

Impacts of projected precipitation changes on sugar beet yield in Eastern England

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Short title: Precipitation projections and sugar beet yield

Manuscript submitted as an original Research Article to Meteorological Applications in March 2016 and re-submitted/accepted in this form in June 2016.

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1 **Abstract**

2

3 Projected increasing temperatures and reduced summer rainfall in the UK pose a
4 sustainability and food security challenge for the agricultural industry. This study investigates
5 the potential impact of precipitation changes on Eastern England sugar beet yield.

6 Precipitation data over Eastern England from weather stations (1971-2000) and a range of
7 CMIP5 climate models (“historical” for 1971-2000; and RCP45 and RCP85 for 2021-2050)

8 were examined. A good agreement was found between the observations and the

9 overlapping model grid cell. The study then investigated the impact of likely future rainfall

10 changes on yield by applying controlled watering regimes informed by the CMIP5 projections

11 to 150 sugar beet plants grown in a greenhouse – the use of CMIP5 projections in this way

12 is a first. Watering regimes that represent “present day” and “future” precipitation

13 characteristics were calculated: 0.46L of water was applied every other day to each plant in

14 the “present day” category; 0.39L was applied every other day to each plant in the “future”

15 category. This reflects the 16% reduction in future rainfall that was calculated from the

16 climate models. Results from the greenhouse experiment showed a statistically significant

17 ($p < 0.01$) reduction in soil moisture in the “future” category, which was related to a statistically

18 significant ($p < 0.05$) reduction in mean tuber wet mass: mean of 360g for “present day”; and

19 319g for “future”. The results for dry mass were less significant ($p = 0.11$) but indicated a

20 reduction in the future category (95.2g vs. 88.2g). These findings imply a potential yield

21 reduction of 11% by 2050.

22

23 **Keywords:** agriculture; climate change; CMIP5; UK rainfall

24 **1. Introduction**

25

26 *1.1 Precipitation changes and impacts on agriculture*

27

28 Climate change is one of the biggest challenges facing societies today and reviews of its
29 impacts on agriculture have shown considerably more negative effects than positive (IPCC,
30 2014). The reason for this is because agriculture is inherently sensitive to climate: any
31 change in climate will almost certainly affect plant growth positively or negatively. These
32 effects are already detectable where, for example, temperature changes have been shown
33 to have an impact on growing season (Menzel *et al.*, 2006). This type of sensitivity is
34 reflected where and when food prices increase following cases of extreme weather events in
35 food producing areas (IPCC, 2014). In the light of this, it is important to understand potential
36 impacts of climate change for different regions to enable the agricultural industries to
37 prepare and adapt to the changes that are likely to occur.

38

39 The highest profile agricultural losses occur at the hands of extreme events and in recent
40 years the UK, for example, has experienced a number of extreme rainfall events that have
41 impacted the agricultural community. January and February 2014 in England saw rainfall
42 totals of approximately 150 mm and 109 mm, respectively, which are well above the average
43 rainfall values for these months (Met Office, 2014). This resulted in around 49,000 ha of
44 farmlands being flooded in a single event during February 2014 in Somerset and the
45 Thames and Severn catchments (EFRA Committee, 2014). The extent and duration of this
46 flood resulted in more than 44,000 ha of farmland being underwater for more than one day
47 and 40% of that area (17,800 ha) being flooded for 15 days causing significant damage to
48 the farmland and harvest ready crops, and loss of income to the farmers (DEFRA, 2014).

49

50 These extreme events are likely to become more frequent and more intense (IPCC, 2013)
51 but the impact on crop yield from extreme events is difficult to calculate and adapt to: in the
52 isolated regions where the floods occur, yield is reduced to zero but other areas may not be
53 affected. Furthermore, analyses of extreme events over future timescales are likely to be
54 dominated by uncertainty due to the nature of modelling studies (Maraun *et al.*, 2010).

55 Conversely, a more climatological analysis has the potential to produce results that can
56 more confidently be used to plan and adapt operating practices. There are robust signals in
57 climatic variables on the seasonal timescale, including precipitation, which can be used to
58 understand potential future impacts. For the UK, this signal tends to be wetter winters and
59 drier summers (UKCP, 2009; IPCC, 2013). How this will impact agricultural yields requires
60 further investigation.

61

62 1.2 Sugar beet production in the UK

63

64 Sugar beet in the UK is usually sown between March and April and harvested between
65 September and February (British Sugar, 2011). The tuber contains 15-17% sugar (FAO,
66 2009) and accounts for 50% of the sugar consumed in the UK. It is an important agricultural
67 crop in the UK: the sugar industry contributes significantly to the UK rural economy and
68 supports around 13,000 jobs in the supply chain (British Sugar, 2011). Approximately 3,000
69 farmers grow the crop, predominantly in Eastern England, on over 170,000 ha of farmland
70 (British Sugar, 2011).

71

72 Sugar beet productivity in the UK is increasing: annual farmer delivered yield between 1976
73 and 2004 increased by 111 kg/ha (Jaggard *et al.*, 2007). Further, British Sugar (2011)
74 reported an average increase of 11 tonnes of sugar beet per hectare (an approximate
75 increase of 60% between 1981 and 2011). These increases are generally assumed to result
76 from improved agronomy, seed variety and favourable weather, but these assumptions
77 cannot be justified without taking the climate related changes and local weather patterns into
78 consideration. According to IPCC (2013), warming of the climate system is unequivocal and
79 has resulted in a lot of changes in the climate system with positive and negative impacts on
80 agriculture. Therefore, it is important to factor climate and weather related variables into yield
81 analysis.

82

83 The most important economic aspects of sugar beet for farmers are the size of the root yield
84 and its sugar content, which are influenced by a number of environmental factors, including
85 weather patterns and soil conditions. Sugar beet farming in England is over 95% rain-fed
86 with the use of irrigation being minimal (British Sugar, 2011). Water volume and timing is
87 critically important to the successful growth of sugar beet plants, as indicated by Richter *et al.*
88 (2006) who modelled the variability of UK sugar beet under climate change using a
89 regional climate model. They found that water will be a major stress factor in the future and
90 that relative soil moisture will be reduced under high greenhouse gas emissions scenarios.
91 The analysis presented in the paper here extends the work of Richter *et al.* (2006) by using
92 daily precipitation projections from a climate model ensemble to inform a controlled watering
93 experiment in a greenhouse, which is relevant to potential future rainfall conditions in East
94 England under medium and high greenhouse gas emissions scenarios.

95

96 In Europe, sugar beet yield is generally seen to decrease when stressed via low water
97 conditions: Pidgeon *et al.* (2001) estimated potential sugar beet yield losses, calculated from

98 climate and crop model projections due to water stress, vary between 15% and 30% for
99 England. Given the nature of UK sugar beet production, past and present water limitations
100 have most likely been driven by changes in rainfall patterns. Furthermore, many past studies
101 have indicated that sugar beet is, more specifically, sensitive to water supply in terms of:
102 yield (e.g. Jones *et al.*, 2003, Richter *et al.*, 2006, Kenter *et al.*, 2006, Choluj *et al.*, 2014);
103 storage root formation (e.g. Brown *et al.*, 1987; Rytter, 2005); and leaf growth (Rytter, 2005).
104

105 As sugar beet is economically significant in the UK and is sensitive to water supply, we
106 consider it an ideal crop to investigate in the context of future changes in precipitation.
107 Furthermore, there are currently no sugar beet growing experiments in the literature that are
108 informed by ensemble model projections – one of the aims of this paper is to address this.
109

110 *1.3 Aims and scope*

111

112 The main aim of this study was to understand the impact of climatological precipitation
113 changes in Eastern England on sugar beet yield. State-of-the-art ensemble climate model
114 projections will be used to inform a greenhouse experiment in a novel way. In this paper, the
115 following results are presented and interpreted:
116

- 117 • An examination of precipitation data from weather station observations and climate
118 model projections for Eastern England;
 - 119 • A series of watering regimes, calculated from the precipitation examination, which
120 represent the climatological precipitation levels delivered to Eastern England for
121 “present day” and “future” climate scenarios; and
 - 122 • Measures of sugar beet productivity from a greenhouse experiment, where 150 sugar
123 beet plants were grown with the application of the calculated watering regimes.
- 124

125 This investigation only considered climatological changes in the precipitation over the sugar
126 beet growing season. Wet and dry tuber mass were used as the main measure of sugar beet
127 productivity. The changing nature of precipitation event size and frequency, and the sugar
128 concentration of the tubers, were not examined in this study. Furthermore, this work only
129 considers the impact of the different watering regimes on the plants once they were
130 developing a tuber; all plants were treated equally through the germination and juvenile
131 stages so that the impact on yield could be assessed and not the impact on germination.
132 Furthermore, the historic, longer term relationship between farm yield data and precipitation
133 was not investigated here.

