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An Analysis of the Efficiency of the Sugar Beet Crop in Exploiting the Environment

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This review outlines the way measurements of carbon dioxide exchange have provided the basis for the analysis of the efficiency with which sugar beet (*Beta vulgaris* L.) exploits the English environment. It then examines the influence of seasonal weather patterns on crop productivity, and the role of fertilizer nitrogen and plant population in aiding the crop to realize its potential. Finally, the theoretical basis and practical operation of a system for yield forecasting is described.

To make the analysis, it was necessary to develop methods of measuring the minute by minute responses of crops to short term changes in weather, and for this measurement to continue throughout the growing season. The equipment had to be sufficiently robust to operate outdoors for a whole season and it had to operate without distorting the environment or the crop's response.

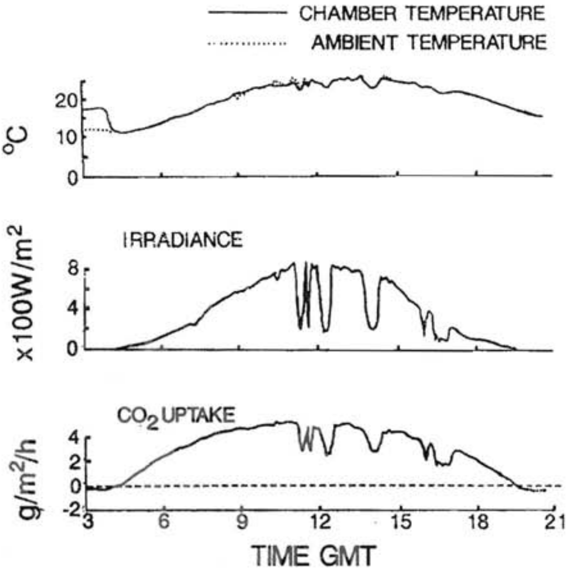

Figure 1. Changes in temperature, irradiance and carbon dioxide uptake by a beet crop during 24 July 1980.

MEASUREMENTS OF GAS EXCHANGE

Monteith's group at Sutton Bonington achieved such an analysis using micrometeorological techniques to measure gas exchange of spring barley crops (Biscoe et al., 1975) and Glauert (1983), guided by Monteith and Biscoe, then monitored gas exchange of sugar beet. For barley, the basis of the method was to estimate fluxes of carbon dioxide from measured profiles of carbon dioxide concentrations in the atmosphere within and above the standing crop. For sugar beet, an enclosure was used. A striking feature was the direct response of the crop's assimilation rate to changes in irradiance — Figure 1 shows this as the sun was temporarily obscured by cloud. When net photosynthesis during any day was plotted against irradiance at the top of the canopy (Fig. 2), there was an increase over the whole range, but with a diminishing response; for the canopy as a whole, light saturation did not occur until late in the season. The continued production of leaves by sugar beet contrasts with the determinacy of barley, so leaf ageing did not restrict the responsiveness of the canopy as a whole until late in the season, by when the potential of the environment was in marked decline. The responsiveness of the canopy to incident radiation was maintained through September, but declined in October and November. Photosynthesis/light response curves were not modified by temperature over the range experienced in

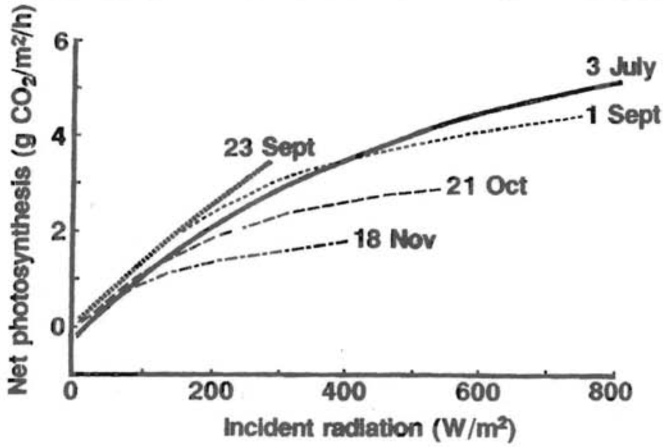

Figure 2. Relationships between net photosynthesis and incident radiation for a beet crop on various dates during summer and autumn.

England; it was the ageing canopy, rather than declining temperatures, that caused the diminished responsiveness late in the season.

