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Thermal time assessment of suitable areas for navy bean (*Phaseolus vulgaris*) production in the UK

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Summary

In field trials at eight sites throughout the UK the mean thermal time requirement for navy beans from sowing to harvest for a standard cultivar, Marcus, was 2069 Ontario Heat Units (OHU). Low level plastic covers increased the range of warm environments at one site and gave a mean thermal time required of 2098 OHU.

Analysis of daily air temperatures from six weather stations throughout the UK over a 29 year period, showed a 14 day possible planting period on the south coast of England, but gave a high probability of crop failure in Scotland.

Maps of England and Wales indicating the probability of achieving 2000 OHU were produced from 5 km grid point temperatures. Less than 2% of the land had more than a 60% chance of receiving 2000 OHU under the present climate, however this area increased to 70% with a mean temperature rise of 1.5 °C. Although 2000 OHU is often used as the thermal time requirement of navy beans, these trials showed that it may be more accurate to use the higher figure of 2087 OHU from sowing to harvest, and restrict the use of 2000 OHU to the period between emergence and harvest. When the map was redrawn using 2087 OHU and current climate, no parts of England and Wales showed a reasonable chance of growing the present cultivars of navy beans.

Key words: Thermal time, Ontario Heat Units, day degrees, mapping, navy bean, *Phaseolus vulgaris*

Introduction

Navy beans (*Phaseolus vulgaris*) are considered to be a marginal crop because the growth of standard North American types is restricted in the UK by cool temperatures normally experienced during the summer months. Attempts have been made to identify suitable areas of Britain for bean production using air temperatures from a limited range of weather stations (Scarisbrick, Carr & Wilkes, 1976; Andrews, Hardwick & Hardaker, 1983). Potential areas of production of other crops marginal to the UK such as maize and outdoor tomatoes have been studied (Hough, 1978; Barrie & Gray, 1980). These workers used the Ontario Heat Unit (OHU) system (Brown, 1972) of thermal time to relate differences in growth and harvest date to climatic conditions. Values of mean daily temperature (T) for the whole of the UK have been plotted by eye (Smith, 1976) to produce contour maps. A linear regression between OHU and T for weather stations in Southern England over the growing period gave a very good fit and enabled potential areas of production to be mapped. Later workers calculated accumulated temperature data, on a 5 km grid basis, using a regression model to relate temperature to altitude, latitude and longitude (Anon., 1989).

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The work presented here investigates the thermal time for navy bean maturity suggested by earlier authors, and used long-term temperature data to produce maps of England and Wales showing suitable areas for navy bean production.

Materials and Methods

Field trials

Trials were carried out at sites listed in Table 1 during 1988, 1989 and 1990, to monitor plant development in relation to air temperature. Navy bean seeds cv. Marcus were hand sown at a spacing of 0.15 m × 0.15 m, in each of two replicate plots of either 1.35 m × 15 m, where detailed growth measurements (G) were taken, or 1.35 m × 5 m where development (D) stage only was monitored. Granular *Rhizobium* inoculant was applied at sowing.

In 1989 and 1990, plastic covering trials were also carried out to extend further the range of possible temperature regimes. Plants were hand sown at 0.15 m × 15 m spacing with a plot size of 1.35 m × 3 m. Sowing dates were 2 May 1989 (S1), 18 May 1989 (S2), 30 May 1989 (S3), and 1 May 1990 (S1), 14 May 1990 (S2), 30 May 1990 (S3). For each sowing date there were four covering treatments: non-covered throughout growth (U1), covered with plastic at sowing and uncovered after two weeks (U2), covered at sowing and uncovered after four weeks (U3), and covered at sowing and uncovered after six weeks (U4). This gave 12 treatment combinations in each year, each replicated four times in a randomised block factorial design. Plant development was monitored using a growth stage key (Anon., 1988), vegetative growth stages were defined by the number of nodes on the main stem and reproductive growth stages were defined in terms of flower and pod development. Harvest maturity (stage R8) was defined as 50% of plants with 95% of pods brown.

Plastic covers consisted of 1.5 m wide polythene sheets with 10 mm perforations at a density of 200 holes m^{-2}. Air and soil temperatures were measured at the centre of the plots every 30 min using 10 K Ω thermistors linked to a 'Delta-T' data logger. Air temperature probes measured 5 mm long by 2 mm wide and were protected from direct sunlight by solar radiation shields. Five white, upturned, 100 mm plant pot saucers were used to produce the radiation shields; saucers were held vertically 10 mm apart using three plastic bolts passing through all five saucers and the resulting structure resembled a pagoda. Air temperature probes were positioned vertically at the centre of the stack of saucers allowing all round air circulation.