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2. Data, materials and methods

2.1 Precipitation: weather station observations and climate model projections

The present day precipitation regime for Eastern England was determined from 6 weather stations that have operated in the region for periods greater than 30 years with little or no missing data. These are: Terrington St Clement (2 m above sea level (asl), 0.29 ° E, 52.745 ° N); Santon Downham (6 m asl, 0.675 ° E, 52.458 ° N); Coltishall (17 m asl, 1.356 ° E, 52.756 ° N); Writtle (32 m asl, 0.432°E, 51.733°N); Manston (44 m asl, 1.35°E, 51.35 N); and Stansted Mountfichet (70 m asl, 0.184°E, 51.897°N). See Figure 1 for the locations of these weather stations. All the analyses of precipitation data in this study only considered the key growing period for sugar beet (i.e. May-October).

To determine the likely climatic changes over Eastern England, precipitation projections from a range of climate models were examined. The projections were taken from the 5th Phase of the Coupled Model Intercomparison Project (CMIP5; Taylor *et al.*, 2012). Data were used from three different CMIP5 experiments, two of which aim to assess the impact of different levels of greenhouse gas emissions over the 21st Century: the Representative Concentration Pathways (RCPs; van Vuuren *et al.*, 2011). The RCP45 and RCP85 scenarios were used for the period 2021-2050 – this temporal window was used as it is of interest to the sugar industry for future planning (British Sugar, 2011). These RCPs represent mid-range (RCP45) and high-end (RCP85) impacts on radiative forcing changes in the future, respectively. The third experiment used was called “historical”, which provides a benchmark period that allows the model data to be compared with observations. This was used for the temporal window of 1971-2000. For each CMIP5 experiment, a multi-member ensemble of model runs was used. The individual members of the ensemble were initiated using slightly different, though equally realistic, initial conditions for each of the model runs in order to capture some element of internal climate variability – see Taylor *et al.* (2012) for further details.

The particular models examined here had to meet the following criteria: the model should be an Earth System Model (ESM) or a Coupled General Circulation Model (CGCM); daily precipitation data for the “historical”, RCP45 and RCP85 experiments should be available; and the experiments should have been run as ensembles. Table 1 gives details of the models that met these criteria. Data from these models were retained for further analysis based on how closely they replicated precipitation observations for the region (see Section 3).

171

172 *2.2 Calculation of water regimes*

173

174 The aim of this work was to investigate climatological changes in precipitation from climate
175 model projections. In this respect, the watering regimes were not designed to replicate
176 realistic precipitation events. Instead, they delivered the total growing season (i.e. May-
177 October) precipitation in a series of regular and equal watering events. In short, all the plants
178 were watered every other day (i.e. watering day – dry day – watering day – dry day and so
179 on) with the same amount of water per watering day for each watering regime.

180

181 There was a “control” watering regime where precipitation observations for the period 1971-
182 2000 and the recommended level of water for a successful sugar beet crop from the Food
183 and Agricultural Organisation of the United Nations (Brouwer and Heibloem, 1986) were
184 used to calculate the watering event size. Secondly, there was a “future” watering regime,
185 which was based on a modification of the “control” regime watering event size determined by
186 the growing season (i.e. May-October) changes in precipitation from the RCP45 and RCP85
187 CMIP5 climate projections for the period 2021-2050.

188

189 Plants were allocated into the “control” or “future” watering regimes and the different
190 watering regimes were implemented after the plants had reached their 10-12 leaves growth
191 stages and had started forming tubers. To account for natural variability in plant sizes, the
192 plants assigned to each watering regime were selected to result in an equal distribution of
193 plant sizes in each watering regime. Allocation of plants to the watering regimes was done at
194 this time to coincide with the rainfall analysis from May to October for the study periods and
195 also because the biggest rainfall changes are projected for the summer. Changes in rainfall
196 from the analysis conducted were imposed on the plants in the future category, which had a
197 reduction in rainfall amount.

198

199 *2.3 Plant variety*

200

201 Apart from the effect of growing conditions, yields are also influenced by the chosen variety
202 of seeds. Some varieties have high tuber yields but low sugar percentage while others may
203 have low yield with high sugar percentage (BBRO, 2013). Pelleted sugar beet seed of the
204 same variety (SY Muse) were used for all replicates in this experiment. According to the
205 British Beet Research Organisation (BBRO, 2013), SY Muse is a high yielding variety that
206 performs consistently well with excellent establishment and resistance to drought and
207 rhizomania and it is widely used by UK farmers. SY Muse compares favourably well with

208 other varieties and is third on the official yield variety list of the BBRO (2013) in terms of root
209 yield and sugar content. It is rated “3” and “4” on a scale of 1 to 9, with 1 being “susceptible”
210 and 9 being “tolerant” on the BBRO (2013) rust and powdery mildew disease scales,
211 respectively. As SY Muse is not extreme on these scales, this was considered further
212 justification for its use in this experiment.

213

214 *2.4 Greenhouse experiment*

215

216 The sugar beet plants were grown in individual pots in a greenhouse located on the Brunel
217 University London campus. The greenhouse is an ideal environment for the experiment as it
218 allows the watering to be controlled. Temperature and humidity were not controllable in the
219 greenhouse but these variables were consistent for the different watering regime groups.
220 Furthermore, once classified into the different watering regimes, the plants were distributed
221 systematically around the greenhouse so there would be no bias in temperature, humidity or
222 sunlight for any group.

223

224 The sugar beet seeds were sown into 150 plastic 33 L plant pots with two seeds per pot in
225 the greenhouse on the 15 April 2014. 30 kg of “John Innes No. 2” compost per pot was used
226 as the planting medium. The soil in the pot was shaken to eliminate pockets of air in the soil
227 and keep the soil level and compact. This enabled the soil to retain moisture after draining
228 off excess water. The timing of watering is important to maximise yields and ensure a fair
229 comparison between the watering regimes. Water was applied in the mornings when the
230 plants can maximise the available water because of lower evapotranspiration. A watering
231 procedure was used that ensured the water was added in a consistent way to all pots and
232 was as uniform as possible around the surface area of the soil.

233

234 This method was successful in terms of germination: 298 seedlings emerged out of the 300
235 seeds sown. Plant seedlings were thinned at their 4-6 leaves growth stages from two to one
236 seedling per pot to encourage uniform establishment.

237

238 As described in Section 2.2, the plants were subsequently classified into the “control” and
239 “future” watering regimes at the 10-12 leaf growth stage. The pots for the plants in each
240 regime were colour coded and colour coded measuring cylinders were used to add the water
241 so that the potential for human error was reduced to a minimum. Each plant was assigned a
242 number so that growth and yield parameters could be recorded for specific plants.

243

244 In the greenhouse study, a number of non-destructive parameters were used to assess the
245 yield potential of the plants over the growing season including: the number of leaves; height
246 of the plants (i.e. height of the tallest stem); the growth ratio of the plants (i.e. height divided
247 by number of stems); leaf width (i.e. width of the widest leaf); and soil moisture. The above-
248 ground parameters were measured with the use of a tape rule while below-ground the soil
249 moisture was measured using a Soil Moisture Meter (Lutron Professional PMS-714). These
250 parameters were measured every 2 weeks to enable the examination of water reduction on
251 the plants' development and productivity; this can place yield in the context of the growing
252 season examined.

253

254 At the end of the experiment, destructive measurements were taken to determine the mean
255 mass of the tubers as harvested and when dried. When harvested, the tubers were uprooted
256 from the soil and washed. Thereafter, the leaves of the plants were cut off from the crown
257 leaving the tubers, which are of most interest in this research. Each individual tuber was
258 weighed without the leaves – these measurements are reported here as the “wet” weight.
259 The tubers were then labelled with their numbers and put in open transparent bags so that
260 the yield data could be added to the database of growth parameters recorded over the
261 growing season. Analysis of the dry weight of the tubers was conducted using a laboratory
262 method to remove the moisture content. Obtaining the dry weight was done by cutting each
263 tuber into smaller pieces to speed the drying rate. The size of the pieces was kept as equal
264 as possible for all tubers so that drying rates were as equal as possible. A tuber of median
265 size was cut into 8 pieces whereas larger (smaller) tubers were cut into more (fewer) pieces.
266 The pieces were put into individual aluminium trays and numbered for identification purposes
267 and then put inside an oven for drying at 80 °C until constancy, as *per* Mohammadzadeh
268 and Hatamipour (2010). The cut tubers were weighed periodically, typically every 2 hours,
269 until there was no more appreciable change in weight. At this point the value was recorded
270 as the “dry” weight.

