Economics of sugar beet irrigation in England

BBRO Project 16 02

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1 Introduction

Sugar beet is an economically important crop in England, and key component for arable rotation in many areas. It can be grown profitably in contrasting climatic and edaphic environments and is currently grown on four continents (Draycott 2006). The yield of sugar beet is sensitive to water stress and therefore in some places it is commonly irrigated. In England, irrigation of sugar beet is uncommon, however there are increasing concerns regarding the long-term viability of rain fed production and the potential impacts of increased rainfall uncertainty and drought risk on current beet management strategies. The aim of this project was to review and assess the costs and benefits of irrigating sugar beet in England and its sensitivity to changing agroclimate (rainfall), management (labour, energy) and market (price) conditions. The study used a combination methodology integrating data from literature review, with estimates of yield and water use from biophysical crop modelling, with spreadsheet analyses to assess the financial benefits (and sensitivity) of irrigation. Work in this area is especially timely given the uncertainty arising from deregulation of the sugar market.

2 Literature review

2.1 Drought impact on sugar beet

2.1.1 Drought tolerance

Sugar beet is moderately tolerant to drought - more so than potatoes but less than winter cereals. Limited periods of water deficit do not normally have an effect on final yield, but prolonged dry periods can be detrimental to crop development and yield formation. Therefore, in regions where sugar beet production is largely dependent on rainfall, reported yield losses due to prolonged dry conditions are more common (Ober & Rajabi 2010). In the UK, it has been estimated that, on average, 10% of potential sugar beet yield is lost every year due to insufficient soil moisture, with considerably larger losses in dry years (Jaggard et al. 1998; Qi & Jaggard 2006).

Adequate water supply is necessary for seed germination and emergence. Seedlings are especially sensitive to low temperatures and lack of moisture until the two-leaf stage. Early in crop development, water deficits affect fibrous root growth and can hasten the loss of roots in the upper soil layers. Leaf expansion is sensitive to water deficit and rapid establishment of the canopy is critical to capture as much radiation as early as possible. Thus, any treatment that can increase initial growth (including first irrigation) should contribute to greater yields (Draycott 2006). The most critical period when drought can affect yield is during germination and early plant development (Yonts n.d.).

2.1.2 Drought response

Early research by Jaggard et al. (1998) compared the sugar yield loss (t/ha) with the cumulative potential soil water deficit for June–August (Figure 1), based on data from field experiments conducted at ADAS Gleadthorpe (1979-94) and Broom's Barn (1965-95). As expected, sugar beet grown on low moisture retentive sandy soils was more severely affected by drought than beet grown in a sandy loam, with reported sugar yield losses reaching more than 5 t/ha for a 200 mm potential deficit, compared to 0.8 to 4.5 t/ha for a sandy loam.

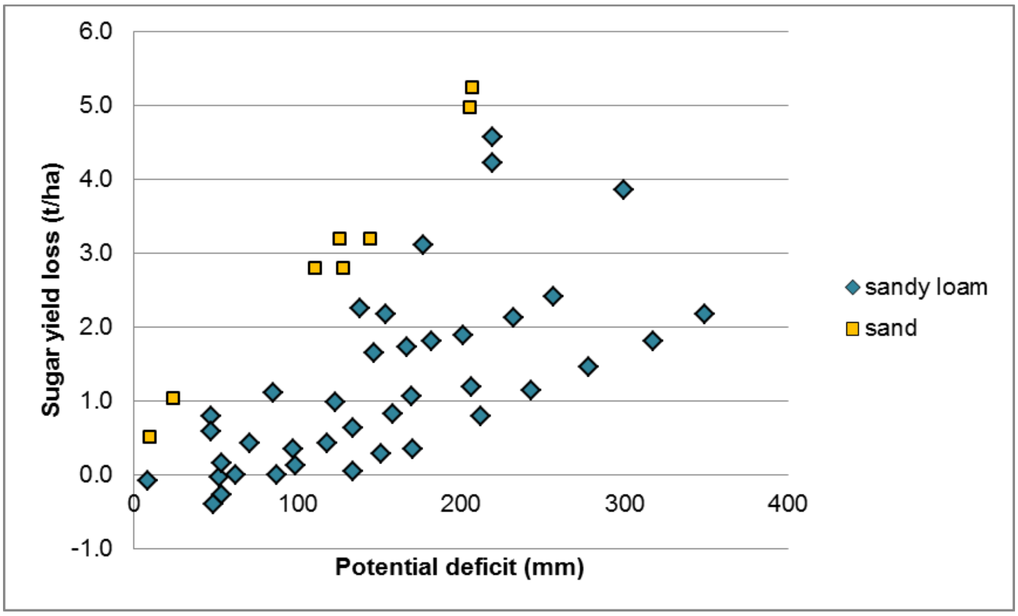


Figure 1. Sugar yield losses (t/ha) due to cumulative potential soil water deficit for June–August (mm) from June to August on two soil types based on experimental field trials at Gleadthorpe and Brooms Barn. Source: Jaggard et al. (1998)

2.1.3 Early vs. late drought

Brown et al. (1987) assessed the severity of the effects of drought at Brooms Barn depending on the growth stage at which the crop experienced the drought event, distinguishing between early (June-July) and late (August-September) drought. In an early drought, the root system had not fully developed to access deep soil water. Without sufficient water (from rainfall and/or irrigation), fibrous roots can die in the topsoil and the growth of deeper roots slows down. On the other hand, a crop experiencing a late drought would have already developed an extensive rooting system and attained full crop canopy cover, thus allowing access to a larger soil water volume. Compared to the early drought, the overall effects of late drought on crop cover and radiation interception were reported to be smaller (Brown et al. 1987; Yonts n.d.). Thus, the final yield reduction in a late drought would be less than that induced by an early drought. In Canada, Alberta Agriculture and Forestry (2012) showed similar results, with yields significantly reduced due to an early drought than a late drought, and with both of them reporting significantly lower yields compared to those from the irrigation control trials. According to Brown et al. (1987), while early irrigation before a long late drought led to a higher sugar content, late irrigation after an early drought reduced the sugar percentage.

Irrigation applied before complete canopy closure (16-leaf growth stage) should meet crop water requirements and build up soil water to near field capacity in the 0.5 to 1.0 m depth for use during the peak water demand period. Sugar beet will reach canopy closure early if soil water in the 0 – 0.5 m depth is maintained at greater than 60%of available water (Alberta Agriculture and Forestry 2012).

2.2 Irrigation of sugar beet in England

In southern Europe, including Spain, Portugal and Greece, sugar beet is typically fully irrigated due to the high temperatures and semi-arid environment. In contrast, in the UK, Germany, France, Sweden and the Netherlands due to the humid or temperate conditions the proportion of the crop that is typically irrigated is relatively small (CIBE/CEFS, 2003). In England, the irrigated area has decreased from 9,700 ha in 2001 to 6,200 ha in 2010 and is now concentrated on 265 holdings (Defra & NS, 2011). The 2010 Defra Irrigation Survey (Defra,

2011) reported that sugar beet accounted for 8% of the total irrigated area. Although beet is grown in the driest parts of England and often on low moisture retentive or droughty soils, it is estimated that only about 5% of the total beet area is irrigated, the remaining 95% is dependent on summer rainfall, which is usually insufficient to meet the crop water requirements (Ober et al. 2004; Groves & Bailey 1997).

2.2.1 Irrigation need

In the UK, the majority of sugar beet is grown in Eastern England, where the average summer rainfall is 150 mm, and average reference evapotranspiration (ETo) is 300 mm (Jaggard et al. 1998). Irrigation requirements are typically about 100 mm per year, and yield responses are usually favourable (BBRO 2002). Irrigation requirements vary across locations, and the crop's response to irrigation depends on the soil moisture deficit, the amount of water applied and soil texture (among other factors). In northern temperate areas, solar radiation limits beet yield more than water supply in many cases.

While for most crops the coincidence of stress and phenology has a big impact on final yield, sugar beet has no stress-sensitive reproductive phase and thus yield is largely a function of water use and simply dependent on vegetative growth (Ober et al. 2004; Dunham 1993; Draycott 2006).

2.2.2 Timing of irrigation

The timing of irrigation appears to be more important than irrigation amount (depth applied) (Draycott & Messem 1977; Eckhoff et al. 2005), as the duration of the water deficit is the main determining factor affecting final yield.

- *Early season:* In experiments at Broom's Barn, the crop did not show any response to irrigation in May, even in very dry years (Bailey 1990).
- *Peak water use:* In England, the June to August period (normally characterized by an increasing soil water deficit and high temperatures) is crucial in determining beet yield (Aiming Qi & Jaggard 2006; Jaggard et al. 1998). Experiments at Broom's Barn showed that irrigation in June or July both produced larger average sugar yield increases than irrigation in August and September (Draycott & Messem 1977). According to experiments conducted in 1971 at the same location, irrigation progressively increased top dry matter until the end of August (by up to 2 - 5 t/ha) but the increase in root dry matter remained at about 0 - 8 t/ha (Draycott et al. 1974).
- *End of irrigation:* Stopping irrigation before harvest to increase the sugar percentage by root dehydration is a technique often used by farmers. The increase in sugar concentration must be set against applying too much stress that any late season sugar yield gains are then lost. Many studies have been conducted to investigate the optimum dates for stopping irrigation before harvest (Draycott 2006). Irrigation can be stopped around August 1st with little or no yield loss if an additional 200 mm of water can be supplied by soil moisture storage, irrigation and/or rainfall.

  Irrigation in September does not appear to increase sugar yield as any increase in fresh root weight is offset by a decrease in sugar percentage. However, at ADAS Gleadthorpe, experimental results showed that the irrigation of sugar beet late in the season (September-October) can pay dividends on very light soils in those seasons where the crop has received very little irrigation and the soil moisture deficit (SMD) is high. Thus, in dry years, irrigating in the autumn could compensate to some extent the yield lost previously (Bailey 1990). In most cases, transpiration requirements in October and November are satisfied entirely from soil water stored at depth (Draycott & Messem 1977).

- *Harvest:* Some irrigation water may be applied just prior to harvesting to maintain soil moisture slightly above 60 per cent of available for ease of lifting (Alberta Agriculture and Forestry 2012).