Table 1. *Site location*

Site	Altitude (m)	Latitude	Soil type
Aberdeen University (D)	100	57°15′N	Sandy loam
Dundee (SCRI) (D)	45	56°28′N	Sandy loam
Stockbridge House HRI (G)	8	53°50′N	Sandy loam
Kirton HRI (D)	4	52°56′N	Silty loam
Thornhaugh (PGRO) (G)	20	52°35′N	Sandy loam
Wellesbourne HRI (G)	49	52°12′N	Light sandy loam
Wye College (D)	56	51°11′N	Brick earth
Littlehampton HRI (G)	3	50°48′N	Brick earth
Efford HRI (D)	10	50°46′N	Sandy silt loam

G – detailed growth measurements.
D – development stage only.

Table 2. *Sowing and harvest dates, days and 'thermal' times to harvest maturity*

1988	Sowing	Harvest	Days	Day deg	OHU	OHD2000	OHD2087
Thornhaugh	17 May	3 Oct	139 +26	612.4	2176	124 +15	131 +8
Wellesbourne	23 May	14 Oct	144 +31	650.4	2235	119 +25	127 +17
Littlehampton	27 May	29 Sept	125 +12	664.2	2211	113 +12	118 +7
Efford	26 May	10 Oct	137 +24	634.0	2237	117 +20	123 +14
1989	Sowing	Harvest	Days	Day deg	OHU	OHD2000	OHD2087
Aberdeen	16 May	28 Sept*	135	453.3	1733	—	—
Dundee	16 May	20 Sept	127 +14	555.0	1932	132 −5	139 −12
Thornhaugh	17 May	20 Sept**	126	818.0	2372	—	—
Wellesbourne	15 May	30 Aug	107 −6	722.8	2027	106 +1	112 −5
Wye	16 May	24 Aug	100 −13	708.9	1998	101 −1	105 −5
Littlehampton	17 May	17 Aug	92 −21	644.5	1847	100 −8	104 −12
Efford	18 May	17 Aug	91 −22	684.7	1902	96 −5	100 −9
1990	Sowing	Harvest	Days	Day deg	OHU	OHD2000	OHD2087
Aberdeen	15 May	23 Oct*	161	421.2	1783	—	—
Dundee	15 May	16 Oct	154 +41	580.2	2160	138 +16	147 +7
Stockbridge House	15 May	5 Oct	143 +30	712.3	2313	117 +26	122 +21
Kirton	15 May	6 Sept	114 +1	681.5	2046	111 +3	116 −2
Wellesbourne	16 May	11 Oct**	148	865.5	2573	—	—
	18 May	8 Sept	113 0	744.3	2109	107 +6	111 +2
Wye	15 May	3 Sept	111 −2	660.4	1966	113 −2	118 −7
Littlehampton	16 May	22 Aug	98 −15	544.1	1714	112 −14	117 −19
Efford	16 May	13 Sept	120 +7	725.0	2237	107 +13	112 +8

Days are from sowing to harvest, +/− difference from overall mean.

OHD2000 and OHD2087 are the number of days to reach 2000 or 2087 OHU, +/− difference between OHD2000 or OHD2087 and days from sowing to harvest.

* Beans were not mature at harvest (they reached growth stage R7, plants yellowing, but not R8 pods brown – harvest maturity (Anon., 1988)).

** Seedling emergence was delayed by 2–3 wk.

These data (*, **) were not used in subsequent calculations.

Analysis of long-term weather data

Ontario Heat Units for individual sites were calculated from daily maximum (Tmax) and minimum (Tmin) screen air temperatures as follows:

Day term: $Y = 3.33(\text{Tmax} - 10) - 0.084(\text{Tmax} - 10)^2$
for Tmax greater than or equal to 10 °C; $Y = 0$ otherwise.
Night term: $X = 1.8(\text{Tmin} - 4.4)$
for Tmin greater than or equal to 4.4 °C; $X = 0$ otherwise.
$\text{OHU} = (X + Y)/2$ (Hough, 1978).

Ontario Heat Units were tabulated each day from sowing to several weeks beyond harvest. This allowed the number of days from sowing to overall mean number of OHU to be calculated (OHD2000 and OHD2087, Tables 2 and 3) for all crops including those which matured with less than the mean number of OHU.