271

272 Measurements and data collected at different stages of the plants' growth, and following
273 harvest, were statistically analysed to enable quantification of impacts. All measured
274 parameters were tested for normality, which then determines the type of statistical test to be
275 carried out. Parametric tests were conducted where data was normal and non-parametric
276 tests were conducted where data was skewed. Following this, a two tailed t-test was carried
277 out for the two watering regimes. The outcome of the experiment was assessed using the
278 null hypothesis: “there is no difference in the categories”. Therefore, applying a confidence
279 interval (CI) of 95% with alpha set at 0.05%; the p-value then gives an indication if significant
280 differences exist in the parameters assessed.

281

282 3. Results

283

284 3.1 Precipitation analysis

285

286 Figure 2 shows the comparison of the “historical” phase of the CMIP5 data with the local
287 weather station data. The precipitation characteristics of the majority of the stations show a
288 good agreement across the region. Only the median and distribution of Manston look
289 different to the other stations – Manston, however, is not representative of the region where
290 most of the farming occurs (Figure 1) so this difference was not considered important. 3 of
291 the CMIP5 model medians are very similar to median values of the stations that represent
292 the farming region. These 3 models – CCCma, MOHC and EC-Earth – will be discussed
293 further whilst the remaining 5 were rejected at this point.

294

295 The range and distribution of the modelled precipitation from these 3 models are not as wide
296 as those of the observations but this is to be expected as models do not represent the
297 extremes of precipitation variability well (Maraun *et al.*, 2010). Again, this is not seen as a
298 problem here as we are examining mean conditions and not extremes. Nonetheless, the
299 distribution of precipitation from the MOHC HadGEM2-ES model is much closer to that of the
300 observations than the CCCms and EC-Earth models. Therefore, the MOHC HadGEM2-ES
301 projections will be used in further calculations in this paper. Furthermore, Brands *et al.*
302 (2013) and McSweeney *et al.* (2014) have shown that MOHC HadGEM2-ES generally
303 outperform other models in Europe.

304

305 Calculation of the “control” daily mean watering amount was based on the mean seasonal
306 water requirements of sugar beet plants and the mean number of sugar beet growing days,
307 as reported by Brouwer and Heibloem (1986). The mean daily water value was calculated in
308 terms of mm day^{-1} , which was then converted into a volume in litres that would be applied to
309 the plants by multiplying the area of the compost at the level of the surface (mm^2) by the
310 precipitation value (mm day^{-1}) to get a volume per day. In practice, the plants were watered
311 every other day with two times this volume. The values in mm^3 are converted to litres (L) by
312 dividing the results by 1,000,000. Using this method, the “control” watering regime was
313 calculated as 0.230 L day^{-1} , or 0.46 L every other day

314

315 Figure 3 presents the ensemble means of May-October precipitation data from the CMIP5
316 “historical”, RCP45 and RCP85 experiments for the 3 models identified as representing the
317 observations well. All the projections indicate that UK rainfall decreases in the models, apart

318 from RCP85 in EC-Earth. Of these models, MOHC HadGEM2-ES shows the largest
319 negative changes in precipitation. Therefore, and further to the reason outlined above, the
320 MOHC HadGEM2-ES data will be used as the basis for the “future” precipitation calculations
321 so that a plausible but relatively extreme scenario is being investigated – this is a scenario
322 that may stress the UK industry so it worth investigating.

323

324 Table 2 shows that the difference between the RCP45 and RCP85 experiments was
325 minimal. As a result, two watering regimes were used: “historical”, or “control”; and “future”
326 (i.e. the mean of RCP45 and RCP85). Statistical analysis showed a significant difference
327 (reduction) of 15.8% between the “historical” (1971-2000) and the “future” (2021-2050)
328 regimes. This 15.8% reduction in precipitation from 1971-2000 to 2021-2050 was applied to
329 the calculated watering amount for the “control” group to give the value for the “future”
330 watering regime as 0.195 L day^{-1} , or 0.39 L every other day

331

332 These watering quantities were applied to the two watering regime groups from 7 June 2014
333 (i.e. when the plants reached their 10-12 leaf stage) until harvesting on 23 November 2014
334 (i.e. growing day 220, which was used in the calculation of the watering regime). The growth
335 of the plants was measured with a tape rule and observations showed that the plants’ leaf
336 formation occurred early (see also Scott and Jaggard, 1993; Kenter *et al.*, 2006); but
337 increased steadily in multiples of two throughout the growing season.

338

339 *3.2 Non-destructive measurements*

340

341 Table 3 shows the means of the final set of non-destructive measurements taken. Only the
342 final values are presented here because these data give an indication of the ultimate effect
343 of the different watering regimes. In all cases, the “control” group had higher values than the
344 “future” group but the difference between the groups was not statistically significant.

345

346 *3.3 Wet yield*

347

348 All the sugar beet tubers were harvested on 23 November 2014 (Day 220). The mean “wet”
349 tuber mass was calculated for both regimes with the “control” having a mean tuber wet
350 weight of 359.5g and the “future” with 318.5g. Figure 4a shows the boxplot of the wet yield
351 data and Figures 4b and 4c show histograms of the complete data sets, which clearly have
352 different distributions. An independent sample t-test was performed on these data with the
353 hypothesis that there is no difference in the mean tuber mass of the “control” and “future”
354 watering regimes. These calculations were based on mean statistics and normality of data

355 with a 95% confidence interval. The result shows that a statistically significant difference
356 existed in the yield of the “control” and “future” watering regimes with a p-value of 0.034, with
357 the future category showing a reduction in yield compared to the control.

358

359 *3.4 Dry yield*

360

361 Figure 5a shows a boxplot of the dry weight matter and Figures 5b and 5c show histograms
362 of the “control” and “future” data sets. Statistical analysis of the dry weight showed that the
363 control group had a mean of 95.2g (73.5% reduction from the “wet” weight) and the future
364 group a mean of 88.2g (72.3% reduction). This result equated to a p-value of 0.11 with a null
365 hypothesis that there was no difference between the watering regimes. This indicates that
366 the statistical significance of this result is just outside of the 10% level often applied to
367 determine significance. This, by implication, suggests that the difference in mass is a result
368 of the different moisture content in the tubers of both watering regimes. Despite the lack of a
369 statistical basis for rejecting the null hypothesis, there are still differences worthy of
370 comment. In particular, the largest tubers from the “control” group (i.e. greater than 150g)
371 are absent from the “future” group and the mean for the “future” group is noticeably lower.

372

373 *3.5 Soil moisture*

374

375 The mean growing season (May-October) soil moisture data collected during the watering
376 regimes is shown in Figure 6a and the mean monthly soil moisture data are presented in
377 Figure 6b. The difference between the two watering regimes was assessed using the null
378 hypothesis that there was no difference in the two groups. The result of the independent
379 sample t-test carried out using a 95% confidence level showed a significant reduction in the
380 level of soil moisture in the future category with a p-value of 8.7×10^{-06} . In short, the analysis
381 showed that the future group had a significant reduction in soil moisture.

382

383 To further examine the impact on yield, the relationship between soil moisture and wet tuber
384 mass was examined using the Pearson Correlation test. This showed that 43% of the
385 variability in wet mass in the “control” group could be explained by the variability in soil
386 moisture. Conversely, 57% of the variability in wet mass in the “future” group could be
387 explained by the variability in soil moisture. In summary, there was a strong negative linear
388 relationship between the yields and soil moisture in the experiment.

389

390 **4. Discussion**

391

392 The findings from this study suggest that a potential change in future precipitation, as
393 interpreted from the medium and high greenhouse gas emissions scenarios (RCP45 and
394 RCP85) in an ensemble of MOHC HadGEM2 daily mean precipitation data, is likely to
395 reduce sugar beet yield in the UK by 2050. The mean daily precipitation analysis result from
396 May to October for the two different time slices under “historical” (1971-2000) and “future”
397 (2021-2050) categories in this research showed a 16% reduction in mean daily rainfall for
398 the “future” group. The output from the individual ensemble members showed slight
399 differences but when combined together they clearly reflect a reduction in future rainfall. This
400 result is consistent with the result reported by UKCP (2009) of future reduction in UK
401 summer rainfall. This is an important development for research into sugar beet as its primary
402 growing season is in the spring/summer time and this study represents one of the first times
403 that CMIP5 climate model data has been used to inform a greenhouse experiment.