With Glauert's apparatus, it was possible to estimate dark respiration throughout the season. There was no seasonal drift and the loss of biomass during the night remained about

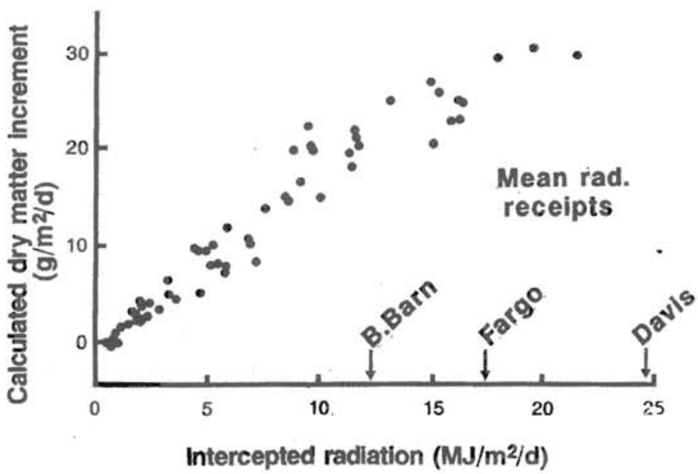

Figure 3. The correlation between the increment of dry matter (calculated from integrals of the daily CO_2 uptake) and radiation intercepted by the foliage of a beet crop on 60 days throughout 1980. The arrows mark average values for radiation receipts per day over the growing season at three locations.

$2g/m^2/night$. On days when the assimilation rate was high, i.e, in excess of $15g/m^2$, respiration during the two hours after dusk was markedly greater, sometimes doubled, compared with the usual value.

Taking the season as a whole, the increment in biomass over any 24h period, calculated from net gas exchange, was directly proportional to the amount of radiant energy intercepted by the foliage during the day (Fig. 3). There were certain very bright days when, for many hours, the canopy was operating over the least responsive section of the light response curve; as a consequence the conversion coefficient (g biomass per MJ radiation intercepted) was somewhat diminished, but overall the 'efficiency' was well maintained throughout. For this reason, yields at the end of the season would be expected to relate directly to the amount of radiation intercepted by the foliage from crop emergence until harvest.

SEASONAL VARIATION IN YIELD

To analyse the effects of weather patterns on growth and yield of sugar beet, a crop has been grown in a standard way each year since 1978 at Broom's Barn. Through-out this period, the seed has come from only two batches. Sowing was as soon as the soil was fit after the date when the risk of excessive vernalization had passed; harvest was late and by hand, so the seasonal influence was complete and not overridden in any way by differences in harvesting efficiency. All crops were irrigated to requirement so that yields reflected seasonal differences in temperature and radiation, rather than water stress. The range of yields was striking, from 17-27 t/ha total biomass and 8-15 t/ha sugar. Figure 4 shows that over this yield range, the relationship with season-long radiation interception holds, with a conversion coefficient for sugar close to 1g/MJ (Fig. 4).

What is the feature of the weather in England that leads to a range of total radiation interception of 1,000-1,700 MJ/m^2, equivalent on average, to the amount of solar energy received during five weeks of summer in NW Europe? The seasonal drift in incident and intercepted radiation for a typical crop reveals that the period May-July has a high and maintained level of incident radiation, but from August onwards there is a progressive decline. In relation to the potential, the crop is usually strikingly inefficient at intercepting radiation from April-June. From July onwards, around 85% of incident irradiation is intercepted. The years of large yields are those when crops make exceptional use of May and June radiation. Usually, the crop is well able to exploit whatever radiation is available in autumn. For growers in the UK, the message is clear — it is crucial to do everything possible to maximize interception of radiation in May and June

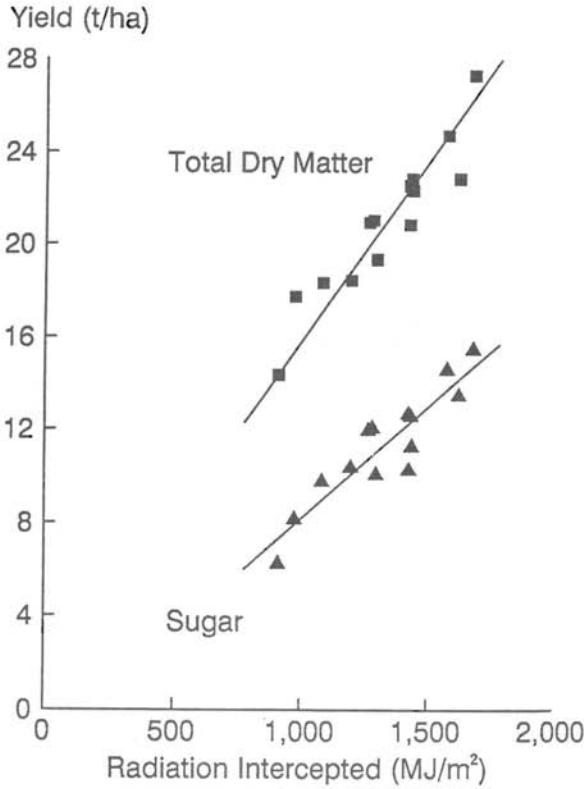

Figure 4. Relationship between the amount of solar radiation intercepted by the foliage throughout the growing season and total dry matter and sugar yield. Each data point represents a crop grown with recommended husbandry, including irrigation at Broom's Barn Experimental Station between 1978 and 1990.