Table 3. *Plastic covering trial, days and logged thermal times to harvest maturity*

1989

Treatment	Days		AHU	AHUconv	OHU	OHD2000		OHD2087	
S1U1	103	−10	746	589	1961	104	−1	108	−5
S1U2	101	−12	818	560	1856	107	−6	111	−10
S1U3	103	−10	927	545	1787	112	−9	117	−14
S1U4	102	−11	1009	542	1826	109	−7	114	−12
S2U1	99	−14	756	597	1951	100	−1	105	−6
S2U2	100	−13	856	585	1901	106	−6	112	−12
S2U3	107	−6	985	624	2053	104	−3	109	−2
S2U4	120	+7	1143	659	2196	110	+10	115	+5
S3U1	109	−4	802	649	2122	101	+8	107	+2
S3U2	103	−10	873	620	2043	99	+4	105	−2
S3U3	121	+8	1108	666	2186	110	+11	115	+6
S3U4	121	+8	1208	647	2184	110	+11	115	+6
Mean	107.4		935.7	606.8	2005.4				
S.E.D. (33 D.F.)	2.37		12.99	12.33	41.76				
CV	3.1		2.0	2.9	2.9				

1990

Treatment	Days		AHU	AHUconv	OHU	OHD2000		OHD2087	
S1U1	119	+6	805	654	2252	108	+11	112	+7
S1U2	122	+9	937	661	2269	111	+11	115	+7
S1U3	115	+2	980	603	2107	111	+4	115	0
S1U4	115	+2	1044	603	2167	107	+8	112	+3
S2U1	118	+5	802	656	2270	104	+14	108	+10
S2U2	117	+4	939	649	2211	105	+12	109	+8
S2U3	115	+2	1007	653	2261	103	+12	106	+9
S2U4	106	−7	1038	598	2129	101	+5	104	+2
S3U1	109	−4	782	637	2163	101	+8	106	+3
S3U2	101	−12	806	613	2135	94	+7	99	+2
S3U3	101	−12	877	615	2183	92	+9	96	+5
S3U4	96	−17	912	588	2149	90	+6	94	+2
Mean	111.3		910.6	627.4	2191				
S.E.D. (33 D.F.)	3.49		24.79	21.50	70.1				
CV	4.4		3.8	4.8	4.5				

Days are from sowing to harvest, +/− difference from overall mean.
OHD2000 and OHD2087 are the number of days to reach 2000 or 2087 OHU, +/− difference between OHD2000 or OHD2087 and days from sowing to harvest.

Day degrees were calculated each day as ((Tmax + Tmin)/2) − 10 for Tmin above 10 °C, for Tmin below 10 °C an adjustment was carried out using the method of Snyder (1985).

Accumulated Heat Units (AHU, similar to day degrees) from the plastic covering trials were simply calculated from the hourly logged air temperatures above 10 °C. Hourly temperatures were then transformed using modified growth parameters from the BEANGRO model (Hoogenboom, White & Jones, 1988) to produce AHUconv. This model gives a linear increase in growth between 8 °C and 20 °C, constant growth between 20 °C and 28 °C and a linear decrease in growth between 28 °C and 40 °C. One parameter in the model was modified to give a base temperature of 10 °C to make the data more comparable with day degrees. Abbreviations used in weather data calculations are summarised as follows:

AHU – Accumulated heat units (hourly)
AHUconv – Accumulated heat units (hourly) transformed using the BEANGRO model

ATS – Accumulated temperature above 0 °C, April to September
Day deg – Day degrees, base temperature 10 °C
OHU – Ontario heat units
OHD2000 – Number of days required to achieve 2000 Ontario Heat Units
OHD2087 – Number of days required to achieve 2087 Ontario Heat Units

Maps giving a complete coverage of Ontario Heat Units were derived from the accumulated temperatures, April to September (ATS) data set which is based on the altitude, latitude and longitude of each 5 km grid point. A regression between ATS and OHU from weather stations throughout England and Wales produced the equation $OHU(15/5-30/9) = 145 + 0.753ATS$ (J. Minhinick, personal communication) which accounted for a very high proportion of the variation in OHU. The standard deviation of OHU calculated from these weather stations was approximately 200. From this was calculated the probability of achieving 2000 OHU at any point, given the mean number of OHU at that point (Fig. 2*a,c*). A figure of 2000 OHU was chosen as it has been widely used (Hardwick, 1988), however Fig. 2*b* was produced using 2087 OHU, the mean value calculated from the results given below. The percentage land area falling within each of the five probability classes was also calculated. The 5 km grid point OHU values were then interpolated to produce a map and plotted out using Uniras graphics packages on a MicroVAX computer.

