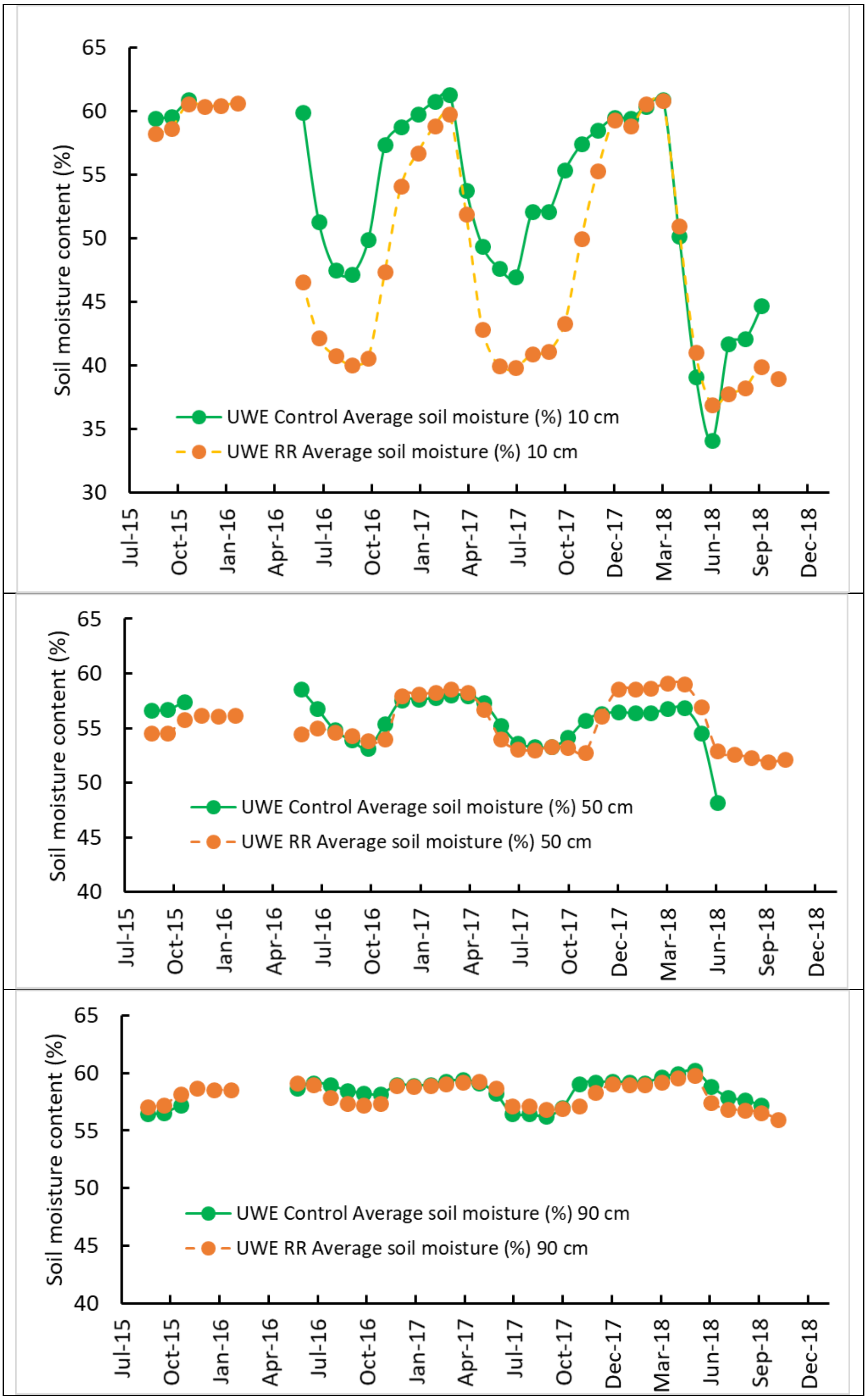


Figure 3.6. Soil moisture content (%) for Control and RR plots at UWE, at 10 cm, 50 cm and 90 cm. Values are averaged across the site.

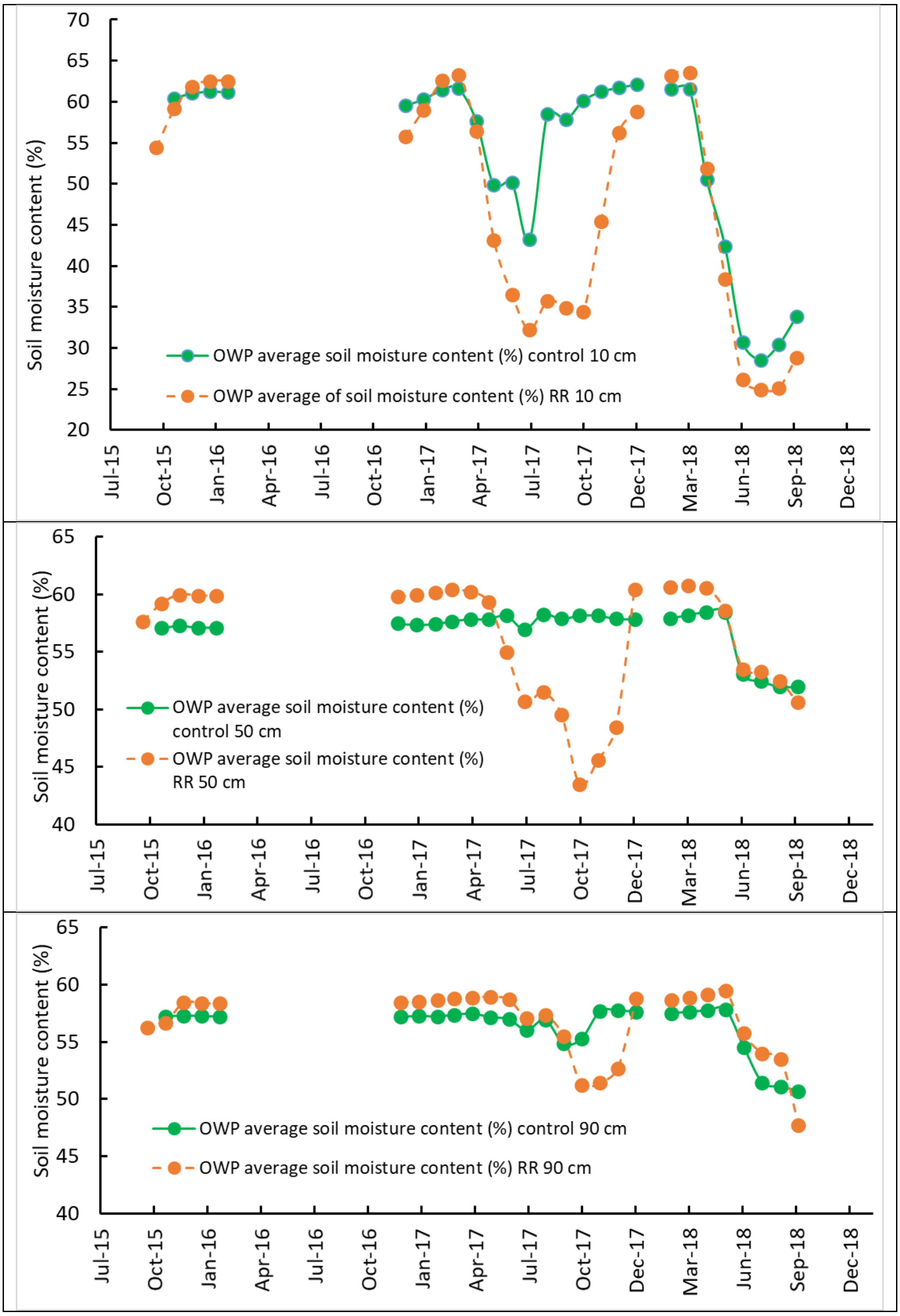


Figure 3.7. Soil moisture content (%) for Control and RR plots at OWP, at 10 cm, 50 cm and 90 cm. Values are averaged across the site. For technical reasons the data presented are for only one experimental block.

Seasonal patterns of changes in soil moisture tension and soil moisture content were similar at both sites. Soil moisture content (%) decreased and soil moisture tension (kPa) increased during the peak growing season (April to September). During the autumn and winter months (October to March), when incident rainfall exceeded the amount of water taken up by the grassland plants, soil moisture content increased and soil moisture tension decreased (Figures 3.3 to 3.7).

Soil moisture characteristic curves (soil moisture tension vs soil moisture content), prepared for each of the two sites (Figure 3.8 and 3.9) indicate that at UWE -59 KPa occurs at ~ 44% moisture, and at OWP ~ 50 % moisture. At -491 kPa, the UWE soil contained ~36% moisture and the OWP soil,~ 34% moisture. Thus, there was more soil water available, for plants to use, between -59 and -491 kPa at OWP (~16%) than at UWE (~8%).

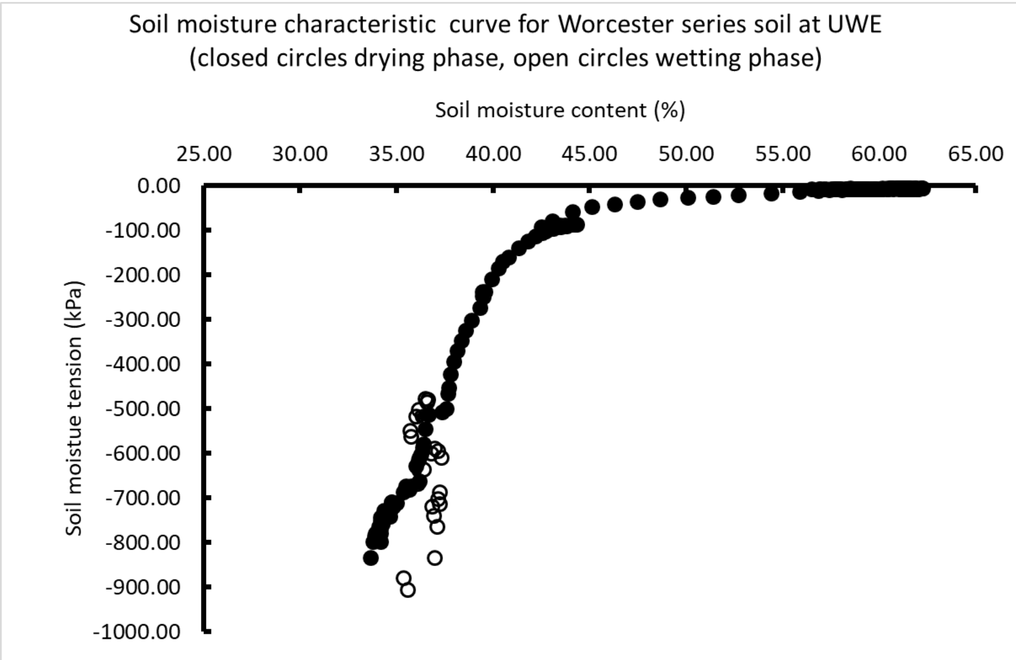


Figure 3.8. Soil moisture characteristic curve, at 10 cm, for Worcester series soil at UWE.

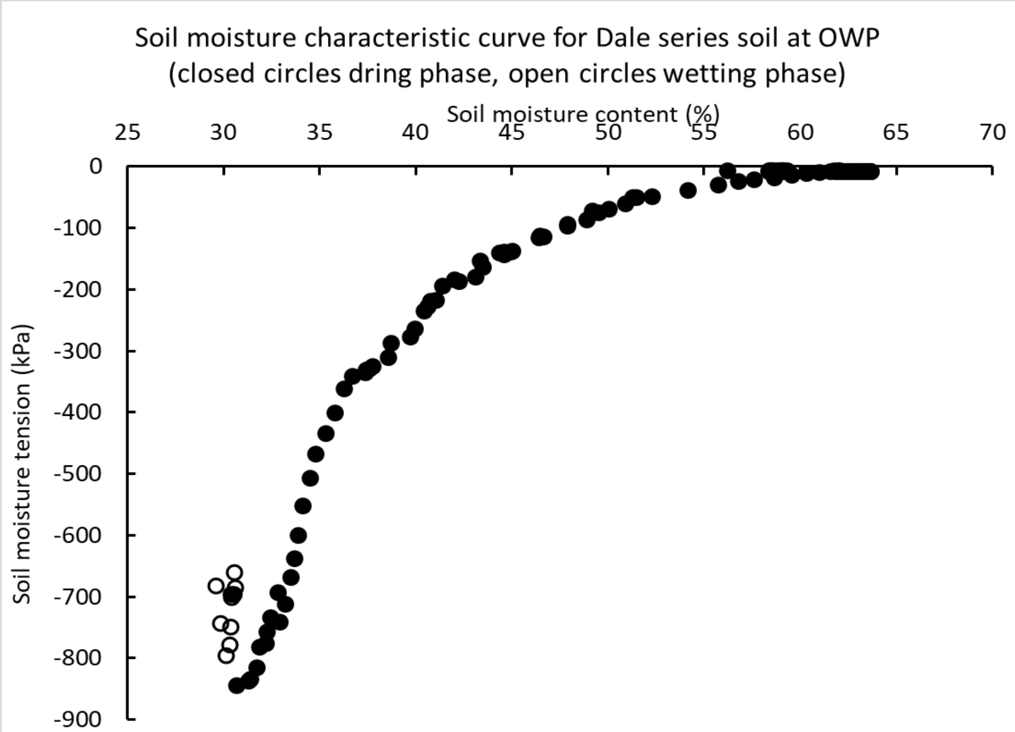


Figure 3.9. Soil moisture characteristic curve, at 10 cm, for Dale series soil at OWP

At both sites, UWE and OWP, soil moisture content during the summer, was reduced in the RR plots compared to the Control plots (Figures 3.3 to 3.7), with the decrease in soil moisture content beginning earlier in the year in the RR plots (Figures 3.3 to 3.7). At both sites, soil moisture content and soil moisture tension at 10 cm was much more strongly affected by the RR treatment compared to that at 50 cm or 90cm. This has also been reported in other rainfall manipulation studies (Vogel et al., 2013; Picon–Cochard et al., 2014), and reflects the fact that in pastures in the UK, and elsewhere, most roots (65-90%) occur in the top 10 cm of soil (Macklon et al., 1994; Dawson et al., 2000 and Brown et al., 2010). In RR and Control plots, at both sites, soil moisture returned to field capacity during the winter period. In a mesocosm experiment investigating the effect of 38 % reduction in spring and summer rainfall on yield of perennial rye grass, reported by Grove and Monaghan (2019), return of the soil water content to field capacity was considered to be one of the most important factors enabling crops to maintain productivity under dry summer conditions. When soil moisture tension increases to below -490 kPa, plants experience moisture stress (Berglund, 2020). At UWE, at -490 kPa the soil moisture content was around 36%; once soil moisture tension increased beyond -59 kPa, only 8% water was available. In contrast, at OWP at -490 kPa soil moisture content was 34 %, and between -59 and -490 kPa there was 16% soil water available.

3.1.3 *Air temperature*

Over the course of the experiment air temperatures (MetPak) at UWE ranged from -6.4 °C to 32 °C, and at OWP from -7.9 °C to 31.7 °C. Average, maximum and minimum air temperatures were similar at the two sites (Table 3.2), although OWP was slightly cooler.

Table 3.2. Date and value of highest and lowest daily maximum, minimum and average air temperature (°C) recorded between October 2015 and October 2018 at OWP and UWE.

	University of the West of England		**Oldwood Pits**	
	Date	**Temperature (°C)**	**Date**	**Temperature (°C)**
Highest max. daily air temp.	21 June 2017	32.0	19 July 2016	31.7
Lowest max. daily air temp.	1 March 2018	-2.0	11 March 2018	-3.2
Highest min. daily air temp.	25 July 2018	17.5	23 July 2018	17.1
Lowest min. daily air temp.	20 January 2016	-6.4	27 February 2018	-7.9
Highest av. daily air temp.	21 June 2017	24.4	20 June 2017	23.6
Lowest av. daily air temp.	1 March 2018	-3.6	1 March 2018	-4.8

Air temperatures (MetPak) inside (measured below the roof) and outside the rainfall shelters were similar. Figure 3.10 shows monthly average temperatures inside and outside one rainfall shelter at OWP; the two plots are almost coincident. The differences between average air temperature inside and outside the rainfall shelters (Table 3.3) are within the accuracy of the readings (± 0.1 °C [Gill Instruments, Lymington, UK]) (Table 2.1). At both OWP and UWE, inside the shelters, the average maximum temperature was slightly higher than outside and the average minimum temperature was slightly lower (Table 3.3). Although care was taken to position the temperature sensor so that it recorded representative conditions under the roof, we cannot rule out some element of shading or that on cool days and at night the metal of the frame acted as a heat sink.

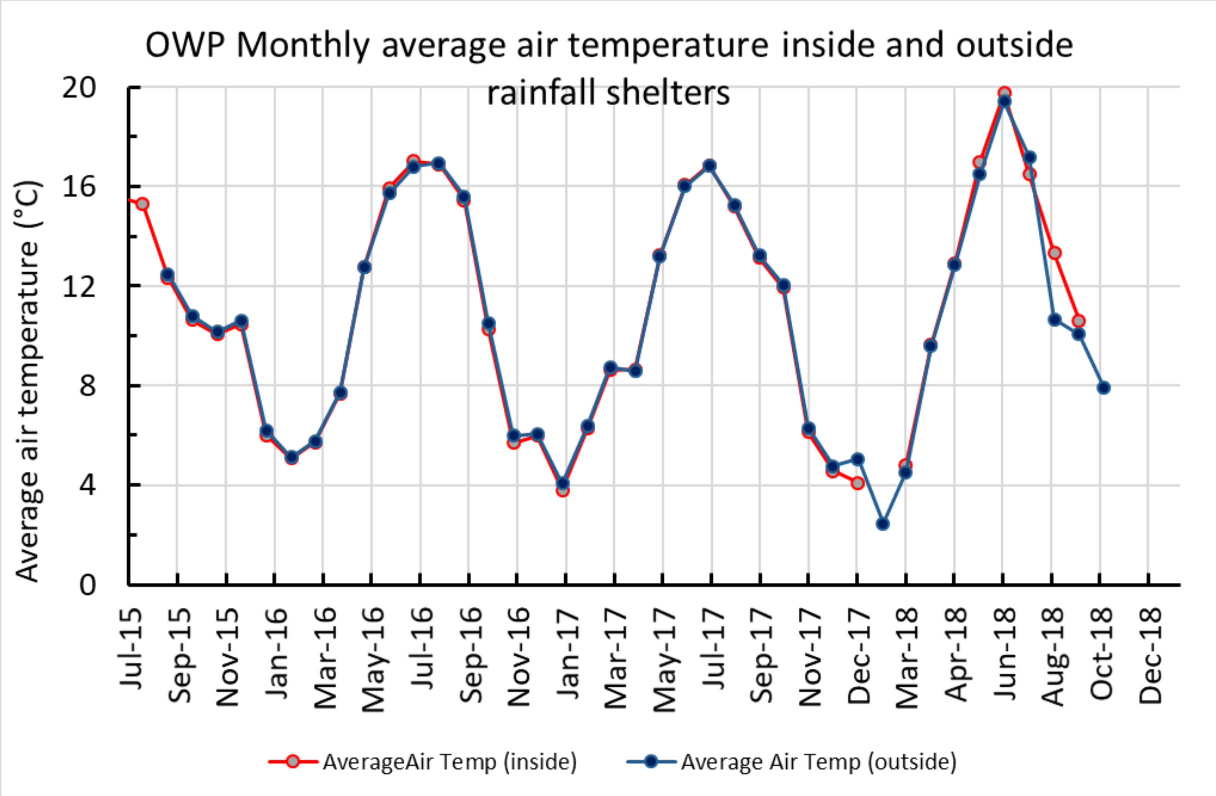


Figure 3.10. Monthly average air temperature at Oldwood Pits measured inside and outside the rainfall shelters.

Table 3.3 Average daily maximum, minimum and average air temperature (°C) inside and outside the rainfall shelters at University of the West of England and Oldwood Pits for the period October 2015 to October 2018. Using data only from days where there was a complete set of values from instruments inside and outside the shelters.

	University of the West of England						**Oldwood Pits**					
	Outside			Inside			Outside			Inside		
	n	mean	s.d.	n	mean	s.d.	n	mean	s.d.	n	mean	s.d.
Average max. daily air temp. °C	949	15.5	5.8	949	15.9	6.1	990	15.1	6	990	15.5	6.2
Average min. daily air temp. °C	949	7.5	5.0	949	6.7	5.0	990	6.6	5.1	990	6.2	5.2
Average av. daily air temp. °C	949	11.5	5.2	949	11.3	5.2	990	10.9	5.2	990	10.8	5.3

3.1.4 *Soil Temperature*

At both sites (UWE and OWP), average soil temperature at 10 cm (Decagon MPS6 sensor) was slightly higher, under the rainfall shelters than in Control plots, during the cooler winter months, and slightly lower during the warmer summer months. Figure 3.11 shows a representative set of data for one block of plots at OWP. This agrees with field observations that frost always cleared more quickly from the RR plots. In a grassland drought experiment, in eastern central Germany, (using frames with roofs to intercept rainfall) Vogel et al. (2013) observed a similar effect; soil temperatures at 7cm (under frames) were slightly decreased on warm days but increased on cool days.