404

405 These results raise questions regarding the viability of the sugar beet industry in the UK,
406 which depends on 95% rain-fed production (British Sugar, 2011), particularly in terms of
407 water resources. This is against a background of EU policy changes that potentially
408 undermine the economic model for the industry (Burrell *et al.*, 2014). The combination of
409 these challenges raises questions about the future of particular agricultural practices and,
410 therefore, calls for creative and innovative adaptation strategies. However, this will depend
411 on the impacts of climate change in other key growing regions, which have not been
412 considered here.

413

414 The sowing, growing and harvesting of all the sugar beet plants was carried out under the
415 same environmental conditions but separate watering regimes. The watering regimes were
416 devised based on FAO recommendations of average water need for a sugar beet plant
417 during the growing season (Brouwer and Heibloem, 1986) and precipitation observations
418 from weather stations in Eastern England, which is the dominant production region of sugar
419 beet in the UK. Emergence and establishment was excellent with 298 pairs of cotyledonary
420 leaves emerging out of the 300 seeds sown. All plants were grown under the same water
421 management regime until the plants were categorised into the different treatments; this
422 occurred when they started forming tubers. Ideally, temperature and humidity would also
423 have been controlled but, given that all plants experienced the same conditions, the
424 experimental design is sound in its aim to test the impact of different watering regimes.

425

426 General observations of the plants throughout the season showed that early sowing,
427 adequate watering and radiation capture aided full canopy development with the leaves
428 completely shading the pot circumference. Achieving full canopy cover is likely to have

429 helped improve plant and tuber growth (Kenter *et al.*, 2006). The role of watering in the
430 plants' tuber development is key and, therefore, a 16% reduction in future rainfall will
431 seriously challenge sugar beet production. The impact of water reduction was measured via
432 the number of leaves, width blade of leaves, plant height, soil moisture and the wet tuber
433 mass.

434

435 Overall, the plants in each watering regime were exposed to the same environmental
436 conditions with the plants in each watering regime evenly distributed throughout the
437 greenhouse. The amount of sunlight on different sides of the greenhouse varied, for
438 example, but the systematic distribution of the members of each watering regime meant that
439 there was no bias in such uncontrolled variables. Moreover, the parameter measurement
440 only commenced after the plants had started forming tubers after their juvenile stages.
441 Therefore, the real progress of the tubers can be estimated from the changes in the tubers in
442 both watering regimes and places yield in the context of the mean growing season
443 conditions.

444

445 Event based impacts resulting from changes in weather patterns such as high temperatures,
446 had negative impacts on the plants. During high temperature events, the leaves wilted and
447 went into early senescence; Lambers *et al.* (1988) report that such water stress affects the
448 growth and productivity of sugar beet and would have affected the plants in this study. The
449 high temperatures in the months of June and July (Met Office, 2016) drove this problem, with
450 leaves from the bigger plants wilting at the first signs of stress and the leaves from the
451 smaller plants wilting later. This was reported by Hsaio (2000) in a previous study that
452 showed large leaves are usually the first to diminish at the first sign of water stress.
453 Importantly, the wilting of the leaves did not affect one watering regime more than the other
454 and, therefore, the results of the experiment were not biased by the extreme weather events.
455 In spite of this, plants from both categories exhibited remarkable characteristics of
456 adaptability in their high rate of recovery after watering following each stress episode. Figure
457 6b shows the impact that the high temperature had on soil moisture in July. It is important to
458 discuss wilting because the leaves capture the energy that is converted to sugar and, in so
459 doing, play a key role in the final yield of the crops. Hsaio (2000) reported that a number of
460 plant functions are affected under water stress conditions but the leaves are usually the first
461 to be affected by wilting. Milford and Lawlor (1976) claimed that the younger leaves remain
462 turgid until the stress becomes severe which is supported by observations from the current
463 study. Other studies have shown that sugar beet can exhibit signs of retardation of leaf area
464 increase emanating from temporary drought during the different stages of development.
465 Choluj *et al.* (2004) reported a 6% reduction in relative water content of young and old

466 leaves while Mohammadian *et al.* (2005) reported a loss of 14.1% in leaf area index of sugar
467 beet plants as a result of water stress. Scott and Jaggard (1993) indicated in their study that
468 one of the components to determine sugar beet yield is the amount of radiation it intercepts
469 through the leaves and Choluj *et al.* (2014) more recently observed a 60% and 70%
470 decrease in the leaf area index of some sugar beet genotypes as a result of water deficit
471 compared to their control experiment.

472

473 The impact of water stresses will be further compounded by predicted increases in
474 temperature and rising levels of carbon dioxide. By the year 2050, the atmospheric CO₂
475 concentration is likely to exceed 500 ppm (IPCC, 2013) and, all other things being equal, this
476 increase may result in an increase in yields of C3 crops, including sugar beet, of 13%
477 (Jaggard *et al.*, 2010). However, the continued increase of CO₂ and its impact on other
478 variables will, after a point, cause a decrease in the quality of the sugar beet (Myers *et al.*,
479 2014). Additionally, future predicted increases in temperature by 2050 will increase
480 evaporation during the growing season, especially in the months of June and July, which will
481 be challenging for sugar beet production and will require further research into water
482 management to maintain and sustain productions in order to maximise yields. Again, more
483 complex experimental procedures, with further variables being controlled, could answer
484 more complex questions but the results reported here are robust and address a fundamental
485 issue in a controlled way.

486

487 The yield of the different watering regimes showed a statistically significant ($p < 0.05$)
488 reduction in “future” wet yield. Figures 4a and 4b-c show the box plot and the distribution of
489 the mean wet tuber mass from the “control” and “future” watering regimes, respectively. The
490 different watering regimes did result in a statistically significant impact on the root yield
491 between the two groups. This result is in line with Kenter *et al.* (2006) who showed that dry
492 root matter in field studies towards the end of a growing season depended on the availability
493 of water in the soil. Analysis of the bi-weekly soil moisture measurements showed a
494 statistically significant difference between the two groups. These results confirm that the
495 experimental design had a direct impact on the growing environment, which was then
496 reflected in the “wet” yield data: the mean mass of the “control” category was 359.5g; the
497 mean in the “future” group was 318.5g. This is consistent with Richter *et al.* (2006), who
498 modelled the response of UK sugar beet under climate change and found that water will be a
499 major stress factor in future and relative soil moisture will be reduced under a high
500 greenhouse gas emissions scenario.

501

502 The “dry” mass of plants in both groups did not indicate a significant difference ($p=0.11$).
503 This implies that the difference in the tuber mass of both groups was, to a certain extent, a
504 result of water retention. There was, nonetheless, a noticeable difference in the mean of the
505 two groups, which would have been mostly linked to sugar content because once the water
506 has been removed from the tuber, the majority of the remaining mass will be sugars.

507

508 A recent study conducted by Chami *et al.* (2015) on the economics of irrigating wheat in East
509 England reported that the use of supplementary irrigation by farmers will be justified by
510 increase in yields. The study asserts that the increment in yield from irrigation will be more
511 beneficial in dry years and in reducing inter-annual yield gaps. Results from the current study
512 align with the result of Chami *et al.* (2015) study in considering irrigation as a management
513 option for sugar beet farmers in order to remain viable in future growing seasons. However,
514 no statistically significant evidence is presented here that suggests sugar content would
515 increase with the implementation of irrigation.

516

517 This result shows that under a future of warmer and dryer summers, and all other things
518 being equal, yields will reduce unless other alternatives such as irrigation are considered.
519 Investigations into the effect of other variables are also required. Nonetheless, the
520 observations from this experiment also show that sugar beet is relatively resilient to
521 increased temperatures and that the overall sugar content of the crop is not particularly
522 sensitive to a moderate (16%) decrease in seasonal water availability.

523

524 **5. Conclusions**

525

526 The experimental implementation of a 16% water reduction applied to sugar beet plants
527 grown in a greenhouse implies that reduced summer rainfall will have a significant impact on
528 soil moisture (12% decrease; $p<0.05$) and “wet” sugar beet yield (11% decrease; $p<0.05$).
529 This relatively small “precipitation” decrease was calculated from a comparison of the MOHC
530 HadGEM2-ES CMIP5 daily precipitation field of the mean of the medium and high
531 greenhouse gas emissions scenarios (RCP45 and RCP85; 2021-2050) with model output
532 from the “historical” phase (1971-2000).

533

534 The result for “dry” yield did not show a statistically significant result (7.4% decrease;
535 $p=0.11$) but it is a far from conclusive acceptance of the null hypothesis. This is a key result
536 for understanding the how the UK sugar beet industry needs to adapt to future climate
537 changes and work to determine what proportion of this yield decrease is linked to sugar

538 content is underway during a second experimental season using the same greenhouse
539 facility.