Results

Field trials

Plants reached harvest maturity at all sites except Aberdeen. Growth and development were particularly advanced in 1989 and 1990, which were two of the warmest years ever recorded in England. However there was a late harvest at all sites in 1988 (Table 2). The weather conditions in late summer and early autumn were cool and wet in this season, resulting in the growth of *Botrytis* on pods and a high level of fungal seed damage. Few fungal problems occurred in 1989 and 1990 and then only late in the season at the more northerly sites.

The number of days from sowing to harvest generally decreased from north to south. Anomalies such as Wellesbourne in 1990 were explained by delayed emergence caused by drought. Thermal time expressed as day degrees or OHU showed little overall trend, the figure varied by less than 20% from the overall mean, compared with a 27% variation in the number of days to maturity.

The comparison between methods of calculating thermal time was further examined in the plastic covering trials (Table 3). Treatments which remained covered the longest received the most accumulated heat units (AHU). However when these data were transformed to reduce the influence of super optimal temperatures (AHUconv and OHU), covering had no consistent effect on the heat unit requirement. In regions of the world receiving high temperatures or when plastic covers are used, AHU or day degrees are unlikely to be suitable measures of thermal time as they do not take account of temperatures which are super optimal for plant growth. Under plastic covers, temperatures showed a greater diurnal range than in the open, maximum air temperatures exceeding 50 °C during still, cloudless weather. A few plants experiencing these extreme conditions died, others were stunted, however most survived and developed normally.

The overall mean number of days from sowing to harvest combining the remote sites and plastic covering trials was 113.5, and the overall mean number of OHU was 2087. The