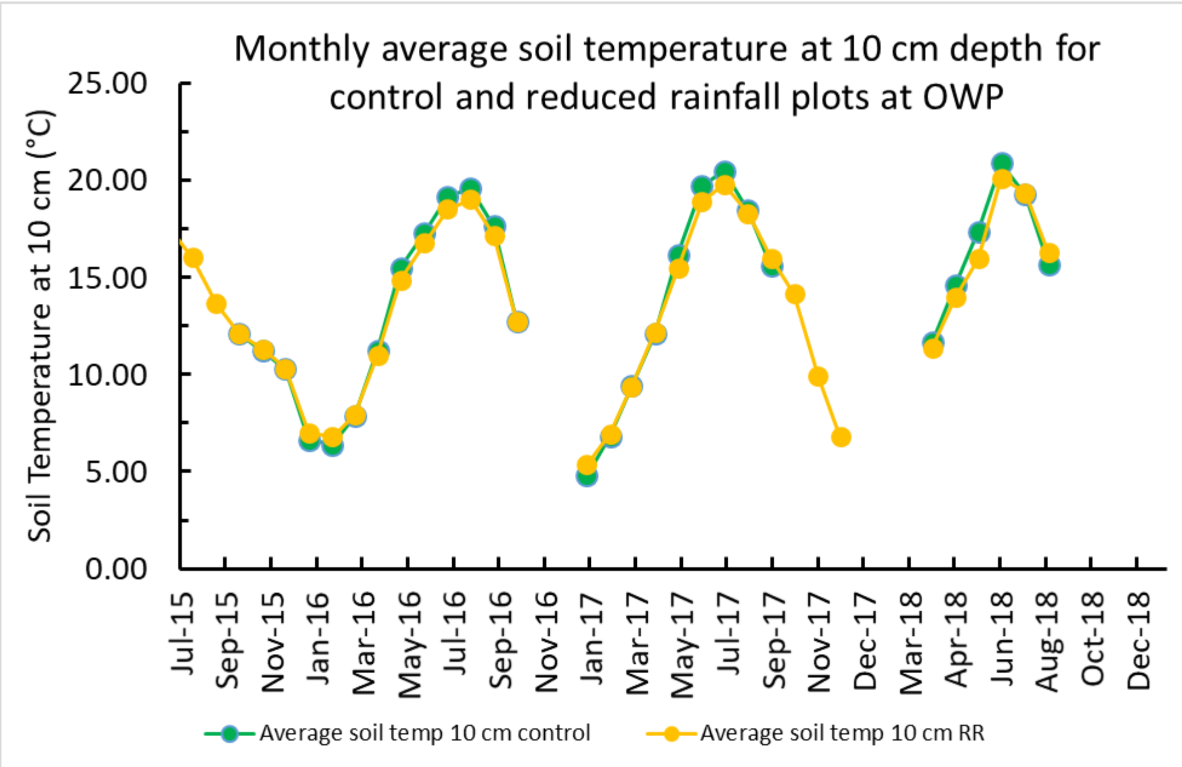


Figure 3.11. Monthly average soil temperature at 10 cm in Control and reduced rainfall plots at OWP.

3.1.5 *Photosynthetically active radiation (PAR)*

The sensors recorded incident PAR, from July 2015 until the roofs were put on in October 2015, and as can be seen in the example set of data from OWP (Figure 3.12) recorded similar values. After roof installation, the PAR was lower (77% - 95%, average 85%) under the roofs than outside (Figure 3.12). PAR was reduced by the roof material (PEGT), and short-term condensation and frost on the roof elements.

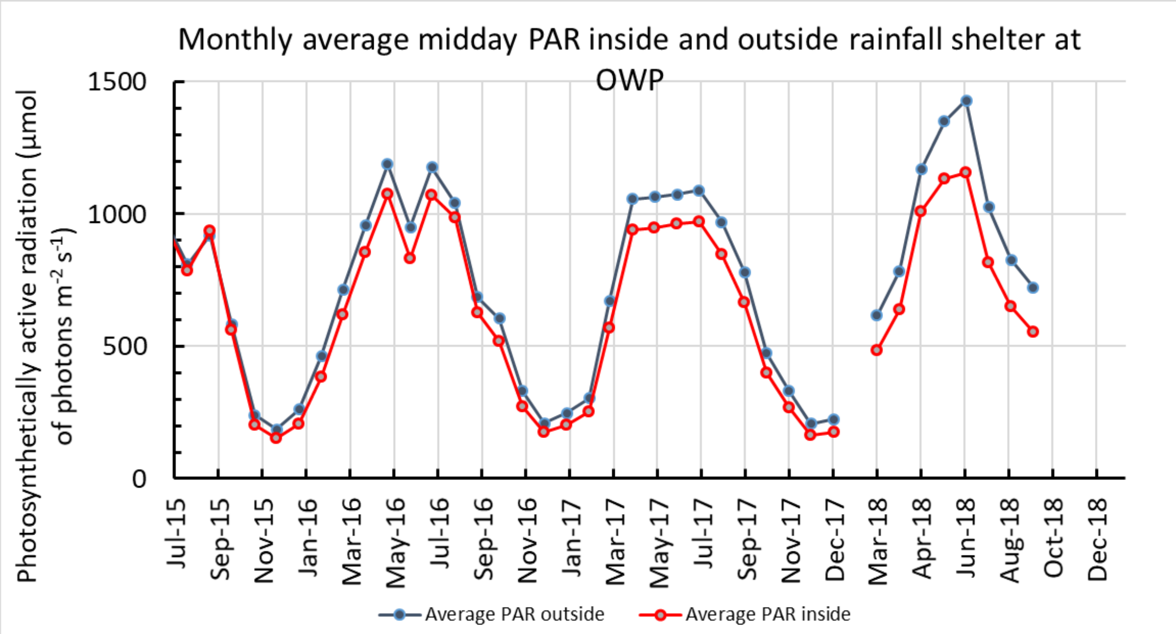


Figure 3.12. Monthly average of midday photosynthetically active radiation (PAR) in µmol of photons m^{-2} s^{-1} at Oldwood Pits (OWP), measured outside and under the roof of Reduced Rainfall plots.

Reduced midday PAR, under rainfall shelters, has been noted in other studies (Vogel et al., 2013). In our experiment, in the R. Frome catchment, above ground plant biomass production was similar in RR and Control plots, and sometimes slightly higher in the RR plots (Figure 3.13). This suggests that the reduction was not sufficient to significantly reduce photosynthetic activity. Many glazing materials commonly used in commercial glasshouses can reduce PAR by up to 25 %, but this effect is not considered significant during the summer growing season (Bartok, 2018).

3.2 Biomass

3.2.1 *Total amount of dry matter*

The weight of samples collected in September 2015 is included in Figures 3.13 and 3.14 because it gives an indication of the initial variability between plots, and the productivity of the fields. At UWE, we were not certain that mechanical cutting of the vegetation by the farmer in 2014 before the experiments were set up in 2015 removed the same amount of plant material from the plots as our hand cutting and collecting in 2015, 2016, 2017 and 2018. At OWP in 2015, while the experiment was being set up, sheep were kept in the field and no summer hay crop was taken. We then cut the plots in late September/early October. Therefore, to be confident that we were making valid comparisons, we have excluded data from samples collected in October 2015 (at the start of the experiment, before attaching the roofs) from the main analysis.

At both UWE and OWP, there was considerable plot-to-plot variation in the mass of above ground dry matter (biomass) produced (Figure 3.13 and 3.14 and Tables 3.4 and 3.5).

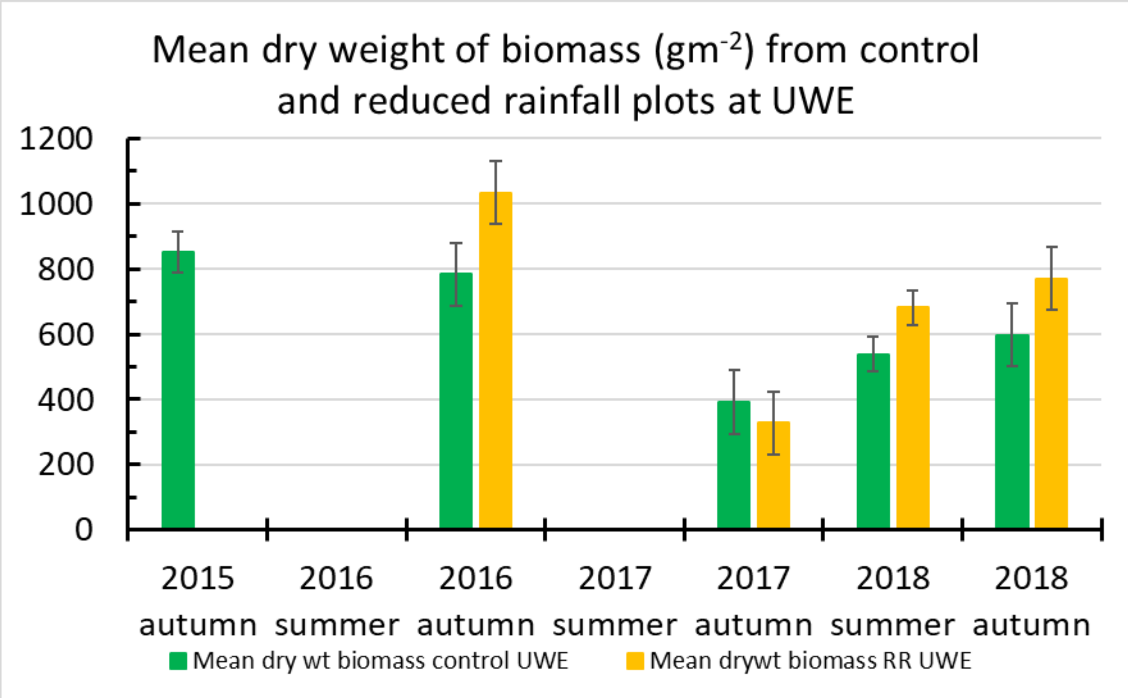


Figure 3.13. Dry weight of above ground plant material (biomass) at University of the West of England (UWE) site. Values are mean with SE, n=6 (12 in 2015). Plots were cut in early October.

Table 3.4. Amount of dry biomass produced at UWE (g m^{-2}), samples were collected in late September/early October of each year. Mean with standard deviation (s.d.).

	Control			**Reduced rainfall**		
Harvest Year	Mean (g m^{-2})	s.d.	n	Mean (g m^{-2})	s.d.	n
2016	783.8	213.6	6	1034.2	394.8	6
2017	391.6	110.8	6	327.6	103.8	6
2018	597.4	80.2	6	770.6	281.6	6

At UWE, univariate analysis of variance suggested that overall there was no statistically significant difference between the amount of biomass produced in Control or RR plots (p=0.12) (Figure 3.13). Year had a large effect on amount of biomass recorded (p<0.0001), and explained 92% of the variation. There was no statistically significant interaction between treatment and year.

At UWE, 2017 was the only year in which less biomass was produced in the RR plots (327.6 g m^{-2}) than in the Control plots (391.6 g m^{-2}) (Figure 3.13 and Table 3.4). In 2016 and 2018, the RR plots produced slightly more biomass than the Control plots (2016, 1034.2 g m^{-2} RR, compared to 783.8 g m^{-2} Control, and 2018, 770.6 g m^{-2} RR compared to 597.4 g m^{-2} Control) but these differences were not statistically significant (Figure 3.13).

In 2017 at UWE, in both Control and RR plots, less biomass was produced compared with 2016 (p<0.0001) or 2018 (p= 0.001). In 2018, less biomass was produced at UWE compared with 2016 (p= 0.022) (Figure 3.13).

At UWE in late June 2018, slightly more biomass was collected from the RR plots than from the Control plots (Figure 3.13) but the difference was not statistically significant *(p*=0.086).

At OWP, we collected samples twice each year, in summer (late June/early July) to simulate a summer hay cut, and in autumn (late September/ early October) to simulate early autumn grazing.

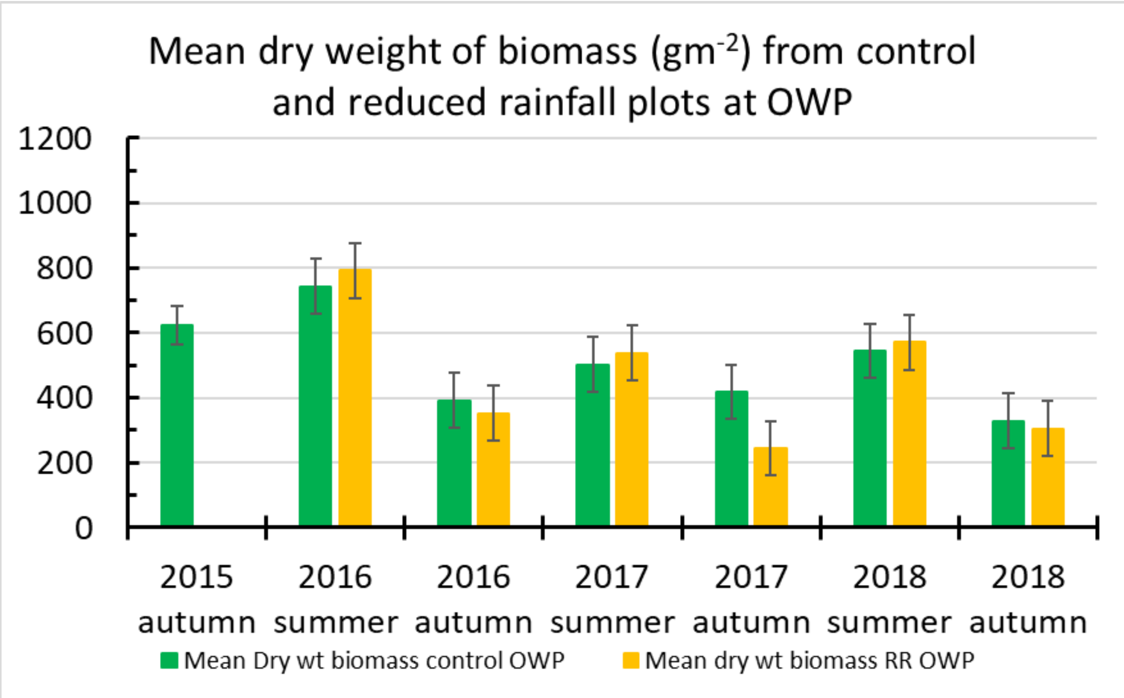


Figure 3.14. Above ground dry matter (biomass) at OWP (g m^{-2}). At OWP plots were cut in early July and early October. Values are mean ± SE n=6, 12 in 2015.

At OWP, univariate analysis of variance indicated that overall the reduced rainfall (RR) treatment had little effect on the total annual biomass (summer and autumn samples combined) produced by the plots each year (p=0.478) (Table 3.5). There were small differences between years in the annual total amount of biomass produced (p=0.065), and year accounted for 94% of the variation in annual total biomass. At OWP, in 2017 and 2018, significantly less biomass was produced, in both Control and RR plots, than in 2016 (2016 vs 2017 p=0.021, 2016 vs 2018 p=0.032) (Figure 3.14 and Table 3.5). There was no statistically significant interaction between year and treatment.

Table 3.5. Total dry weight (g m^{-2}) of dried plant material collected in late June/early July (summer) and at the end of the growing season (late September/early October, autumn) at OWP.

		Control			Reduced Rainfall		
Year	**Season**	mean	s.d.	n	mean	s.d.	n
2016	**summer**	742.6	217.4	6	791.6	118.9	6
2016	**autumn**	392.1	87.2	6	352	82.3	6
2016	**annual**	1134.7	209.7	6	1143.6	98.0	6
2017	**summer**	502.9	410.1	6	537.4	470.3	6
2017	**autumn**	418.7	80.7	6	244.8	52	6
2017	**annual**	921.6	431.7	6	782.2	448.8	6
2018	**summer**	544.3	186.7	6	571.4	150.2	6
2018	**autumn**	328.2	54.6	6	305.3	63.7	6
2018	**annual**	872.6	207	6	876.8	127.4	6

Total biomass production, across both sites (UWE and OWP), ranged from 392 – 1134 g m^{-2} for Control plots, and 328 – 1144 g m^{-2} for RR plots. This is similar to other rainfall manipulation experiments that have recorded grassland productivity using small samples; 200 – 300 g m^{-2} (Cole et al., 2019) for an unproductive upland calcareous grassland in Yorkshire, UK and 800 g m^{-2} from a lowland grassland pasture in Switzerland (Finger et al., 2012). The average yield of grass in UK is 7.3 t ha^{-1} Dry Matter (Berry and Newell-Price, 2016). In a modelling study of likely changes in grassland productivity in UK, associated with climate change, 8.7 t ha^{-1} was taken as the 2010 benchmark value (Qi et al., 2018). These values are comparable to those from our experiment, 3.9 – 7.8 t ha^{-1} at UWE and 8.7 – 11.3 t ha^{-1} at OWP. Thus, the dry mass of above ground plant material in our experiment is comparable with that recorded in other rainfall manipulation experiments and with that harvested on UK farms. Overall, the amount of biomass collected from UWE was slightly less than that collected from OWP (Table 3.4 and 3.5). This difference may be partly due to inherent differences in productivity between the two sites, and partly because at OWP the vegetation was cut twice each year and the cutting stimulated the plants to produce new growth.

The high plot-to-plot variability reflects the diversity and species distribution of the vegetation and the relatively small areas sampled. The vegetation at both sites was diverse and species rich (see 3.4). In grasslands, high plant diversity can increase the resistance of plant productivity to climate extremes, particularly drought (Tilman and Downing, 1994). In our study, the coefficient of variation, for weight of biomass samples collected in 2016, 2017 and 2018, averaged across UWE and OWP, was 29%. Coefficients of variation from other UK rainfall manipulation experiments, in which small samples were used to estimate productivity, are similar, for example, 19.2% for an unproductive grassland in Yorkshire (Grime et al., 2008), and 22 % for a lowland limestone grassland in Oxfordshire (Grime et al., 2000). Larger samples might have given a smaller coefficient of variation but would have been impractical because of the time needed to sort the biomass samples into the component parts.

At both OWP and UWE, the reduced rainfall (RR) treatment had only small effects on total annual biomass production compared to the strong year-to-year variation (Figures 3.13 and 3.14 and Table 3.4 and 3.5). In a rainfall manipulation experiment on calcareous grassland in Yorkshire, UK, a 100 year summer drought had no significant effect on biomass production (Coles et al., 2019) although, as in our experiment, biomass production was slightly higher in the droughted plots. In a mesotrophic grassland in Berkshire, UK, 30 % reduction in rainfall (between March and August) had no significant effect on biomass production, assessed by using plant height as a proxy for biomass, until the third year of the experiment (Lee et al., 2014). In a study of Canadian bunchgrass grasslands, excluding rain during the main growing season was associated with a slight increase in biomass production (Carlyle et al., 2014).

At OWP, there was a strong seasonal effect (p=0.000) with more biomass collected each year in July (615 ± 48.6 g m^{-2}, mean ± SE) than in October (340.2 ± 14.6 g m^{-2}), (Figure 3.14). We have therefore separately analysed the data for summer and autumn biomass.

3.2.2 *Summer harvested biomass*

We only have one set of data for early summer biomass production for UWE. More biomass was collected from RR plots than from Control plots but this difference was not statistically significant (Figure 3.13).

At OWP in summer, overall RR plots produced slightly more biomass (633.4 g m^{-2}) than Control plots (596.6 g m^{-2}) (Figure 3.14). Univariate analysis of variance indicated that the difference in summer biomass production between RR plots and Control plots was statistically significant (p= 0.029). Year had a strong impact on biomass production (p=0.002). In 2016 in summer, more biomass was collected from both RR and Control plots at OWP than in 2017 (p=0.046) or 2018 (p=0.088) (Figure 3.14).

At OWP (and in the single sampling from UWE), more biomass was collected in late June/early July from the reduced rainfall (RR) plots than from the Control plots; this is reflected in the figures for total annual biomass production. A review of anticipated changes to grassland associated with climate change (Hopkins and del Prado, 2007) suggested that on sites, in North and Northwest Europe, where water is not a limiting resource, increased winter temperatures would be likely to increase herbage growth. Computer modelling of future grass yields in Ireland indicated that early season growth of grass, especially in the West of the country, was likely to increase (Holden and Brereton, 2002). At OWP and UWE rainfall, even in the RR plots, was sufficient to return the soil to field capacity (Figures 3.3 to 3.7) and this combined with the slightly higher winter soil temperatures, (Figure 3.11) may have stimulated growth of the grass sward during the early part of the growing season.

3.2.3 *Autumn harvested biomass at OWP*

At OWP, reduced rainfall had a very strong negative effect on the regrowth of grass after cutting in early July in all years (Figure 3.14 and see results section 3.5). The weight of biomass harvested in the autumn (following late summer cutting to simulate hay removal) was less in RR plots (300.6 g m^{-2}) that in Control plots (379.6 g m^{-2}) (p=0.000) (Figure 3.14). More biomass was produced in autumn 2016 than in 2017 or 2018 (Figure 3.14). The amount of biomass harvested in the autumn showed a strong interaction between treatment and year (p = 0.028).

3.3 Effect of reduced rainfall (RR) on biomass of different functional species types at UWE and OWP.

We wanted to know if the proportion of the total biomass contributed by different functional groups (dead material, live broadleaved plants, live bryophytes or live graminoid plants) was altered by the reduced rainfall (RR) treatment.

At both UWE and OWP, effects of the reduced rainfall (RR) treatment on the proportion of the different components of biomass were small, in comparison with year to year and seasonal effects (Figure 3.15 and 3.16). Plants with woody stems and pteridophytes were in too few plots for statistical analysis.