2.3 Yield response to irrigation

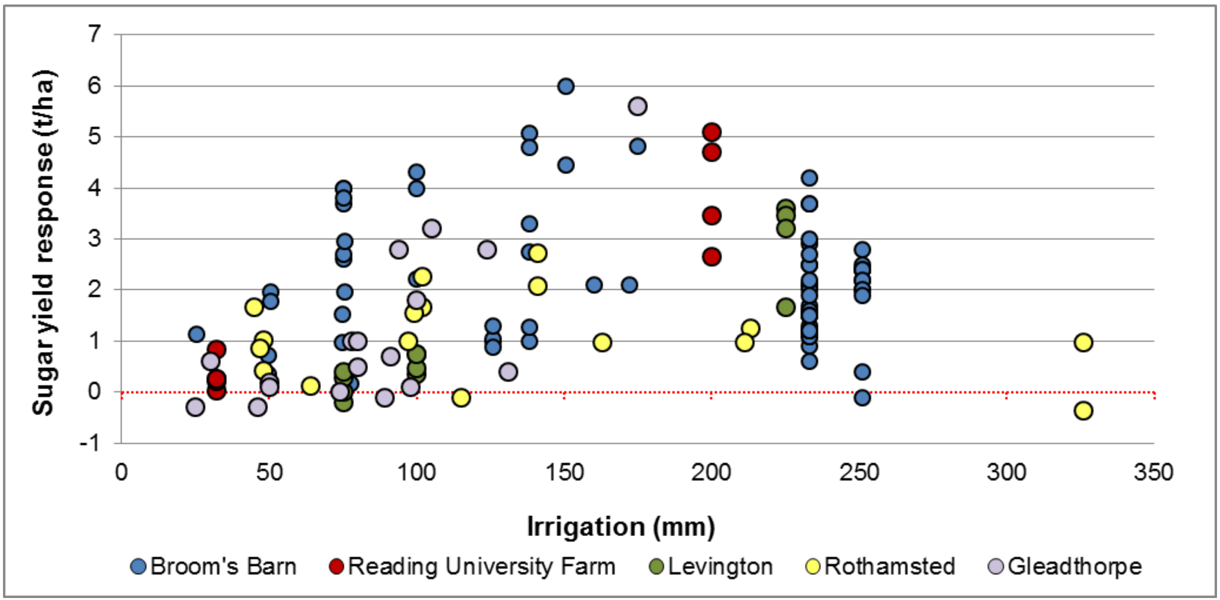
There is very limited recent published evidence that describes field experimental research that has assessed sugar beet yield response to irrigation in England, and how that response interacts with other factors including plant density, N intake or resistance to pests and diseases. The key findings are briefly summarised below.

2.3.1 Sugar yield

The proportion of assimilates between sugar storage, shoot and root system dry matter is strongly impacted by water and nitrogen availability, amongst other factors. The harvest index (ratio of sugar to total dry matter) is typically around 0.5 (Draycott 2006). However, under water deficit and low nitrogen conditions, canopy growth is reduced more than sugar accumulation, resulting in a higher harvest index (Scott et al. 1994).

Draycott (2006) previously analysed 27 years of irrigation experiments conducted in the UK. The average yield response to irrigation, compared with unirrigated crops, was 1.1 t sugar/ha. In general, results from those experiments showed little response to irrigation if soil moisture deficits (SMD) were less than 75 mm. Where SMD were greater than 75 mm, the crop response to irrigation was around 2 t sugar/ha per 100 mm water applied. Because of sugar beet's deep rooting system, which can extract water to depth of 0.90 to 1.05 m, in a deep soil with no restrictive horizons, the effects of temporary deficits can be marginal if water is available in the root zone (Neibling & Gallian 1978). Irrigated crops normally extract water near the soil surface, while withholding irrigation eight weeks prior to harvest resulted in substantial changes in the proportion of water removed from the deeper soil layers (Draycott 2006). According to experiments conducted at Broom's Barn, the crop loses approximately 1 t/ha sugar for each 25 mm of water that is not used (Bailey 1990).

Figure 2 shows the sugar yield response to irrigation (t sugar/ha) from experiments across England (mostly on sandy loam and silty soils). Most experiments took place at Broom's Barn (Suffolk) where the water requirement of sugar beet ranges from 400 to 480 mm between May and October (Bailey 1990). The results show that for the same amount of irrigation, sugar beet yield response can vary considerably due to several factors, such as soil texture, crop variety, rainfall, management practices and experimental design. There can also be a large discrepancy between water applied and water actually used by the crop (Bailey 1990). This is because irrigation water can be lost in a number of ways other than transpiration, such as surface runoff, drainage beyond the root zone, and by direct evaporation from the soil (Brown et al. 1987).



Sources: Penman 1951; Draycott & Messem 1977; Draycott & Webb 1971; Draycott et al. 1974; Penman 1970; K. Brown et al. 1987; Ober, Chris J.A. Clark, et al. 2004; Ober & Rajabi 2010; Jaggard et al. 1998; Harris 1972; Holmes & Whitear 1976; Rajabi et al. 2009; A Qi & Jaggard 2006; Bailey 1990

Figure 2. Sugar yield response to irrigation (t/ha). Data from field experiments in the UK. Sites: Broom's Barn, Reading University Farm, Levington, Rothamsted Experimental Station (Woburn) and Gleadthorpe.

Sugar beet yield responses to irrigation vary from year to year, and may be linear or curvilinear (both concave and convex). Although generally linear, the relationship often becomes curvilinear (convex) when the irrigation applied exceeds the crop water requirements (Groves & Bailey 1994). There is also an inverse relationship between summer rainfall and response to irrigation. Greater responses are generally associated with less rainfall (Bailey 1990). At ADAS Gleadthorpe, for example, the average sugar yield increase due to irrigation was reported to be 5.37 t/ha for those years when summer rainfall was below 100 mm, and 0.31 t/ha when rainfall was over 140 mm (Bailey 1990). At Broom's Barn there was some evidence that the relationship ceases to be linear with less than 100 mm rainfall (Draycott & Messem 1977).

Table 1 summarises the experimental results of sugar yield response to irrigation form 1948-2006. Both rain fed and irrigated yields are low compared to current yields, reflecting the changes in variety and crop husbandry. In addition, the rain fed yields reflect different amounts of rainfall in different years. Some years were drier, and therefore showed a greater response to irrigation, whereas in other years the wetter conditions resulted in a reduced response. The recorded rainfall was not always published. Some experiments (e.g. Ober et al., 2004) also involved covering the non-irrigated crop for part of the season to invoke drought conditions on the growing crop. Consequently, it is difficult to draw too many conclusions from the individual results. However, is it clear that, in most experiments, the sugar yield from an irrigated crop was typically 1 to 2 t/ha greater than that obtained from an equivalent rain fed crop.

Table 1 Average rain fed and irrigated sugar yield and sugar response to irrigation (t/ha) from field trials in England (1948 – 2006).

Published source	n	Year (from)	Year (to)	Sugar yield, t/ha		Sugar yield response, t/ha
				Rain fed	Irrigated	
Bailey (1990)	19	1955	1988			1.5
Brown et al (1987)	1	1983	1983	9.9	12.0	2.1
Draycott and Webb (1971)	1			6.6	6.8	0.2
Draycott et al (1974)	6	1970	1972	7.2	8.4	1.2
Floyd (1984)	5	1976	1976	1.3	2.3	1.0
Harris (1972)	9			7.4	9.3	1.9
Holmes and Whitear (1976)	12	1968	1970	5.0	6.2	1.2
Ober et al (2004)	63	1999	2001	5.5	7.7	2.2
Penman (1952)	17	1948	1950	4.9	6.0	1.1
Penman (1970)	3	1963	1965	7.5	8.8	1.3
Rajabi et al (2009)*	12	2004	2005	6.9	10.1	3.3

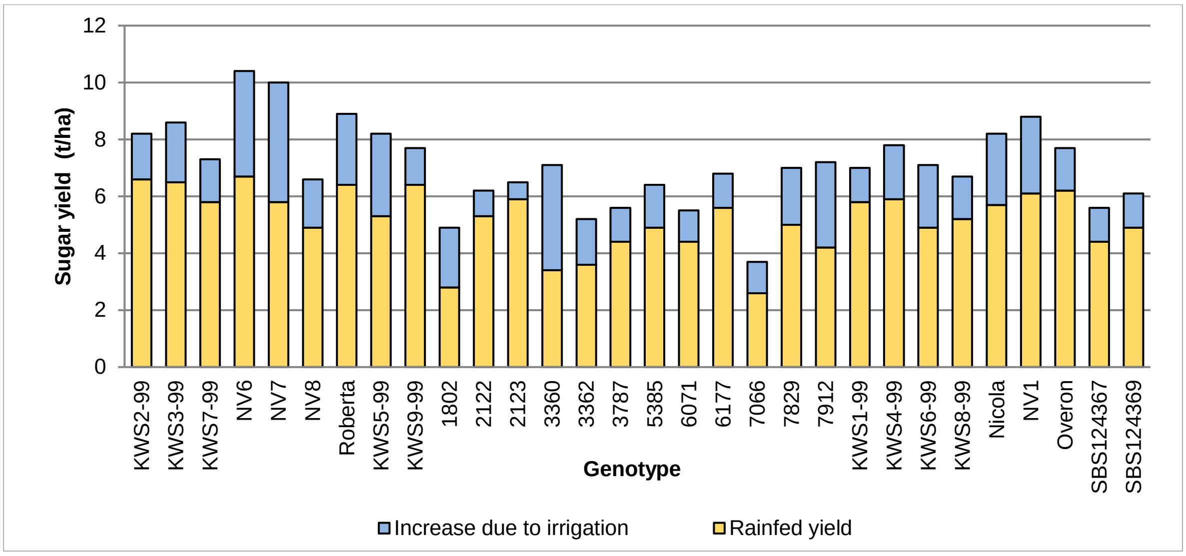
Note: Blank denotes values not reported. The 'total' figure is weighted according to the number of trials (n). * In the study reported by Rajabi et al (2009), the crop was covered with semi-permanent polythene tunnels to induce drought.

Sources: Bailey (1990), Brown et al (1987), Draycott and Webb (1971), Draycott et al (1974), Floyd (1984), Harris (1972), Holmes and Whitear (1976), Ober et al (2004), Penman (1952), Penman (1970), Rajabi et al (2009).

2.3.2 Effect of genotype

There are differences regarding drought tolerance among genotypes, determined by characteristics such as leaf maintenance, root-to-leaf ratio or the accumulation of osmotically active compounds (Bloch & Hoffmann 2005). Figure 3 shows the range of droughted and irrigated sugar yields from an experiment conducted at Broom's Barn with 46 genotypes (Ober et al., 2004). There were large reported differences in sugar yield between the different genotypes, which mostly were due to differences in root yield. As such, the response to irrigation ranged from 0.3 to 4.6 t sugar/ha depending on genotype. There was no indication that genotypes with higher potential yields were more susceptible to drought.

Figure 3. Droughted sugar yield (t/ha) and yield increase due to irrigation for different genotypes. Experiment at Broom's Barn in 1999. Source: Ober et al. (2004).



2.3.3 Irrigation interactions

The irrigation and drought interact with other factors, such as N intake, pest and disease, planting density. Table 2 summarises some examples of these interactions found in the literature.

Table 2. Synthesis of reported factors found to interact with irrigation in sugar beet production.