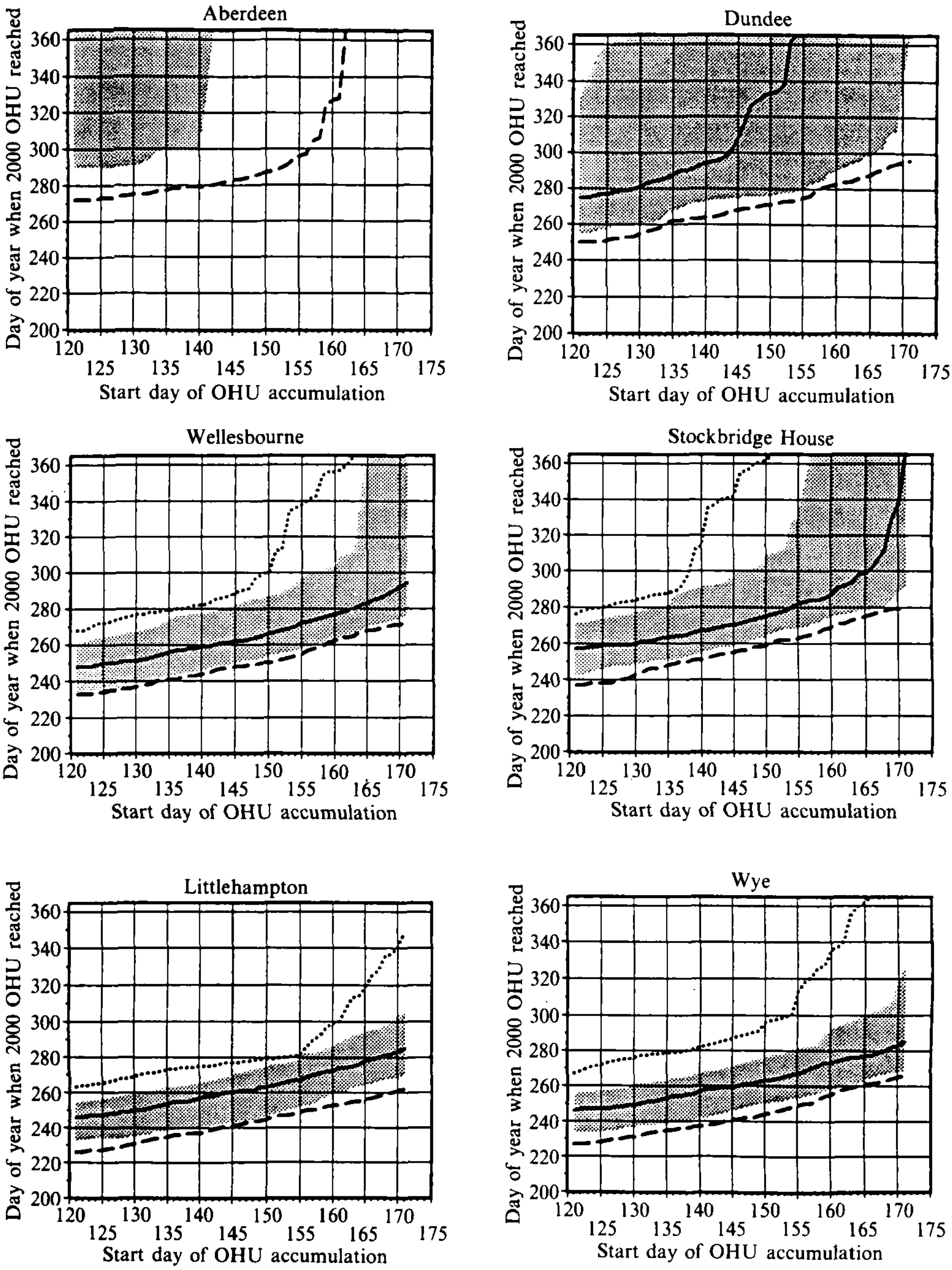

Fig. 1. Long-term OHU calculations from six weather stations. For each starting date median (——), min (— —), max (· · · · · · ·), and 90 percentile (shaded area) dates of 2000 OHU attainment are shown. Dates are days after January 1.

number of days after sowing required to reach the mean OHU figure allows a comparison to be made between OHU and days (Bunting, 1976). The overall variance of days was calculated as

$$\frac{\Sigma\,(days\text{-}meanday)^2}{n\text{-}1}$$

and variance of OHD2000 and OHD2087 as

$$\frac{\Sigma\,(days\text{-}OHD2000 \text{ or } OHD2087)^2}{n\text{-}1}$$

Variances decreased in the order 218.10 for days, 116.72 for OHD2000, and 80.54 for OHD2087. Lower variances indicate less variability and so a more reliable measure of date of maturity.

Long-term weather data

Long-term historic weather information was used to predict the date on which 2000 OHU would be achieved from any given sowing date (Fig. 1). These graphs were calculated using Ontario Heat Unit sums from every starting day between 1 May and 20 June and for every year between 1959 and 1987. For sowings during the late spring and early summer at the southerly sites, the date of 2000 OHU attainment can be predicted to within 10 – 15 days using the 90 percentile (shaded area). Percentile rather than confidence interval was used as the data did not appear to be normally distributed. Later in the season and at the more northerly sites this prediction error rapidly increased. Under UK conditions, a sowing date between mid May and early June (days 135 – 155) is most likely as this avoids low soil temperatures and poor growth in spring (Hardwick, 1988). The date at which conditions become unsuitable for harvesting at the more southerly sites varies between early September and mid October (days 250 – 290) depending on rainfall patterns and temperature, however a single date 30 September (day 273) is often used. Littlehampton and Wye have at least a 14-day period for sowing dates with a high probability of successful harvest (Fig. 1); at Wellesbourne and Stockbridge House an early sowing date (days 135 – 140, May 15 – 20) is important if 2000 OHU are to be reliably achieved; at Aberdeen and Dundee it is very unlikely that the crop will mature irrespective of sowing date (Fig. 1).

Maps of OHU values show that only 1.2% of England and Wales has a greater than 60% probability of achieving 2000 OHU under current climatic conditions (Fig. 2*a*). However this area increases to 70% in Fig. 2*c* with a 1.5 °C increase in temperature. Raised temperatures are likely to alter the year to year variability and the regression between temperature and OHU, however, these effects cannot be calculated and have been shown as remaining constant between the two maps.

