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An arithmetic method to determine the most suitable planting dates for vegetables

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ABSTRACT

Optimum crop yield is greatly affected by proper planting and sowing times. The objective of this research was to develop an algorithm that uses the heat unit concept to determine the most suitable planting times for vegetable crops. The developed algorithm was programmed in a database environment with sample climatic data for the Kingdom of Saudi Arabia. The model was tested by validation (comparison to experts' estimations), verification (statistical comparison to formal published data), and evaluation (by professionals, landowners, and farmers). The overall results of the model were highly acceptable. The model needs more verification and validation in different environments and with various crops.

1. Introduction

Food security and water scarcity urge researchers to maximize crop yields with minimum possible water consumption. Maximizing crop yields involves several practices, including the selection of a proper planting time that matches the crop species and the region's environment throughout the entire growing season. Temperature plays a central role in a plant's life cycle, affecting its growth, development, and yield (Adam et al., 1994). Since it was developed, the heat unit concept has been widely used to determine the length of the growing season for vegetables and field crops (McMaster and Wilhelm, 1997; Chen, 1973). Most of the research on field crops has been for Maize (e.g. Gesch and Archer, 2005; Nielsen et al., 2002), Wheat (e.g. Haider et al., 2003; Pal and Murty, 2010), and Sunflower (e.g. Qadir et al., 2007; Kaleem et al., 2011). Studies for vegetables include: Potatoes (Yuan and Bland, 2005; Alsadon, 2002), Tomatoes (Perry et al., 1997), Cucumber (Perry and Wehner, 1990, 1996; Perry et al., 1986), and others (Bossie et al., 2009; Petkeviciene, 2009; Filho et al., 1993).

The concept of heat units (HUs) is expressed in growing degree-days (GDDs), which is calculated (Chen, 1973; Pal and Murty, 2010) as:

$$\mathrm{HU} = \sum_{i=1}^{cSL} \mathrm{GDD}_i \tag{1}$$

$$\mathrm{GDD} = \left(\frac{T_x + T_n}{2}\right) - cT_b \tag{2}$$

where T_x and T_n are the maximum and minimum daily temperatures respectively, cT_b is the crop base temperature, i indicates the growing day in the crop's season, and cSL is the season length in days.

Several investigations had been performed to enhance the biological meaning of GDD (McMaster and Wilhelm, 1997), helping to avoid the errors that occur if the GDD formula returns a negative number. The most spread method considers the following correction:

$$\mathrm{GDD} = \mathrm{MAX}\ \{0\ ,\ (T_x + T_n)/2 - cT_b\} \tag{3}$$

where the 'MAX' function returns the maximum value of either zero or the value returned from Eq. (2) which ensures no negative value from the equation. The other method takes a deeper look at the formula and considers the following:

$$\mathrm{GDD} = \mathrm{MAX}\begin{bmatrix} & (cT_b + T_n)/2 - cT_b & T_x < cT_b \\ 0, & (cT_b + T_x)/2 - cT_b & T_n < cT_b \\ & (T_x + T_n)/2 - cT_b & T_n \geqslant cT_b \end{bmatrix} \tag{4}$$

Although the two correction methods seem similar, in some cases the difference between them may reach 83% (McMaster and Wilhelm, 1997). Several comparisons and reviews of GDD

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calculation methods were achieved for some vegetable crops (Perry et al., 1986, 1997; Perry and Wehner, 1996, 1990), indicating that the optimum method varies according to crop and regional climate.

Overall, the concept of heat units has succeeded in predicting a reliable approximate harvest time (Haider et al., 2003; Salassi et al., 2002; Black et al., 2008; Chen, 1973; Alsadon, 2002). Most vegetable crop species have a well-known approximate life duration (LD) from sowing to harvest. Hence, working backwards the sowing/planting date (SPD) can also be determined using the HU concept. The degree of confidence of the predicted SPD depends on the validity of the estimated/known LD of the crop.

The aim of this work is to develop a combined algorithm that uses the HU concept to predict a satisfactory estimation of the SPD for vegetable crops.

2. Materials and methods

2.1. The arithmetic model development

A computer model was developed to benefit from the historical weather data in prediction of suitable or optimal sowing/planting dates. The algorithm is simplified in the following steps:

1. For each crop/crop species, we have the following thermal characteristics:
   - Base temperature cT_b.
   - Optimum growing temperature cT_{opt}.
   - Maximum tolerable temperature cT_x.
   - Minimum tolerable temperature cT_n.
   - Optimum seasonal heat units HU_{opt}, calculated by the following formula:

$$HU_{opt} = (cT_{opt} - cT_b) \times cSL_h, \tag{5}$$

where cSL_h is the season's length for the crop obtained from historical data (days).