— leaf cover then is precious, but the crop will take care of itself later in the season.

The factor that controls the time of canopy closure, and the one the farmer can do nothing about, is temperature: it controls the rates of germination, leaf production and leaf expansion. Since 1978, when we started to grow the standard crops, there has been a marked range of Leaf Area Index (LAI) and percentage of sunlight intercepted; for example, on midsummer day, 31% was intercepted in 1987 but 72% in 1990. These differences relate directly to the accumulated temperature experience of the crops (Milford et al., 1985).

Although emphasis has been given to light interception and therefore expansion of the leaf canopy throughout this section of the paper, studies were made of growth of the fibrous root sys-

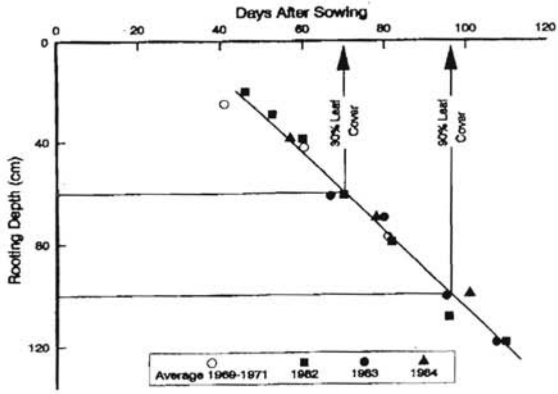

Figure 5. Relationship between time after sowing and depth of rooting by standard crops grown at Broom's Barn (after Brown and Dunham, 1986).

tem in some of these experiments. From measurements made by washing cores of soil through sieves, the fibrous root system seemed to penetrate down through the soil in a surprisingly consistent way. From about 40 days after sowing, the rooting front moved down at 1.6 cm/d (Fig. 5), almost irrespective of how rapidly or slowly the storage root and foliage were growing (Brown and Dunham, 1986). Similar values were obtained from observations made by neutron moderation of drying of soil profiles Dunham et al., 1993). Had we been working in a drier environment, then no doubt the small variations in root proliferation and penetration would have taken on more significance, especially as large portions of the root system seem to die when the soil becomes thorougly dry (Brown et al., 1987).

This analysis of the causes of seasonal variation in yield provides a basis for an insight into agronomy and a framework for a system to forecast yield.

THE ROLE OF FERTILIZER NITROGEN

It is now possible to explain the benefits of using fertilizer nitrogen in terms of the promotion of leaf growth early in the season. In essence, any benefits from the fertilizer derive from allowing the nutrient status of the plant to be adequate to expand its leaf surface at the potential rate dictated by spring and summer temperatures. A key point is that increases in LAI associated with the use of N over the range 0-3, will enhance radiation interception (Fig. 6), but above 3, the energy cost of leaf production is greater than the benefit in terms of extra radiant energy intercepted. Figure 7 shows that over the first increments of N applied, there is a distinct benefit to leaf cover and

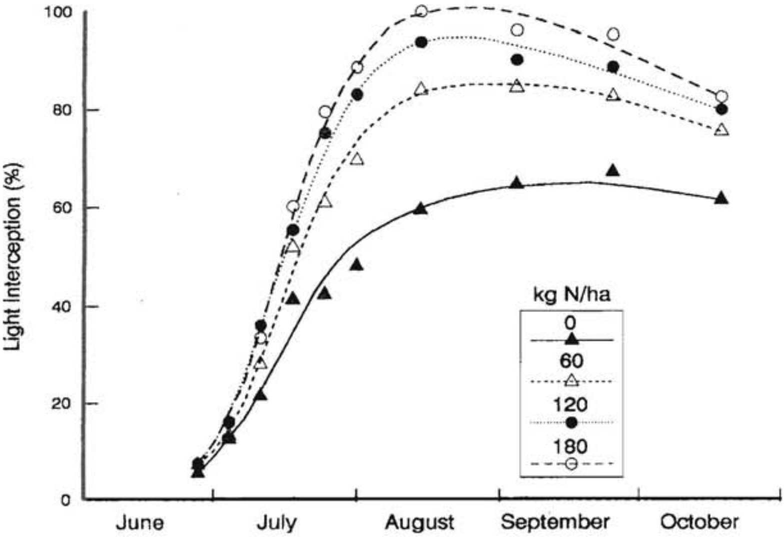

Figure 6. The effect of fertilizer nitrogen on light interception by the canopy.

radiation interception but as progressively more is applied, so the benefit diminishes. The limit to the benefit from N application is reached with a smaller amount of fertilizer when sugar production is considered rather than total biomass (storage root + foliage). More N stimulates the growth of petioles and laminae and any extra radiant energy intercepted produces dry matter which remains in the foliage and is not recovered as sucrose in the storage root.