Discussion

These trials have shown that navy bean cv. Marcus can reach maturity in many parts of the UK during warm years. The mean thermal time requirement of beans growing at sites between 56°28′N and 50°46′N was 2069 OHU, and from plastic covering treatments the requirement was 2098 OHU. These values are similar to the figure of 2000 OHU given by Hardwick (1988). Variability in the number of OHU required to reach maturity was small. There was a maximum of 18% difference from the mean in the remote trial sites and a maximum 15% difference with the plastic covering treatments. Comparisons of methods of predicting time to maturity showed that OHU were more consistent across sites than day degrees; OHU and hourly temperatures modified using BEANGRO parameters (AHUconv)

(*a*)

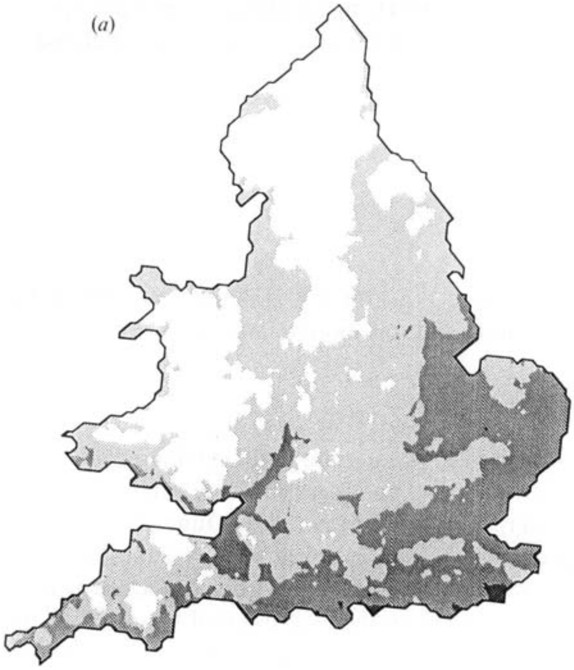

Fig 2*a*

% Probability of 2000 OHU	Mean OHU 15/5 – 30/9	Area %
Above 80	Above 2170	0.0
60 – 80	2051 – 2170	1.2
40 – 60	1949 – 2051	27.8
20 – 40	1830 – 1949	43.6
Below 20	Below 1830	27.5

Fig. 2(*a*). *Probability of achieving 2000 OHU average 1961–80*

(*b*)

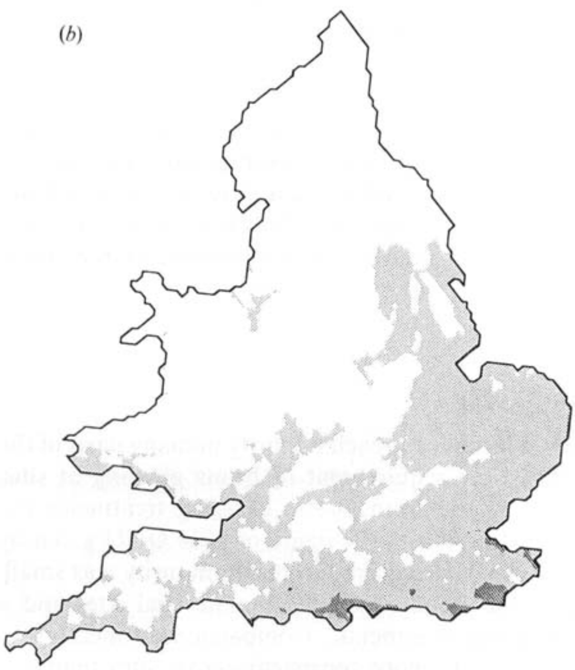

Fig 2*b*

% Probability of 2087 OHU	Mean OHU 15/5 – 30/9	Area %
Above 80	Above 2255	0.0
60 – 80	2138 – 2255	0.0
40 – 60	2036 – 2138	3.0
20 – 40	1919 – 2036	40.4
Below 20	Below 1919	56.7

Fig. 2(*b*). *Probability of achieving 2087 OHU.*

(*c*)