540 **References**

541

542 BBRO. 2013. *BBRO Recommended Varieties List 2013*. British Beet Research Organisation:
543 Norwich, UK.

544

545 Brands S, Herrera S, Fernández J, Gutiérrez JM. 2013. How well do CMIP5 Earth System
546 Models simulate present climate conditions in Europe and Africa? A performance
547 comparison for the downscaling community. *Clim. Dyn.* **41**: 803–817.

548

549 British Sugar. 2011. *UK Beet Sugar Industry: Sustainability Report 2011*. British Sugar plc
550 and NFU Sugar: Peterborough and Stoneleigh, UK.

551

552 Brouwer C, Heibloem M. 1986. *Irrigation Water Management: Irrigation Water Needs*. Food
553 and Agriculture Organization of the United Nations: Rome, Italy.

554

555 Brown KF, Messem AB, Dunham RJ and Biscoe PV. 1987. Effect of drought on growth and
556 water use of sugar beet. *J. Agric. Sci.* **109**: 421–435.

557

558 Burrell A, Himics M, Doorslaer Bvan, Ciaian P, Shrestha S. 2014. *EU sugar policy: A sweet
559 transition after 2015?* Report EUR 26530 EN. European Commission, Joint Research
560 Centre: Sevilla, Spain.

561

562 Chami DE, Knox JW, Daccache A, Weatherhead EK. 2015. The economics of irrigating
563 wheat in a humid climate – a study in the East of England. *Agr. Syst.* **140**: 19–25.

564

565 Choluj D, Karwowska R, Jasińska M, Haber G. 2004. Growth and dry matter partitioning
566 insugar beet plants (*Beta vulgaris* L.) under moderate drought. *Plant Soil Environ.* **50**: 265–
567 272.

568

569 Choluj D, Wisniewska A, Szafranski K M, Cebulac J, Gozdowski D, Podlaski S. 2014.
570 Assessment of the physiological responses to drought in different sugar beet genotypes in
571 connection with their genetic distance. *J. Plant Physiol.* **171** :1221–1230.

572

573 DEFRA. 2014. *Agriculture in the United Kingdom*. Department for Environment, Food and
574 Rural Affairs (DEFRA): London, UK.

575

576 EFRA Committee. 2014. *Winter flood 2013–2014*. Environment, Food and Rural Affairs
577 (EFRA) Committee, House of Commons: London, UK.
578

579 FAO. 2009. *How to feed the world in 2050*. Food and Agriculture Organization (FAO) of the
580 United Nations: Rome, Italy.
581

582 Gianessi L. 2013. *Highest sugar beet yields ever in the UK thanks to new fungicides*. Crop
583 Protection Research Institute: Washington DC, USA.
584

585 Hsaio TC. 2000. Leaf and root growth in relation to water status. *Hort. Sci.* **35**: 1051–1058
586

587 IPCC. 2013. *Climate Change 2013: The Physical Science Basis. Contribution of Working
588 Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*,
589 Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V,
590 Midgley PM (eds.). Cambridge University Press: Cambridge, UK and New York, USA.
591

592 IPCC. 2014. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Contribution of
593 Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate
594 Change*, Field CB, Barros VR, Dokken DJ, Mach KJ, Mastrandrea MD, Bilir TE, Chatterjee
595 M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S,
596 Mastrandrea PR, White LL (eds.). Cambridge University Press: Cambridge, UK and New
597 York, USA.
598

599 Jaggard KW, Qi A, Semenov MA. 2007. The impact of climate change on sugar beet yield in
600 the UK: 1976-2004. *J. Agr. Sci.* **145**: 367-375.
601

602 Jaggard KW, Qi A, Ober S. 2010. Possible Changes to Arable Crop Yields by 2050. *Phil.
603 Trans. R. Soc. B.* **365**: 2835–2851.
604

605 Jones PD, Lister DH, Jaggard KW, Pidgeon JD. 2003. Future climate change impact on the
606 productivity of sugar beet (*Beta vulgaris* L.) in Europe. *Clim. Cha.* **58**: 93–108.
607

608 Kenter C, Hoffman C, Marlander B. 2006. Effects of weather variables on sugar beet yield
609 development (*Beta vulgaris* L.). *Eur. J. Agron.* **24**: 62–69.
610

611 Lambers H, Chapin FS, Pons TL. 1998. *Plant Physiological Ecology*. Springer: New York,
612 USA.

613
614 McSweeney CF, Jones RG, Lee RW, Rowell DP. 2015. Selecting CMIP5 GCMs for
615 downscaling over multiple regions. *Clim. Dyn.* **44**: 3237–3260.
616
617 Maraun D, Wetterhall F, Ireson AM, Chandler RE, Kendon EJ, Widmann M, Brienen S, Rust
618 H, W, Sauter T, Themeßl M, Venema VKC, Chun KP, Goodess CM, Jones RG, Onof C,
619 Vrac M, Thiele-Eich I. 2010. Precipitation downscaling under climate change: Recent
620 developments to bridge the gap between dynamical models and the end user. *Rev.*
621 *Geophys.* **48**: RG3003.
622
623 Menzel A, Sparks TH, Estrella N, Koch E, Aasa A, Ahas R, Alm-Kübler K, Bissolli P,
624 Braslavská O, Briede A, Chmielewski FM, Crepinsek Z, Curnel Y, Dahl Å, Defila C, Donnelly
625 A, Filella Y, Jatzcak K, Måge F, Mestre A, Nordli Ø, Peñuelas J, Pirinen P, Remišová V,
626 Scheifinger H, Striz M, Susnik A, Van Vliet AJH, Wielgolaski F-E, Zach S, Zust A. 2006.
627 European phenological response to climate change matches the warming pattern. *Glob.*
628 *Change Biol.* **12**: 1969–1976.
629
630 Met Office. 2014. *The recent storms and floods in the UK*. Met Office: Exeter, UK.
631
632 Met Office. 2016. *2014 weather summaries* [Online]. Met Office: Exeter, UK. Available at:
633 <http://www.metoffice.gov.uk/climate/uk/summaries/2014> [Accessed: 10 March 2016].
634
635 Milford GFJ, Lawlor DW. 1976. Water and physiology of sugar beet. In *Proceedings of the*
636 *39th Winter Congress of the International Institute for Sugar Beet Research, Brussels, Feb*
637 *1976*. International Institute for Beet Research: Brussels, Belgium.
638
639 Mohammadian R, Moghaddam M, Rahimian H, Sadeghian SY. 2005. Effect of early season
640 drought stress on growth characteristics of sugar beet genotypes. *Turk. J. Agric. For.* **29**:
641 357–68.
642
643 Mohammadzadeh M, Hatamipour MS. 2010. Effects of dry conditions on properties of dried
644 sugar beet. *Iran. J. Chem. Eng.*, **7**: 81–87.
645
646 Myers SS, Zanolatti S, Kloog I, Huybers P, Leakey ADB, Bloom AJ, Carlisle E, Dietterich
647 LH, Fitzgerald G, Hasegawa T, Holbrook NM, Nelson RL, Ottman MJ, Raboy V, Sakai H,
648 Sartor KA, Schwartz J, Seneweera S, Tausz M, Usui Y. 2014. Increasing CO₂ threatens
649 human nutrition. *Nature*. **510**: 139–142.

650
651 Pidgeon JD, Werker AR, Jaggard KW, Richter GM, Lister DH, Jones PD. 2001. Climatic
652 impact on the productivity of sugar beet in Europe, 1961–1995. *Field Crops Res.* **109**: 27–
653 37.
654
655 Richter GM, Qi A, Jaggard KW. 2006. Modelling the variability of UK sugar beet under
656 climate change and husbandry adaptations. *Soil Use Manage.* **22**: 39–47.
657
658 Rytter RM. 2005. Water use efficiency, carbon isotope discrimination and biomass
659 production of two sugar beet varieties under well-watered and dry conditions. *J. Agron. Crop.*
660 *Sci.* **191**: 426–438.
661
662 Scott RK, Jaggard KW. 1993. Crop physiology and agronomy. In *The sugar beet crop*,
663 Cooke DA, Scott RK (eds.). Chapman and Hall: London, UK; 179–237.
664
665 Taylor KE, Stouffer RJ, Meehl GA. 2012. An overview of CMIP5 and the experiment design.
666 *Bull. Amer. Meteor. Soc.* **93**: 485–498.
667
668 UKCP. 2009. *Adapting to Climate Change: UK Climate Projections*. Department for
669 Environment, Food and Rural Affairs (DEFRA): London, UK.
670
671 van Vuuren DP, Edmonds J, Kainuma M, Riahi K, Thomson A, Hibbard K, Hurtt GC, Kram T,
672 Krey V, Lamarque J-F, Masui T, Meinshausen M, Nakicenovic N, Smith SJ, Rose SK. 2011.
673 The representative concentration pathways: an overview. *Clim. Cha.* **109**: 5–31.