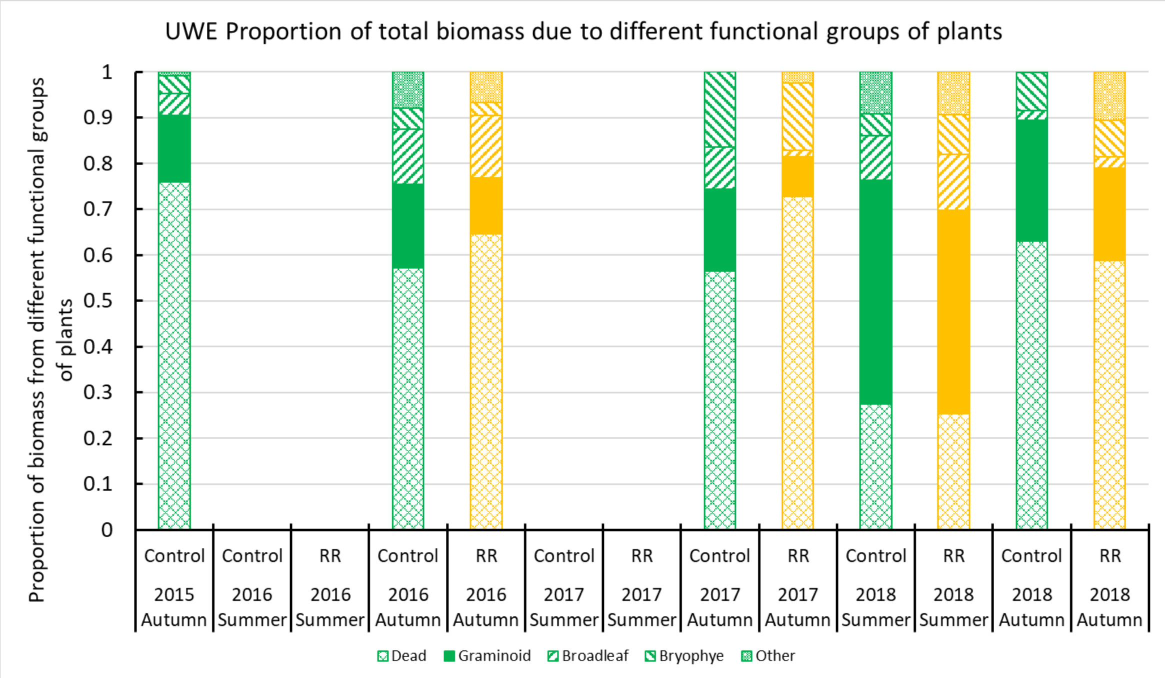


Figure 3.15. UWE Proportion of total above ground dry plant material (biomass) contributed by different functional groups:dead material, live graminoid, live broadleaved plants and live byrophytes (woody material and pteridophytes are grouped as other), in samples collected from Control and RR plots.

At UWE, univariate analysis of variance indicated that overall there was no statistically significant effect of reduced rainfall (RR) on the proportion of biomass from dead material or live broadleaved plants, graminoid plants or bryophytes (Figure 3.15). Year had a statistically significant effect on the proportion of bryophyte (p = 0.026). There was no interaction between treatment and year on the proportion of total biomass due to different vegetation type.

Taking all years together, pair-wise tests indicated that graminoid plants made up a slightly smaller proportion of the total biomass in samples from RR plots (0.143; 103.28 ± 30.16 g m^{-2}) than in samples from Control plots (0.215; 123.73 ± 25.82 g m^{-2}) (p = 0.018).

Pairwise tests suggested that year had a significant effect on the proportion of biomass from broadleaf, bryophyte and graminoid plants when samples from RR and Control plots were grouped togther (Table 3.6). Broadleaved plants were a smaller proportion of total biomass in 2017 and 2018 compared to 2016, while live graminoid plants made up a higher proportion of total biomass in 2018 than in 2016 or 2017.

Table 3.6. Effect of year on the proportion of total dry biomass at UWE from each of dead material, broadleaved plants, bryophtyes, and graminoid plants. Values with the same letter are statistically significantly different from each other, based on pair-wise comparisons. At p= 0.05: a, e; at *p* = 0.01: b, f; at *p* = 0.001: c, d.

Year	**2016**			**2017**			**2018**		
	Dry Wt (g m^{-2})	**s.d.**	**Proportion**	**Dry Wt (g m^{-2})**	**s.d.**	**Propn**	**Dry Wt (g m^{-2})**	**s.d.**	**Propn**
Broadleaved plants	128.4	149.9	0.124 ab	21.9	38	0.046 a	15.9	11.1	0.023 b
Bryophytes	32.3	19.0	0.041 c	47.6	25.6	0.165 cd	55.6	34.8	0.081 d
Dead	558.1	235.3	0.622	229.8	97.8	0.638	414.9	104.1	0.617
Graminoid plants	134.9	59.6	0.156 e	49.4	40.9	0.142 f	156.3	52.5	0.239 ef

At OWP, univariate analysis of variance analysis showed that RR had no significant effect on the proportion of total annual biomass from the functional groups (dead material, live broadleaved plants, bryophytes or graminoid plants), and there was no interaction between treatment and year. However, there was a significant diffence between years in the proportion of graminoid plants (*p*= 0.029) and dead material (*p* = 0.01) (Figure 3.16).

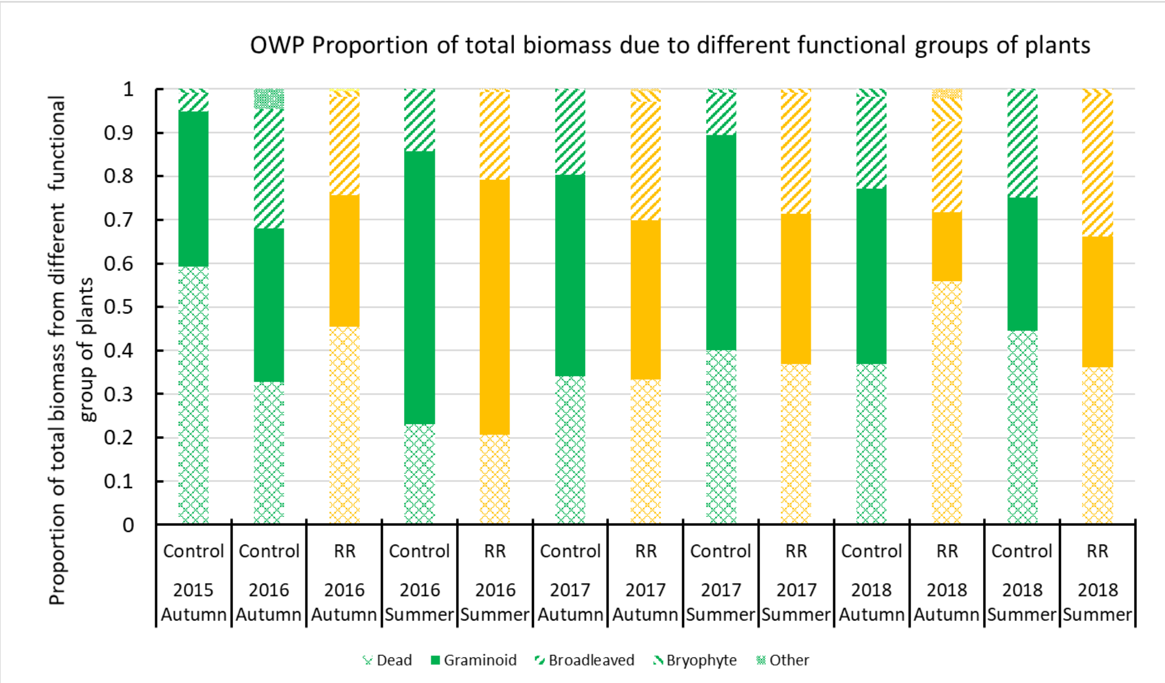


Figure 3.16. OWP Proportion of total above ground dry plant material (biomass) contributed by different functional groups (dead material, live graminoid,live broadleaved plants and byrophytes), woody material and pteridophytes are grouped as rest, in samples collected from Control and RR plots.

Pair-wise comparisons suggested that bryophytes made up a greater proportion of the total annual biomass in samples from RR plots (Table 3.7). In samples collected from RR plots at OWP in the autumn, bryophytes and dead plant material made up a greater proportion and live graminoid plants a smaller proportion of the total biomass than in samples from Control plots (Table 3.7).

Table 3.7. OWP the effect of Reduced Rainfall on on the proportion of total dry biomass at OWP from each of dead material and live broadleaved plants, bryophtyes, and graminoid plants. Values with the same letter are statistically significantly different from each othre, based on pair-wise comparisons. At p = 0.05:a, b, d; at p = 0.001:c.

	Control			**Reduced Rainfall**		
	Dry Wt (g m^{-2})	**s.d.**	**Proportion**	**Dry Wt (g m^{-2})**	**s.d.**	**Proportion**
Annual						
Broadleaved plants	183.0	105.2	0.205	235.4	221.7	0.237
Bryophytes	4.6	5.5	0.005 a	13.3	13.7	0.017 a
Dead	337.8	159.5	0.344	328	110.5	0.365
Graminoid plants	449.7	216.0	0.445	355.7	201.3	0.381
Autumn Harvest						
Broadleaved plants	87.2	51.5	0.233	70.2	46.0	0.241
Bryophytes	2.7	4.7	0.007 d	8.8	11.7	0.03 d
Dead	132.5	40.8	0.351 b	138.2	66.2	0.448 b
Graminoid plants	156.3	60.8	0.404 c	82	38.0	0.277 c

At OWP, as at UWE, year had a strong influence on the proportion of total biomass from each functional group. Pair-wise tests indicated that live graminoid plants made up a smaller, proportion of the annual total biomass in 2017 and 2018 than in 2016 (Table 3.8) and dead material was a larger proportion in 2018 than in 2016 (Table 3.8). For samples collected in the summer, at OWP, dead plant material made up a larger proportion and live graminoid plants made up a smaller, proportion of the total biomass in 2017 and 2018 than in 2016 (Table 3.8). While in samples collected from OWP in the autumn, live graminoid plants were a greater proportion of the total biomass in 2017 than in 2016 or 2018 (Table 3.8).

Table 3.8. Effect of year on the proportion of biomass due to different functional groups (broadleaved plants, bryophytes, dead material and graminoid plants) in samples collected in summer or autumn at Oldwood Pit. Values with the same letter are statistically significantly different from each other, based on pair-wise comparisons,. At *p*= 0.05:f, h, m, p ; at *p* = 0.01: e, g ; at *p* = 0.001: a, b, c, d, k, n.

Year	**2016**			**2017**			**2018**		
	Dry wt (g m^{-2})	**s.d.**	**Proport-ion**	**Dry wt**	**s.d.**	**Propn**	**Dry wt**	**s.d.**	**Propn**
Annual									
Broadleaved plants	227.6	159.6	0.193	172.9	214.9	0.213	227.1	146.6	0.257
Bryophytes	4.6	6.6	0.007	7.6	9.0	0.009	14.6	14.7	0.017
Dead	315	96.7	0.280 k	312.1	186.8	0.363	371.6	108.5	0.420 k
Graminoid plants	589.6	126.1	0.520 mn	358.2	235.3	0.413 mp	260.3	91.1	0.305 np
Summer									
Broadleaved plants	132.1	119.3	0.162	99	192.4	0.203	160.5	130.1	0.274
Bryophytes	3	3.4	0.005	4.2	3.6	0.01	3.5	4.9	0.006
Dead	167.9	105.4	0.217 ab	200	163	0.391 a	224.7	87.7	0.396 b
Graminoid plants	464.8	121.5	0.617 cd	216.7	202.6	0.395 c	169.2	78.4	0.323 d
Autumn									
Broadleaved plants	95.4	59.1	0.252	74	50.4	0.231	66.6	32.9	0.228
Bryophytes	2.6	5.2	0.008 h	3.4	6.5	0.016	11.1	12.6	0.032 h
Dead	147.1	50.6	0.402	112.1	54.4	0.336 e	146.9	54.5	0.461 e
Graminoid plants	124.8	48.5	0.331 f	141.6	67.8	0.415 fg	91.1	64	0.275 g

Overall, the reduced rainfall treatment had few effects on the proportions of biomass from different functional groups at both OWP and UWE. At UWE, there was a smaller proportion of live graminoid species in samples from RR plots compared to Control plots; it is likely that this reflects earlier senescence of the sward in the RR treatment. At OWP, we noticed a small increase in the proportion of bryophytes in RR plots; our hand cutting and removal of grass may have allowed more light to reach the lower part of the sward than sheep grazing or mechanical harvesting but we do not have any data about light levels within the sward.

3.4 Plant Species composition

At OWP, 63 species of flowering plant, 1 pteridophyte and 10 species of bryophyte were recorded. At UWE, 80 species of flowering plant, 1 pteridophyte and 9 species of bryophyte were recorded. We almost certainly underestimated the number of species of bryophyte because many species cannot easily be distinguished in the field using just a hand lens. Similar numbers of species are found in other UK semi-natural grasslands (Sternberg et al., 1990). In species-rich grasslands, the high plant diversity can increase the resistance of plant productivity to drought (Tilman and Downing, 1994, Vogel et al., 2012). Both of our experimental sites were species rich.

Canonical Correspondence Analyses, carried out by Dr A Gray (UK CEH Edinburgh), indicated that the reduced rainfall treatment had no significant effect on plant species composition and % cover (Table 3.9).

Table 3.9. Results of Canonical Correspondence Analyses on plant species composition and % cover data from OWP and UWE.

Site	**Treatment term**	**% variation explained**	**Pseudo-F**	**P**	**P(adj)**
OWP	RR	5.4	0.7	0.708	1
	Control	5.1	0.7	0.736	1
UWE	RR	4.1	0.6	0.954	1
	Control	4.9	0.7	0.864	1

3.5 Plant Height

In this experiment, we used regular measurements of plant height to understand how individual plant species and the overall height of the sward might be affected by reduced rainfall. We made three different types of measurements: maximum height of selected species, maximum height at random points and the tallest plant in each plot. The numbers of records for each type of measurement are shown in Table 3.10.

Table 3.10. Number of occasions with plant height data for UWE and OWP. Measurements at UWE commenced in March 2016 and at OWP in January 2017 this is why there are fewer records for OWP.

Type of measurement	**Number of occasions data collected**	
	UWE	**OWP**
Maximum effective height	83	37
Height at random points	47	34
Tallest plant	58	18

3.5.1 *Maximum effective height of selected species*

The measurements of maximum effective plant height were made on species that are easy to identify at all stages of growth. At UWE, the choice of species was influenced by the need to have species that volunteers, who were not professional botanists, would be able to learn to identify accurately and confidently. The plant species measured at UWE and OWP are listed in the methods (Table 2.4 and 2.5).

Most of the species monitored occurred in the majority of plots, and can therefore be considered representative of the vegetation of the whole experimental area. Tables 3.11 and 3.12 list in how many of the plots the different species occurred and the number of occasions on which they were observed.

A few species occurred in a restricted number of plots. At UWE, Field horsetail (*Equisetum arvense*) occurred in 10 plots (two blocks) and not in the block of five plots in the south west part of the experimental site. Field horsetail was included because it was the only pteridophyte within the experimental area. Dandelions and Ox-eye daisies, at UWE, were in only 7 and 9 plots respectively. These were added, as species to measure, in November 2017 because they are an important source of food for pollinating insects. The grass, Tall fescue (*Festuca arundinaceae*), was found in 7 plots at UWE, and was included from October 2017 because it appeared to be increasing in abundance within the surrounding field (https://www.plantlife.org.uk/uk/about-us/news/climate-change-the-uks-wild-flowers-are-on-the-move). Including tall fescue provided an opportunity for the volunteers to learn how it differed from another tussock forming perennial grass, Cocksfoot (*Dactylis glomerata*). Some species, such as Field bindweed (*Convolvulus arvensis*) and Field horsetail (*Equisetum arvense*), do not have above ground parts for the whole year and were not recorded, at UWE, on every occasion, while others, such as Mouse-ear chickweed (*Cerastium fontanum*) and *Geranium* spp., are annuals. In early part of the year, these may be hidden by other vegetation, difficult to identify, or not yet present. At OWP, most of the species were found in most plots. Red and White clover (*Trifolium pratense and T. repens*) tended to occur distinct patches at OWP, and were not present in all plots. Silverweed (*Potentilla anserina*) occurred in only three plots at OWP, but when present was one of the most dominant species.

Table 3.11. UWE frequency of occurrence of each species for which maximum effective height was recorded

		Number of plots species was found in				Number of times species was observed				
Species at UWE		**Total No. of plots**	**no. of reduced rainfall plots**	**no. of control plots**	**no. of roof control plots**	**Total no. of occasions seen**	**no. of occasions reduced rainfall**	**no. of occasions control**	**no. of occasions roof control**	**total no. occasions when observations were made**
Yorkshire fog	*Holcus lanatus*	15	6	6	3	85	85	84	84	85
Common sorrel	*Rumex acetosa*	15	6	6	3	85	76	82	67	85
Creeping buttercup	*Ranunculus repens*	15	6	6	3	76	62	69	55	85
Creeping thistle	*Cirsium arvense*	15	6	6	3	34	34	30	28	35
Tares	*Vicia tetrasperma, V. hirsuta,*	15	6	6	3	85	85	84	81	85
Hogweed	*Heracleum spondylium*	15	6	6	3	33	32	32	33	33
Geraniums	*Geranium spp.*	15	6	6	3	27	23	24	28	33
Cocksfoot	*Dactylis glomerata*	14	5	6	3	35	35	33	25	35
Red fescue	*Festuca rubra*	14	6	6	2	20	20	7	19	29
Docks	*Rumex spp.*	14	6	6	2	33	33	33	6	33
Field bindweed	*Convolvulus arvensis*	14	6	5	3	20	20	19	19	29
Common mouse ear	*Cerastium fontanum*	13	5	6	2	28	24	27	2	32
Willow herbs	*Epilobium spp.*	13	5	6	2	32	30	32	22	32
Common horsetail	*Equisetum arvensis*	10	4	5	1	64	62	61	57	84
Ox-eye daisy	*Leucanthemum vulgare*	9	4	4	1	32	18	31	3	33
Dandelions	*Taraxacum agg.*	7	3	3	1	27	26	3	24	33
Tall fescue	*Festuca arundinacea*	7	4	2	1	33	33	5	4	33

Table 3.12. OWP frequency of occurrence of each species for which maximum effective height was recorded.

		Number of plots species was found in				Number of times species was observed				
Species at OWP		Total No. of plots	no. of reduced rainfall plots	no. of control plots	no. of roof control plots	Total no. of occasions seen	no. of occasions reduced rainfall	no. of occasions control	no. of occasions roof control	total no. occasions when observations
Creeping buttercup	*Ranunculus repens*	15	6	6	3	37	37	37	37	37
Meadow buttercup	*Ranunculus acris*	15	6	6	3	37	37	37	37	37
Yorkshire fog	*Holcus lanatus*	15	6	6	3	37	37	37	37	37
Cocksfoot	*Dactylis glomerata*	15	6	6	3	30	29	30	21	37
Red fescue	*Festuca rubra*	15	6	6	3	31	31	31	30	37
Common sorrel	*Rumex acetosa*	15	6	6	3	37	37	37	37	37
Rye	*Lolium perenne*	15	6	6	3	35	35	34	33	37
Birdsfoot trefoil	*Lotus corniculatus*	13	6	5	2	35	35	34	5	37
Luzula	*Luzula campestris*	12	6	4	2	33	32	33	31	37
White clover	*Trifolium repens*	10	4	4	2	32	25	28	28	37
Red clover	*Trifolium pratense*	10	4	4	2	36	33	32	14	37
Creeping thistle	*Circium arvense*	9	4	4	1	30	23	20	22	37
Silver-weed	*Potentilla anserina*	3	1	1	1	22	20	1	22	37

There was large plot–to–plot variation in the heights recorded for individual plant species (see below), therefore to make comparisons between plants in different treatments we used a value of 50 mm. At UWE, based on 26 plant species years (*E. arvense* recorded in

2016, 2017 and 2018 is three species years), plants of the selected species were taller (by at least 50 mm) in RR plots than in Control plots on 17 occasions, shorter (by at least 50 mm) on 9 occasions, and reached their maximum height earlier in the growing season on 19 occasions. The highest median maximum effective height reached by each of the five plant species that were monitored for all three years of the experiment is shown in Figure 3.17. On most occasions, the differences in height between plants in the two treatments was small. If the comparisons are made on year-by-year basis, to allow for the differences in the annual rainfall patterns and using only data for the five species that were monitored throughout, in 2016 one of five species was shorter (by at least 50 mm) in the RR plots, in 2017 three of five species and in 2018 one of five.

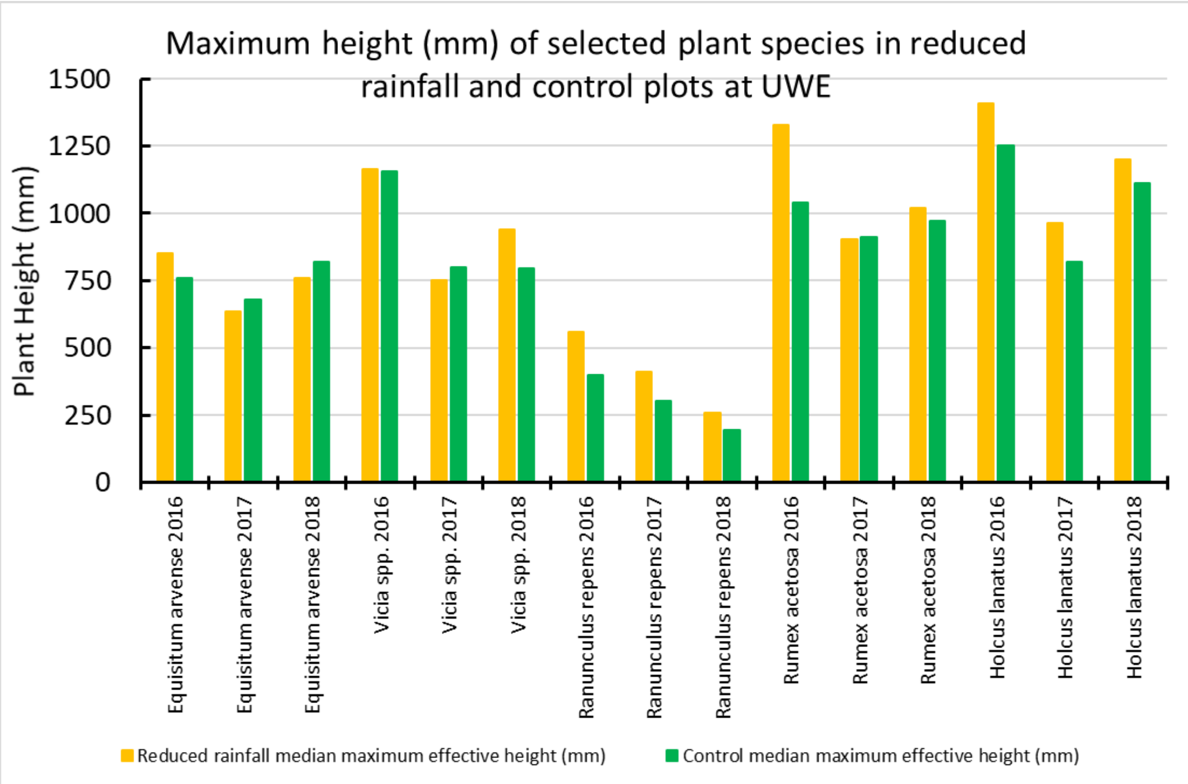


Figure 3.17. Maximum height (mm) of selected plant species in reduced rainfall and Control plots at UWE. Values are the highest median maximum effective height recorded at any time during the growing season.