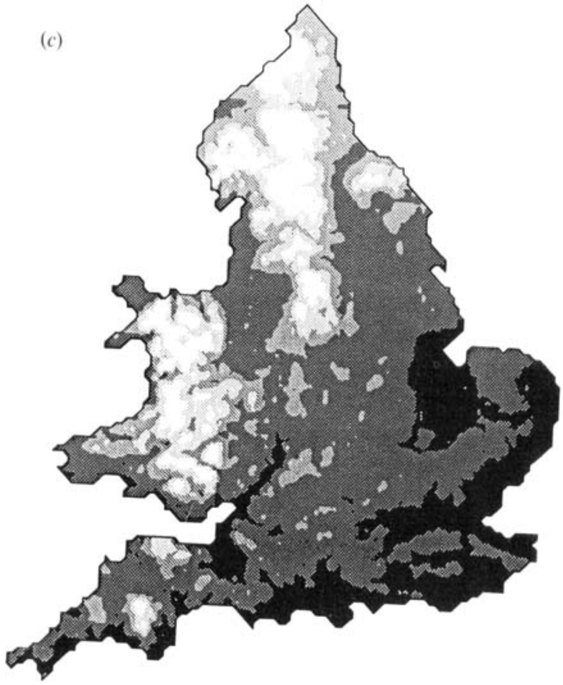

Fig 2*c*

% Probability of 2000 OHU	Mean OHU 15/5 – 30/9	Area %
Above 80	Above 2170	23.4
60 – 80	2051 – 2170	46.5
40 – 60	1949 – 2051	14.4
20 – 40	1830 – 1949	8.2
Below 20	Below 1830	7.5

Fig. 2(*c*). *Probability of achieving 2000 OHU with 1.5°C temperature rise.*

both provided a good description of time to maturity under plastic. However, the frequently measured temperatures required by AHUconv were not available at the remote sites. To compare Ontario Heat Units with calendar days, both needed to be on similar scales. This was achieved by calculating the number of days from sowing to the overall mean number of OHU, shown as OHD2087 in Tables 2 and 3. The variance of OHD2087 was lower than for calendar days, indicating that OHD2087 was a better measure of predicting time to maturity. Bunting (1976), Lipari, Mauromicale & Cosentino (1988) and Mauromicale, Cosentino & Copani (1988) working with a range of different plant species also found that thermal time gave a more accurate indication of crop development than calendar days.

Analyses of historic weather data were carried out before results of the field trials were available. The existing standard figure of 2000 OHU was used for the following thermal time summations, however field trials during 1988, 1989 and 1990 indicated that this figure was perhaps better used as the thermal time from emergence to maturity rather than from sowing to maturity. Long-term daily temperature records from individual weather stations in southern England (Fig. 1, Wye and Littlehampton) show that 2000 OHU is achieved by the end of September in 9 years out of 10 from a mid May starting date. This suggests that navy beans can be grown at present in many parts of the south. However, the overall picture (Fig. 2*a*) indicates a more restricted area for crop growth. The difference between the two results (Figs 1 and 2*a*) can be explained by the different methods of calculation. Fig. 2 was produced using a single regression model derived from weather stations throughout England and Wales. This gives good overall coverage, but since it is based on one regression it cannot be as accurate as data from a weather station covering the exact local climate.

Scarisbrick *et al.* (1976) working with navy bean cv. Seafarer (similar to Marcus) at Wye College suggest 2000 OHU are required from emergence to maturity and that from initial sowing to maturity 2100 OHU are needed. This latter figure is close to the overall mean of 2087 OHU obtained when results from all sites and plastic covering trials were combined. The map showing suitable areas of bean production using 2087 OHU (Fig. 2*b*) would indicate that beans could not be grown reliably in the UK. There is some confusion in the literature as to the start of OHU summation, either from sowing or from emergence. The difference between the two possible start dates has only a 5 – 10% effect on total OHU but this difference has a substantial effect on the area of the country with potential for bean growth, as seen by comparing the middle scale band of Figs 2*a* and 2*b*.

Fig 2*c* shows the potential area for navy beans, using a target of 2000 OHU, if the long-term temperature were to increase by 1.5 °C as a result of global warming (Hansen & Lacis, 1990). Trials were carried out in two exceptionally warm years, 1989 and 1990, in which the temperature difference from long-term average for much of the UK was 1.3 – 1.5 °C. With this temperature rise, virtually all the existing arable farming areas of the UK become suitable for navy bean growth in terms of heat units, other factors such as drought may then become the most important constraints on bean crops.

Higher temperatures may allow earlier planting and overcome a secondary problem of the navy bean crop, that of limited light interception. Detailed measurements with tube solarimeters at four of the remote sites indicated that maximum leaf area index occurred a month after the peak of solar radiation and that less than 30% of the total yearly light was intercepted by the plants. Navy bean types with earlier maturity have been developed at Wellesbourne. Two of these lines matured in the years of the above trials after an average of 1800 OHU, which would allow them to be grown throughout England and Wales under current conditions. However, yields of these two lines are, at present, lower than standard cultivars. This may be due to a further reduction in the period of light interception in the short growing season.

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