A recent analysis has allowed us to regard management of N nutrition in terms of managing a canopy. Over the range of N availability found in the field, it is the size of the leaf surface, rather than its greenness, that controls the rate of dry matter production — dark green leaves photosynthesize little, if any, faster than their pale green counterparts (unpublished data). A series of steps provide the basis to explain the effects of N. First, the amount of mineral N in the soil in spring, together with that supplied as fertilizer, can be related, through an efficiency value, to crop uptake. Second, the amount of N in the crop directly relates (cm^2/g) to the size of the leaf surface (Fig. 8). Third, the assimilatory capacity relates to the relationship between LAI and radiation interception. Boiling this down, the key is to ensure that sufficient fertilizer N is supplied to augment the soil N to the extent that the plants can take up the N at a rate, and in an amount, necessary to reach LAI of 3 as rapidly as temperatures dictate. With a required uptake of 40 kg/ha for each unit of LAI, 120 kg/ha N must be within the crop by mid-June.

Usually, soils at Broom's Barn contain 80 kg/ha N early in the season. With a requirement of 120 and a recovery efficiency of 60%, this means that 120 kg/ha must be provided as fertilizer. Nothing more is required; any uptake required from July onwards can be met from N mineralized from soil organic matter and, in the rare occurrence that there is a shortfall, the plants can redistribute sufficient N from foliage to the storage roots to maintain their growth (Armstrong et al., 1986). Far more likely than a late shortage of N, is a surfeit of N release as warm soils rewet from August onwards, an effect exacerbated wherever poultry manure or other N-rich organic residues are present. The extra foliage has only a trivial effect on radiation interception and is a net 'draw' on assimilate (Fig. 7).

On the evidence of the standard crops grown at Broom's Barn, current varieties may have a more economical pattern of assimilate distribution between storage roots and foliage. For the first four years the variety was Bush Mono G, but to keep up with contemporary conditions, Regina was grown thereafter. With Bush Mono G, the average Harvest Index (the ratio of sugar yield to total biomass) was 0.495 (range 0.46-0.53), but with Regina, the average was 0.56 (0.52-0.59). A comparison of growth patterns of the two varieties in the same experiment revealed similar radiation interception and assimilate partitioning until late July, but from then on Regina retained less in the foliage and, entirely as a result of this more economical growth pattern, Regina produced 2t/ha more sugar, without producing any extra biomass. If this is a general characteristic of modern varieties, then it explains part of the upward trend in yield.

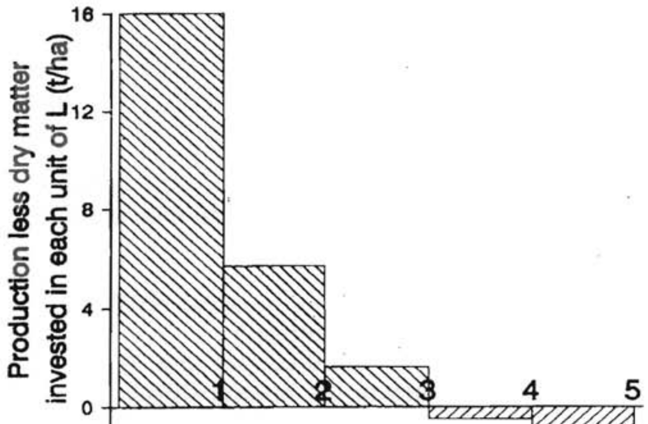

Figure 7. Net changes in biomass productivity with each increment of Leaf Index Area.

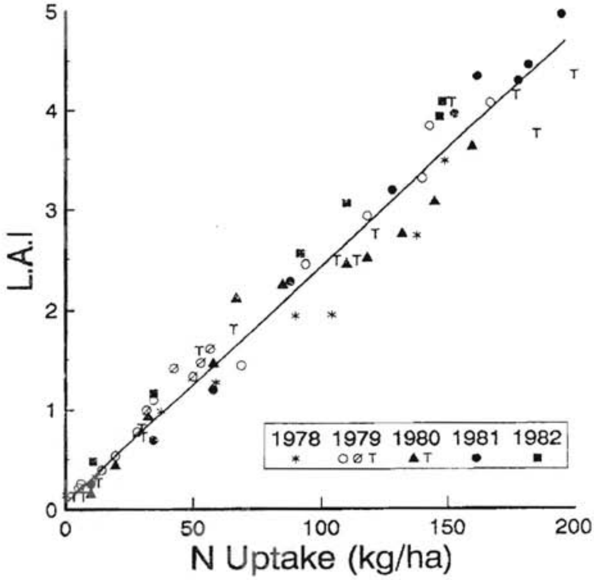

Figure 8. The relationship between nitrogen uptake by the crop and Leaf Area Index. Data points represent crops grown at a range of sites with and without fertilizer over the years specified.