Factor	Description of interaction	Reference
N intake	Several studies found that irrigation decreases the sugar beet response to nitrogen, though the reduction was small and not consistent. In contrast, Price & Harvey (1962) found a greater response to nitrogen with irrigation in years when irrigation had a large effect on yield, and Draycott & Webb (1971) reported a response to a higher rate of nitrogen with irrigation than without it.	Holmes & Whitear, 1976; Draycott & Webb, 1971; Price & Harvey, 1962
	Drought responses were not related to nitrogen uptake. The amount of nitrogen fertilizer needed for maximum sugar beet yield was not affected by irrigation.	Last et al., 1983; Brown et al., 1987; Draycott, 1972
	N uptake was linearly related to water use. Irrigation increase crop water use and dry matter yield, with a resulting increase in N uptake.	Groves & Bailey, 1997

Factor	Description of interaction	Reference
	There was a positive and additive interaction between irrigation and N fertilizer	Draycott, 2006
Pests and diseases	The incidence of beet mild yellowing virus was greater in irrigated plots, but the yield loss caused by the disease was reported to be less than the gain from irrigation.	Heathcote, 1974
	Several sugar beet diseases require high soil moisture for development. For instance, development of Rhizomania, Pythium and Phytophthora root rot is maximum at soil saturation and decreases as the soil dries.	Neibling & Gallian, 1978
	Although sprinkler irrigation can wash organisms and spores from foliage, turgid leaves and high humidity favours the development of certain foliar diseases. Conversely, plants affected by drought are more susceptible to Fusarium root rot.	Draycott, 2006
Plant density	Sugar beet response to irrigation varied considerably with plant population. Early in the season, the effect of increased crop cover on soil water depletion is the dominant effect of plant population. Later in the season, if early rainfall is adequate, the dominant effect will be the increased rooting depth, and crops grown at a high plant population will suffer less from water stress.	Harris, 1972
	Experiments at Broom's Barn showed that changing the plant density affected the amount of water used by the crop.	Draycott & Webb, 1971, Draycott & Durrant 1971 Draycott et al., 1974
	Without irrigation, maximum sugar yield was achieved at a density of 74 000 plants/ha, but higher densities gave slightly larger yields when irrigated.	Draycott & Messem, 1977
	Low planting density (50,000 plants/ha) limits yield, whatever the amount of water applied. The yield response to irrigation increases with plant density.	Draycott, 2006

2.4 Irrigation scheduling

2.4.1 Limiting soil moisture deficit (SMD)

Different irrigation management strategies can be used to achieve maximum yield. For example, high-frequency irrigation on heavier soils starting at field capacity was reported to provide satisfactory results even if the total volume applied was well below ET (Draycott 2006). Where irrigation is applied, it is usually scheduled according to soil texture and crop growth stage (Draycott & Messem 1977). Irrigation can be scheduled to ensure that the inputs (rainfall and irrigation) balance outputs (crop evapotranspiration, ETc). However, a more efficient approach is to allow the crop to use the stored soil water, up to the limiting soil moisture deficit (limiting SMD). Beyond this point, the plant growth rate and water use start to decrease (Brown et al. 1987). This requires knowledge of the allowable or permitted depletion level ; i.e. what percentage of the available soil water can be depleted without leading to any yield reduction (Draycott 2006). In general, for sugar beet, irrigation should start when the SMD approaches 40% of available water (Alberta Agriculture and Forestry 2012). As the rooting system develops, so the available water reserve increases; thus there is an increase in the limiting SMD as the season progresses. Also, as potential transpiration decreases from mid-June to harvest, limiting deficits can be allowed to increase (Last et al. 1983). Based on published literature, the recommended SMD at which to irrigate sugar beet in England (according to crop-stage and soil texture) are summarised in Table 3.

Table 3. Soil Moisture Deficit (SMD, mm) at which to irrigate sugar beet in England according to crop-stage and soil texture. After Draycott (2006); Qi & Jaggard (2006); Jaggard, et al. (1995); Bailey 1990.

Crop stage	Soil texture			
	Coarse sand	Loamy sand	Sandy loam	Clay loam
Mid-June	25	30	35	50
Mid-July	35	40	50	100
Mid-August	50	60	75	125
Mid-September	65	75	125	150

2.4.2 Irrigation application and method

Any application method can be used to irrigate sugar beet. Worldwide, surface gravity-fed furrow irrigation is the most widespread technique used, although in European and Mediterranean countries overhead sprinkler irrigation is favoured (Draycott, 2006). A number of studies have compared different irrigation methods for sugar beet (see Draycott (2006), p 239-240). In general, higher yields were reported for sprinklers compared to furrow irrigation; in semi-arid environments where drip irrigation is used on sugar beet it is associated with higher yields and lower volumes of water being applied. However, in the UK, hose-reels fitted with either rain guns or booms are most commonly used with ≈25 mm of water being applied on each occasion.

3 Modelling sugar beet response to irrigation

3.1 Description of the model

The model used to predict yield for this work was the BeetGro model as presented by Qi et al (2005). It is process-based, weather-driven and uses a daily time-step simulation. It was developed from observations on beet crops grown at Broom's Barn and assumes a plant population density of ≥75,000/ha. The model assumes that pests, disease and crop nutrition are not limiting to production (i.e. only water limitation has been considered).

A series of model treatments were applied to vary (a) site (weather) (b) soil and (c) irrigation regime. The model simulations were performed using a fully factorial arrangement (i.e. every soil type and irrigation regime considered was simulated at each site), giving a total of 4,900 and 16,100 simulations for the two simulation sequences respectively. In each simulation sugar yield (t/ha) and adjusted beet yield (t/ha) were predicted. Beet yield is expressed at a sugar percentage of 16% consistent with industry practice.

The model parameters used are summarised in Appendix 2.

3.2 Scenarios

3.2.1 Sites

The model was run for the locations of the four sugar factories in England which were considered as being representative of the main sugar beet growing areas. It was also run for Knaresborough, N Yorkshire.

Table 4 Location of stations used in simulation

Station	Latitude, °N	Longitude, °E
Bury St Edmunds	52.1631	0.7365
Cantley	52.5250	1.7076
Wissington	52.5912	0.5698
Newark	53.0730	-0.7517
Knaresborough	54.0808	-1.5814

Rainfall

Daily rainfall was retrieved from CEH 'Gridded estimates of daily and monthly areal rainfall for the United Kingdom' [*CEH-GEAR*] (Tanguy et al., 2016; Keller et al., 2015). This dataset provides 1 km^2 gridded estimates of daily and monthly rainfall for Great Britain and Northern Ireland from 1890 to 2014. The rainfall estimates were derived from the Met Office national database of observed monthly and daily precipitation totals using the natural neighbour interpolation method.

For this study, daily rainfall data was extracted from *CEH-GEAR* as the mean rainfall value within in a 2 km radius around the centroid of each site from 1900 to 2015.

The accuracy of the data is limited by the areal density of rain gauges throughout the period of study. Only a fraction of the pre-1961 rain gauge data is available in digital form, and data in regions with a low density of rain gauges before 1961 should be used with care, especially where the nearest observation station is further than 15 km from the point of interest (Keller et al., 2015). High errors are expected in higher altitude areas in the north and west of the UK due to orographic enhancement during periods of frontal or pre-frontal rainfall. Conversely, in low lying undulating areas in eastern and southern UK the errors will be higher for localised convective storms rather than for frontal systems.

For each factory site used, the nearest weather station was within 20 km since 1910 (except for Wissington) and within 15 km since 1920.

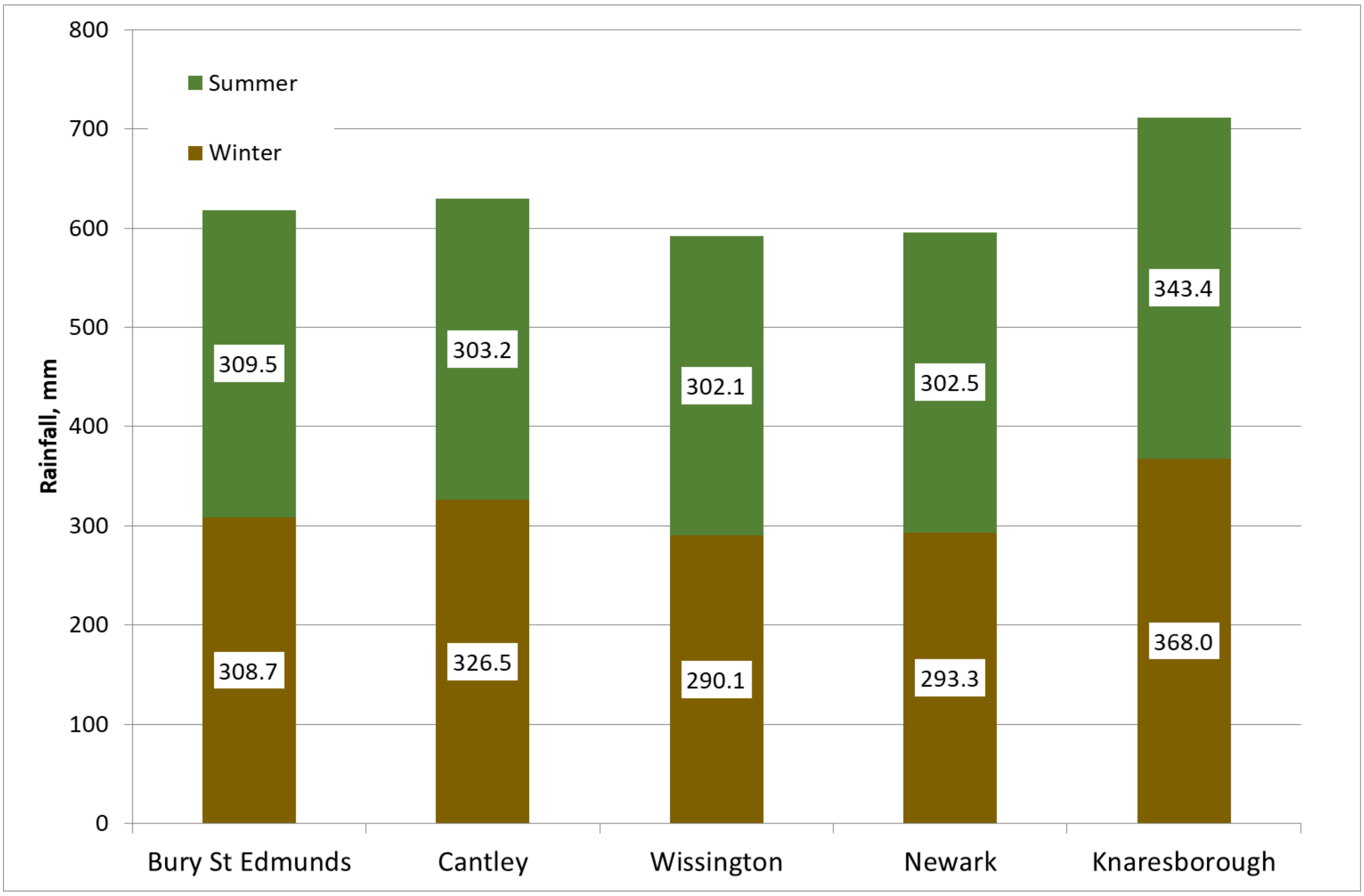


Figure 4 Average seasonal and annual rainfall (mm) at five stations, (1900 – 2014).