At OWP, the plots were cut in late June /early July and therefore the data have been divided into those collected before and those collected after the cut.

For measurements made before the late June/early July cut at OWP we have 23 comparisons. On three occasions plants in the RR plots were taller (by at least 50 mm) than those in the Control plots, and on 19 occasions were shorter. On nine occasions plants in the RR plots reached their maximum height before plants in the Control plots.

For measurements made after the late June/early July cut at OWP, of the 24 comparisons on only two occasions were plants in RR plots taller than those in Control plots (by at least 50 mm), on 22 occasions they were shorter (by at least 50 mm). On seven occasions plants in the RR plots reached their maximum height before plants in the Control plots.

The highest median maximum effective height reached by each plant species in each year, at OWP, is shown in Figure 3.17. Comparing the data on a year-by-year basis, in 2017 eight of eleven species in RR plots were shorter than those in control plots (by at least 50 mm) before the late June/early July cut and 11 of twelve species were shorter after. In 2018, before the late June/early July cut eleven of twelve species were shorter in RR plots than in Control plots, and after, eleven of eleven species were shorter in RR plots than in Control plots.

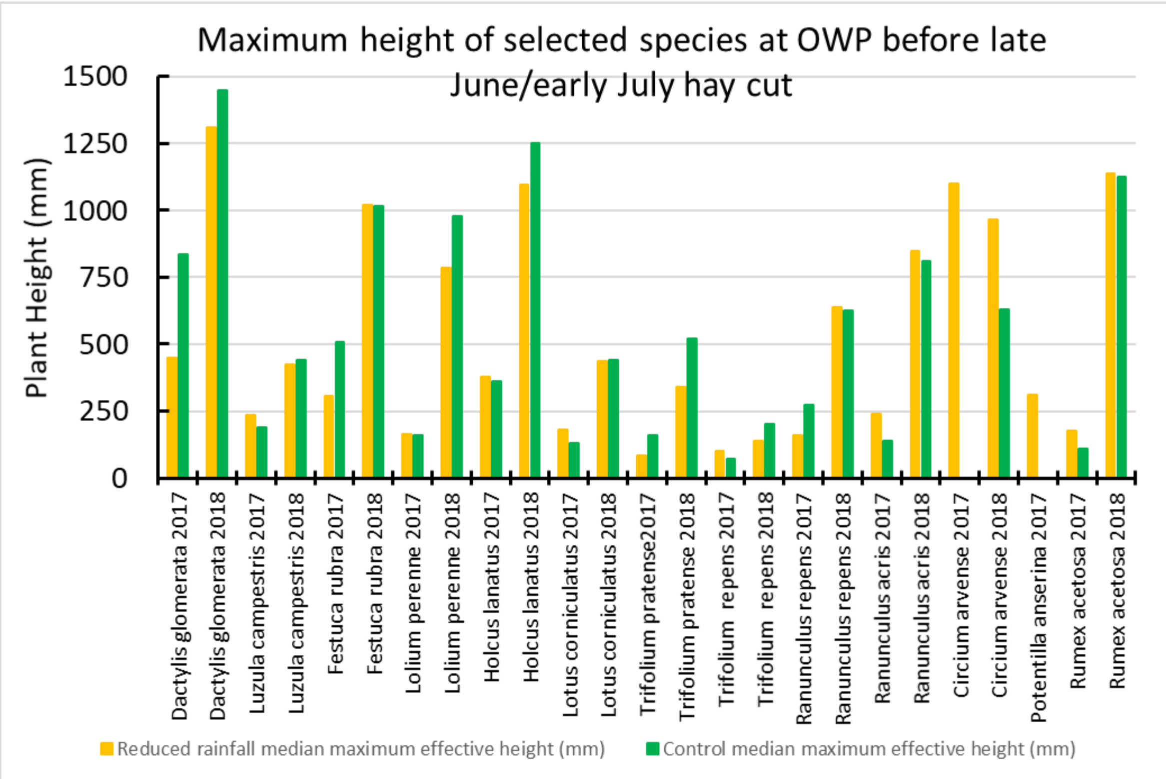


Figure 3.18. Maximum height (mm) of selected plant species in reduced rainfall and Control plots recorded before the late June/ early July cut at OWP. Values are the highest median maximum effective height recorded at any time during the growing season.

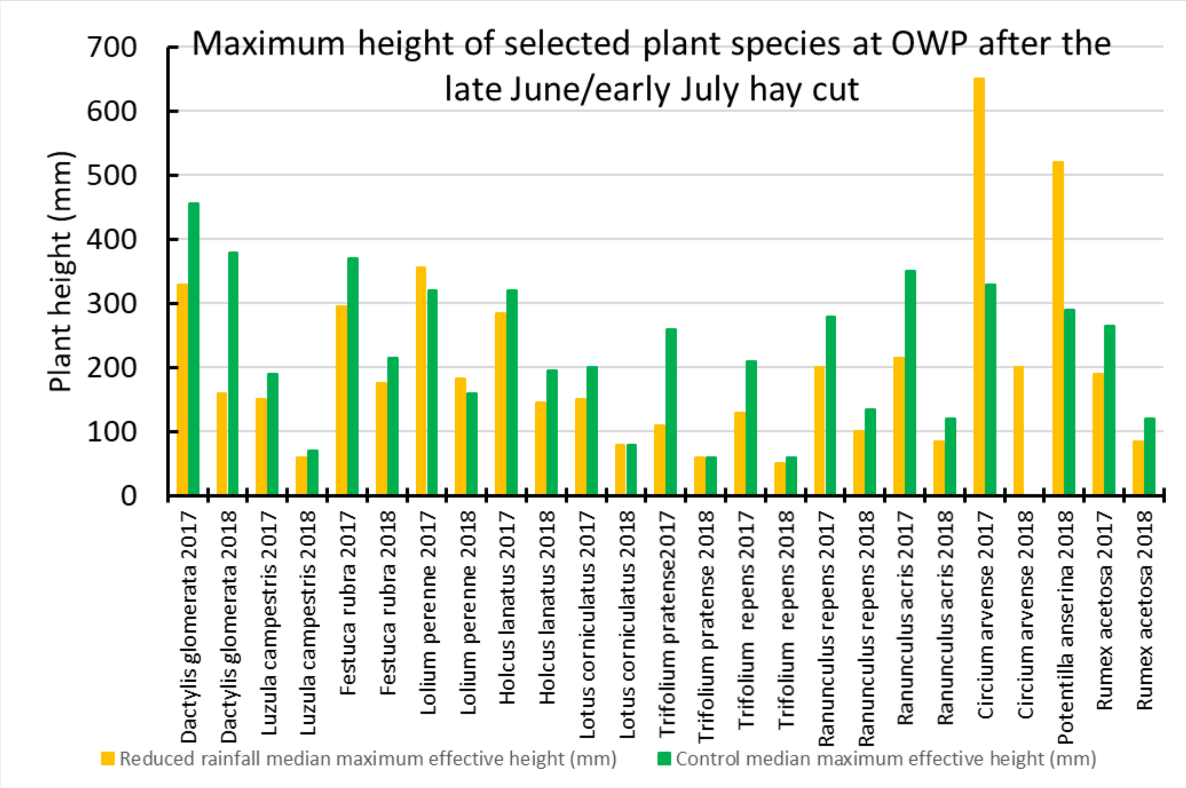


Figure 3.19. Maximum height (mm) of selected plant species in reduced rainfall and Control plots recorded after the late June/ early July cut at OWP. Values are the highest median maximum effective height recorded at any time during the growing season.

Maximum effective heights over time are presented for three species, with contrasting growth habits, that grew at both sites (Yorkshire fog (a perennial grass), creeping buttercup (an adventitiously rooted perennial) and common sorrel (a tap rooted perennial)). Tares (annual leguminous plants) at UWE are compared with Birdsfoot trefoil (a perennial tap rooted leguminous plant) at OWP. To make comparisons between the sites easier, the data have been plotted using the same time scale, but there are differences in the Y-axis (vertical) scale.

The grass, Yorkshire fog (*Holcus lanatus*) was an important component of the vegetation at both sites. It is the second most abundant grass in the UK and although common in damp sites, is also considered to be moderately tolerant of dry conditions. It is a perennial grass and might benefit from a longer growing season created by warmer conditions during the winter (NERC, 2016; Watt, 1978; http://www.nerc.ac.uk/planetearth/stories/239/). The maximum effective heights of Yorkshire fog recorded at both sites were similar, but there were large differences between years in the height that the grass attained (Figures 3.20 and 3.21). The maximum height given for Yorkshire fog in the UK by Hubbard (1968) is 1000 mm, and many of the plants measured in our experiment were taller than this. The tallest plants of Yorkshire fog were at UWE in 2016, and the shortest at both sites were in 2017 (Figure 3.20 and 3.21). Yorkshire fog in reduced rainfall plots at UWE tended to be slightly taller than those in Control plots but this is within the plot to plot variability (Figure 3.20). At OWP before the late June/early July cut, there was little difference in maximum effective height between Yorkshire fog plants in RR plots and plants in Control plots, but after the late June/early July cut plants in Control plots were slightly taller (Figure 3.21).

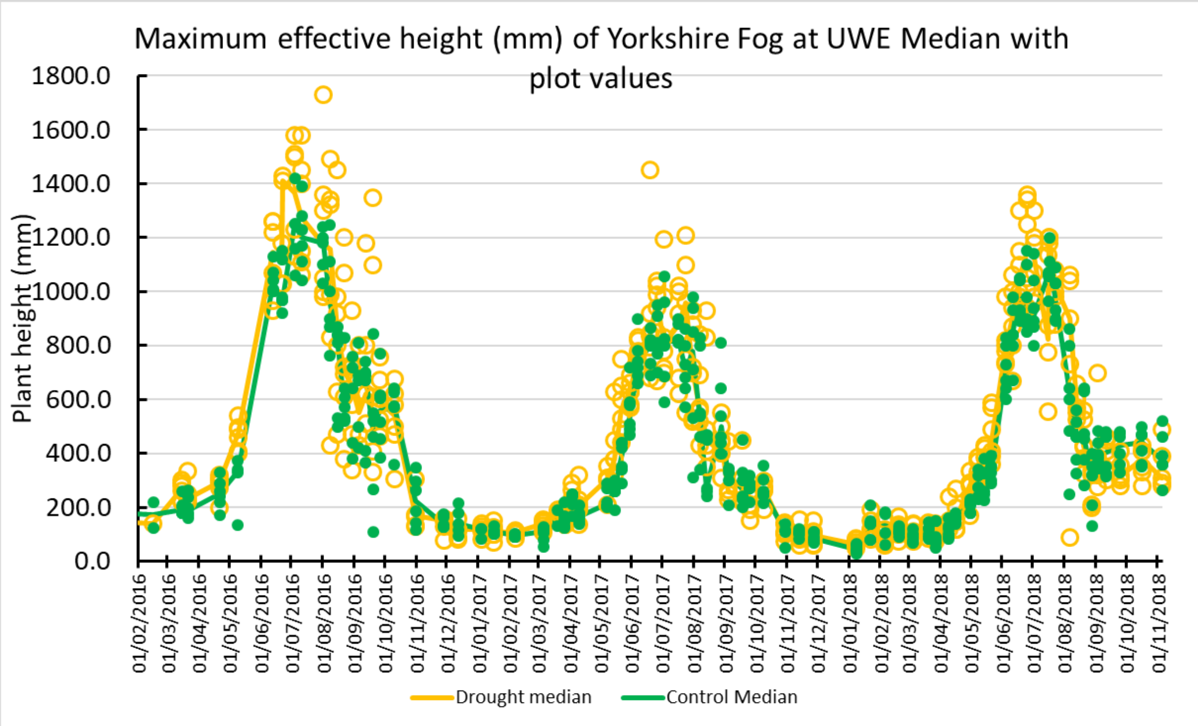


Figure 3.20. UWE Maximum effective height of Yorkshire Fog

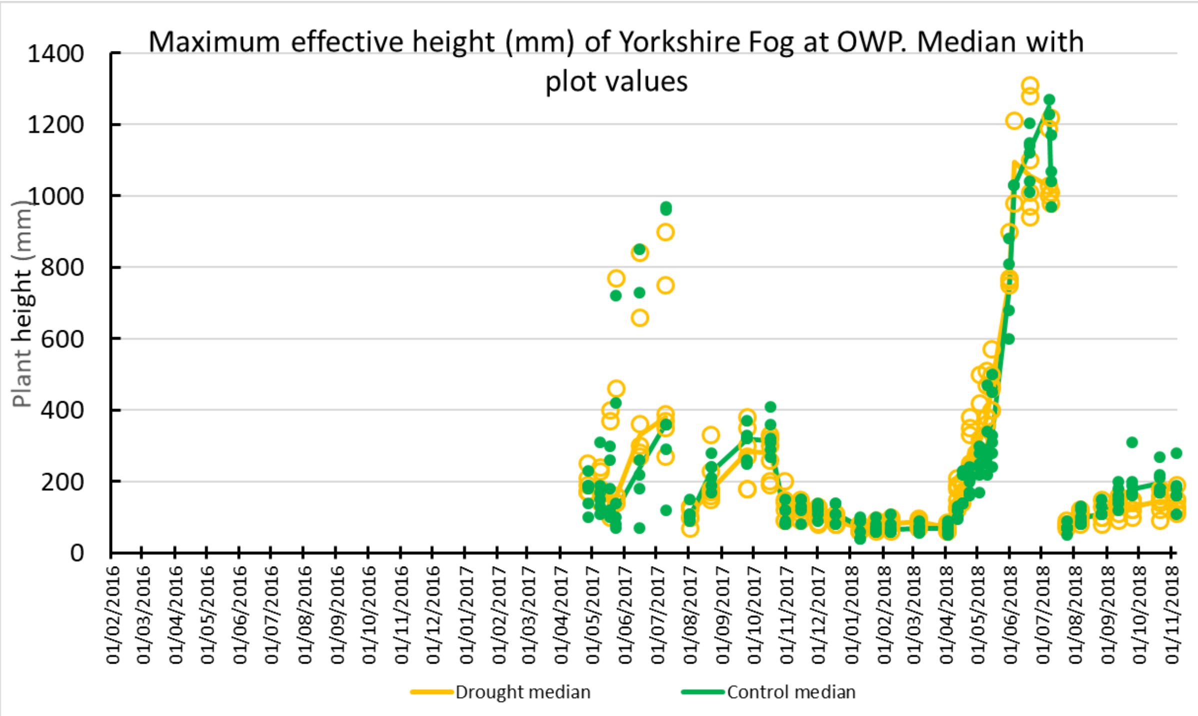


Figure 3.21. OWP Maximum effective height of Yorkshire Fog

Creeping buttercup (*Ranunculus repens*) is a perennial that spreads by long creeping stems. It is characteristic of wet grassland, and thus might be negatively affected by reduced rainfall. At both sites, the maximum effective height was within the range of up to 60 cm given by Stace (2014), but there was large variability in the data. At OWP, there were two other species of buttercup present, meadow buttercup (*R. acris*) and bulbous buttercup (*R. bulbosus*), and although care was taken, it is possible that identification errors may have added to the natural plot to plot variability. At UWE in 2016 and 2017, creeping buttercups in RR plots were slightly taller than those in Control plots and reached their maximum height earlier in the year (Figure 3.22). The height of the creeping buttercups at UWE decreased over the course of the experiment; the maximum effective height reached in 2018 was only 285 mm compared with 630 mm in 2016 (Figure 3.22). There were more records for *R. repens* in 2016 than in 2018, creeping buttercup plants became less common and were possibly being out competed by more vigorous grasses. At OWP, there was no clear difference between the maximum effective height of creeping buttercup plants in the Control plots, and those in the RR plots before the late June/early July cut (Figure 3.23). After the cut, plants in the Control plots tended to be taller.

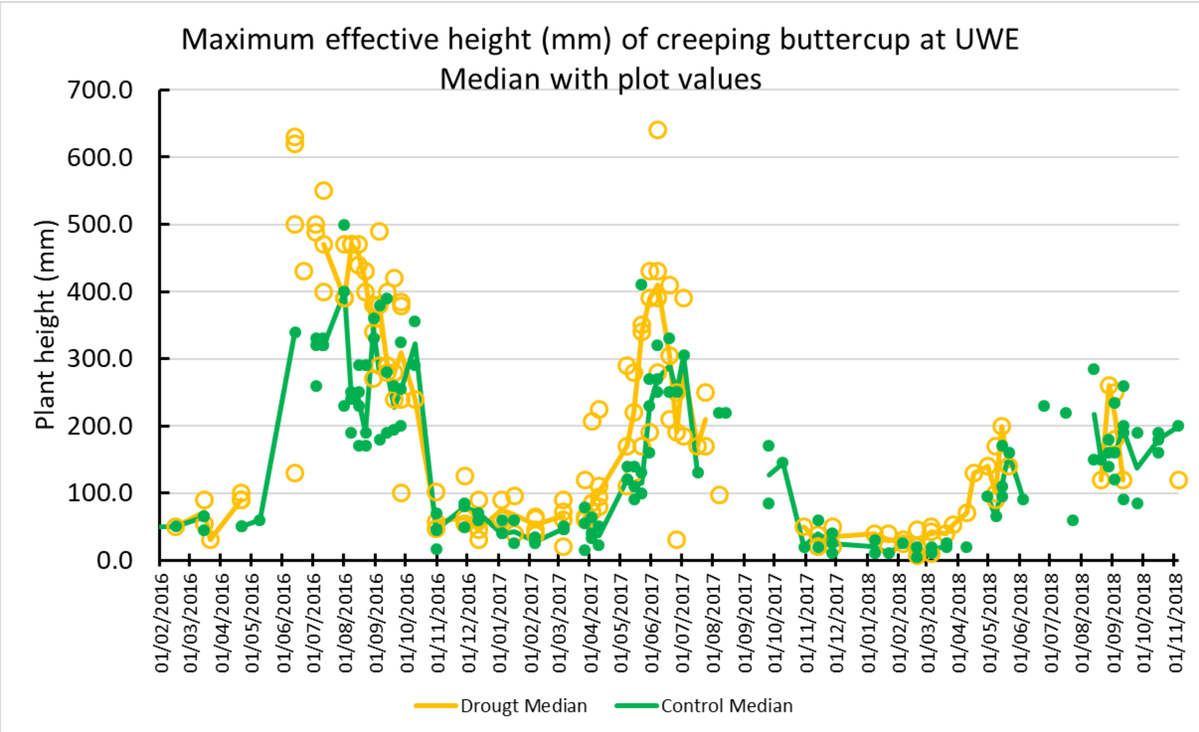


Figure 3.22. UWE Maximum effective height of creeping buttercup

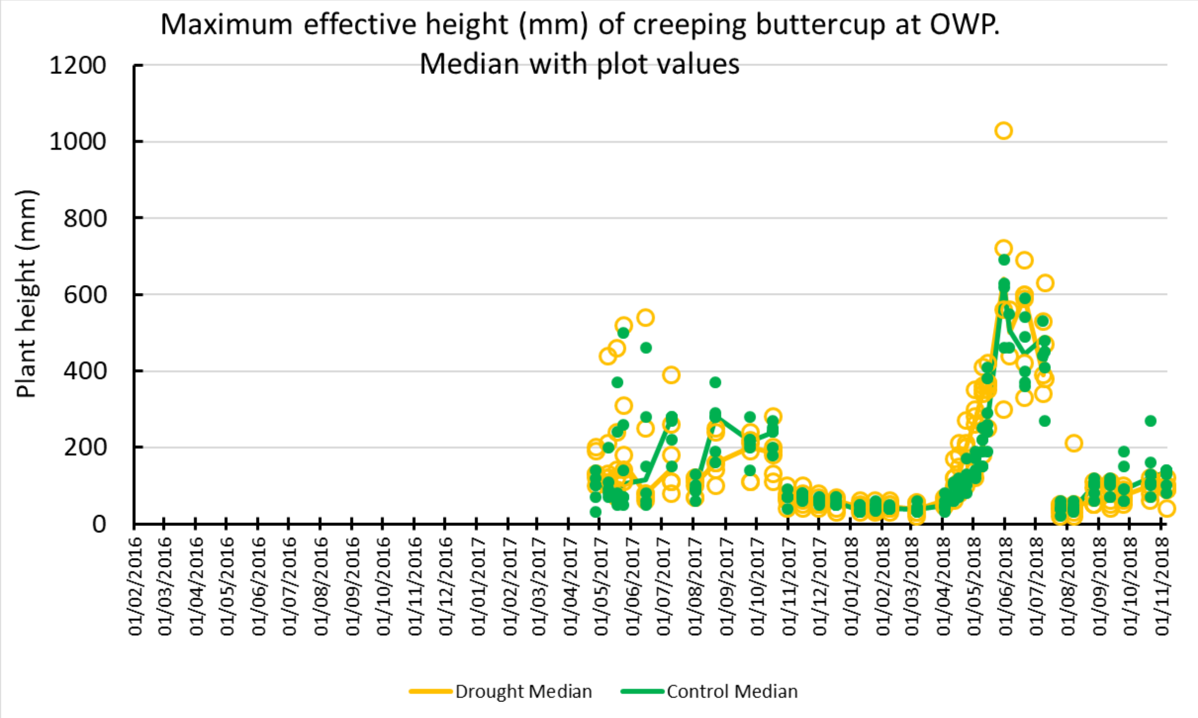


Figure 3.23. OWP Maximum effective height of creeping buttercup

Common sorrel (*Rumex acetosa*) is a tap-rooted perennial. The tap root means that the plant can access a greater depth of soil than adventitiously rooted species, and this may make it more tolerant of dry conditions. At both sites, plants of common sorrel were similar in height in each year of the experiment (Figure 3.24 and 3.25), and taller than the usual height range of 300 – 800 mm (Rose, 1981). At UWE, plants of common sorrel tended to be slightly taller in the reduced rainfall plots, but there was no clear difference in height between plants in either RR or Control plots (Figure 3.24). At OWP, before the late June/early July cut, plants in RR plots were a similar height to, or slightly taller than, plants of common sorrel in Control plots (Figure 3.25). After the cut, plants of common sorrel in the Control plots were slightly taller than those in RR plots (Figure 3.25).