As a conclusion to this section, it should be pointed out that, from an important environmental perspective — nitrate pollution of water supplies — the residue of leachable N left by sugar beet is very small. A crop given the minimum amount of N fertilizer required for maximum yield will, by harvest, have drawn down the available N content of the top metre of soil to about 30 kg/ha (Allison, 1991). This compares with approximately 60 and 130 kg/ha for winter wheat and maincrop potatoes respectively (MacDonald et al., 1990).

PLANT POPULATION AND ARRANGEMENT

In a similar way to nitrogen, the effects of changing plant population and arrangement can be examined on the basis of effects on radiation interception. Aerial photographs of experiments in which plant population was a treatment reveal the effects on radiation interception, with 75,000 plants/ha forming a closed canopy from July onwards but with bare ground clearly visible in populations less than this. The overall relationship between plant population and sugar yield has been investigated with plants grown 'on the square' so that changes in arrangement were not confounded with changes in plant population (Scott and Jaggard, 1993). Over the range 15-40 thousand plants/ha, sugar yield increased proportionately; then there was a dimininishing response from 40-75 thousand/ha. Beyond this, yields change little over a wide population range. Can this pattern of response be explained in terms of light interception? In sparse populations and gappy stands, there are major difficulties in measuring interception; many solarimeters would be needed in order to span such a large ground area. One plant population experiment (Scott, 1964) did however measure radiation interception where 37.5 and 75 thousand plants/ha were growing in rows 50 cm apart. Crop growth rates were directly related to amount of radiation intercepted. From the time when the leaf surface was maximal in each treatment, the sparse populations intercepted 75% and the dense population 89% of the incident radiation.

Why do yields not increase beyond 75,000 plants/ha when there must, at least for some time, be an advantage in terms of radiation interception from crowding more plants on the land surface? The answer is that the advantage is only shortlived. For example, when light interception was measured in populations of 75 and 150 thousand plants/ha, differences in leaf cover had disappeared by the beginning of July, when cumulative radiation in the two populations was 65 and 80 MJ/m^2 respectively. At the end of the season, equivalent values were 1370 and 1410 MJ/m^2 and there was no difference in yield. When plants are grown in dense populations, the leaves of neighbouring plants soon overlap (even when overall leaf cover is as little as 10%) and the benefit to light interception is soon eroded.

When monogerm varieties became predominant and drilling-to-a-stand became general practice, the experiments that had provided the basis for selecting plant populations lost much of their relevance. Then information was required on how to assess whether the environment was fully exploited by the plant distribution patterns that resulted when drills were set to place seeds at particular intervals, and when specific proportions of seeds produced established plants. Wherever plants are too far apart to form a closed canopy, yield will be lost. To determine the critical gap length, plant population experiments provided a starting point. When plants were grown on the square, 75,000/ha exploited the environment fully and aerial photographs show that a closed canopy was formed. Lesser populations failed to reach that stage. Thus, it seems that plants can spread their foliage to form a complete canopy over a distance of 25.5 cm (half the diagonal of the distribution pattern with 75,000 plants/ha grown on a square with sides 36 cm long). Further evidence was provided where a standard population was grown in different arrangements by varying the ratio of between- and within- row distances. Where 75,000 plants/ha were grown in five arrangements from 1:1 to 1:6 ratios of between- to within- row spacings, yield fell wherever the distance between rows exceeded 50 cm.

Thus, it seems that for mineral soils in England, the limit from the seedling position to the point where leaves of adjacent plants form a complete canopy extends to 25 cm. There are some fertile soils, particularly organic ones, where as few as 60,000 plants/ha can attain potential yield (Knott et al., 1976) — the more luxuriant foliage bridges a larger gap.

It is possible (Ehnrot 1965) to predict the frequency of distances between plants if the inter-seed spacing and establishment percentage are defined. This is done on the basis of the binomial theorem, and assumes that the pattern of establishment failure is randomly distributed, i.e., such factors as soil pests that might cause aggregated damage are not operative. Our surveys show that this is the usual situation in beet fields. An expansion of the polynomial theorem then defines the growing space for each plant (Jaggard, 1979) and with the knowledge of the relationship between the weight of the individual plant and population density (Bleasdale and Nelder, 1960), it is possible to construct the yield response of the crop as a whole to changes in inter-seed spacing and establishment percentage (Fig. 9a). The validity of this model was checked in an experiment where yields were measured in large plots representing the factorial combinations of inter-seed spacing of 15 or 22 cm and seedling establishment percentages of 33, 50 and 70% (contrived by mixing different proportions of live and dead seeds). For all six treatments, yields were within 3% of the values predicted by the model (Fig. 9b).