Knaresborough is wetter than the other stations; however, there is no significant difference in average summer rainfall between the other four stations. In the winter, Bury St Edmunds, Newark and Wissington all receive similar average rainfall, with Cantley slightly wetter and Knaresborough wetter still. All stations show a similar seasonal distribution in rainfall.

Other weather data

For this study, a new climatology termed *Hindcast* (Guillod, 2016) was used to obtain radiation, temperature humidity and potential evapotranspiration (PET) data for each site. *Hindcast* is a time-specific, model-based reconstruction of past climatology derived with Met Office's HadRM3P model driven at its lateral boundaries by the Twentieth Century Reanalysis Project (Compo et al., 2011) and run at a 25 km grid resolution over Europe. This dataset is one of the main outcomes from the NERC MaRIUS project[1]. The *Hindcast* dataset runs from 1851 through to 2014. Data were extracted from the grid cell where the central coordinates of each site were located (Table 5 and Table 6).

The long term (1900 – 2014) average mean daily temperatures and solar radiation is lower at Knaresborough compared to the other four stations reflecting its higher latitude. Cantley is

[1] http://www.mariusdroughtproject.org/

warmer and has higher solar radiation than Bury St Edmunds, Wissington or Newark especially in the late season (from September to December) suggesting better growth potential.

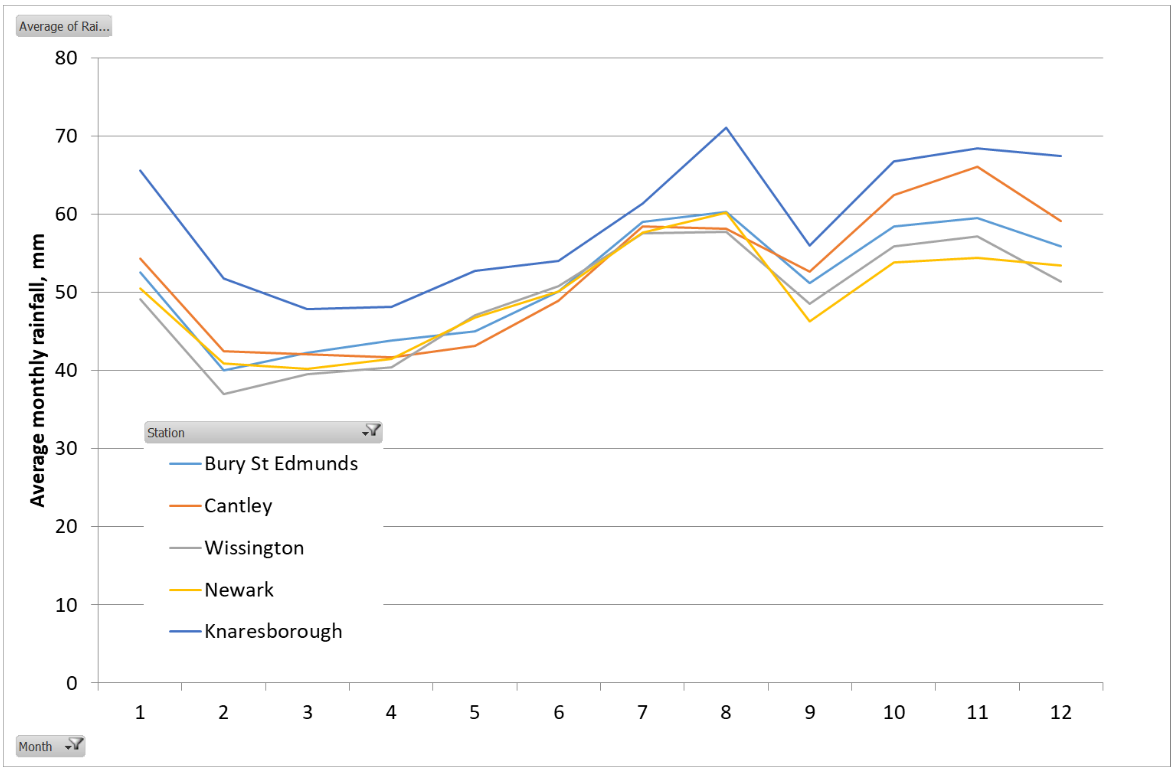


Figure 5 Average monthly rainfall at five stations, mm (1900 – 2014)

Weather type

For each station, the summer (April to September) rainfall was ranked and divided into quintiles, ranging from "Very dry" (i.e. the driest 20% of years) to "Very wet" (i.e. the wettest 20% of years).

Table 5 Long term (1900 – 2014) average mean daily temperature, °C

Month	Bury St Edmunds	Cantley	Wissington	Newark	Knaresborough
January	2.9	3.9	2.9	2.9	2.6
February	3.2	4.1	3.2	3.2	2.8
March	5.3	6.0	5.3	5.3	4.8
April	8.3	8.7	8.1	8.2	7.7
May	12.6	12.7	12.3	12.2	11.6
June	16.4	16.2	16.1	15.9	15.2
July	18.6	18.2	18.2	17.9	16.9
August	17.5	17.6	17.2	16.8	15.7
September	14.0	14.8	13.8	13.6	12.8
October	9.7	11.0	9.7	9.5	9.0
November	5.7	7.1	5.7	5.6	5.3
December	3.6	4.8	3.6	3.6	3.3

Table 6 Long term (1900 – 2014) average mean daily solar radiation, W/m^2

Month	Bury St Edmunds	Cantley	Wissington	Newark	Knaresborough
January	2.6	2.9	2.9	3.9	2.9
February	2.8	3.2	3.2	4.1	3.2
March	4.8	5.3	5.3	6.0	5.3
April	7.7	8.2	8.1	8.7	8.3
May	11.6	12.2	12.3	12.7	12.6
June	15.2	15.9	16.1	16.2	16.4
July	16.9	17.9	18.2	18.2	18.6
August	15.7	16.8	17.2	17.6	17.5
September	12.8	13.6	13.8	14.8	14.0
October	9.0	9.5	9.7	11.0	9.7
November	5.3	5.6	5.7	7.1	5.7
December	3.3	3.6	3.6	4.8	3.6

3.2.2 Soil texture

The model was run with four soil textures, namely a Sand (1.6), Loamy Sand (1.9), Sandy Loam (2.1) and Clay Loam (2.6). The figure in parentheses is the hydrological 'b' parameter used in the model to represent the influence of soil texture on water storage and availability. In the model, soil texture has no influence other than on soil water retention.

3.2.3 Irrigation schedules

The critical soil moisture deficits used to trigger an irrigation event were defined on the basis of evidence extracted from the literature review (Table 7). Six irrigation schedules were defined and simulated.

1. *Maximum Practical Irrigation*: Irrigation is scheduled between June and September using the critical deficits listed in Table 7Table 3, according to soil texture. Apply 25 mm at 25 mm soil moisture deficit each irrigation;
2. *June*: As above, but irrigation only allowed during June;
3. *July*: As above, but irrigation only allowed during July;
4. *August*: As above, but irrigation only allowed during August;
5. *September*: As above, but irrigation only allowed during September, and;
6. *Rain fed*: No irrigation.

Table 7 Soil moisture deficits (mm) used to trigger an irrigation event for the months and soils considered.

Soil/Month	June	July	August	September
Sand	25	35	50	65
Loamy sand	30	40	60	75
Sandy loam	35	50	75	125
Clay loam	50	100	125	150

3.2.4 Harvest date

The model was run with two harvest dates (Table 8).

Table 8 Sowing and harvest dates used in beet crop model.

Run name	Sowing date	Harvest date
Early harvest	DOY 69 (March 10th)	DOY 279 (Oct 6th)
Typical harvest	DOY 69 (March 10th)	DOY 340 (Dec 6th)

3.3 Results

The results below are presented for a sugar beet crop grown on a loamy sand soil near Bury St Edmunds, and defined as the "typical" case. "Irrigated" refers to the Maximum Practical Irrigation scenario. Deviations due to climate and soil type are then considered in a sensitivity analysis. Full results for all stations and soils are presented in Appendix 4.

3.3.1 Summer rainfall

Summer (April to September) rainfall in Bury St Edmunds averaged 309.5 mm, but ranged from 154.1 mm (1921) to 575.5 mm (1946) (Figure 6).

3.3.2 Sugar yield

Long-term average (1900 – 2014) adjusted sugar yield is 11.5 (±0.25) t/ha without irrigation and 13.2 (±0.21) t/ha with irrigation. These yields are greater than those reported in the literature but are in-line with recent industry reported sugar yields. The model is hind-casting the expected yield from contemporary varieties, had they been grown under the weather conditions of the past. We would therefore expect the model to over-predict yield compared to the historical yield data.

Table 9 Modelled average (1900 – 2014) sugar yield, t/ha, under rain fed and irrigated conditions by location and soil type.