   - Maximum tolerable heat units HU_x, calculated as:

$$HU_x = (1 + H_{tol}/100)HU_{opt}, \tag{6}$$

where H_{tol} is the percent heat tolerance above optimal [%].

2. For each region, there are some basic climatic loggings for each Julian day j:
   - Maximum daily dry bulb temperature T_x.
   - Minimum daily dry bulb temperature T_n.
   - Average daily dry bulb temperature T_a.
3. For any day within the cSL_h duration, if $T_x > cT_x$ then the crop has a heat shock, and the 'heat' flag parameter (F_h) should be increased by 1.
4. For any day within the cSL duration, if $T_n < cT_n$ then the crop has a cold shock, and the 'cold' flag parameter (F_c) should be increased by 1.
5. For the known cSL_h duration, starting from the suggested SPD in Julian format (j), HU_{SL} is calculated as:

Table 1
Thermal parameters of vegetable crops.

Common name	Binomial/trinomial name	cT_x (°C)	cT_n (°C)	cT_b (°C)	cT_{opt} (°C)	cSL_h (days)	H_{tol} (%)
Bell pepper	*Capsicum annum L.*	35	15	10	24	100	30
Cabbage	*Brassica oleracea var. capitata L.*	30	10	4	20	105	30
Carrot	*Daucus carota L.*	28	6	4	19	120	30
Cauliflower	*Brassica oleracea var. botrytis L.*	30	10	4	21	90	30
Celery	*Apium graveolens var. dulce (Mill.)*	24	10	4	17	105	30
Chard	*Beta vulgaris var. cicla L.*	35	4	4	19	60	30
Chicory	*Cichorium intybus L.*	27	5	4	18	90	50
Common beans	*Phaseolus vulgaris L.*	35	15	10	25	90	30
Cowpea	*Vigna unguiculata L. Walp.*	35	10	10	24	90	30
Cucumber	*Cucumis sativus L.*	35	16	10	25	105	30
Eggplant	*Solanum melongena L.*	35	15	10	24	105	30
Faba bean	*Vicia faba L.*	30	10	4	18	130	30
Garlic	*Allium sativum L.*	30	8	4	18	210	30
Leek	*Allium ampeloprasum* var. *porrum* L.	33	10	5	23	180	30
Lettuce	*Lactuca sativa L.*	27	5	4	16	100	50
Melon	*Cucumis melo L.*	38	15	10	26	100	30
Mulukhiyah	*Corchorus olitorius L.*	35	15	10	27	60	25
Muskmelon	*Cucumis melo var. Reticulatus L.*	35	15	10	26	100	30
Okra	*Abelmoschus esculentus L. Moench.*	35	15	10	30	75	20
Onion	*Allium cepa L.*	35	2	2	20	150	20
Parsley	*Petroselinum crispum (Mill.)*	27	10	4	17	90	50
Peas	*Pisum sativum L.*	29	4	4	16	105	30
Potato or Irish potato	*Solanum tuberosum L.*	27	7	6	16	100	70
Pumpkin	*Cucurbita maxima Duch.*	38	15	10	25	120	30
Purslane	*Portulaca oleracea L.*	30	10	10	21	60	30
Radish	*Raphanus sativus L.*	30	10	4	18	60	30
Rocket (salad)	*Eruca sativa (Mill.)*	38	5	4	14	45	30
Snake cucumber	*Cucumis melo var. flaxuosus L.*	40	15	10	30	100	20
Soya bean	*Glycine max L. Merr.*	35	15	10	25	85	35
Spinach	*Spinacia oleracea L.*	25	4	4	18	60	30
Sweet corn	*Zea mays saccharata L.*	40	10	10	26	105	30
Sweet potato	*Ipomoea batatas L. Lam*	32	15	12	25	150	30
Table beet	*Beta vulgaris var. Crassa L.*	35	10	4	18	90	30
Tomato	*Solanum lycopersicum L.*	35	14	10	24	100	30
Turnip	*Brassica rapa* var. *rapa L.*	35	10	4	18	75	30
Watermelon	*Citrullus lanatus (Thunb.)*	37	15	10	30	105	20
Wild leek	*Allium ampeloprasum L.*	30	10	5	20	180	30
Yam	*Discorea alata L.*	35	20	15	28	120	30
Zucchini	*Cucurbita pepo L.*	38	15	10	25	75	35

Table 2
Geographic and thermal properties of studied regions.