The model was used in 1977 to estimate how far the national crop fell short of potential because of gappiness. Plant distribution assessments were made in 46 randomly selected fields in eastern England, and yield losses were estimated for each field. Averaged overall, the estimated loss then was 10%. There is a limit, mainly imposed by the need for the topping mechanism on the harvester to re-adjust to different crown heights of adjacent plants, as to how close seeds can be placed (15 cm is about the limit). The output from the model highlights the crucial importance of achieving satisfactory establishment where seeds are 15 cm apart or more — 70% is the value below which yield is lost. The steady improvement in the quality of seed, as indicated by the percentage germination in the laboratory, supplied to the sugar industry in England (89% in 1979 and 95% in 1990) has undoubtedly contributed to the increased national yields over the period. It is important to appreciate that for English conditions, the standard row width of 50 cm is at the limit of the plant's ability to form a complete canopy. Where there is a particular risk that establishment will be poor and stands gappy (for example in fields where soil-resident pests are common and

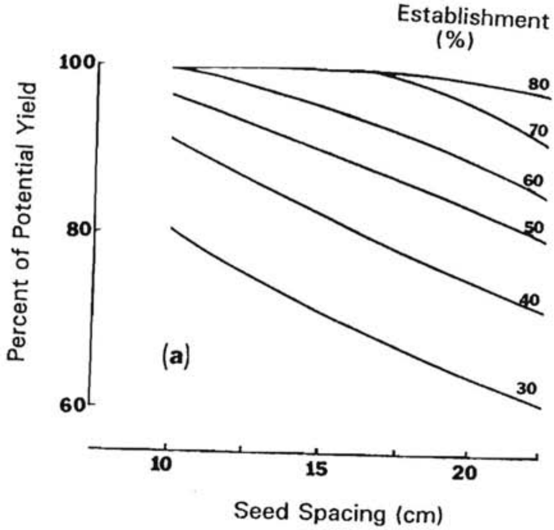

Figure 9a. The predicted effects of seed spacing and seedling establishment on sugar yield.

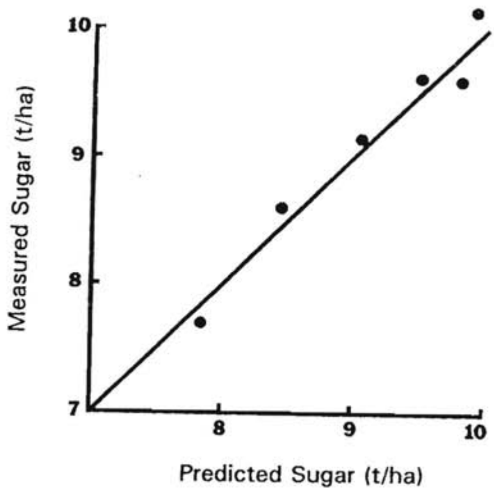

Figure 9b. A comparison of predicted and measured yields for combinations of spacing (15 or 22 cm) and establishment (33, 50 or 70%).

troublesome), there will be benefit from having rows closer than 50 cm apart. If establishment is really poor, for example about 30%, then the rows themselves have to be very close, around 30 cm apart for a complete canopy to be created. In these circumstances, a bed system is required to allow the passage of tractor wheels. Although a bed system does offer yield advantages where establishment is substandard, this does not hold true when establishment is 70% or greater.

FORECASTING YIELD

Turning now to the way in which the analysis of seasonal variation in yield provides a basis for a system of forecasting yield, the emphasis again falls on the rapidity with which leaves cover the ground. A small change in leaf cover during the long bright days of May, June and July, can make a significant difference to radiation interception over the season as a whole. Unlike cereals and most potato crops, sugar beet yield continues to increase for as long as the environment allows, and beet crops that grow rapidly at the beginning of the season are at least as capable of using radiation efficiently during autumn as crops which start by growing slowly or late in spring. How efficiently radiation is exploited depends on the extent of drought and disease, particularly the yellowing viruses. There is no basis for assuming that 'early' crops should be consistently more at risk from these stresses than late starters. With yellows, the reverse would tend to be true, because the aphid vectors of the disease are attracted to alight in crops where the canopy is incomplete and where bare soil is visible. Examination of data from experimental crops that have been subject to growth analysis, together with the information from British Sugar's annual crop sampling programme, reveal that the ranking order of yield tends to be maintained throughout the season. In contrast with potatoes, where early planted crops senesce early and later crops often overtake them, this cross-over is rare in beet.

The rapid decline in potential for growth from August onwards, and the declining responsiveness of the ageing canopy, each mitigate against large shifts in yield away from the norm. This allows, in principle, accurate forecasts of yield to be made long before harvest. A forecasting system is now in place that uses a Spectral Ratio meter fitted to a helicopter that overflies about 350 fields distributed throughout the beet-growing regions in England (Jaggard and Clark, 1990). A helicopter, rather than a satellite, is used for two reasons. Firstly, cloud cover is frequent and secondly, the 'turn-around-time' of data from the satellite is too long. The Spectral Ratio meter estimates the extent of foliage cover on the basis of the differential reflection characteristics of radiation in the red and near infra-red wavebands by leaves and bare soil, a vegetation index. Foliage strongly absorbs red and strongly reflects infra-red, whereas soil, particularly when damp, has a much more gradual increase in reflectivity across the spectrum. The first helicopter flight is in June along a track designed to sample the major producing regions. Flights continue over the same track at 2-3 weekly intervals from June until August. A yield estimate is obtained by correcting the daily values of incident radiation for fractional interception, and summating the intercepted radiation to date, then adding the average amount of radiation (corrected for ground cover) likely to be received (on the basis of historical measurements) from the most recent sampling date until harvest. Values of intercepted radiation are converted to estimates of sugar yield on the basis of 1g sugar per MJ radiation inter-