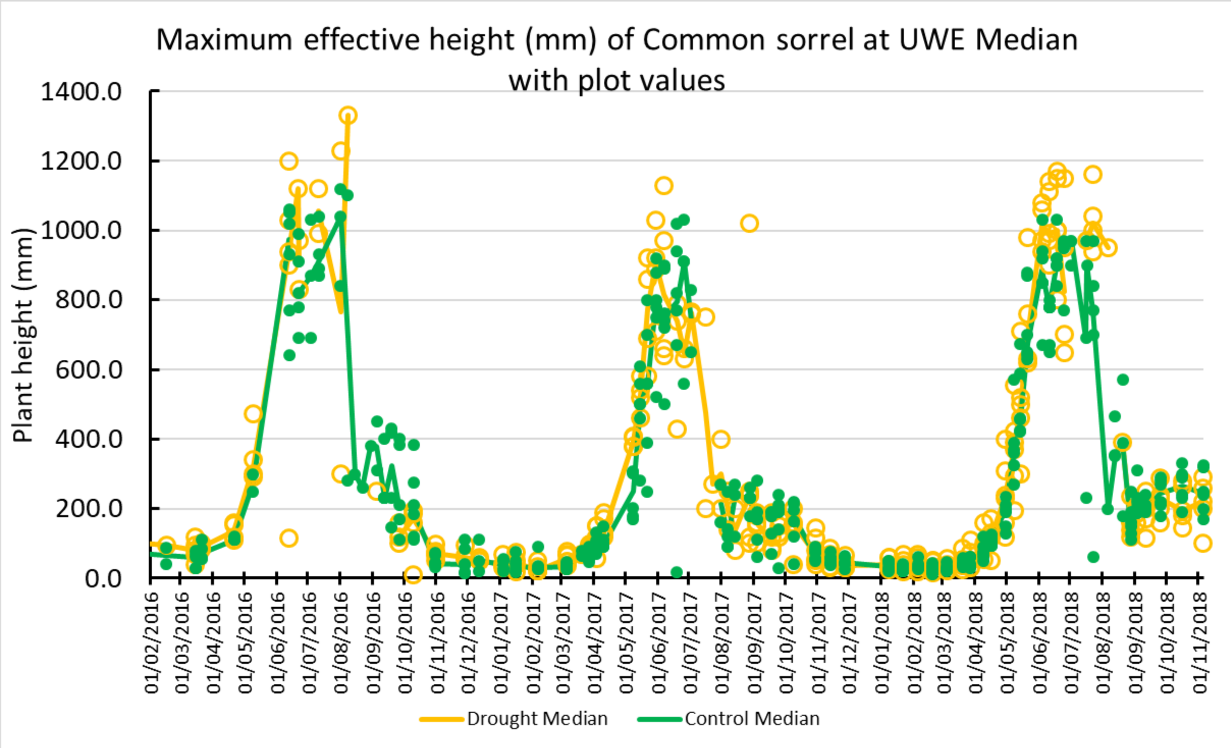


Figure 3.24. UWE Maximum effective height of common sorrel

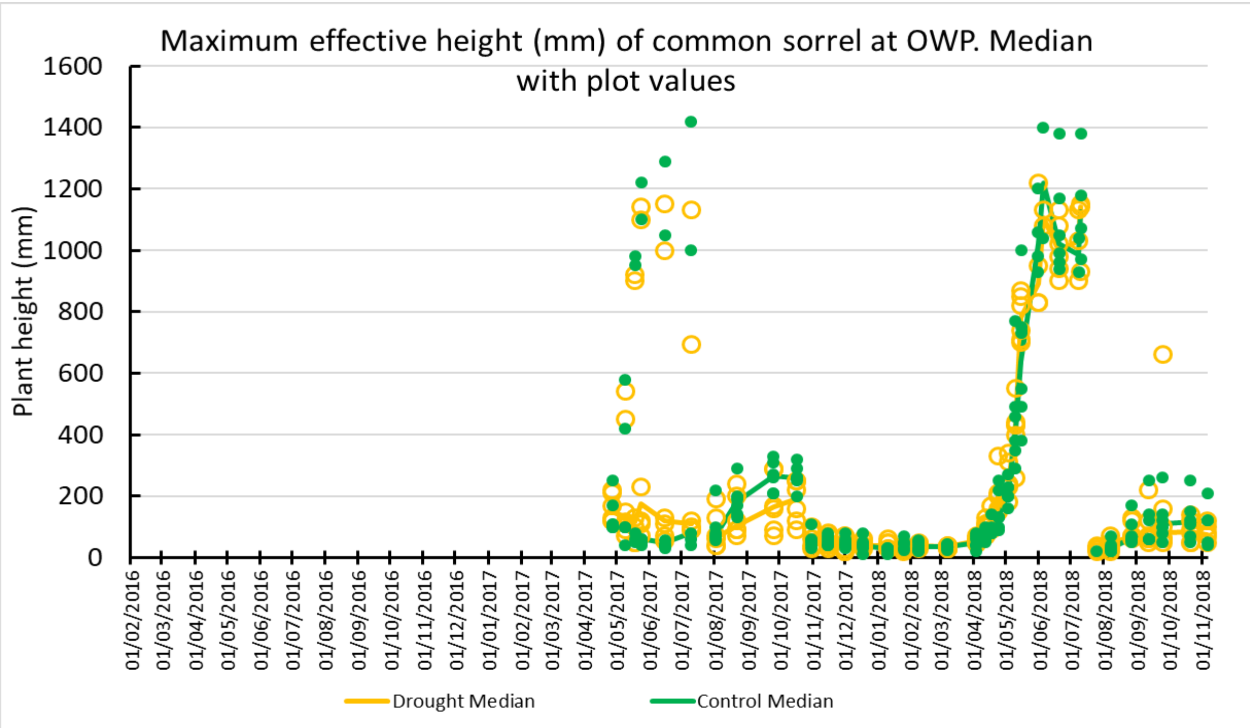


Figure 3.25. OWP Maximum effective height of common sorrel

Tares (*Vicia tetrasperma and V. hirsuta*) are annuals with a sprawling habit in contrast to birdsfoot trefoil (*Lotus corniculatus*), which is a creeping perennial. At UWE, the tares were slightly taller in 2016 than in 2017 or 2018, and were similar in height to the grass (Yorkshire fog) and the sorrel, reflecting that they are supported other plants. There was a slight tendency for tares in RR plots to be taller than those in Control plots, but there was no clear separation between tares in RR plots and tares in Control plots on the basis of height (Figure 3.26). At OWP, plants of birdsfoot trefoil in RR plots were similar in height or slightly taller than those in Control plots before the late June /early July cut (Figure 3.27), but after, particularly in 2017, plants in RR plots tended to be shorter than those in Control plots (Figure 3.27).

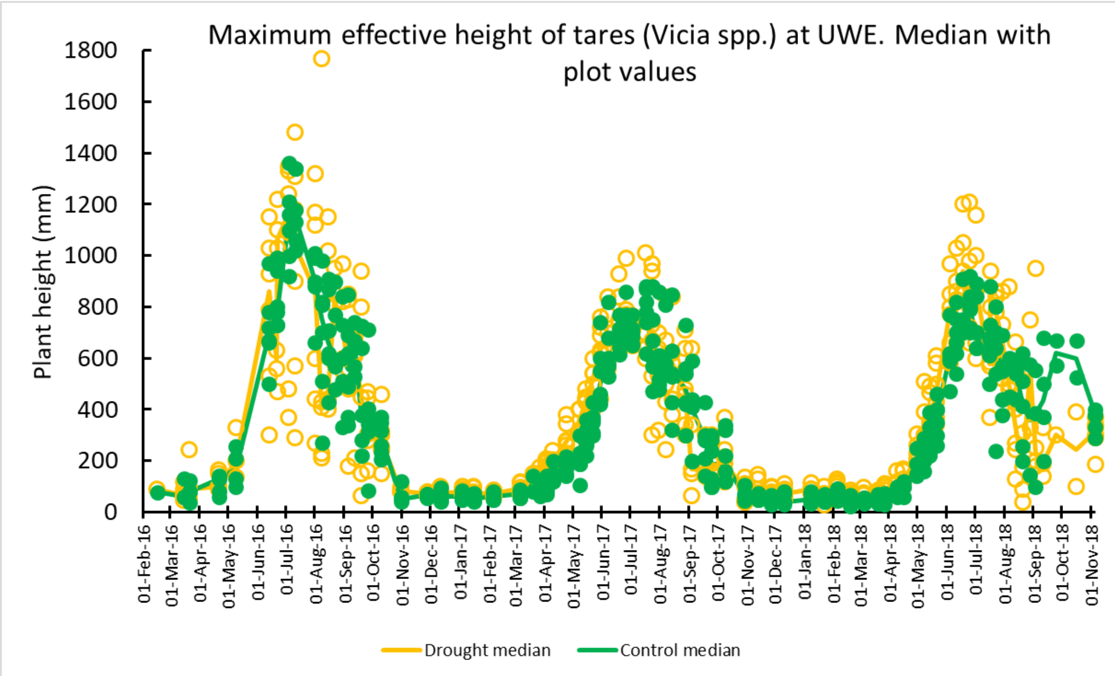


Figure 3.26. UWE Maximum effective height of tares

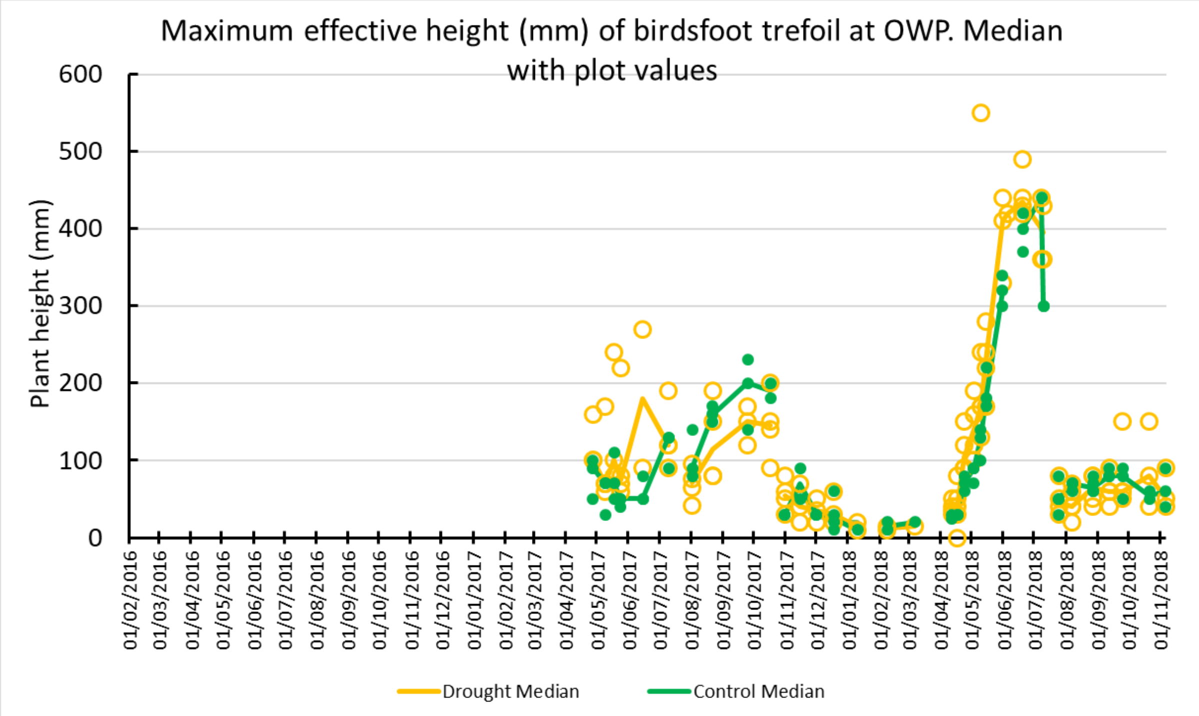


Figure 3.27. OWP Maximum effective height of Birdsfoot trefoil

At UWE, the maximum effective height of the plant species that were monitored in the RR plots was similar, and sometimes slightly greater than the maximum effective height of the same species measured in the Control plots. This effect was clearest for tall perennial plants such as the grass, Yorkshire fog, and Common sorrel (Figure 3.20 and 3.24). At OWP, differences between plants in RR and Control plots before the late June/early July cut were smaller and difficult to separate from between plot variation, but median values were lower in plants from RR plots (Figure 3.18, 3.21,.3.23, 3.25 and 3.27). After the late June/early July cut at OWP, the maximum effective height of plants in the RR plots was less (the plants were shorter) than that of plants in Control plots (Figure 3.19, 3.21, 3.23, 3.25 and 3.27). The pattern seen in the data, from each site, about maximum effective plant height is similar to that seen in the biomass data (Figure 3.13 and 3.14).

3.5.2 *Maximum plant height at random points*

The measurements made at random points gave us an opportunity to estimate the *average* maximum height of the sward, within each treatment. At UWE, the vegetation in the RR plots was slightly taller than in the Control plots (Figure 3.28), and this difference though small, was statistically significant (t= -5.376, p= 0.000, 1471 degrees of freedom). Figure 3.29 shows data for one RR plot and one Control plot, at UWE, to illustrate the within plot variability.

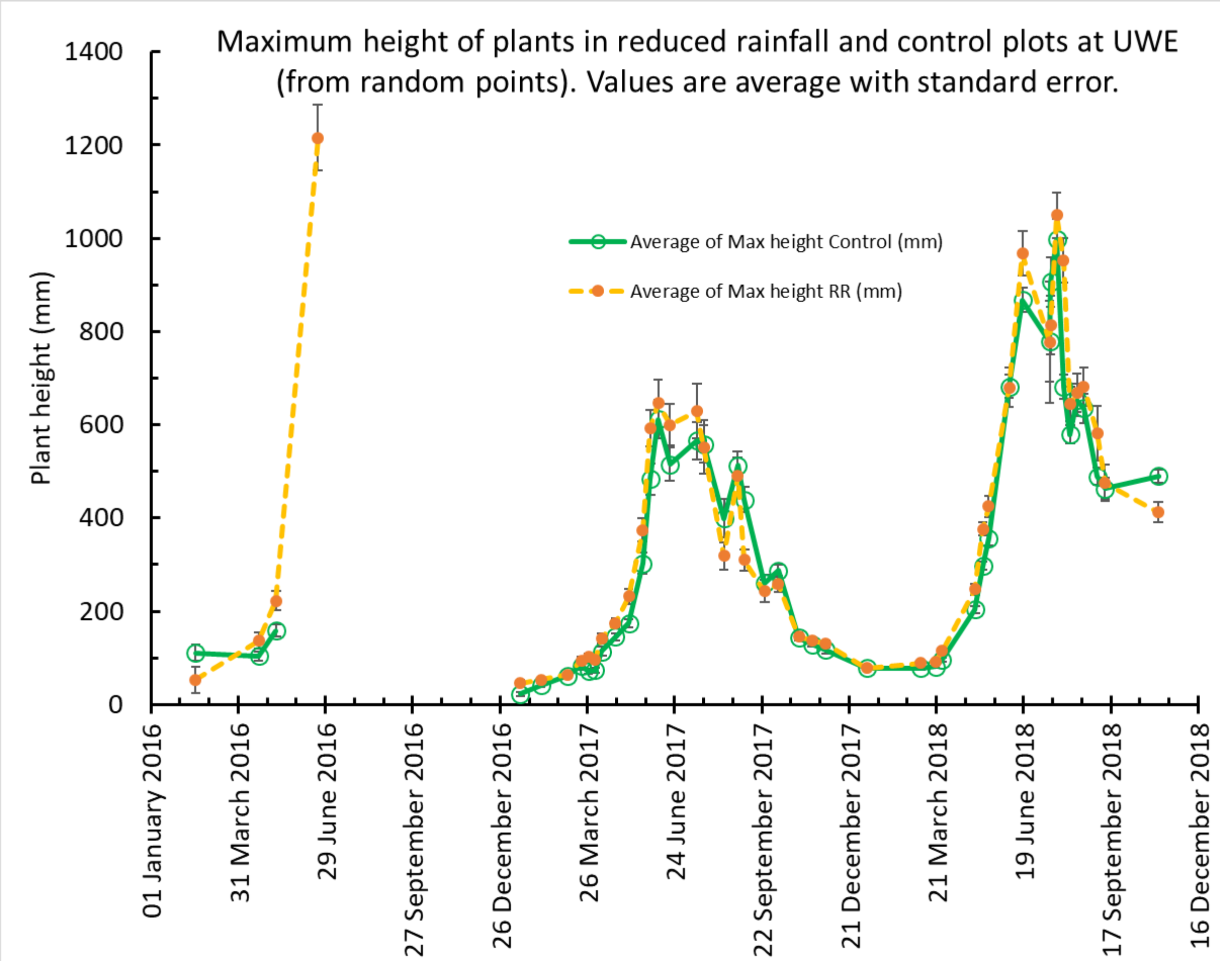


Figure 3.28. UWE maximum height of vegetation (from random points) in Control and reduced rainfall plots.

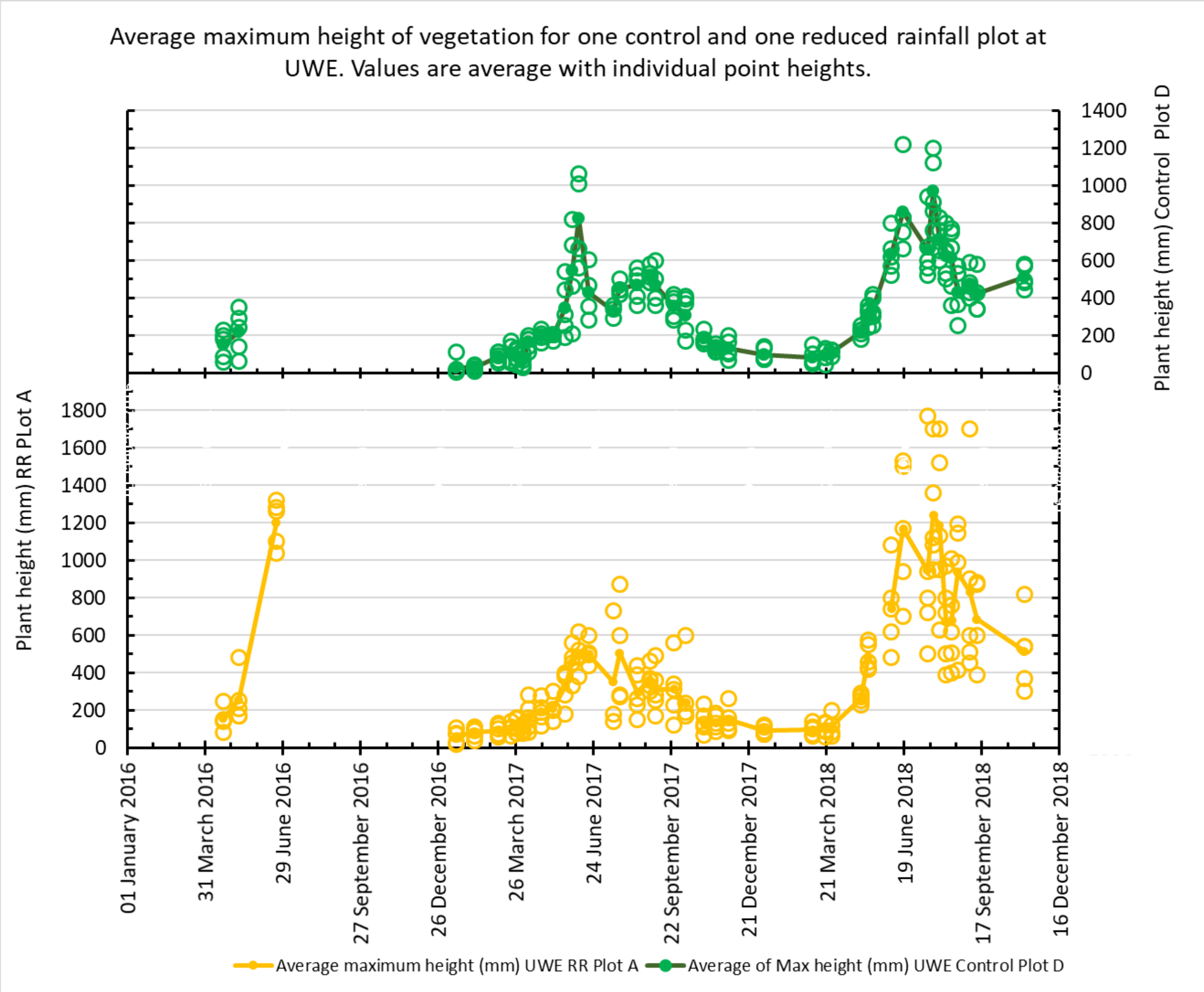


Figure 3.29. UWE Average maximum height for example Control and reduced rainfall plots