Rain fed	Sand	Loamy Sand	Sandy Loam	Clay Loam
Bury St Edmunds	10.9	11.5	11.7	12.1
Cantley	12.0	12.7	13.0	13.4
Wissington	10.8	11.3	11.6	11.9
Newark	10.6	11.2	11.4	11.7
Knaresborough	11.3	11.8	12.0	12.2

Irrigated	Sand	Loamy Sand	Sandy Loam	Clay Loam
Bury St Edmunds	13.2	13.2	13.1	12.8
Cantley	14.7	14.7	14.6	14.3
Wissington	12.8	12.9	12.8	12.5
Newark	12.7	12.7	12.7	12.4
Knaresborough	12.8	12.8	12.7	12.5

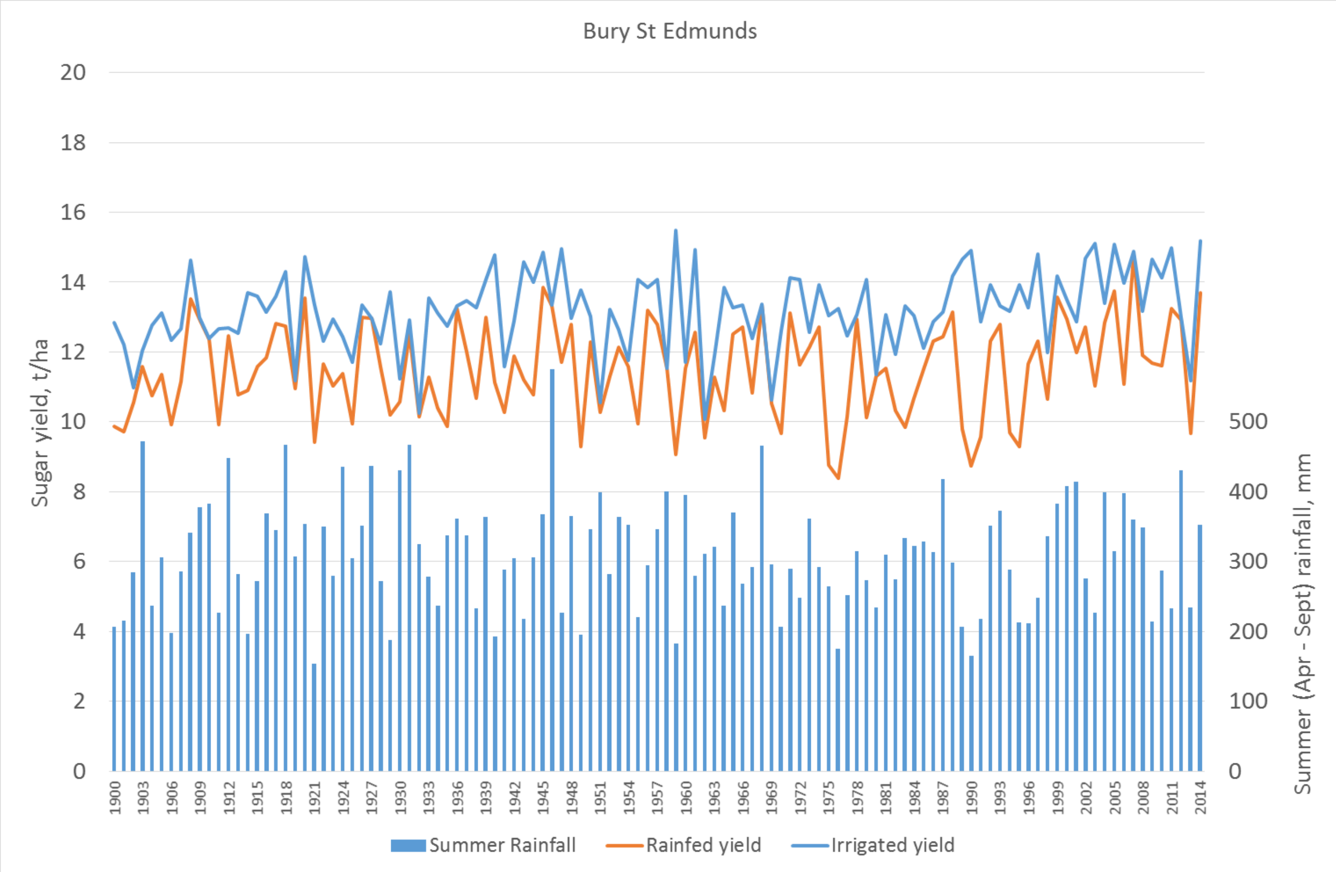


Figure 6 Simulated rain fed and irrigated yield, t sugar ha^{-1} year^{-1} (1900 – 2014), for Loamy Sand soil in Bury St Edmunds by year

3.3.3 Irrigation

Table 10 shows the average number of irrigations per year according to location and soil type for 'Maximum Practical Irrigation'; however, the average conceals significant inter annual variation. For example, on a loamy sand soil at Bury St Edmunds, on average 4.3 x 25 mm irrigations applications would have been applied, ranging from zero in a wet year to ten in 1959 when the summer (April – September) rainfall was only 183 mm compared to the average of 309 mm.

Table 10 Simulated average number of irrigations per year (1900 – 2014) according to location and soil type for 'Maximum Practical Irrigation'.

Soil texture	Bury St Edmunds	Cantley	Wissington	Newark	Knares-borough
Sand	4.8	5.0	4.4	4.5	3.3
Loamy sand	4.3	4.5	3.9	4.0	2.9
Sandy loam	3.3	3.5	3.0	3.1	2.3
Clay loam	1.4	1.6	1.2	1.2	0.7

3.3.4 Response to irrigation

Response to irrigation is the difference between yield under "Maximum Practical Irrigation" and "Rain fed" yield. The average response to irrigation was 1.7 (±0.26) t/ha which corresponds well with the average of the reported experimental data (Table 1). In wet years

(1910, 1946, 1968 and 1980) there was no response to irrigation, even though one or two irrigations would have been applied. The maximum modelled responses were in the very dry years of 1959 (6.4 t/ha) and 1990 (6.2 t/ha).

If irrigation is only used in one month, the maximum response was found to occur in July (1.4 t/ha) and there is little response to irrigation in September. This aligns with the experimental results (above).

The yield response is greater on lighter soils. Table 11 shows that the average response to irrigation ranges from 2.3 t/ha on sandy soils to 0.7 t sugar/ha on clay loam soils.

Table 11 Simulated average annual sugar yield by irrigation schedule and average response to irrigation, t sugar ha^{-1} year^{-1} (1900 – 2014) for Bury St Edmunds.

Soil texture	**Maximum Practical Irrigation**	**Practical Irrigation for June**	**Practical Irrigation for July**	**Practical Irrigation for Aug**	**Practical Irrigation for Sept**	**Rain fed**	**Average response to irrigation**
Sand	13.2	12.1	12.6	12.0	11.3	10.9	2.3
Loamy sand	13.2	12.4	12.9	12.4	11.8	11.5	1.7
Sandy loam	13.1	12.5	12.9	12.5	11.9	11.7	1.4
Clay loam	12.8	12.5	12.4	12.4	12.2	12.1	0.7

4 Economics of irrigating sugar beet in England

For a given water deficit, sugar beet is better able to produce a yield than many other crops and there is no marked quality improvement derived from irrigating sugar beet (Bailey 1990). Hence, for this and other economic reasons, where irrigation is available, water is normally allocated first to other high-value crops and/or those more sensitive to water stress. According to a British Sugar survey in the 1980s, the amount of irrigation applied to sugar beet in the UK poorly matched the needs of the crop (Bailey 1990). The reasons for this could be related to the poor financial incentives to irrigate sugar beet, including the challenges in justifying the capital investment for irrigation solely based on the returns for sugar beet.

For many beet growers, the fundamental question regarding the decision to irrigate and/or invest in irrigation infrastructure is whether the benefit from irrigating will exceed the costs of investment in equipment, energy, labour and water. These will depend on the local farm context, climate variability and market prices. For those who have the capacity to irrigate the key questions are "when are the most critical timings for applying irrigation?", "how do I prioritise beet irrigation against other crops in my rotation?" and "how might future drought risks and rainfall uncertainty impact on my rain fed beet yields?"

Only a few published studies have investigated the economics of irrigating sugar beet in different countries. For instance, irrigating sugar beet in Macedonia would lead to an increase of income of 10.1% and 17.6% of profit in comparison with no irrigation, despite the increase in labour costs of 32% (Maksimovic et al. 2010). Irrigation costs (including pumping, repairs and maintenance and water) represents almost 8% of variable costs in Oregon (Locke & Turner 1995). ARD (2013) estimated that the irrigation fuel costs are 9.8% of the total variable costs for sugar beet production in Alberta (Canada), according to a survey with 21 enterprises.

4.1 Benefit of irrigation

The value of sugar was calculated assuming the 2018/19 contract price of £22.50 per adjusted tonne less levy contributions (£0.08 for NFU and £0.14 for R&D per adjusted tonne plus VAT @20%). Extra harvest costs were estimated at £3.50/t beet (Nix, 2015) giving a value to the grower of £95 - £130/t sugar, depending on the assumed sugar % of the beet (Table 12). Market-linked Bonus and Late Delivery Allowance have been ignored, so the actual benefit may be greater.

As the model outputs sugar yield adjusted to 16% sugar content, the benefit of additional sugar production has been valued at £118.49/t.

Table 12 Value of sugar yield by sugar %, £/t sugar.

Sugar %	Sugar factor[2]	Adj tonnes	Price of beet, £/t beet	Levies, £/t beet	Extra harvest costs, £/t beet	Value, £/t beet	Value, £/t sugar
13	0.715	0.715	16.09	0.19	3.50	15.90	95.37
14	0.815	0.815	18.34	0.22	3.50	18.12	104.45
15	0.915	0.915	20.59	0.24	3.50	20.35	112.31
16	1.010	1.010	22.73	0.27	3.50	22.46	118.49
17	1.100	1.100	24.75	0.29	3.50	24.46	123.29
18	1.180	1.180	26.55	0.31	3.50	26.24	126.32
19	1.250	1.250	28.13	0.33	3.50	27.80	127.87
20	1.320	1.320	29.70	0.35	3.50	29.35	129.26

4.2 Cost of irrigation

Given the competition for water and sugar beet's relative higher tolerance to drought, sugar beet growers generally irrigate sugar beet in a given season only if they have spare capacity and the crop is visibly suffering from water stress. For the purpose of this study, it was assumed that the irrigation system was already in place and normally used for other crops, therefore, capital costs were not included in the analysis. A similar assumption was made for repairs and maintenance (R&M) costs. As growers will use the irrigation system each year for other crops and only under certain circumstances will irrigate sugar beet, they will incur those R&M costs every year irrespective of whether sugar beet is irrigated or not.

Therefore, the operating costs of irrigating sugar beet are: water charges derived from abstracting the water required for irrigation; fuel costs to pump the water from the water source (river or borehole); labour costs for irrigation; tractor costs related to irrigation activities; and costs associated with the extra production (extra yield) due to irrigation.

The irrigation system assumed in this study was a hose reel fitted with a rain gun, and assuming an irrigated area of 50 ha. Using costs data from Nix (2015), the features described in Appendix 3, and assuming irrigation applications of 25 mm, Table 13 shows the total cost of one 25 mm application is £53/ha comprising labour, tractor hire, water and diesel for pumping.

Table 13. Operating costs associated with applying a 25 mm irrigation to sugar beet.

Description	Unit	Unit per ha	Cost per unit, £	£/ha
Labour	h	1	10.35	10
Tractor hire (including fuel)	h	1	14.5	15

[2] Conversion factor for adjusted beet tonnage based on sugar content from the Inter-professional Agreement, May 2016.

Water*	m^3	314	0.035**	11
Diesel for pumping	litres	38	0.45	17
Total				**53**

4.3 Cost / benefit comparison

For each combination of soil type, weather station and irrigation schedule, the benefit of irrigation was compared against the cost of irrigation using the modelling results described in Section 3.3.

The benefit (i.e. the value of the extra sugar yield less additional harvest costs) ranged from zero in 1927 and 1958 (when no irrigation was needed) to >£700/ha in the drought years of 1959 and 1990.

In Figure 7, the years have been divided into five quintiles according to summer rainfall; therefore each value represents the average from 23 years simulation data. In a 'very dry' year (expected on average one year in five) the average benefit is £424/ha, whereas in an average year the benefit would be £152/ha.