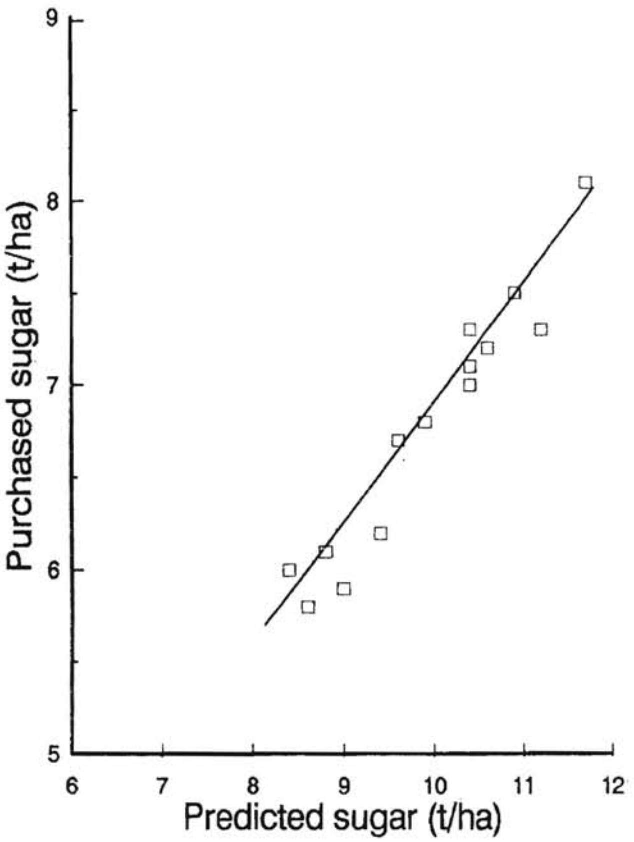

Figure 10. Correlation between yields forecast for 31 October each year and the yields purchased by British Sugar. The line represents an adjustment of 0.7 - see text.

ed. Since the system first operated in England in 1987 values of sugar yield predicted in late August have always been within 0.2t/ha of the amount purchased (Fig. 10).

Several factors, the most immediately obvious being losses at harvest, combine to necessitate a downward adjustment from the yield estimate obtained in this way to the 'ground truth.' Forecasts of yield of individual large fields have been compared with actual yields measured by the sugar factory weighbridge and tarehouse. Also, forecasts of yield for particular groups of factories have been compared with the amounts of sugar purchased. In both cases, the ratio of actual to estimated yield has

Table 1. Contributions to the yield forecast adjustment in the UK.

	Contribution (%)	Running adjustment (%)
Potential yield	-	100
Cropped area versus declared area	8	92
Headlands (15% loss on 15% area)	2.25	90
Harvesting losses	10	81
Storage (0.1% per day for 25 days)	2.5	78.9
Loading losses	3	76.5
Early harvest	6	71.9

been 0.7 (±0.01). Can we account for the downward adjustment required? The steps involved and our best estimates at each stage are shown in Table 1.

The 8% downward adjustment for cropped versus declared (that includes verges, hedges and ditches) area, is the value obtained from measurements made on the property of several large farming companies in E England. Measurements of headland areas were made in the same survey and on average, they occupied 15% of the sown area (Jaggard et al., 1984). Yields were measured separately on the headlands and in the 'centre' areas of the fields and were 15% less on the headland. Measurements of the efficiency of recovery via mechanical harvesting have averaged close to 90%. Losses in clamp have averaged 0.1% per day (Oldfield et al., 1980): allowing an average period in clamp of 25 days, the loss was estimated at 2.5%. Loading losses were estimated from measurements made while cleaner/loaders were used to fill trucks, with provision for small additional losses of tails and chips in the factory washers. The factory campaign in England extends from late September until

February. The yield estimates from intercepted radiation are made assuming that all crops grow until 31 October. In practice, about 40% of the national crop is lifted before this date, so an adjustment based on yield trends over the harvesting period was required to allow for early harvest; this adjustment was a 6% drop.

Throughout this review we have emphasized the extent to which, in England, yield is driven by the interception of radiant energy; minimal reference has been made to the importance of changes in efficiency of conversion of absorbed energy to biomass and sugar. It is known that drought and disease can depress the efficiency, but for most sites and seasons, crops in England seem to operate with a conversion of about 1g of sugar produced for each MJ radiation intercepted.