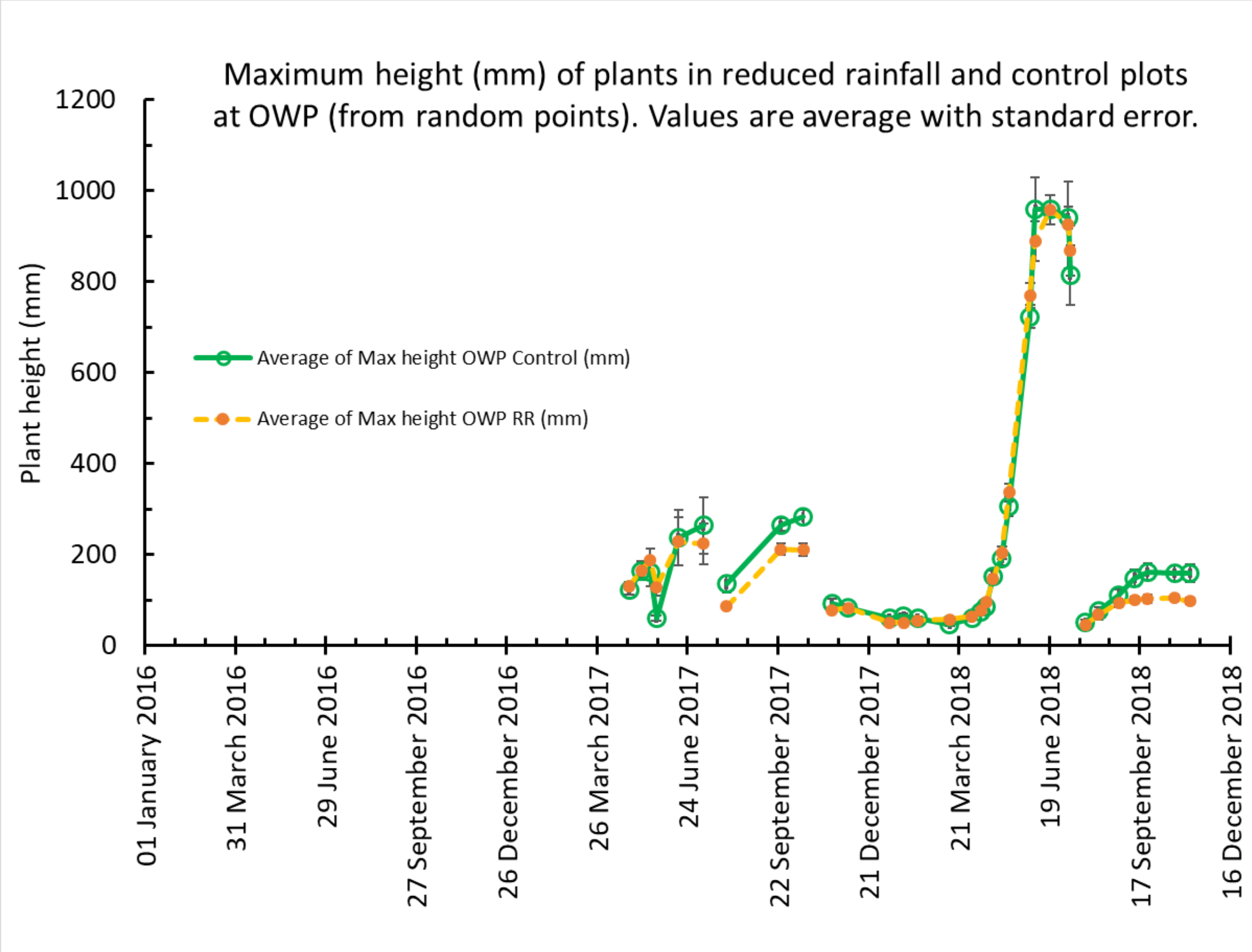


Figure 3.30. OWP maximum height of vegetation (from random points) in Control and reduced rainfall plots.

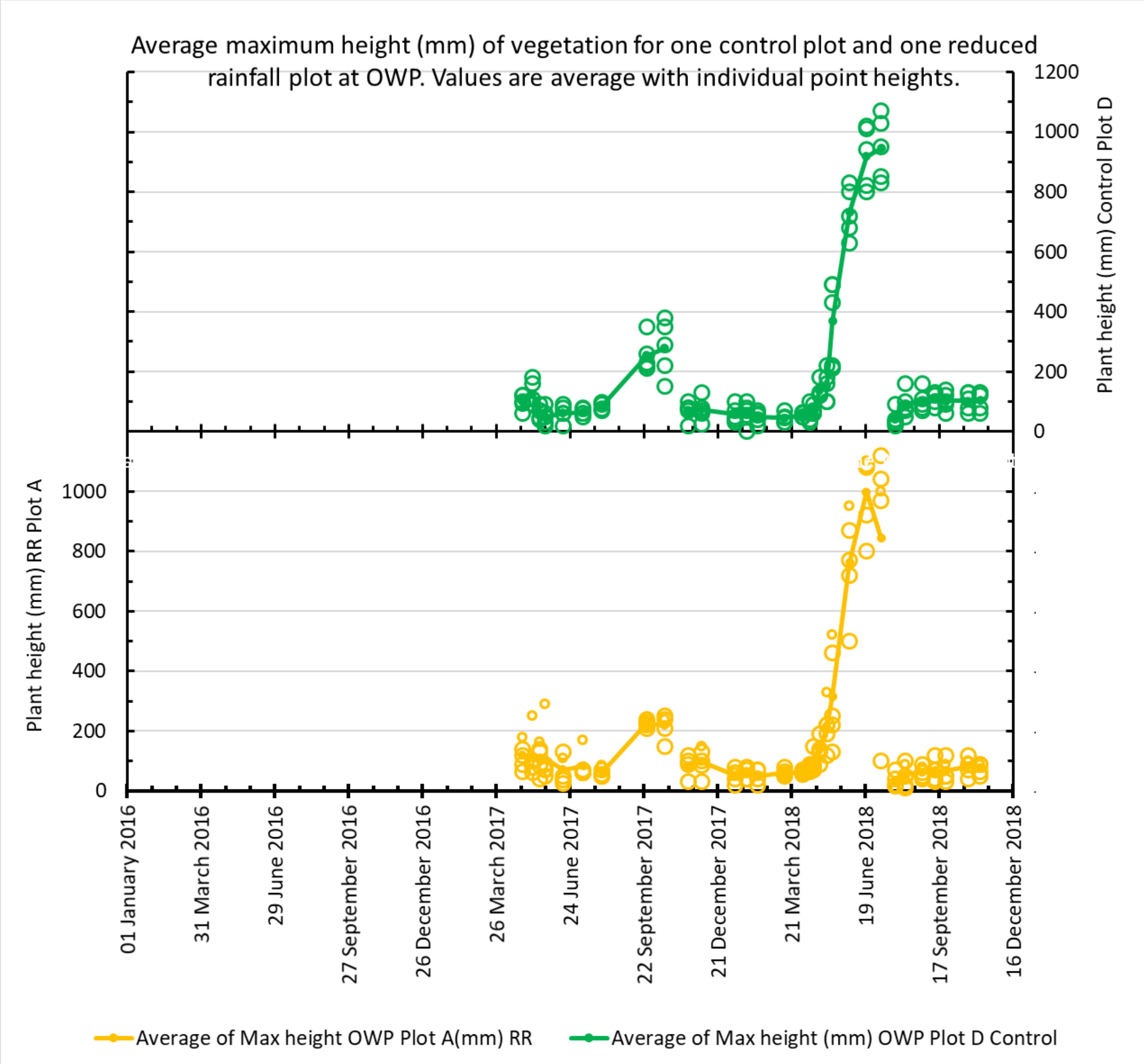


Figure 3.31. OWP Average maximum height for example Control and reduced rainfall plots

At OWP, there was little difference in height between the plants in the RR plots, and those in the Control plots for the period before the late June/early July cut (t=0.635, *p*=0.513, 692 degrees of freedom). As is shown clearly in Figure 3.30, after the cut, plants in RR plots were shorter than those in Control plots, and this difference was statistically significant (t= 5.349, *p* = 0.000, 209 degrees of freedom). Example data for one Control plot and one RR plot, at OWP, are shown in Figure 3.31. These data, about average maximum height, show a similar pattern to those from the measurements of maximum effective height of selected species. In a phenology study at OWP, during 2015/2016, *Lolium perenne* plants in RR plots were taller in late June (by about 100 mm) than *L. perenne* in Control plots. After the plots were cut in early July, *L. perenne* plants in RR plots grew more slowly, and in early September were 100 mm shorter than *L. perenne* plants in Control plots (Cairney, 2016).

There was much less within plot variation in the heights of plants measured at the random points at OWP than at UWE, and this agrees with field observations that the sward at OWP was more even and had fewer tussocks than that at UWE.

3.5.3 *Height of the tallest plant*

The tallest plants at UWE were grasses, Cocksfoot (*Dactylis glomerata*) and False oat grass (*Arrhenatherum elatius*), and hogweed (*Herculaneum spondylium*). At UWE, there was no difference between Control and RR plots in the height of the tallest graminoid or the tallest broadleaved plants (Table 3.13) averaged over all three years of the experiment, but there was considerable plot to plot variation.

At OWP, the tallest plants were grasses, Meadow foxtail (*Alopeceurus pratense*), Cocksfoot (*Dactylis glomerata*) and Yorkshire fog (*Holcus lanatus*), common sorrel (*Rumex acetosa*) and creeping thistle (*Cirsium arvense*). There was no large difference in the height of the tallest plants measured in control or RR plots at OWP (Table 3.13), although broadleaved plants in RR plots were shorter. As at UWE, there was considerable plot-to-plot variation.

At both sites, the tallest plants were all perennials and therefore would have been able to access water from more of the soil profile than annual plants. The soil moisture profiles show that at UWE, there was little difference between RR and Control plots in the % soil moisture content at 50 cm and at 90 cm (Figure 3.6), and it seems likely that at UWE, the tallest plant species were able to avoid summer moisture stress and draw on soil reserves of water. These perennial plant species may have benefited from the slightly warmer sub-surface conditions of the soil during the early spring. In contrast at OWP, although we only have data for 2018, the broadleaved plants were shorter in RR plots; two things may partly explain this. One of the tallest plants at OWP was creeping thistle, an adventitiously rooted species that would have been likely to experience water stress during the summer in both RR and Control plots. At OWP, the % soil moisture content at 50 cm and 90 cm in RR plots (Figure 3.6) declined during the summer so that even deep rooted perennials may have experienced some water stress.

Table 3.13. Average height (mm) of the tallest graminoid or broadleaved plant measured in each plot for Control and reduced rainfall plots at UWE and OWP.

Treatment		**Control**				**Reduced rainfall**			
		Height of tallest graminoid plant (mm)		Height of tallest Broadleaved plant (mm)		Height of tallest graminoid plant (mm)		Height of tallest Broadleaved plant (mm)	
Year	**Site**	Mean	SE (n)	Mean	SE (n)	Mean	SE (n)	Mean	SE (n)
2016	**UWE**	1597	57 (6)	1443	61(5)	1804	124 (6)	1514	97 (6)
2017	**UWE**	1464	44 (6)	858	74 (6)	1492	61 (6)	886	113 (6)
2018	**UWE**	1582	18 (6)	958	30 (6)	1602	25 (6)	1144	46 (6)
2018	**OWP**	1217	71 (6)	1139	76 (5)	1193	62 (6)	952	148 (6)

At both sites, UWE and OWP, Yorkshire fog and Common sorrel were slightly taller than the height given in standard reference works (section 3.5.1) (Hubbard, 1976; Stace, 2014; Rose, 1981), and the tallest plants tended to be so-called 'coarse grasses' such as Cocksfoot and False oat grass (section 3.5.3). There is some evidence that the height of coarse perennial grasses may be increasing in the UK, and elsewhere in Europe, because of deposition of atmospheric nitrogen released from vehicle exhausts (Marren, 2000; WHO, 2000). The UWE site is close to the M32 motorway and is very likely to receive some air borne pollutants from the traffic. However, OWP is in a rural area where airborne pollution might be expected to be lower. Between 1961 and 2015, average air temperatures in Great Britain have risen by 0.20 ± 0.13 °C decade^{-1} (Blyth et al., 2019), and in the period 2009-2018, there have been 15% fewer days of air or ground frost, compared with 1961-1990 (Kendon et al., 2019). This warming may have permitted vigorous perennial plants at both sites to start growth during the winter and early spring.

The data collected from the three different methods used to measure plant height at the two field sites complement each other and the data about biomass. At UWE, the vegetation in the RR plots was slightly taller than in the Control plots, and slightly more biomass was collected from RR plots than from Control plots (Figure 3.13). At OWP, there was little difference in height between plants in the RR and Control plots before the late June/ early July cut, but after the cut plants in the Control plots were taller. The amount of biomass was similar in all plots before the cut but at the September harvest, more biomass was collected from Control plots than RR plots (Figure 3.14).

3.6 Numbers of flowers and pollinators

Flowers and pollinators were recorded at UWE on 56 occasions, and at OWP on 35 occasions.

At UWE, the earliest date that flowers were recorded was 20 March 2018 and the latest 27 September 2016 (Figure 3.32). At OWP, the earliest date that flowers were recorded was 28 March 2017 and the latest 17 October 2017 (Figure 3.32). Data were collected on average once every two weeks; it is possible that the flowering period was almost three weeks longer than our record. Some data about flowers and pollinators at OWP were collected in the spring of 2016, but time demands from other field tasks prevented data being collected for the rest of 2016. The flowering period at both sites would have been curtailed by the late September/early October grass cut, but at OWP, a few flowers of creeping buttercup were observed after the grass had been cut. At both UWE and OWP, the flowering season finished slightly earlier in 2018 (Figure 3.32), and this may have been due to the high temperatures and dry conditions experienced in June and July 2018 (Figures 3.1and 3.2, Table 3.2).

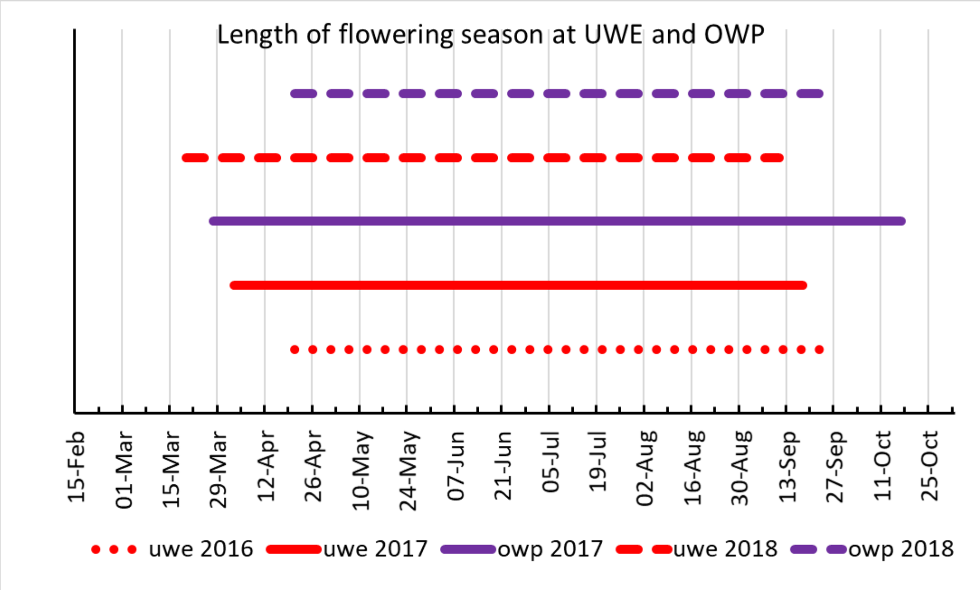


Figure 3.32. Length of flowering season at UWE and OWP

At both UWE and OWP, as might be expected, numbers of flowers and pollinators were higher during the summer months (Figure 3.33 and 3.34). To simplify the analysis, closely related species, especially if present in low numbers, were combined e.g. all types of tare were combined, all types of grass and all types of willowherb.

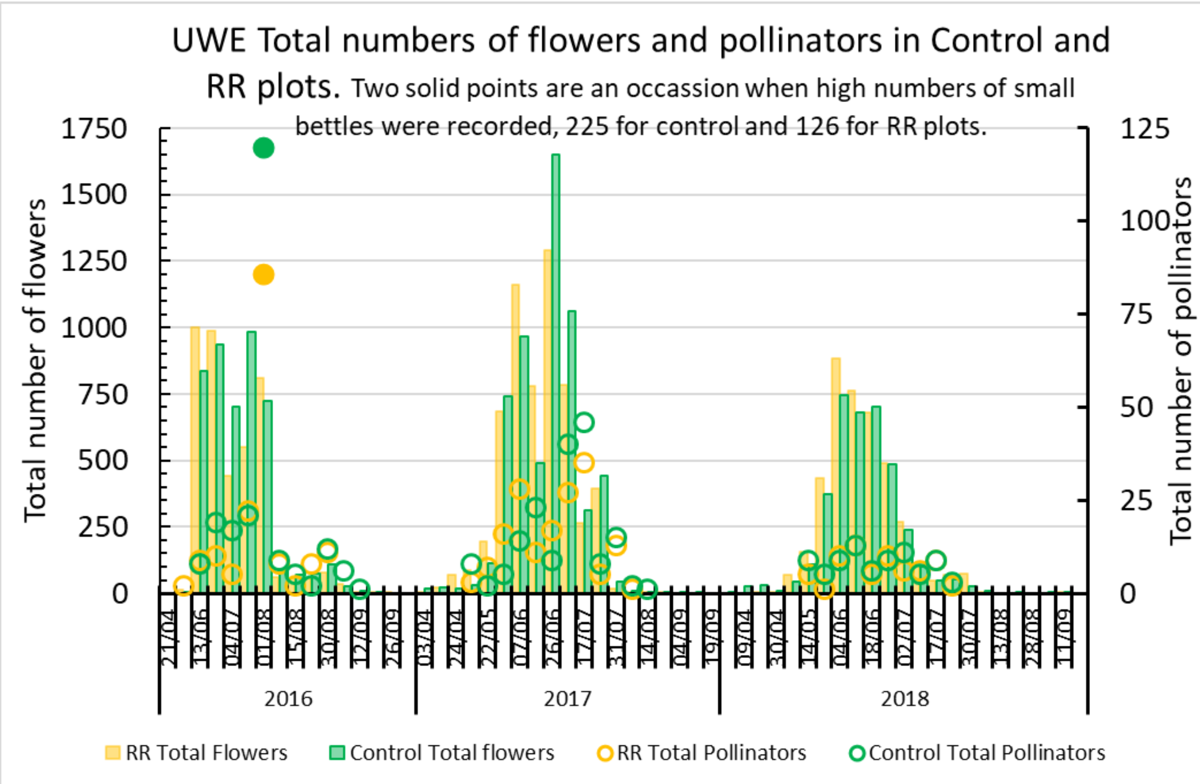


Figure 3.33. UWE Total numbers of flowers and pollinators in Control and reduced rainfall plots

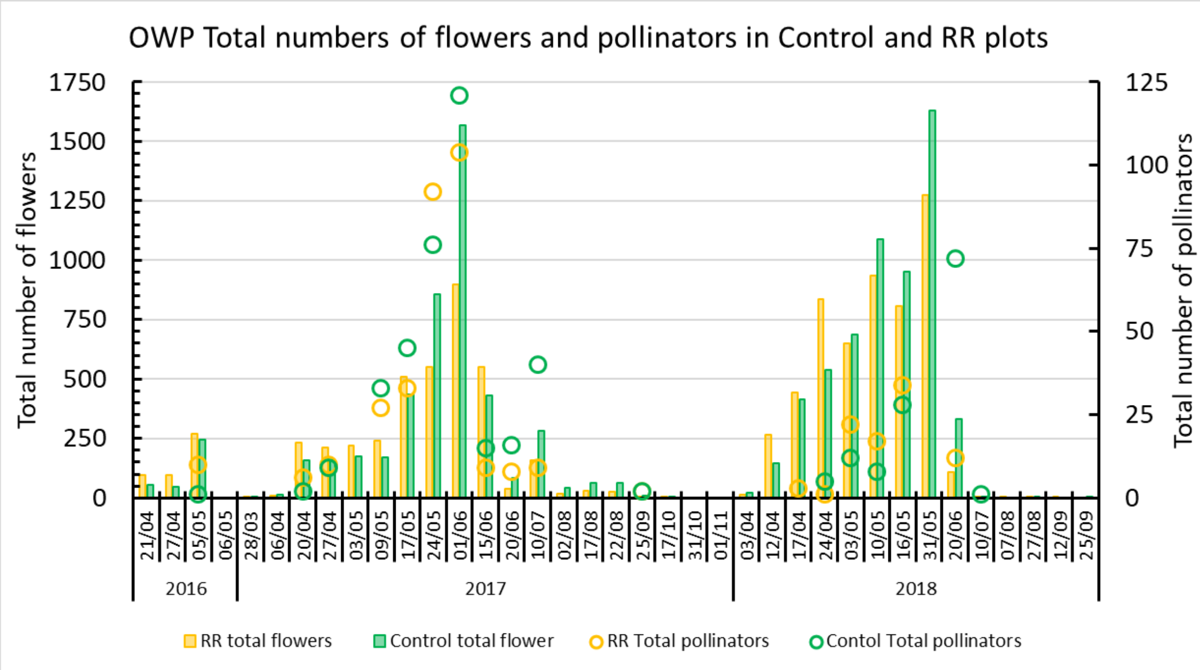


Figure 3.34. OWP Total numbers of flowers and pollinators in Control and reduced rainfall plots

At both UWE and OWP, grasses were the most frequently observed flowering plants. Grasses (and woodrushes and sedges) are wind-pollinated but many beetles feed on the pollen, and these beetles may then pollinate other types of plant; for the same reason sporulating horsetail cones were counted. Of the different types of non-graminoid flowering plant, the flowers counted most frequently at UWE were tares, and at OWP Meadow buttercups (Meadow and Bulbous buttercups combined). The largest number of flowers recorded at UWE were of tares and at OWP of Common sorrel (Figure 3.35). At both sites, despite the large number of different species present (see 3.5), most of the total number of individual observations were of three or four plant species (or groups of similar species): tares, Field bindweed and Common sorrel at UWE, and Meadow buttercups, Creeping buttercups, Birdsfoot trefoil and Common sorrel at OWP (Figure 3.35). There was no statistically significant difference between the number of flowers, recorded on each occasion, in Control plots and the number recorded from RR plots at either UWE or OWP. At both sites, in the early part of the growing season, there were slightly more flowers in RR plots than in Control plots, and in the later part of the growing season, more flowers in the Control than the RR plots (Figure 3.33 and 3.34).