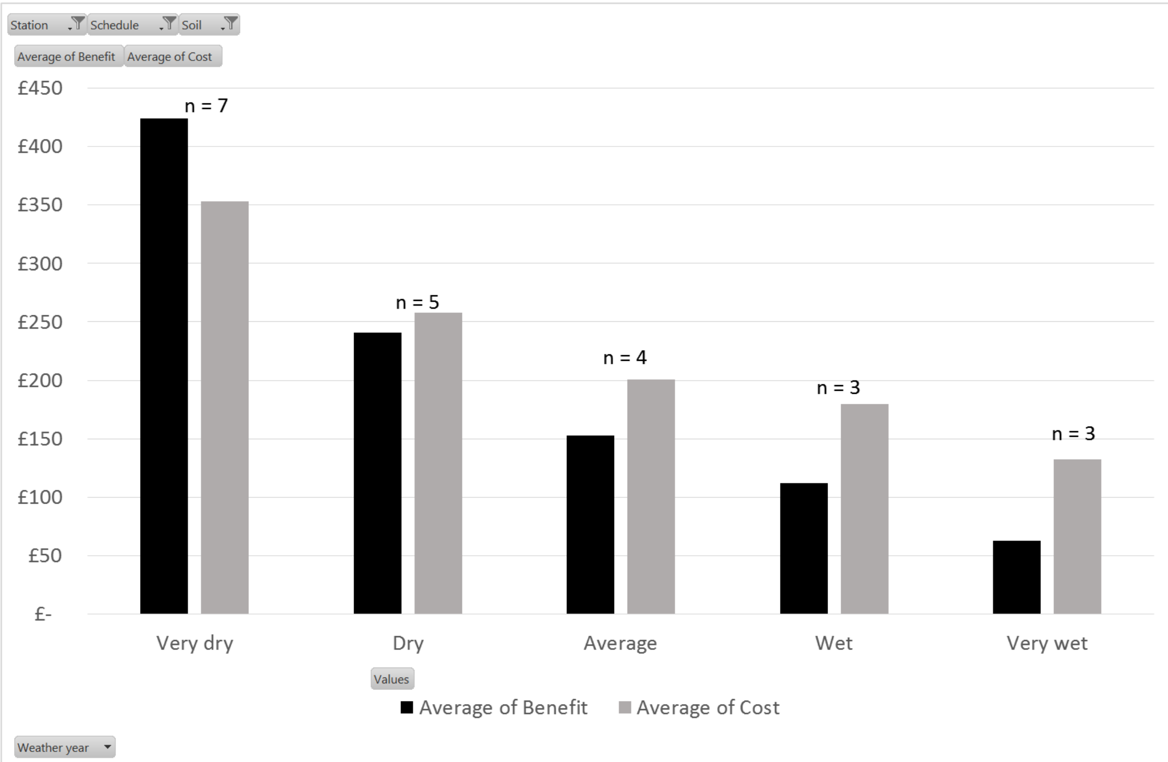


Figure 7 Estimated benefit and cost of irrigation, £/ha, for maximum practical irrigation at Bury St Edmunds on loamy sand soil (1900 – 2014) in years of different summer rainfall. n is the average number of irrigations.

The *net benefit* is the difference between the benefit and the cost of irrigating. In the example in Figure 7, in 35 out of 115 years (30%) there was a positive net benefit from irrigation. However, in 70% of cases the cost of irrigating would have been greater than the value of the

* Assumes an efficiency of 80%.

** Average for all EA regions.

additional sugar produced. The average net benefit over all years was -£25/ha (i.e. on average, the cost of irrigation exceeded the additional benefit by £25/ha).

Clearly that the benefit of irrigating is higher in dry years. On average, in a "very dry" year (expected on average one in five years) 7 irrigations would be applied and the average net benefit would be £71 whereas in a "very wet" year 3 irrigations would be applied, but the cost of irrigating would exceed the benefit by £70/ha.

When a reduced irrigation schedule (Table 7) is considered, it is evident that irrigation in September would not produce sufficient yield response to justify the additional costs (Table 14) and that the benefit of irrigation in August was marginal. However, if irrigation had been restricted to June or July then the average net benefit would have been £27/ha or £13/ha, respectively. The average net benefit represents the net benefit over a long period (>100 years) and can be influenced by a few drought years where high benefits arise. Therefore the range represented by the upper and lower 10% in Table 14 reflects the range of net benefit that can be expected in 4 years out of 5.

Earlier harvest does not affect the number of irrigations or irrigation amount (as all irrigation will be finished in September) but results in reduced yields under all scenarios, therefore the net benefit of irrigation is reduced very slightly.

Table 14 Average net benefit, £/ha, from irrigation of sugar beet according to irrigation schedule (on loamy sand at Bury St Edmunds) 1900 – 2014.

Typical harvest (December)

Irrigation schedule	**Sugar yield, t/ha**	**Irrigation, mm**	**n**	**Net benefit, £/ha**		
Rain fed	11.5			**Average**	**Upper 10%**	**Lower 10%**
June	12.4	36	1.5	£27	£104	-£49
July	12.9	70	2.8	£13	£128	-£102
August	12.4	66	2.6	-£36	£39	-£111
Sept	11.8	52	2.1	-£75	-£16	-£134
Maximum Practical	13.2	107	4.3	-£28	£69	-£124

Early harvest (October)

Irrigation schedule	**Sugar yield, t/ha**	**Irrigation, mm**	**n**	**Net benefit, £/ha**		
Rain fed	9.8			**Average**	**Upper 10%**	**Lower 10%**
June	10.7	36	1.4	£27	£102	-£49
July	11.2	70	2.8	£12	£127	-£102
August	10.7	66	2.6	-£37	£36	-£109
Sept	10.1	52	2.1	-£76	-£17	-£135
Maximum Practical	11.5	107	4.3	-£29	£65	-£123

Similar results were found for all soil types (Table 15) with higher average net benefits on more droughty sand soils and lower net benefits on sandy loam and clay loam soils.

Table 15 Average net benefit, £/ha, from irrigation of sugar beet according to irrigation schedule and soil type at Bury St Edmunds 1900 – 2014.

Irrigation schedule	Sand	Loamy sand	Sandy Loam	Clay Loam
June	£48	£29	£22	£10
July	£49	£15	£8	£8
August	-£13	-£35	-£32	-£1
September	-£57	-£74	-£13	-£9
Maximum practical	£13	-£25	-£9	£4

The estimated value of irrigation for sugar beet grown at Bury St Edmunds, Wissington and Newark were all similar, with higher net benefits at Cantley. All four stations have similar average monthly rainfall but Cantley has higher temperatures and greater solar radiation in the latter part of the season which may explain the higher yields and greater benefits of irrigation (Table 9).

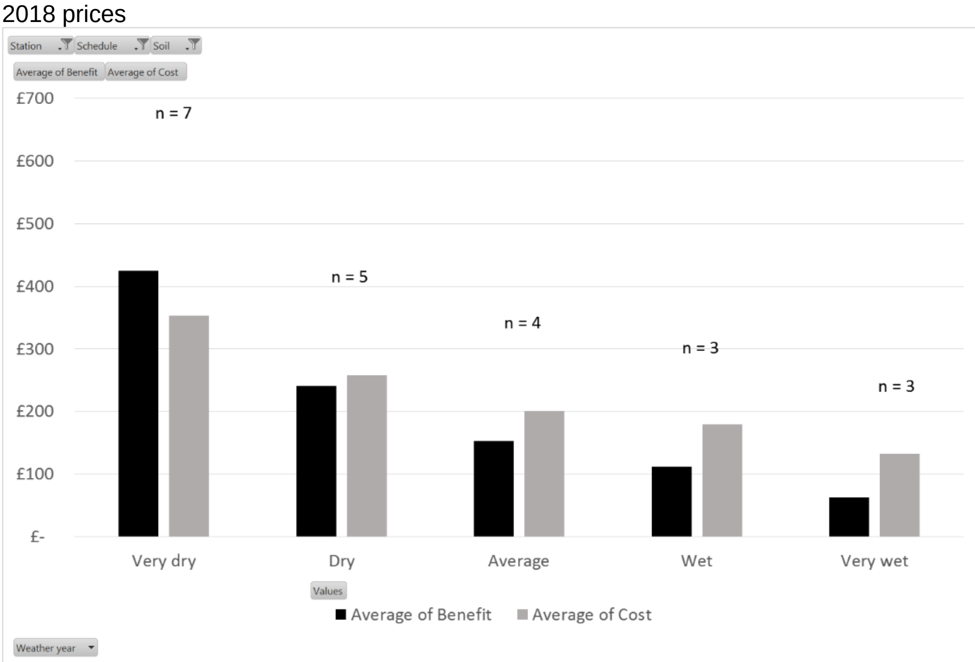
Table 16 Average net benefit, £/ha, from irrigation of sugar beet according to irrigation schedule and weather for loamy sand soil 1900 – 2014.

Irrigation schedule	Bury St Edmunds	Cantley	Wissington	Newark	Knares-borough
June	£29	£45	£27	£31	£13
July	£15	£33	£8	£5	-£11
August	-£35	-£33	-£41	-£44	-£41
September	-£74	-£76	-£75	-£73	-£53
Maximum practical	-£25	-£2	-£28	-£25	-£35

4.4 Sensitivity to contract price

The contract price for sugar has varied significantly in recent years, ranging from £20.30 (2016) – £31.67 (2014). Therefore the current beet price is close to the low value. Figure 8 shows that under current process, irrigation is only worthwhile in the very dry years, however, under 2014 beet prices (at Bury St Edmunds on loamy sand soil) irrigation would have generated a positive net benefit in all but wet and very years.