674 **Tables**

675

676 **Table 1:** Details of the CMIP5 models examined in this paper.

Model name	Resolution (lat x long)	Institution
CanESM2	64 x 128 (2.8 x 2.8)	Canadian Centre for Climate Modelling and Analysis (CCCma), Canada
CSIRO-Mk3.6.0	96 x 192 (1.875 x 1.875)	Commonwealth Scientific and Industrial Research Organisation (CSIRO) in collaboration with the Queensland Climate Change Centre of Excellence (QCCCE), Australia
HadGEM2-ES	145 x 192 (1.25 x 1.875)	Met Office Hadley Centre (MOHC), UK
EC-EARTH ESM	160 x 320 (1.125 x 1.125)	EC-Earth consortium; data managed by the Irish Centre for High-End Computing (ICHEC)
IPSL-CM5A-LR	96 x 96 (1.875 x 3.75)	Istitut Pierre-Simon Laplace (IPSL), France
MIROC5	128 x 256 (1.41 x 1.41)	Atmospheric and Ocean Research Institute, Japan
MPI-ESM-LR	96 x 192 (1.875 x 1.875)	Max Planck Institute for Meteorology (MPI-M), Germany
CCSM4	192 x 288 (0.94 x 1.25)	National Centre for Atmospheric Research (NCAR), USA

677

678 **Table 2:** MOHC HadGEM2-ES precipitation data analyses for the sugar beet growing
679 season (May-October).

Experiment	Period	Mean daily precipitation (mm day⁻¹)	Difference from “Historical” (%)
“historical”	1971-2000	1.625	0
RCP45	2021-2050	1.352	-16.8
RCP85	2021-2050	1.382	-14.9
Mean of RCP45 and RCP85	2021-2050	1.368	-15.8

680

681 **Table 3:** means +/- 1 S.D. of the final measurements of non-destructive parameters from the
682 control and future watering regimes.

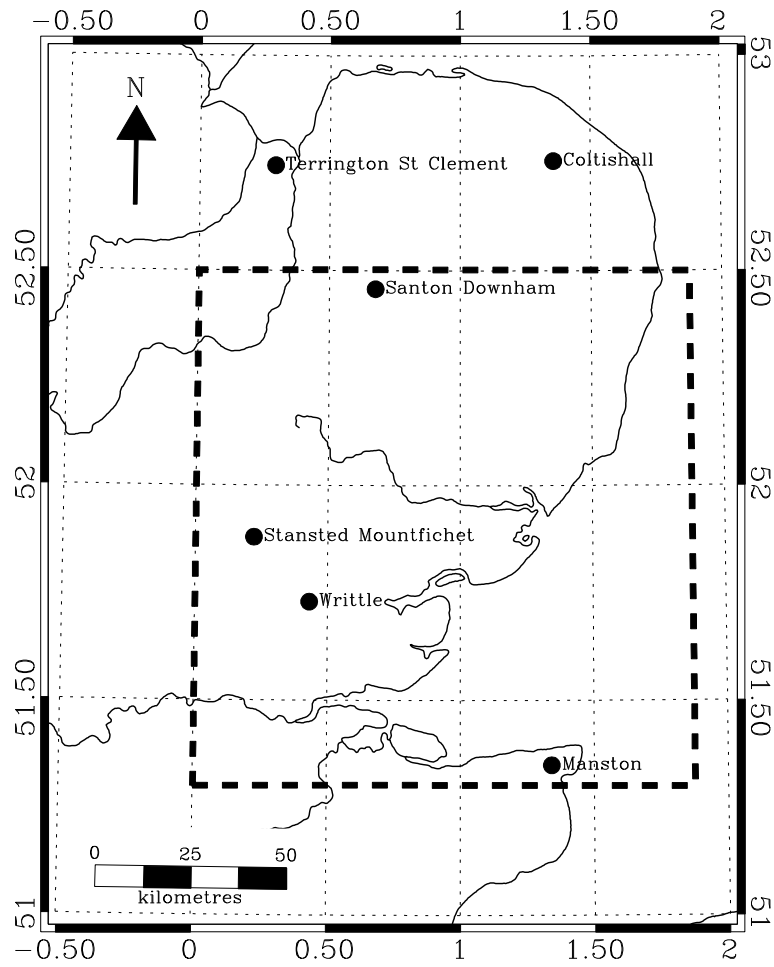
Parameters	Control (Mean +/- 1 S.D.)	Future (Mean +/- 1 S.D.)
Highest tip of plants (cm)	49 ± 8.8	41.4 ± 10.43
Number of leaves	34.3 ± 7.2	31.0 ± 7.5
Growth Ratio (cm)	1.5 ± 0.3	1.4 ± 0.1

Leaves width (cm)	10.0 ± 2.2	9.6 ± 2.3
Seasonal Soil Moisture (%)	19.3 ± 1.6	18.0 ± 2.1

683

684 **Figures**

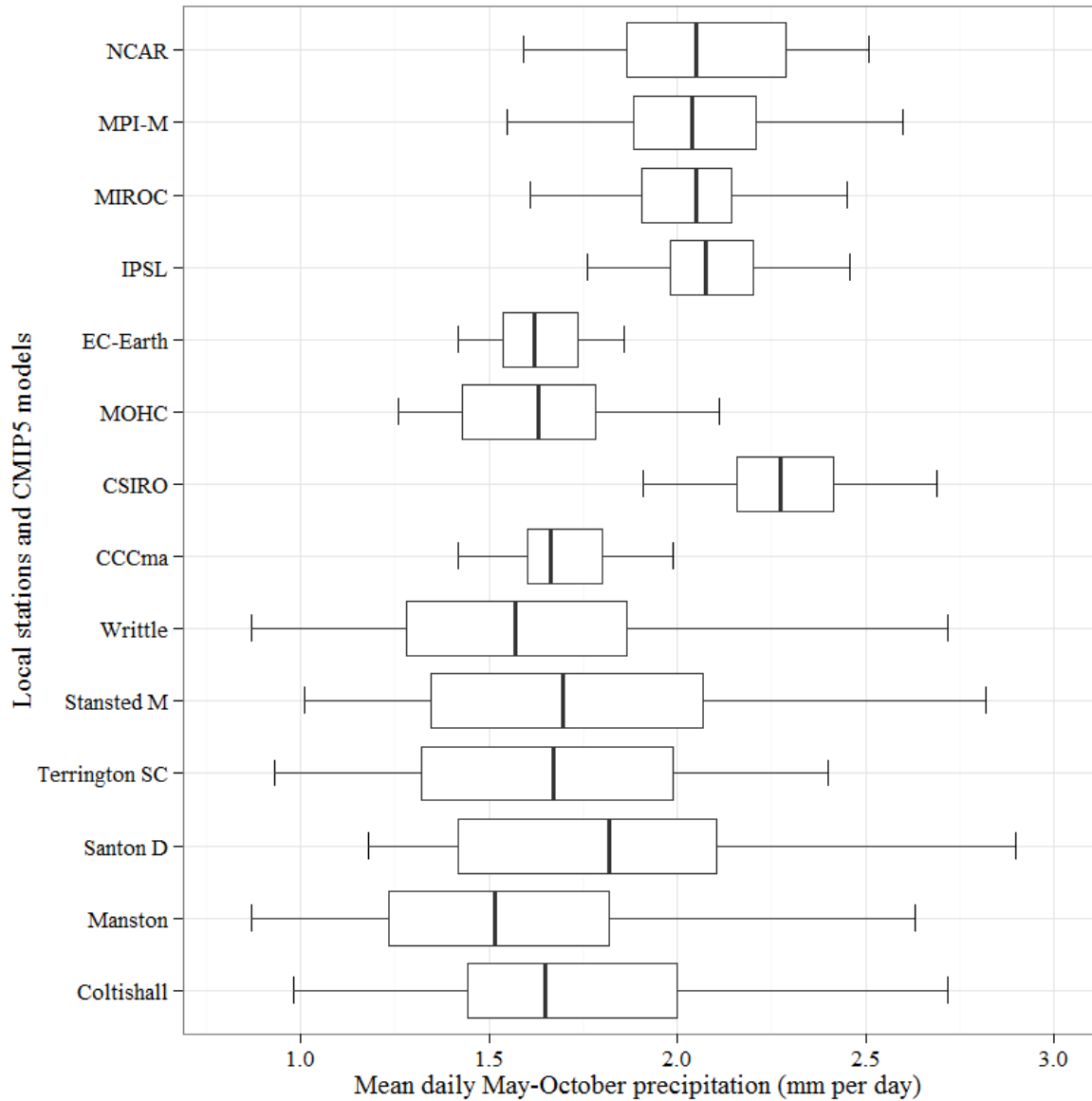
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687 **Figure 1:** Map of the study area. The locations of the weather stations examined in the
688 analysis are plotted. The dashed line indicates the area covered by the MOHC HadGEM2-
689 ES model grid cell used here.