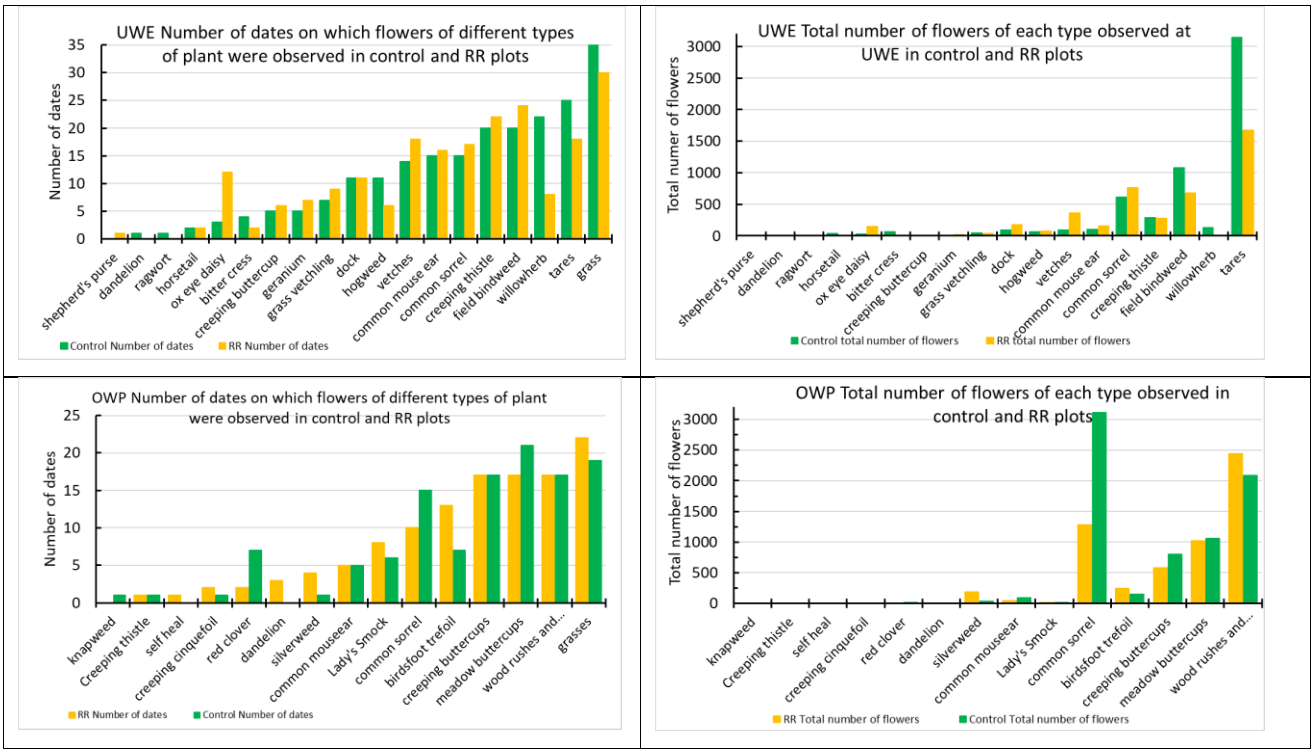


Figure 3.35. Number of dates and total number of each type of flower seen at UWE and OWP

At both UWE and OWP, flies and hoverflies were the most abundant pollinators (Figure 3.36). There are some differences between the two sites in how often different types of pollinator were seen. At UWE, all types of pollinator were seen similar numbers of times. In contrast, at OWP beetles and flies and hoverflies were seen more often than types of bee, wasps or butterflies (Figure 3.36). The farmer at OWP keeps bees and has large nectar producing flower beds and an orchard; it seems likely that bees, wasps and butterflies were attracted to these nectar rich food-sources and did not forage in the meadow. More individual pollinators were observed on each occasion at OWP (28) compared with UWE (11).

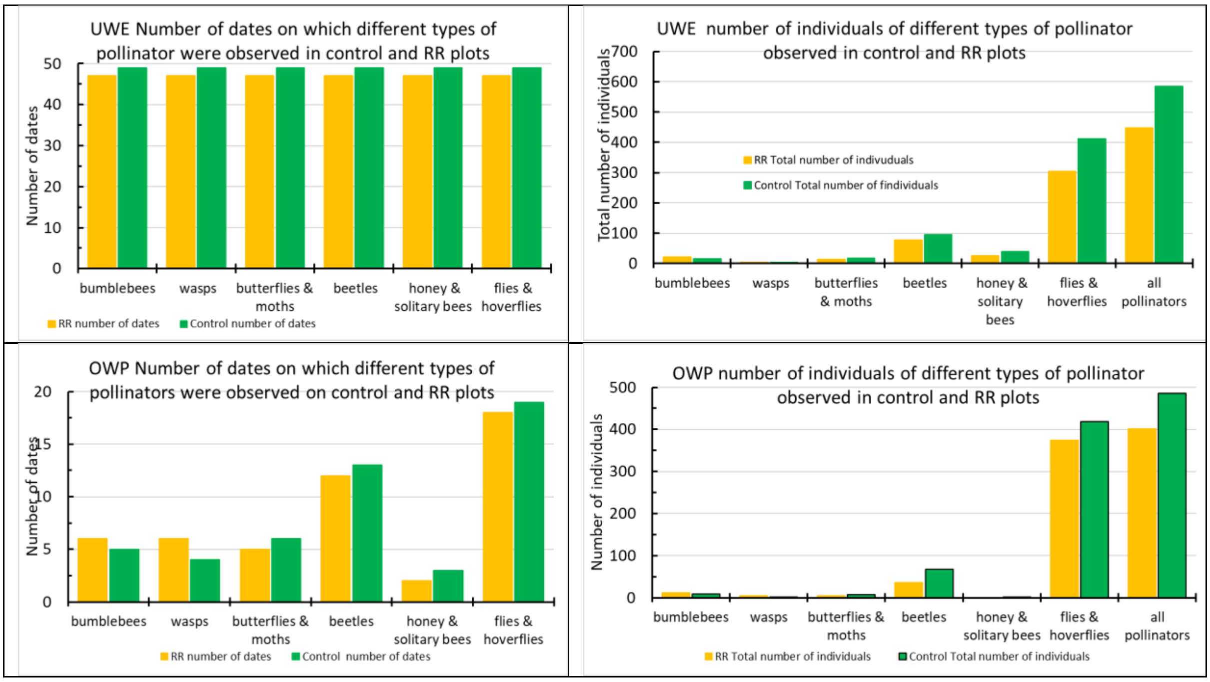


Figure 3.36. Number of dates and number of individuals of each type of pollinator seen at UWE and OWP.

The number of pollinators seen on each occasion was low and very variable. Spearman's rank correlation suggested that there was a statistically significant weak positive correlation between total number of flowers and total number of pollinators (Table 3.14), particularly at UWE. Regression analysis indicated no strong linear relationship between number of flowers and number of pollinators (Table 3.14). There was no statistically significant difference between the number of pollinators, recorded on each occasion in Control plots, and the number recorded from RR plots at either UWE or OWP, although at both sites slightly higher numbers of pollinators were observed in Control plots (Figure 3.36).

Fewer pollinators were recorded on each occasion at UWE than at OWP. However, because of the high variability within the observations, it is impossible to know if this was a genuine difference or a disturbance artefact, caused by the observers. At UWE, there was usually a minimum of two, and often four, observers present in the field at one time, but at OWP there was usually only one recorder. At UWE, the field margins contained many plants of bramble, and these appeared to attract many more pollinators than were observed in the experimental plots.

At both sites, flowers were available throughout the growing season. Drought stress can reduce numbers of flowers, flower size and volume of nectar (Phillips et al., 2018, Rering et al., 2020), but at UWE and OWP, there was no significant difference in the numbers of flowers recorded from Control and RR plots. However, during the early part of the growing season, when there were slightly more flowers in the RR plots, measurements of soil moisture tension and moisture content indicated that the plants were unlikely to be experiencing moisture stress (Figures 3.3, 3.4, 3.6, 3.7). In contrast during the latter part of the growing season when the RR plots were experiencing water stress (Figures 3.3, 3.4, 3.6, 3.7), more flowers tended to be found in the Control plots.

Table 3.14. Relationship between total number of flowers and total number of pollinators in Control and RR plots at UWE and OWP (linear regression and Spearman's rank correlation).

Site	UWE		OWP	
Treatment	Reduced Rainfall	Control	Reduced Rainfall	Control
Regression equation	5.717 + 0.016x	8.013 + 0.015x	4.345 + 0.044x	6.203 + 0.048x
R^2	0.149	0.083	0.204	0.377
Spearman's rank correlation	0.564	0.578	0.459	0.525
Significance (*p*)	0.001	0.000	0.064	0.030

Chapter 4 General Discussion

4.1 The relationship between biomass and rainfall

When the weight of biomass (yield) at UWE and OWP was plotted against annual rainfall, the data from the Control and RR plots fell into two separate groups. At both sites, for Control and RR plots, the amount of biomass tended to increase with increasing rainfall (Figure 4.1). The same pattern was seen if biomass production was plotted against rainfall as a percentage of the long-term average rainfall. We observed no further increase in biomass once rainfall exceeded around 550mm per year. Grass crops, in the UK, are reported to use around 600 - 900 mm water per year (Grove and Monaghan, 2010). Intensively managed pastures, such as rye grass leys, that are fertilized, continually grazed or harvested several times each year, and have only one or two often high yielding hybrid varieties of rye grass produce more than 20 t ha^{-1} (Jones and Humphries, 1999) need large amounts of water to sustain the production of grass. The water requirement of these non-intensively managed permanent pastures in the Bristol Frome catchment may be closer to 550-600 mm.

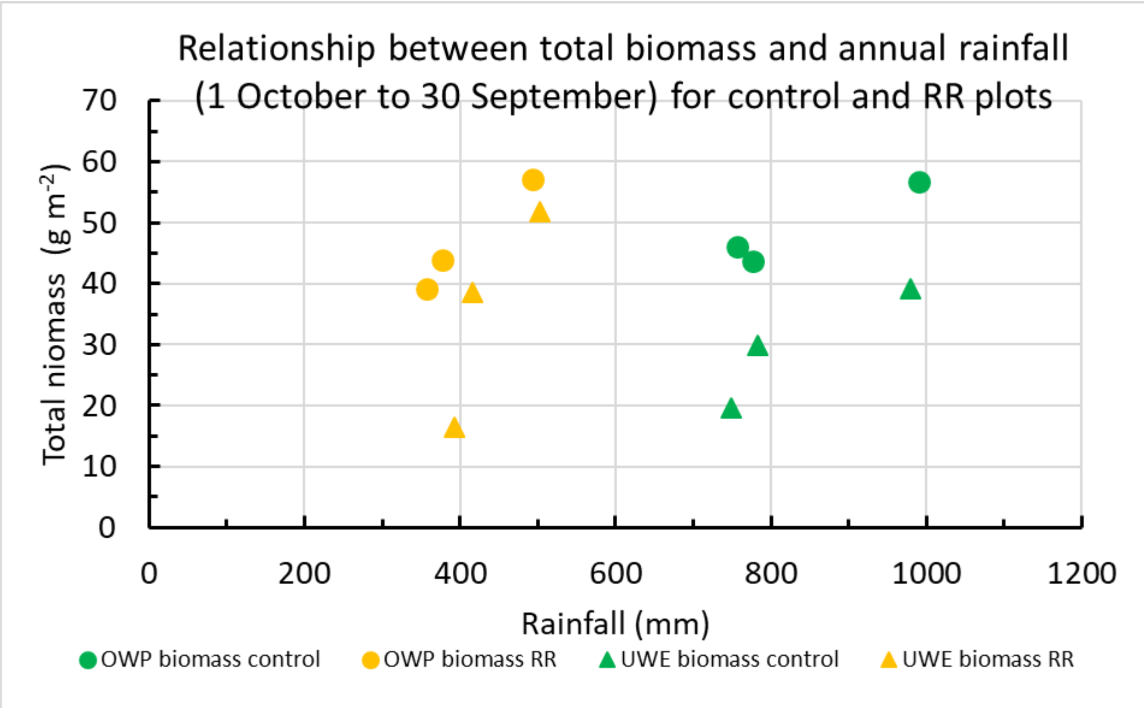


Figure 4.1. Relationship between total annual biomass production and annual precipitation at UWE and OWP for Control and RR plots.

Although total biomass did increase in the Control pots with increasing rainfall, it was never higher than the amount of biomass collected from the RR plots in 2016 (the wettest year).

The pattern of monthly rainfall was very different in each of the three years (Figures 3.1 and 3.2). Rainfall during the cooler months when evaporation and evapotranspiration is low is important for recharging groundwater reserves (Afzal and Ragab, 2019). In UK pastures, many grasses have the bulk of their roots (75-90%) in the surface 15 cm of the soil (Macklon et al., 1994), and are therefore influenced by incident rainfall as well as amount of stored moisture, particularly at times of rapid growth. To investigate the interaction between seasonal rainfall and total yield, we compared the amount of biomass produced in Control or RR plots with annual, January to March, April to June, December to April, and March to May rainfall. These comparisons highlighted some interesting differences between the two sites (see below).

At UWE, total biomass from Control and from RR plots was correlated with rainfall over each of the periods selected, and the correlation was statistically significant (Table 4.1). At OWP, total biomass from Control plots was only weakly correlated with rainfall whilst that from RR plots was correlated with annual, winter and spring rainfall, but not with December to April or March to May rainfall (Table 4.1).

Table 4.1. Correlations between total biomass (g m^2) and rainfall (mm) n=18

Site	**OWP**				**UWE**			
Treatment	**Control**		**RR**		**Control**		**RR**	
Rainfall period	**Pearson Correlation**	**Statistical significance (*p*)**	**Pear. Correl.**	**Stat. signif. (*p*)**	**Pear. Correl.**	**Stat. signif. (*p*)**	**Pear. Correl.**	**Stat. signif. (*p*)**
Annual		ns	0.52	0.028	0.70	0.001	0.66	0.003
Winter (Jan-Mar)		ns	0.49	0.038	0.77	0.000	0.74	0.000
Spring (Apr-Jun)		ns	0.52	0.028	0.69	0.001	0.65	0.003
Dec-Apr		ns		ns	0.70	0.001	0.71	0.001
Mar-May		ns		ns	0.67	0.002	0.64	0.004

It is possible to make an estimate of how much biomass is produced for each mm of rain - the ‘water productivity’. Water productivity was greater in the RR plots than in the Control plots. Within each treatment, water productivity was similar across all three years of the experiment, with one exception. If the continued rainfall reduction had altered the way that the plants utilized water, we might have expected the water productivity to increase. The year 2017, for RR plots at UWE, stands out because the water productivity was so low. At UWE in 2017, biomass production, compared to that measured in 2016, was reduced in Control plots to 50%, and in RR plots to 32%. In contrast in 2018, equivalent figures were 76% and 75% for Control and RR plots. At OWP, biomass production was less variable. Total biomass in 2017 compared to 2016 was 81% in Control plots and 68% in RR plots, and in 2018, biomass at OWP was 77% of the 2016 value.

Table 4.2. Water productivity (g m^{-2} mm^{-1}) of Control and RR plots at UWE and OWP

Harvest Year	UWE		OWP	
	Control	RR	Control	RR
2016	0.8	2	1.2	2.4
2017	0.6	0.8	1.2	2.2
2018	0.8	1.8	1.2	2.4

At both OWP and UWE, less biomass was produced in 2017 and 2018 than in 2016 (Figure 3.13 and 3.14). Annual rainfall at both sites in 2017 and 2018 was about 92 % of the 1961-2017 catchment average in Control plots and 46 % in RR plots, in contrast to 2015/16 when rainfall was 120% of long-term average in Control and 60% in RR (Table 3.1). In 2015/2016, RR plots received less rainfall than Control plots did in either 2016/2017 or 2007/2018, so the difference in productivity between years cannot be explained simply in terms of the amount of annual rainfall.

We anticipated that biomass production between July and September would be strongly correlated with rainfall in July, August and September; however, this was not the case. The smallest amount of regrowth was recorded from RR plots in the 2016/2017 season when the July to September rainfall total was the highest (Figures 3.1, 3.2, 3.13 and 3.14).

4.2 The relationship between plant height and rainfall

Measurements of plant height are sometimes used as a proxy for biomass when destructive sampling is not practical or desirable. In a study of the adaptation of a newly established mesotrophic grassland (at Silwood Park, Berkshire UK) to summer drought, Lee et al. (2014) measured plant height in all study years, but only took destructive samples in the final year. In our experiment, the patterns seen in plant height are broadly similar to those seen in the biomass data, but with some exceptions. The vegetation tended to be shorter in 2017 compared with 2016 and 2018.

At OWP, the plots were all cut in late June/early July so we cannot directly compare the relationship between plant height and rainfall with the relationship between biomass and rainfall. For both UWE and OWP, we calculated the amount of rainfall from 1 October until the end of the month before the greatest average maximum height was recorded (for example, if the maximum height was recorded on 7 June, rainfall from 1 October until 30 May was summed). For OWP only, we noted the greatest average maximum height during the period after the late June/early July cut, and summed rainfall from 1 July until the end of the month before the measurement was made. The greatest average maximum height of vegetation was plotted against rainfall for the period preceding the measurement (Figure 4.2). As with the data about biomass, the data fell into two groups, those from Control or those from RR plots. There was a linear relationship between rainfall and plant height (Control plots R^2 =0.73, p = 0.03; RR plots R^2 = 0.82, p = 0.01). Two points seem to fall outside the general trend, and these are both for OWP in 2017 before the late June/early

July cut. If we group data from UWE and OWP together, plant height was strongly and positively correlated with rainfall (Table 4.3). There were too few years of data to make valid statistical comparisons between the two field sites (UWE and OWP).

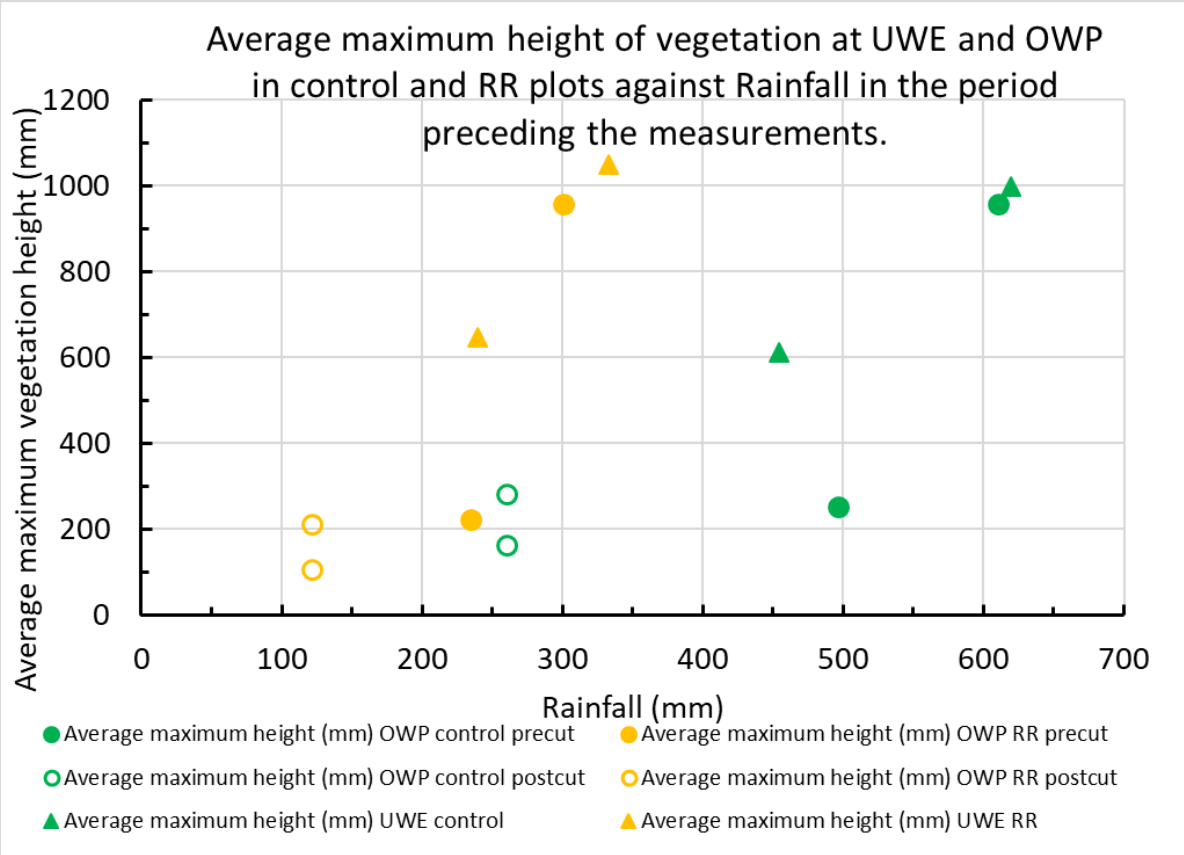


Figure 4.2. Relationship between average maximum vegetation height (mm) and cumulative precipitation (mm) at UWE and OWP for Control and RR plots.

The two outlying points for OWP in early summer of 2017 are interesting. The growth of the pasture in 2017, as measured by plant height, was weak compared with 2018 (Figure 4.2), but there was little difference in the dry weight of biomass collected from the plots in 2017 and 2018. This illustrates the difficulty of using measurements of plant height to estimate biomass. The leaves of most plants are more than 90% water, and the turgor generated by water in the plant is essential for cell expansion (Meidner and Sheriff, 1976). Therefore the length of live leaves is very strongly related to water supply (rainfall). However, in the biomass samples, dead plant material made up 34 – 62 % of the dry matter, and since dead material may contain as little as 25 – 30 % water, the relationship between total biomass and rainfall is weaker. Regression analysis of the data about cumulative rainfall and biomass or plant height (Figures 4.1 and 4.2) supports the view that plant height is more closely related to cumulative rainfall than is total dry biomass. For data about biomass, regression analysis of biomass against cumulative rainfall only explained 40% and 31% of the variation (for Control or RR plots respectively); whereas for plant height, the regression analysis explained 73% and 82% of the variation.