For a yield forecasting system to operate away from the predominantly dull, damp, equable climate of NW Europe, several factors would have to be taken into account. At lower latitudes and in more continental, more cloud-free climates, incident radiation is greater. For example, radiation receipts from April until October at Fargo, N Dakota and Davis, California, are respectively about 50% above and double those at Broom's Barn. Thus, whereas at Broom's Barn the canopy is rarely light saturated, this would not be so true in California (Fig. 11) and the relationship between intercepted radiation and yield might not

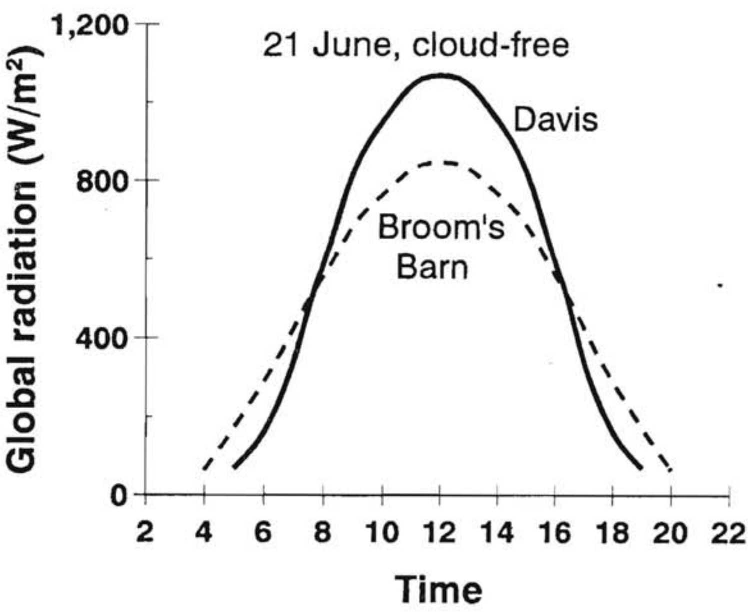

Figure 11. Irradiance throughout a cloud-free midsummer's day in California and England.

be so direct (Figs. 3 and 11). In California, the forecast would almost certainly be better based on water use and water use efficiency, rather than radiation. There is a further factor which would need to be considered in developing an analysis and forecast system in regions like California. As in NW Europe, productivity would be based on water used; the potential for photosynthesis, and thus dry matter production and the potential for transpiration, are both set by the amount of solar radiation intercepted by the canopy. Moreover, the transfer of both carbon dioxide into and water vapour out of the leaves is regulated by the stomatal and boundary layer resistances. However, because the productivity per unit of water transpired is inversely related to the dryness, i.e. the mean vapour pressure deficit of the atmosphere, the water use efficiency will be substantially less in California than in England. Table 2 from Dunham (1993),

Table 2. Estimates of total dry matter and sugar production per unit of water used by experimental sugar beet crops. (After Dunham, 1993.)

		Production per unit water used		
	Sugar beet E_T	(g/kg)		
Place	(mm)	Dry matter	Sugar	Reference
Suffolk, UK	450	6.8	4.0	Dunham (1989)
Germany	500	6.1	—	Roth et al. (1988)
N Dakota	550	5.2	2.4	Stegman & Bauer (1977)
Utah	650	5.5	2.2	Davidoff & Hanks (1989)
Nebraska	800	5.8 (cloudy) 2.7 (sunny)	—	Brown & Rosenberg (1971)
Washington	800	4.9	2.5	Hang & Miller (1986)
California	900	2.3	1.3	Ghariani (1981)
California	1150	2.1	1.1	Howell et al. (1987)
California	1200	—	1.7	Ehlig & Le Mert (1979)
Texas	1250	—	1.1	Winter (1988)

shows the way water use efficiency decreases from region to region as radiation becomes more intense and the atmosphere drier.

In conclusion, we believe that the demonstration of the extent to which seasonal weather patterns in England can change yield has been useful in distinguishing between the effects of factors over which the grower has control from those that are beyond his control. No amount of care and attention or added cost in fertilizers or crop protecting chemicals would have closed the gap in yield between crops grown in 1978 compared with those grown in 1982 or 1992. In passing, it is worth remarking that the yield range associated with differences in the seasonal drift in temperature and radiation exceeds that which is likely within a season, even if no fertilizer were applied or the crop suffered the most severe combination of drought and disease.

In 1978, when the team of agronomists and crop physiologists began working at Broom's Barn (the next phase of the Station's activities after the retirement of Dr Raymond Hull), the aims were:

1. to analyze crop growth in relation to the overall efficiency of radiant energy and water use and to use this analysis as a basis

2. to devise experiments to produce data from which to generalize and thus reconcile results from more empirical experiments done at different sites in different seasons, and

3. to fix yield targets and predict yield given various measured parameters.

Some progress has been made, but there is still scope to achieve more, particularly in relation to extending the analysis to reconcile productivity in strongly contrasting environments.

ACKNOWLEDGEMENTS

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