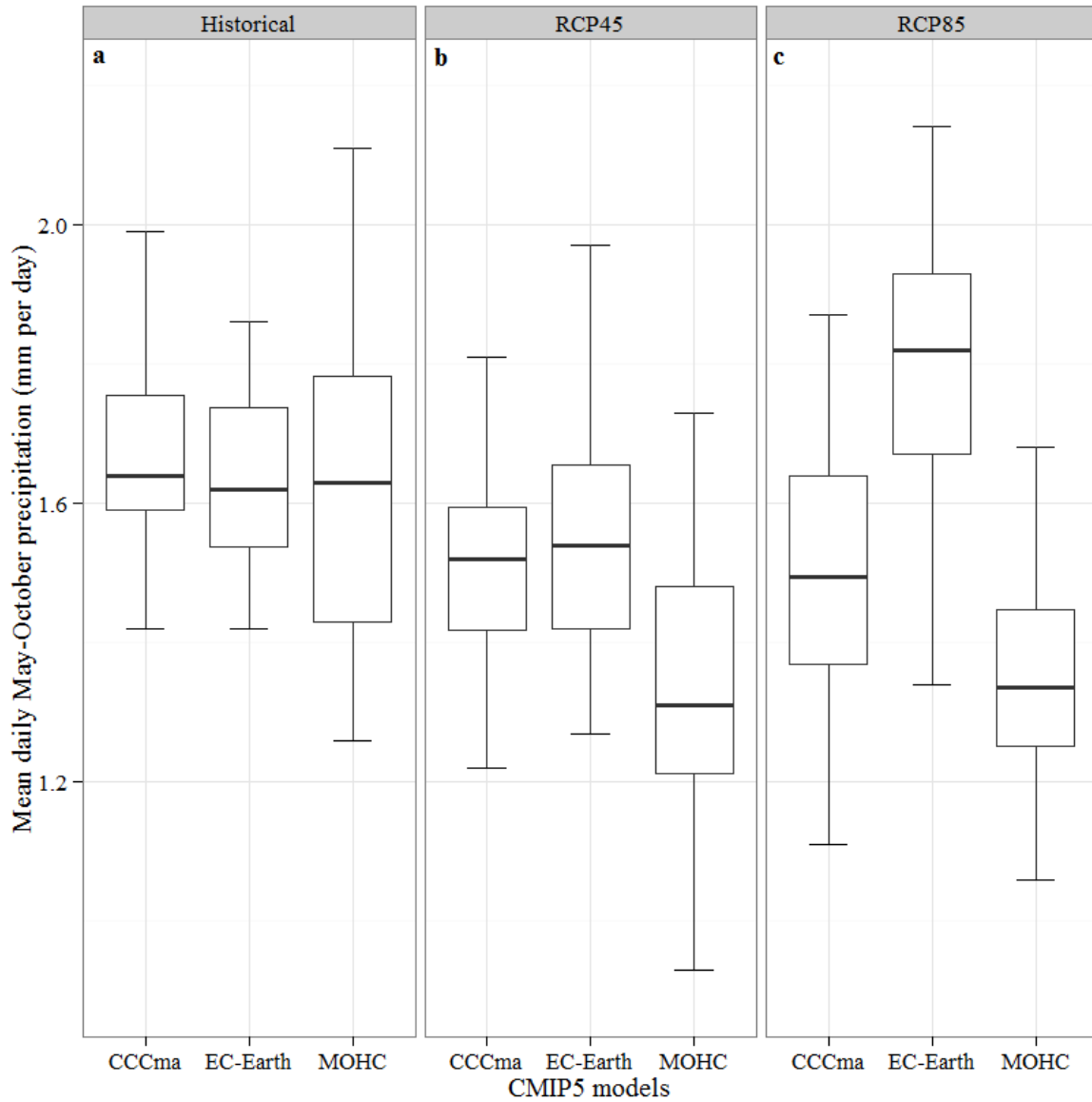
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692 **Figure 2:** Boxplot of the daily May-October precipitation data for 1971-2000 from the
 693 “historical” phase of the CMIP5 climate models and the daily weather station observations
 694 for the same period. The thick black line represents the median (2nd quartile) of the
 695 distribution. The extremes of the box represent the 1st (bottom) and 3rd quartiles (top). The
 696 whiskers indicate the lowest and highest values. Santon Downham had 9 days of missing
 697 data in 1983. Manston had 37 days of missing data in 1999.

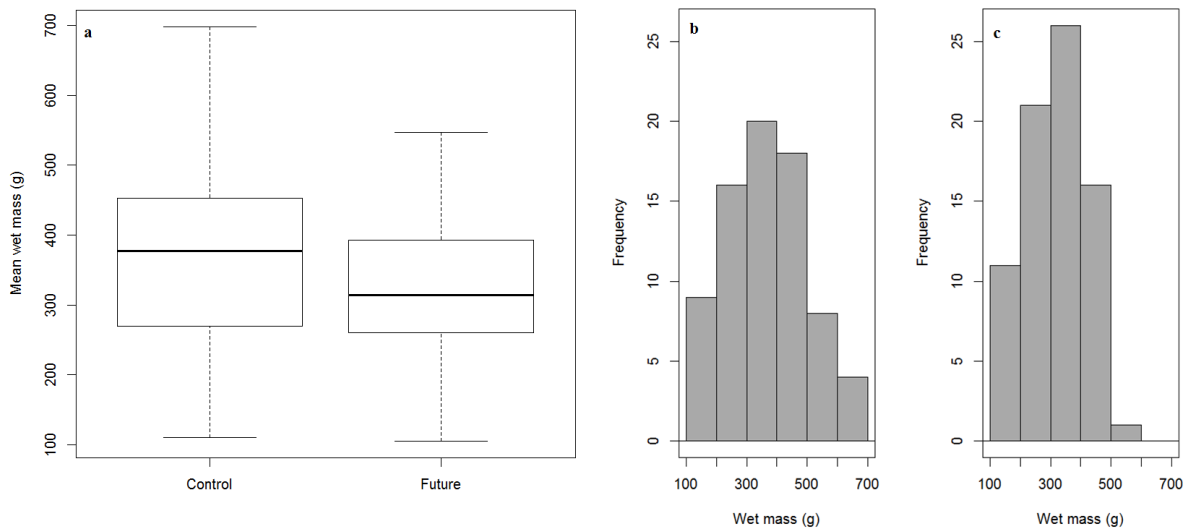
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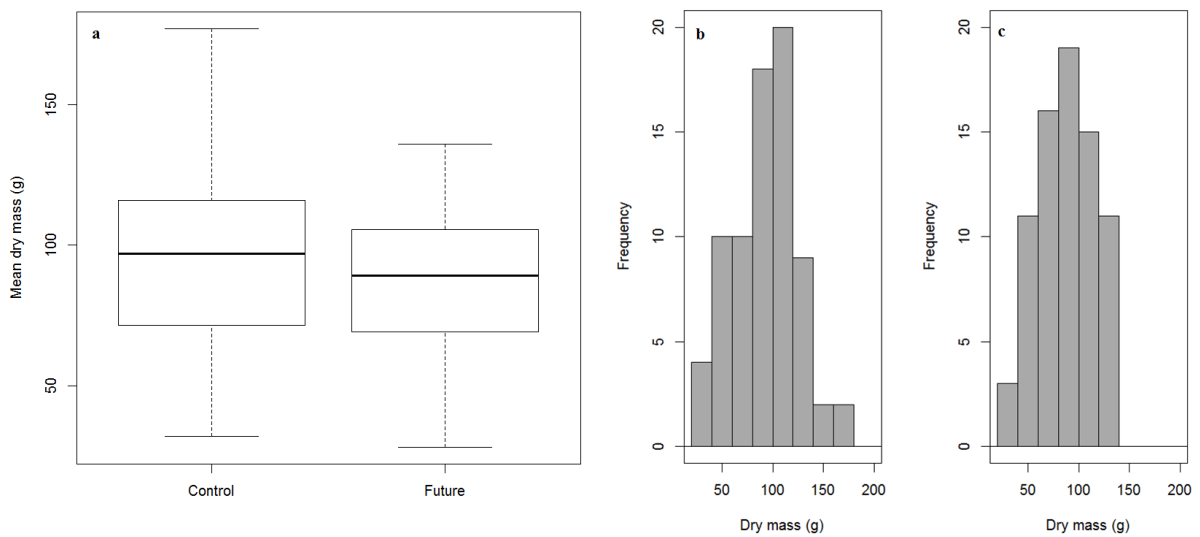
700 **Figure 3:** Boxplot of the daily May-October precipitation data from the a) "historical" (1971-
 701 2000), b) RCP45 (2021-2050) and c) RCP85 (2021-2050) output from the CCCma, MOHC
 702 and EC-Earth climate models. The boxplot details are the same as for Figure 2.