Table 4.3 Pearson Correlation coefficient for relationship between average maximum plant height (mm) and cumulative rainfall (mm) for samples from Control and reduced rainfall (RR) plots at UWE and OWP.

Treatment	Control			RR			All		
	Pearson Correlation	Stat. signif. (*p*)	n	Pear. Correl.	Stat. signif. (*p*)	n	Pear. Correl.	Stat. signif. (*p*)	n
	0.85	0.03	6	0.91	0.01	6	0.68	0.04	12

4.3 Soil moisture and plant growth

The amount of rainfall (or total of all forms of precipitation) combined with the soil type and other climatic conditions influences the soil moisture content and soil moisture tension. Although plants can take up some moisture directly from rainfall through the cuticle (Meidner and Sheriff, 1976), most terrestrial plants rely on water held in the soil.

At both UWE and OWP, in Control and RR plots, in the year 1 October 2015/ 30 September 2016 soil water was freely available to plants until June but in 2016/2017 only until April, and in 2017/2018 until May (Figure 3.3 and 3.4). In 2016/17 and 2017/2018, the plants would have been experiencing some level of water stress during the spring growing season. Soil moisture stress reduces plant growth through effects on turgor and effects on photosynthetic activity (Van Peer et al., 2004).

At UWE, in the summer of 2016/2017 (based on plots of soil moisture content and the soil moisture characteristic (Figure 3.5 and 3.7) of the Worcester series soil), little soil water was available to the plants and this limited growth.

At OWP, there was a positive correlation between the amount of regrowth measured in September, and the average soil moisture content (%) and soil moisture tension (kPa) measured in June of each year (Figure 3.14, 3.4 and 3.6). The smallest amount of regrowth occurred in 2017, the year in which soil moisture tension increased earlier in the year.

A review of the effects of drought on the growth of forage grasses in Poland~~,~~ found that spring droughts often reduced the productivity of pastures, and the early regrowth of meadow swards while summer drought reduced the second regrowth of meadows (Staniak and Kocon, 2015).

There are some differences between these two field sites in the R. Frome catchment. The pasture at OWP is well established, at least 80 years old, and carefully managed. At UWE, the pasture is only 30-40 years old, and receives little regular management. At OWP, soil moisture content % at 50 cm in the RR plots decreased during the summer of 2017 and 2018. At OWP, there is a tightly knit sward with many perennial nitrogen fixing species, such as~~,~~ *Trifolium repens*, *T. pratense* and *Lotus corniculatus*. T~~; t~~hese species have been reported to be able to take up water from about 30% deeper in the soil than rye grass, enabling them to withstand dry conditions (Grieu et al., 2001). In contrast, at UWE, there was no evidence that the vegetation in RR plots was extracting water from a greater depth in the soil than vegetation in the Control plots. Soil moisture content (%) at 50 cm depth, in the RR plots was similar to that in Control plots. The sward, at UWE, is dominated by vigorous but tussock forming grasses and many of the nitrogen fixing plants present are annual species, such as, *Vicia hirsuta* and *V. tetrasperma*. These differences may partly explain why the early season dry conditions of 2016/2017 affected biomass production at UWE more than biomass production at OWP.

4.4 How do our results compare with other studies?

In a meta-analysis of long-term ecological studies in the USA, above ground net primary production was found to be strongly correlated with annual precipitation (Knapp and Smith, 2001). Other meta-analyses that included studies from a wider geographical area (Beier et al., 2012; Wilcox et al., 2016), have found considerable heterogeneity in the responses of grasslands to reduced rainfall. Matos et al. (2020) considered that the relationship between rainfall and productivity is complex with productivity saturating at high rainfall, and declining abruptly when water availability fell below a threshold value. Our data, which show similar yields from the Control and RR plots, support this view (Matos et al., 2020). Many of the published studies about the effects of drought or reduced rainfall on grassland productivity are from semi-arid environments. In a semi-arid Australian grassland, a 50% reduction in rainfall was associated with a decrease in biomass (Gibson-Forty et al., 2016); however in semi- arid environments, rainfall is likely to be a factor limiting productivity. There are fewer studies from regions where rainfall is not generally considered to limit productivity. Other studies of grasslands in UK have shown that reducing summer rainfall has little effect on biomass production (Grime et al., 2000; Fry et al., 2014). Computer modelling of the impacts of climate change, including reduced summer rainfall, on grass yield in Ireland (Holden and Brereton, 2002) foresaw no catastrophic impacts, but noted that yield might increase in the north and decline in the south and east. Many managed grassland systems are considered to have high adaptive potential, and in North and North West Europe, future climate change may lead to increased herbage growth (Hopkins and del Prado, 2007).

Chapter 5 Conclusions

This experiment aimed to understand how predicted changes in the climate, especially a decrease in summer rainfall, will affect the productivity of permanent pastures in UK. The experiment successfully reduced incident rainfall by 50 %.

The plots were not hydrologically isolated; lateral movement of water within the soil would have been possible. Measurements of soil moisture showed that, during summer, at 10 cm moisture content (%) was lower and soil moisture tension was higher in the reduced rainfall plots than in Control plots. At OWP, soil moisture content, during summer, at 50 cm and 90 cm was also lower in RR plots than in Control plots. This indicates that the treatment was successful in reducing soil water content, as well as reducing incident rainfall. In pastures, the majority of grass species have about 75% of roots in the upper 10 - 15 cm of soil (Macklon et al., 1994). Any differences between the two treatments would expected to be greater in the surface layers where moisture content is more strongly influenced by prevailing weather conditions.

Although we succeeded in reducing rainfall by about 50% relative to incident rainfall, this was not the same as reducing rainfall to 50% of the long-term average. Several authors have suggested that well-established grassland communities are already adapted to environmental stress (Grime et al., 2008, Matos et al., 2020), because for rainfall, long-term trends are smaller than inter-annual variation. In our experiment, values of reduced rainfall were within those recorded over the last one hundred years.

In the Bristol Frome catchment and the rest of the UK, future summer rainfall is predicted to decrease, but winter rainfall is predicted to increase (UKCP2018, and Afzal and Ragab, 2019); our experiment reduced rainfall throughout the year. In theory, the drier winter conditions in the RR plots may have influenced the results. However, during the winter months, crop water use is small; once the soil reserves of water are replenished, most rain that falls moves through the soil and either into rivers or ground water reserves. Our measurements of soil moisture indicated that at both OWP and UWE, the soil returned to field capacity by March, the start of the main growing season. A return of the soil to field capacity during the winter is considered crucial for crop growth in the following spring (Grove and Monaghan, 2019). At UWE in 2016/2017, soil moisture content in RR plots had only just returned to field capacity by the end of March 2017. The 2017 harvest, at UWE, was the only one in which we recorded a decrease in biomass production associated with the reduced rainfall treatment.

At the two sites we studied, OWP and UWE, reduced rainfall had no strong negative effect on biomass production. Even when rainfall was reduced to 44 % of long-term average, reduced rainfall was associated with a slight increase in biomass production. Our results for the Bristol Frome catchment are in agreement with studies that suggest reduced rainfall during the summer may lead to increased productivity from well-established and species rich grasslands (Grime et al., 2008; Grime et al., 2000; Van Looy et al., 2016; Fridley et al., 2011; Hopkins and del Prado, 2007). They also show that very dry conditions early in the year, as in 2017, are more likely to reduce productivity than are dry conditions in late June or early July, after grasses have flowered.

Our experiment studied two well-established pastures; newly planted pastures are likely to be more sensitive to lack of summer rainfall. In a one year old pasture in Ireland, ten weeks rain exclusion, starting in July, dramatically reduced biomass (Picon-Cochard, 2014). Both of our sites were extensively managed; more intensively managed pastures, where two to four grass cuts might be taken each year are likely to be more adversely affected by reduced summer rainfall, as illustrated by the effect of reduced precipitation on regrowth at OWP. OWP and UWE are species–rich pastures; the productivity and resilience of species poor pastures might be more sensitive to reduced rainfall. Species diversity in pastures, even at the cost of reduced productivity, is often considered to be an insurance against environmental stress (Sanderson et al., 2007).

Looking to the future, our results indicate that well-established, species-rich pastures are likely to be able to tolerate drier summers at least over three years. However, because variability in weather conditions is also predicted to increase (UKCP2018, Met Office, 2018), farmers may need more flexibility in the way that they manage pastures. Agri-environmental schemes, may need to take this into account.

Part B Engage local people in drought science

Chapter 6 Volunteer Involvement

We recruited volunteers to become citizen scientists through internal University student mailing lists, student volunteering groups, contacting local environmental groups, other members of staff, advertisements on environmental recruitment sites, and social media (https://www.facebook.com/DRYmesocosms/; https://www.facebook.com/DRYproject/). We advertised as widely as practical, and did not limit advertising to student groups within the university. We took advantage of national and local events aimed at increasing public involvement in science, such as British Science Week and Bristol Festival of Nature, to publicise our field experiment and recruit potential volunteers.

Figure 6.1. Volunteers learning to identify grassland plants on the University of the West of England campus and at the UWE field site.

Over the course of the experiment, at least 40 different people volunteered to help with a wide range of tasks:

- Helping to attach the gutters to the frames in October 2015.
- Developing the height measuring protocol during winter and spring 2015-16.
- Sorting samples of cut vegetation (biomass) in 2015, 2016, 2017 and 2018 (Figure 6.2).
- Helping to cut plots in autumn 2015, 2016 and 2017.
- Taking part in training days in 2016, 2017 and 2018 (Figure 6.1).
- Weekly/fortnightly measurements of vegetation height in 2016, 2017 and 2018 (Figure 6.2).

- Counting flowers and pollinators, during the summer months in 2016, 2017 and 2018 (Figure 6.2).
- Taking part in Bristol City Nature Challenge and Bristol Festival of Nature in 2017 and 2018.
- Taking part in a results workshop in 2018. http://dryproject.co.uk/citizen-science/sharing-the-results-citizen-science-workshop/
- Helping to present work from the field experiment at DRY project conference in July 2019

Figure 6.2. From left to right: Volunteers measuring vegetation height at UWE, sorting biomass samples in the laboratory and counting flowers and pollinators at UWE.

Three of the volunteers came more than 20 times. Over the course of the experiment, volunteers contributed around 700 hours; and almost 200 work days. No one individual was involved in all the activities because, over time, the individuals changed, often because of changes in their personal circumstances. Some of the volunteers were students, from UWE, University of Bristol or University of Gloucester, and stopped volunteering when they graduated and moved away from the Bristol area. Other volunteers included people wanting to learn new skills, environmental professionals wanting to update their field skills and people with an interest in climate change and natural history. The majority of volunteer involvement was at UWE, because this site was within walking distance of the University of the West of England campus and many of the volunteers did not have cars.

Volunteers were given the opportunity to take part in the narrative research part of the DRY project. Some attended a storytelling workshop, and others worked with an MSc student from the University of the West of England Science Communication Unit to produce a video about grasslands. One volunteer was recorded for a podcast about the DRY field experiment (https://soundcloud.com/uwebristol/reflecting-on-the-drydrought-risk-and-you-project), while another wrote a blog post for the project website (http://dryproject.co.uk/2016/10/).

We involved the volunteers in developing the protocols used to measure plant height. For counts of flowers and pollinators, time constraints meant that we had to use a published protocol. We chose a method published by the charity ‘Buglife’ so that the data collected could contribute to their records of pollinator numbers in UK. Thus, the volunteers could see how the skills that they learned, used and developed in the DRY project applied elsewhere and maximised the positive impacts of the research.

Part C Provide a focus for engagement activities

Chapter 7 Engagement activities

The engagement activities based on the DRY project field experiment in the R. Frome catchment aimed to raise awareness of the implications of climate change, especially water scarcity, for grasslands and the pollinating insects that rely on them for food. The activities can be divided into two groups: activities open to the general public and academic engagement

7.1 Public engagement activities

Throughout the experiment, we took part in local and national events to raise public awareness and engagement with our work. Some examples are described below.

7.1.1 *Open days*

We held open days at our UWE field site as part of British Science Week in 2016 (Figure 7.1), and 2018 (http://dryproject.co.uk/citizen-science/british-science-week-2018-exploring-the-interactions-between-drought-pollinating-insects-and-plants/). The DRY project took part in Bristol Festival of Nature in 2015, 2016, 2017 and 2018, and in 2018 used our UWE field site for the Bristol City Nature Challenge (Figure 7.1) (http://dryproject.co.uk/citizen-science/dryproject-and-the-city-nature-challenge/).

	
Attendees at a British Science Week event at UWE field site in 2016, after a morning spent measuring vegetation height.	Surveying the UWE field site as part of Bristol City Nature Challenge in 2018.

Figure 7.1 Public engagement at the UWE field site.

7.1.2 Transmission ll

Researchers from the DRY project took part in a collaboration between Hay on Wye Literary Festival and NERC (Natural Environment Research Council) called Transmission ll (https://www.hayfestival.com/hay-on-earth/hay-festival-transmission-ii)

Transmission ll aimed to communicate cutting-edge science to a wide audience by pairing award winning authors with leading environmental scientists. We worked with author Patrice Lawrence to produce a short story that would help a non-scientific audience understand why we need to be aware of the risks associated with drought and other aspects of climate change. Patrice created a story that used a light touch to combine the serious issues associated with climate change with an important but everyday event in the life of a teenager.
A film of the story is available on YouTube (**https://www.youtube.com/watch?v=Rb427N9BWLM)**

We also worked with the artist and animator, Chris Haughton. He drew together themes from the DRY project and two other NERC-funded projects (Peru's 'CASCADA' tropical glaciers research project and Colombia's 'BioResilience' which focuses on biodiversity and indigenous communities). The animation he created highlighted how vegetation that has many different species is more tolerant of environmental stresses, such as water shortage, than vegetation with only a few species present (https://www.hayfestival.com/hay-on-earth/transmission-ii/confluence).

7.1.3 *Webinar*

The field experiment in the R. Frome catchment was used as an example in a webinar 'How will British grassland respond to climate change', in the DRY project webinar series (https://vimeo.com/571801791).

7.2 Academic engagement

7.2.1 *Geography teachers' conference*

In 2015, primary school, secondary school and trainee teachers visited the UWE field site to learn how to survey flowers and pollinators, and how to incorporate field activities into the curriculum as part of the UWE Geography Teachers Conference (Figure 7.3).

Figure 7.3 Geography teachers at the UWE field site.

7.2.2. *Nuffield Research Placements*

During the course of the DRY project field experiment, we hosted eight students supported through the Nuffield Foundation Research Placements Scheme. This scheme offers year twelve students (especially those from schools with limited facilities for STEM subjects) the chance to spend four to six weeks working on a research project. Each of the students was given a research project of their own, and took part in whatever fieldwork was being carried out at the time. The students were encouraged to speak to other staff and students within Geography and Environmental Management Department at UWE Bristol to widen their knowledge of the range of potential careers open to science graduates. At the end of the placement, each student produced a report and a poster presentation, and was encouraged to write a blog post for the DRY project website.
(http://dryproject.co.uk/drought-science/investigating-drought-simulation/
http://dryproject.co.uk/citizen-science/looking-at-mycorrhizal-fungi/
http://dryproject.co.uk/drought-science/kieran-barrow-working-on-the-dry-project/
http://dryproject.co.uk/drought-science/casey-brimble-working-on-the-dry-project/
http://dryproject.co.uk/drought-science/mycorrhizal-fungi-colonisation-investigation/)

7.2.3. *Contribution to University of the West of England educational activities*

Data from the UWE field site are used in a case study and class practical for UWE Physical Geography students, as part of the meteorology unit. During the course of the experiment, the DRY project field sites or data from the field sites formed the basis of three undergraduate and one post graduate dissertations.

Part D Provide information that could contribute to future hydrological models

Chapter 8 Information that could contribute to future hydrological models

From July 2015 until November 2018, the automatic weather stations collected data every 30 minutes (see Table 2.1). These data are stored on a data base at UK Centre for Ecology & Hydrology together with all the data collected about plant growth.

Chapter 9 How well did the experiment achieve its aims?

The experiment was broadly successful in achieving its aims.

The experiment had four aims.

A: Better understanding of how drought might affect UK grasslands

A large amount of data was collected about environmental parameters, soil conditions and plant growth from plots with full incident rainfall and plots which had rainfall reduced by about 50%. These data, which are stored in a data base at UK Centre for Ecology & Hydrology, are being analysed to help us understand how the two grasslands that we studied were affected by reduced rainfall. In common with other studies of the impacts of drought on grassland, we found that it was difficult to separate the effects of long term climate trends from those of year-to-year variation. The results of this experiment suggest that extensively managed species rich grasslands are resilient to reduced rainfall. However, since our experiment only ran for three complete years, we cannot rule out the possibility that there were small cumulative changes in the vegetation that we were unable to detect, but which might have become apparent if the experiment had continued for longer.

B: Engage local people in drought science (volunteers/ citizen science)

More than forty different people volunteered with the DRY project field experiment in the River Frome catchment. For at least three of these, the volunteering experience gave them the confidence to enrol for further training in environmental science. We were successful in engaging local people in the drought science but were aware that because access to the field sites was not easy, and the work was physically demanding, some potential volunteers were excluded. A few people contributed the bulk of the volunteer hours.

C: Provide a focus for engagement activities

The public engagement activities were enjoyed by the participants; some of these people went on to take part in other events organised by the project team or contributed to the narrative research thread of the project. The accessibility of the field site (it was a 25 minute walk from the university campus and not accessible by road) limited the number of people that could visit the site, and prevented the project from having school visits.

D: Deliver detailed information that could contribute to future hydrological models

More than three years of data were collected from each site, UWE and OWP, and these data are stored at UK CEH.

Chapter 10 Outputs and contribution to other projects

10.1 Academic papers

Ayling, S., George, B., & Rogers, J. (2021). Mycorrhizal colonisation in roots of *Holcus lanatus* (Yorkshire Fog) in a permanent pasture under conditions of reduced precipitation. Botany, 99(4), 199-208. https://doi.org/10.1139/cjb-2020-0162

Ayling, S.M., Thompson Jill, Gray, A. & McEwen, L.M. (in press) Impact of reduced rainfall on above ground dry matter production of semi-natural grassland in South Gloucestershire, UK: a rainfall manipulation study. Frontiers in Environmental Science. https://doi: 10.3389/fenvs.2021.686668. Ayling, S.M., Curtis, S, Ramirez, P. et al. Working together: Citizen Science can be much more than data collection. People and Nature (in preparation)

Ramirez, P., McEwen, L., Weitkamp, E. & Ayling, S.M. Citizen Science in drought research: does getting hands-on with ecology alter volunteer perceptions of a "hidden" risk? J. of Citizen Science: Theory and Practice (in preparation)

Thompson J., et al. The influence of rainfall shelters on local microclimate and plant growth (in preparation)

10.2 NERC reports

Ian Holman, Jerry Knox, Tim Hess, Lindsey McEwen, Gloria Salmoral, Dolores Rey Vicario, Jamie Hannaford, Ivan Grove, Jill Thompson, Nevil Quinn:
Coping with drought and water scarcity: lessons for the agricultural sector.
https://aboutdrought.info/drought-and-agriculture-synthesis-report/

Jill Thompson and Sarah Ayling Grasslands Report Card 2020
https://aboutdrought.info/wp-content/uploads/2020/09/AboutDrought-ReportCard-Grasslands-Final.pdf

10.3 University of the West of England Dissertations

Undergraduate dissertations

Belinda George:	An investigation into the extent of arbuscular mycorrhizal fungi colonisation in native European grass *Holcus lanatus* during a simulated winter drought.
Catherine Turner:	An investigation into the effect of drought on the growth of Cock's-foot and Yorkshire fog during winter months
Charlotte Chamberlaine:	An Investigation into Differential Weather Patterns between a Suburban and Non-Urban area in Bristol, England.

MSc. Dissertation

Bethan Cairney:	Will drought conditions affect phenological timings of grassland species in semi-improved grasslands in the South west of England?

10.4 Nuffield Research Placement Reports

Somayah Ahmed:	Investigating Mycorrhizal fungi colonisation in drought conditions in the UK on *H. lanatus*
Kieran Barrow:	The effect of drought conditions and soil temperature on mycorrhiza fungi in Yorkshire Fog roots
Casey Brimble:	The effect of drought on the colonisation of grass roots by mycorrhiza fungi
Aidan Bulmer:	Using reliable rainfall data to study drought
Emily Taylor Kent:	Does Drought Affect Mycorrhiza?
Leah Fitzpatrick:	An investigation for the creation of a controlled drought
Ubah Yusuf:	Does drought affect the colonization of grass roots by mycorrhizal fungi?
Vincent Otterbeck:	How can we compare different sets of rainfall data?

10.5 Contribution to other projects

Data have been contributed to the 2020 Botanical Society of Britain and Ireland (BSBI) plant atlas (https://bsbi.org/atlas-2020), the South Gloucestershire Rare Plants Register, Bristol and Region Environmental Records Centre, and to Buglife Flowers and Pollinators survey (https://www.buglife.org.uk/).

International Litter Decomposition Experiment

The DRY project contributed to the International Litter Decomposition Experiment. At the OWP and UWE field sites, tea bags containing either green or red bush tea were buried in control and reduced rainfall plots. At predefined intervals, tea bags were excavated, cleaned of soil, dried and weighed. Soil samples were also collected so that decomposition rates in different soil types could be compared. Preliminary results have been published, with Jill Thompson, who designed the field experiment, as named contributor.

Ika Djukic, …., Jill Thompson, et al. (2018) Early stage litter decomposition across biomes, Science of The Total Environment, Volumes 628–629, 1369-1394, ISSN 0048-9697, https://doi.org/10.1016/j.scitotenv.2018.01.012.

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