2018 prices



2014 prices

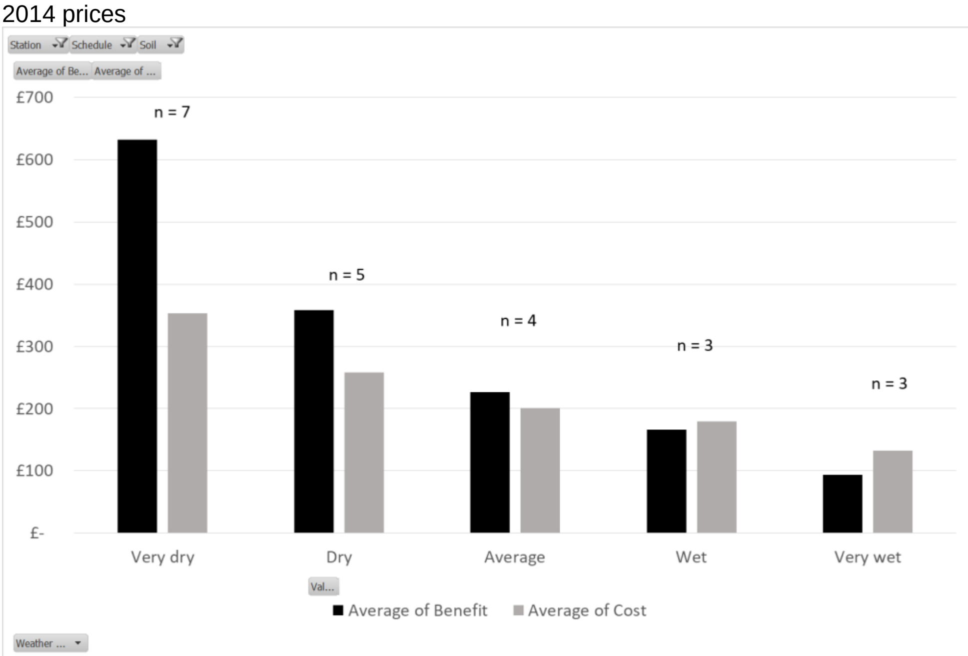


Figure 8 Estimated benefit and cost of irrigation, £/ha, for maximum practical irrigation at Bury St Edmunds on loamy sand soil (1900 – 2014) in years of different summer rainfall, comparing 2014 and 2018 prices.

5 Climate change

This analysis has been based on a long time-series of climate data (1900 – 2014). This time series has included a range of drought and wet years. However, Figure 6 suggests that the modelled yields have been increasing since 1980. When analysed statistically, there is no evidence of any trend in modelled rain fed or irrigated yields between 1900 and 1980. However, from 1980 to 2014 both show a significant ($P = 0.02$) increasing yield trend of ≈0.05 t sugar ha^{-1} $year^{-1}$. As all crop and soil parameters are held constant in the model, this is not due to any change in varieties or farming practices, but is solely an effect of changing weather conditions.

A more detailed analysis of summer (April – September) weather at Bury St Edmunds has shown a highly significant increasing trend in mean air temperature ($p < 0.001$) and solar radiation ($P = 0.025$) since 1980, suggesting increasingly warm and sunny weather, leading to increasing crop water demand ($p = 0.05$). Average summer potential ET in the years 2000 – 2014 was 3.0 mm/d compared to the long-term average (1900 – 1989) of 2.7 mm/d. This is equivalent to over 50 mm additional crop water demand over the summer. As there has been no change in summer rainfall ($p = 0.68$) over that period, it would suggest increasing soil water deficits.

The increase in temperature is consistent with the project future climate change trends for southern England although the projections also suggest a reduction in summer rainfall by the 2080s (Watts et al., 2015).

6 Limitations

Several assumptions have been made and limitations to the modelling have been required. These would not affect the overall messages, but will affect the absolute results.

- The yield modelling has been based on the original BeetGro model (Qi et al., 2005). Since its initial publication, the model has been revised by AB-Sugar to take into account progress in variety development and, in general, the revised model predicts higher yields. However, no changes have been made to the treatment of water stress in the revised model, and, as it is not publically available, it was not used for this study. Hence the modelled yields reflect varieties that are 10 – 15 years out of date. Contemporary yields may be higher under both rain fed and irrigated conditions, but unless modern varieties are more responsive to water stress, the yield increments may be similar.
- The BeetGro model predicts sugar yield adjusted to 16% sugar content and does not (in its present form) output beet and sugar yield independently. Although Bailey (1990) found there is no marked quality improvement derived from irrigating sugar beet, the sugar fraction affects the economics of irrigating as the additional costs of harvesting and transport depend on the clean beet yield. This cannot be accounted for in the present version of the model.
- The yield modelling has tested a limited number of irrigation schedules, covering full irrigation and irrigating in one month only. There is an infinite number of alternative schedules that could be tested, including irrigating at particular growth stages or changing critical deficits. The model could be developed to test any such schedules. However, in reality sugar beet growers are likely to be tactical in the use of irrigation, responding to local weather forecasts and equipment availability rather than following rigid schedules.
- The cost of irrigating has been based on a single scenario of equipment and cropped area. The marginal cost of an extra irrigation will depend on local grower circumstances including the distance and head over which water has to be pumped, cost of farm labour and machinery depreciation costs. If only the cost of water and energy are considered, the cost of irrigating is halved.

7 Conclusions

- There is a lack of recent relevant field research on sugar beet response to irrigation and water stress, with most data dating back to the 1970s and 1980s. The experimental work, therefore, does not reflect modern varieties and husbandry.
- Although the experimental results generally showed a positive response of sugar yield to irrigation up to 2 t sugar/ha, they reflect substantial variability between years and soil types. The effect of irrigation on sugar yield is, unsurprisingly, greater on lighter soils, in warmer drier climate and in dry summers, but there are also large reported differences in sugar yield between genotypes, which were mostly due to differences in root yield.
- Irrigation costs the same irrespective of when it is applied, but the crop's response to water stress varies with growth stage. Irrigation in June or July both produced larger increases in sugar yield than irrigation in August and September therefore the greatest net benefit is from irrigation in June or July. Irrigation in August or September generally does not cover the cost of irrigating. However, June and July is the time of year when other crops on the farm are also likely to be competing for irrigation water and equipment. Decisions about prioritising irrigation among crops will be made upon the basis of expected return.
- Given the current low contract price for beet, full irrigation of sugar beet only shows a positive return in very dry years and on light soils. In other situations the cost of applying water outweighs the value of the extra sugar produced. However, when the contract price is higher (as in 2014) full irrigation is worthwhile in all but the wet and very wet years.
- The benefit from full irrigation can be >£200/ha in an extreme dry summer, but is typically £60 - £200/ha in a very dry summer, expected on average, once in five years. In average, wet and very wet summers, the cost of irrigating outweighs the benefit gained.
- The net benefit from irrigating sugar beet is greatest in dry summers, however, forecasting summer weather is notoriously difficult. Irrigation may take place in June or July in anticipation of a dry summer, only for rain to fall and the benefits to be reduced. However, in most situations irrigation in June and July according to the schedules used here, provides a net benefit, and the small losses in years that turn out to be wet are offset by the gains in dry summers.
- The maximum return on irrigation accrues where other factors that influence final sugar yield are optimised. Therefore, the benefit of irrigation will be greater where higher yielding varieties are used, harvest is late and crop nutrition and pest control are optimised.
- This study has assumed that the irrigation system is already in place and is normally used for other crops, thus, capital costs have not been included in the analysis. The level of return on irrigation shown here is unlikely to justify capital expenditure on irrigation infrastructure.
- There is evidence that summer mean air temperature and solar radiation have been increasing since 1980 leading to higher sugar yield and increased crop water demand. As summer rainfall has neither increased nor decreased, this has led to an increase in the benefit of irrigation in recent years.

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9 Appendix 1 – Literature review methodology

Research questions

- What is the sugar beet yield response to irrigation?
- In what growth stages in the crop more responsive to water application?
- When and how much should sugar beet be irrigated? (scheduling)
- What are the costs and benefits of irrigating sugar beet?

Evidence search

Both peer-reviewed evidence and grey literature will be included in our search

- Scopus
- Web Of Science
- Google search

Search terms

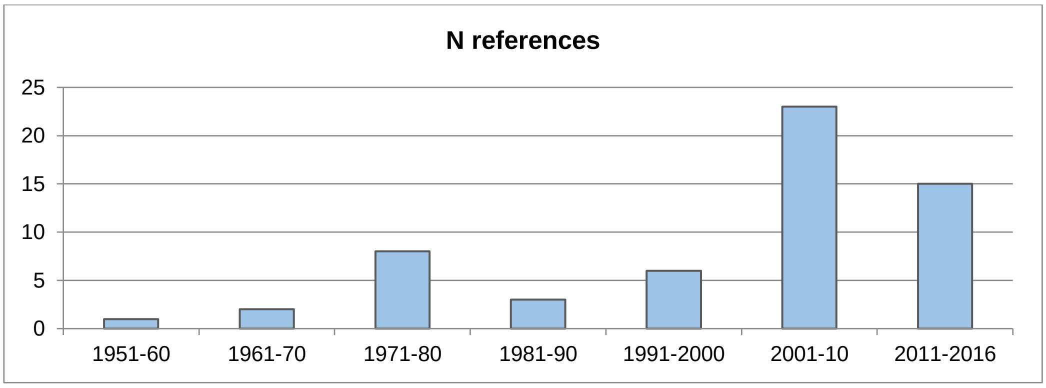
- Sugar beet + irrigat* + yield
- Sugar beet + irrigat* + UK
- Sugar beet + irrigat* + England
- Sugar beet + irrigat* + cost*
- Sugar beet + irrigat* + benefit*
- Sugar beet + irrigat* + economic*

A total of 474 references were included after the initial search (439 after removing duplicates).

Screening and inclusion/exclusion criteria

The references were screened first based on the title and abstract, deleting those that were not focus on sugar beet (n = 261). Then, a more detailed screening was undertaken to assess the relevance of the selected references, excluding those studies based in different climatic regions from the UK and those looking at sugar beet as a bioenergy crop. Also, we removed the references for which full text was not available or those in a different language from English (n = 99). Once we have all the relevant literature, the papers/reports were carefully read. At the end, 63 references were included in this review (36 for the UK).

Figure 9. Number of references included in the review, per decade of publication



10 Appendix 2 – Model Parameters Used

Code Symbol	Value	Description
a1	0.4	Regression coefficient (see Qi et al, 2005 for details)
a2	0.6	Regression coefficient (see Qi et al, 2005 for details)
beta0	0.00935	Rate of increase of root depth (d^{-1})
c1	378.8	Regression coefficient (see Qi et al, 2005 for details)
c2	8	Regression coefficient (see Qi et al, 2005 for details)
delta	0.002715	Rate of decline in root zone expansion (d^{-1})
Dsowing	0.075	Initial rooting depth (m)
fZero	0.000015	Initial foliage cover (m2 m^{-2})
gamma	0.00007	RUE decay coefficient (m^2 g^{-1})
kappa	0.00148	Sugar partitioning coefficient
length0	0.0491	Initial lengthof epicotyl (m)
muMin0	-0.00017	Rate of foliar cover decay with accumulated temperature (d^{-1})
muZero	0.06556	Initial rate of foliage cover expansion (d^{-1})
nuZero	0.005866	Rate of change from muZero to muMin (d^{-1})
psiCrop	-1500	Water potential of the canopy (kPa)
RUEzero	1.8	Potential radiation conversion coefficient (g MJ^{-1})
Tbase	3	Base temperature (C)
Tzero	90	Accumulated temperature from sowing to 50% emergence (C d)