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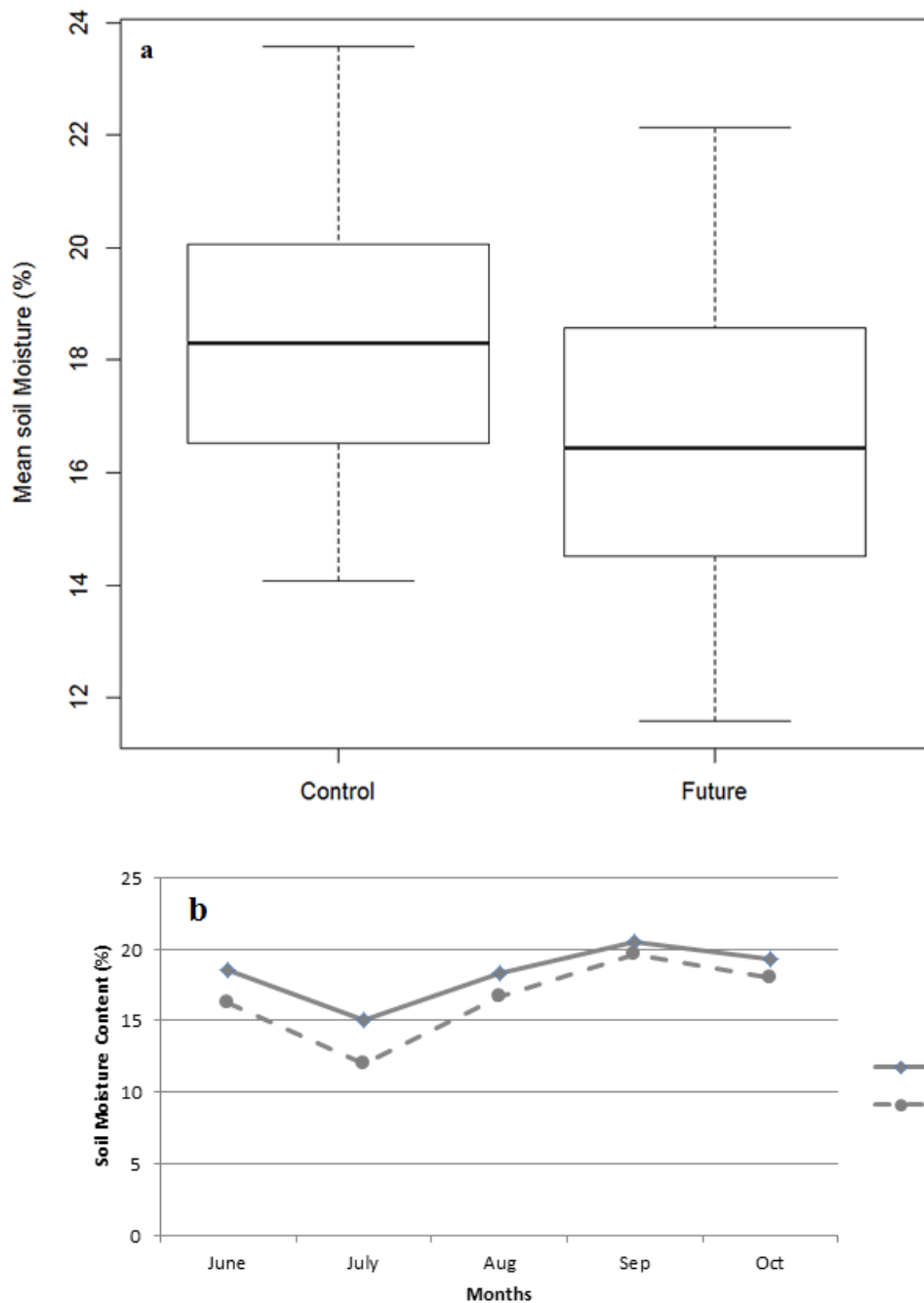
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Figure 4: Results of the tuber “wet” mass data analysis. a) Boxplot showing the tuber “wet” mass data from the “control” and “future” categories. The boxplot details are the same as for Figure 2. b) Histogram showing the distribution of the “wet” mass data for the “control” category. c) Histogram showing the distribution of the “wet” mass data for the “future” category.



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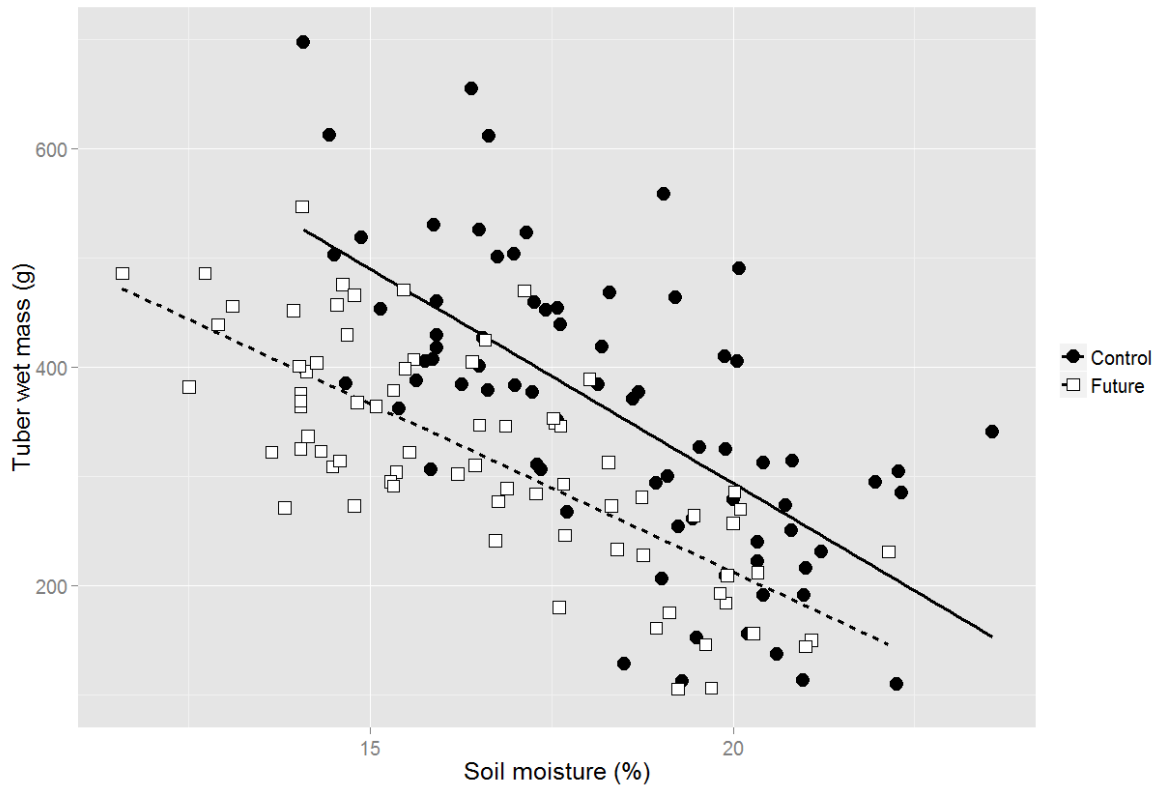
Figure 5: Results of the tuber “dry” mass data analysis. a) Boxplot showing the tuber “dry” mass data from the “control” and “future” categories. The boxplot details are the same as for Figure 2. b) Histogram showing the distribution of the “dry” mass data for the “control” category. c) Histogram showing the distribution of the “dry” mass data for the “future” category.



718

719 **Figure 6:** Results of the soil moisture data analysis. a) Boxplot showing the soil moisture
 720 data from the “control” and “future” categories. The boxplot details are the same as for
 721 Figure 2. b) Line graph showing the mean monthly soil moisture measurements for the
 722 “control” category (solid line) and the “future” category (dashed line).

723



724

725 **Figure 7:** Scatter plot showing the “wet” mass for individual tubers from the “control” (filled
726 circles; solid line) and “future” (open squares; dashed line) categories plotted against the
727 mean soil moisture data for each replicate.