11 Appendix 3 – Irrigation system description

Hose reel + Rain gun	
Life span (yr)	10
Capital costs (£)	25,829
Number	1
Hose diameter (m)	110
Length (m)	400
Diesel engine driven pump	
Life span (yr)	10
Capital costs (£)	16,675
Number	1
Flow rate (m^3/h)	100
Pumping hours (in total if more than 1 pump)	975
Pressure (m)	81
Diesel engine power (kW)	39
Fuel consumption (l/h)	12
Control System including Nutrigation and Filtration (Fixed)	
Life Span (yr)	10
Capital Cost (£)	16,000
Number	2
	Pipes
Underground PVC main pipe	
Life span (yr)	20
Capital costs (£ per m)	12
Length (m)	3,000
Diameter (mm)	160
Hydrants @ 72m spacing	
Life span (yr)	10
Capital costs (£)	320
Number	25
Irrigation efficiency	
Application efficiency (%)	70

12 Appendix 4 – Results by station and soil type

12.1 Bury St Edmunds

Sand (b=1.6)	Sugar yield, t/ha	Average Irrigation, mm	n	Net benefit, £/ha		
Rain fed	**10.9**			**Average**	**Upper 10%**	**Lower 10%**
June	12.1	43	1.7	£48	£135	-£40
July	12.6	73	2.9	£49	£179	-£82
August	12.0	69	2.7	-£13	£84	-£111
Sept	11.3	48	1.9	-£57	-£8	-£107
Maximum Practical	13.2	121	4.8	£13	£142	-£116

Loamy Sand (b=1.9)	Sugar yield, t/ha	Average Irrigation, mm	n	Net benefit, £/ha		
Rain fed	**11.5**			**Average**	**Upper 10%**	**Lower 10%**
June	12.4	36	1.5	£29	£106	-£49
July	12.9	70	2.8	£15	£133	-£102
August	12.4	66	2.6	-£35	£42	-£111
Sept	11.8	52	2.1	-£74	-£15	-£134
Maximum Practical	13.2	107	4.3	-£25	£74	-£124

Sandy Loam (b=2.1)	Sugar yield, t/ha	Average Irrigation, mm	n	Net benefit, £/ha		
Rain fed	**11.7**			**Average**	**Upper 10%**	**Lower 10%**
June	12.5	31	1.2	£22	£90	-£46
July	12.9	60	2.4	£8	£110	-£94
August	12.5	56	2.2	-£32	£36	-£99
Sept	11.9	17	0.7	-£13	£16	-£41
Maximum Practical	13.1	82	3.3	-£9	£84	-£102

Clay Loam (b=2.6)	Sugar yield, t/ha	Average Irrigation, mm	n	Net benefit, £/ha		
Rain fed	**12.1**			**Average**	**Upper 10%**	**Lower 10%**
June	12.5	18	0.7	£10	£53	-£34
July	12.4	14	0.5	£8	£45	-£28
August	12.4	18	0.7	-£1	£32	-£34
Sept	12.2	10	0.4	-£9	£15	-£32
Maximum Practical	12.8	35	1.4	£4	£52	-£44

12.2 Cantley

Sand (b=1.6)	Sugar yield, t/ha	Average Irrigation, mm	n	Net benefit, £/ha		
Rain fed	**12.0**			**Average**	**Upper 10%**	**Lower 10%**
June	13.5	48	1.9	£73	£193	-£48
July	14.0	76	3.0	£72	£234	-£90
August	13.3	72	2.9	-£10	£98	-£118
Sept	12.4	51	2.0	-£59	-£9	-£110
Maximum Practical	14.7	125	5.0	£47	£214	-£121

Loamy Sand (b=1.9)	Sugar yield, t/ha	Average Irrigation, mm	n	Net benefit, £/ha		
Rain fed	**12.7**			**Average**	**Upper 10%**	**Lower 10%**
June	13.8	40	1.6	£45	£146	-£55
July	14.3	75	3.0	£33	£177	-£112
August	13.7	70	2.8	-£33	£49	-£115
Sept	13.0	54	2.1	-£76	-£20	-£132
Maximum Practical	14.7	112	4.5	-£2	£132	-£136

Sandy Loam (b=2.1)	Sugar yield, t/ha	Average Irrigation, mm	n	Net benefit, £/ha		
Rain fed	**13.0**			**Average**	**Upper 10%**	**Lower 10%**
June	13.9	35	1.4	£36	£124	-£51
July	14.3	65	2.6	£22	£144	-£101
August	13.8	58	2.3	-£26	£48	-£101
Sept	13.2	18	0.7	-£12	£18	-£43
Maximum Practical	14.6	89	3.5	£7	£119	-£105

Clay Loam (b=2.6)	Sugar yield, t/ha	Average Irrigation, mm	n	Net benefit, £/ha		
Rain fed	**13.4**			**Average**	**Upper 10%**	**Lower 10%**
June	14.0	22	0.9	£21	£83	-£41
July	13.8	17	0.7	£16	£71	-£39
August	13.8	20	0.8	£3	£43	-£37
Sept	13.5	11	0.4	-£8	£14	-£29
Maximum Practical	14.3	40	1.6	£18	£87	-£51

12.3 Wissington

Sand (b=1.6)	Sugar yield, t/ha	Average Irrigation, mm	n	Net benefit, £/ha		
Rain fed	**10.8**			Average	Upper 10%	Lower 10%
June	11.8	38	1.5	£42	£126	-£41
July	12.4	70	2.8	£43	£165	-£79
August	11.8	67	2.7	-£22	£65	-£109
Sept	11.1	46	1.8	-£57	-£12	-£103
Maximum Practical	12.8	110	4.4	£11	£128	-£105

Loamy Sand (b=1.9)	Sugar yield, t/ha	Average Irrigation, mm	n	Net benefit, £/ha		
Rain fed	**11.3**			Average	Upper 10%	Lower 10%
June	12.2	33	1.3	£27	£100	-£47
July	12.6	66	2.7	£8	£112	-£97
August	12.1	63	2.5	-£41	£29	-£111
Sept	11.6	50	2.0	-£75	-£17	-£133
Maximum Practical	12.9	98	3.9	-£28	£57	-£112

Sandy Loam (b=2.1)	Sugar yield, t/ha	Average Irrigation, mm	n	Net benefit, £/ha		
Rain fed	**11.6**			Average	Upper 10%	Lower 10%
June	12.2	27	1.1	£19	£80	-£43
July	12.6	57	2.3	-£2	£86	-£90
August	12.2	52	2.1	-£34	£21	-£90
Sept	11.7	16	0.6	-£14	£14	-£43
Maximum Practical	12.8	76	3.0	-£16	£60	-£92

Clay Loam (b=2.6)	Sugar yield, t/ha	Average Irrigation, mm	n	Net benefit, £/ha		
Rain fed	**11.9**			Average	Upper 10%	Lower 10%
June	12.2	15	0.6	£7	£44	-£30
July	12.2	11	0.4	£5	£33	-£23
August	12.2	15	0.6	-£3	£20	-£27
Sept	12.0	8	0.3	-£9	£13	-£30
Maximum Practical	12.5	30	1.2	£0	£41	-£40

12.4 Newark

Sand (b=1.6)	Sugar yield, t/ha	Average Irrigation, mm	n	Net benefit, £/ha		
Rain fed	**10.6**			Average	Upper 10%	Lower 10%
June	11.8	40	1.6	£47	£140	-£46
July	12.2	72	2.9	£37	£171	-£96
August	11.6	64	2.5	-£23	£66	-£111
Sept	10.9	47	1.9	-£64	-£12	-£116
Maximum Practical	12.7	112	4.5	£11	£153	-£130

Loamy Sand (b=1.9)	Sugar yield, t/ha	Average Irrigation, mm	n	Net benefit, £/ha		
Rain fed	**11.2**			Average	Upper 10%	Lower 10%
June	12.0	35	1.4	£31	£110	-£48
July	12.4	69	2.8	£5	£126	-£115
August	11.9	63	2.5	-£44	£26	-£114
Sept	11.4	48	1.9	-£73	-£18	-£129
Maximum Practical	12.7	99	4.0	-£25	£81	-£131

Sandy Loam (b=2.1)	Sugar yield, t/ha	Average Irrigation, mm	n	Net benefit, £/ha		
Rain fed	**11.4**			Average	Upper 10%	Lower 10%
June	12.1	30	1.2	£20	£90	-£51
July	12.5	59	2.4	-£1	£100	-£103
August	12.0	50	2.0	-£31	£31	-£93
Sept	11.6	15	0.6	-£11	£14	-£36
Maximum Practical	12.7	78	3.1	-£13	£83	-£109

Clay Loam (b=2.6)	Sugar yield, t/ha	Average Irrigation, mm	n	Net benefit, £/ha		
Rain fed	**11.7**			Average	Upper 10%	Lower 10%
June	12.1	16	0.6	£9	£53	-£35
July	12.0	13	0.5	£7	£46	-£31
August	12.0	15	0.6	£0	£32	-£31
Sept	11.8	9	0.4	-£9	£15	-£33
Maximum Practical	12.4	31	1.2	£7	£59	-£45

12.5 Knaresborough

Sand (b=1.6)	Sugar yield, t/ha	Average Irrigation, mm	n	Net benefit, £/ha		
Rain fed	**11.3**			Average	Upper 10%	Lower 10%
June	12.0	28	1.1	£27	£101	-£47
July	12.5	56	2.3	£19	£131	-£94
August	11.9	49	2.0	-£30	£36	-£97
Sept	11.5	30	1.2	-£45	£9	-£99
Maximum Practical	12.8	84	3.3	-£5	£100	-£110

Loamy Sand (b=1.9)	Sugar yield, t/ha	Average Irrigation, mm	n	Net benefit, £/ha		
Rain fed	**11.8**			Average	Upper 10%	Lower 10%
June	12.3	23	0.9	£13	£72	-£47
July	12.6	53	2.1	-£11	£80	-£102
August	12.2	44	1.8	-£41	£18	-£100
Sept	11.9	31	1.3	-£53	£10	-£115
Maximum Practical	12.8	73	2.9	-£35	£44	-£113

Sandy Loam (b=2.1)	Sugar yield, t/ha	Average Irrigation, mm	n	Net benefit, £/ha		
Rain fed	**12.0**			Average	Upper 10%	Lower 10%
June	12.4	18	0.7	£8	£55	-£38
July	12.6	45	1.8	-£18	£59	-£95
August	12.3	35	1.4	-£33	£17	-£83
Sept	12.0	7	0.3	-£8	£16	-£31
Maximum Practical	12.7	57	2.3	-£27	£39	-£94

Clay Loam (b=2.6)	Sugar yield, t/ha	Average Irrigation, mm	n	Net benefit, £/ha		
Rain fed	**12.2**			Average	Upper 10%	Lower 10%
June	12.4	9	0.4	-£0	£31	-£31
July	12.3	5	0.2	£2	£23	-£19
August	12.3	7	0.3	-£2	£18	-£22
Sept	12.2	4	0.1	-£5	£14	-£23
Maximum Practical	12.5	17	0.7	-£3	£31	-£38