Information station		Geography			Winter			Spring			Summer			Fall/Autumn			Yearly average		
#	Name	Latitude [°N.]	Longitude [°E.]	Altitude [m]	21/12–20/3			21/3–20/6			21/6–22/9			23/9–20/12					
					Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.
1	ABHA	18.13	42.38	2093	33	14	0	32	19	7	35	23	10	30	19	6	32	19	6
2	AHSA	25.30	49.47	179	34	16	0	45	27	8	50	37	19	45	28	12	44	27	10
3	AL JOUF	29.47	40.05	671	35	11	−6	42	22	4	46	32	17	42	24	2	41	22	4
4	ARAR	31.00	41.00	600	31	10	−5	42	22	3	48	33	14	42	23	3	41	22	3
5	BAHA	20.30	41.62	1652	30	17	1	38	23	7	39	29	12	39	23	7	37	23	7
6	BISHA	19.59	42.37	1163	36	19	1	42	26	9	50	32	10	39	25	7	44	26	7
7	DHAHRAN	26.16	50.10	17	39	17	3	46	26	11	51	35	9	46	28	8	45	27	8
8	GASSIM	26.18	43.46	650	40	14	−4	42	25	8	48	35	16	45	26	6	44	25	6
9	GIZAN	16.54	42.35	3	43	26	14	43	30	18	45	33	14	43	31	16	43	30	16
10	HAFR AL-BATIN	28.20	46.06	360	35	13	−3	45	25	5	51	36	21	43	27	8	43	25	8
11	HAIL	27.26	41.41	1013	34	12	−7	39	22	4	45	32	16	43	24	6	40	22	5
12	JEDDAH	21.30	39.11	17	36	24	11	44	28	13	48	32	14	45	29	15	43	28	13
13	KHAMIS MUSHAIT	18.18	42.47	2057	35	15	−1	33	20	6	41	24	9	43	20	3	38	20	4
14	MADINA	24.32	39.42	636	34	19	3	43	28	11	48	36	14	42	30	10	42	28	9
15	MAKKAH	21.40	39.85	213	39	25	9	47	31	13	50	36	21	46	32	19	45	31	15
16	NEJRAN	17.37	44.26	1210	37	19	1	40	27	9	44	32	18	43	25	8	41	26	9
17	QAISUMAH	28.32	46.13	358	33	13	−3	44	25	6	51	36	16	46	27	8	44	25	7
18	RAFHA	29.37	43.28	447	32	11	−6	42	23	1	49	34	10	42	25	4	41	23	3
19	RIYADH	24.63	46.43	611	38	16	0	42	27	11	48	36	14	41	28	11	42	27	9
20	SHARURRAH	17.47	47.10	725	38	21	1	43	30	11	46	35	19	41	28	9	42	29	10
21	TABUK	28.21	36.37	776	32	12	−3	41	22	5	46	31	16	40	23	8	40	22	6
22	TAIF	21.28	40.32	1454	35	16	0	46	23	6	41	29	9	39	24	9	40	23	6
23	TURAIF	31.41	38.40	818	30	8	−7	39	18	0	45	29	14	40	21	4	38	19	3
24	W-DAWASIR	20.50	45.16	652	40	19	1	44	29	11	50	36	13	42	28	11	44	28	9
25	WEJH	26.11	36.27	21	34	20	6	41	24	11	45	29	18	43	27	14	41	25	12
26	YENBO	24.09	38.04	6	42	21	6	47	27	8	49	33	14	46	29	13	46	28	10

Table 3
The probability of matching between model and historic data.

Number of days		Model results (A)		
		Suitable	Unsuitable	Total
Other data (B)	Suitable	A_1B_1	A_0B_1	B^+
	Unsuitable	A_1B_0	A_0B_0	B^-
	Total	A^+	A^-	n

$$\mathrm{HU}_{SL} = \sum_{i=j}^{j+cSL} \mathrm{Max}\left\{ \begin{array}{c} c(T_x + T_n)_i/2 - cT_b \\ 0 \end{array} \right\} \tag{7}$$

6. The Julian day, j, is accepted as a valid SPD if the following conditions are satisfied:
- $\mathrm{HU}_{SL} \geqslant \mathrm{HU}_{opt}$,

to ensure that heat requirements of the crop are fulfilled.
- $\mathrm{HU}_x > \mathrm{HU}_{SL}$,

to ensure that the heat units gained are less than the threshold.

7. The above procedure should be repeated for all days of the year; from Julian day 1 to Julian day 365/366.
8. The most suitable SPD range(s) are selected from the acceptable days in step 6 above, where the F_h and F_c flags are minimized (zero is preferred) to ensure the crop will not be exposed to thermal shocks.

2.2. Parameters determination

The above algorithm has many unknown parameters, especially the crop parameters. The thermal parameters for some vegetable crops were collected from several resources (Maynard and Hochmuth, 2007; Alsadon et al., 1998; and Splittstoesser, 1990) and experts estimations, and are summarized in Table 1. In this table, the maximum, minimum, optimum, and base temperatures for each crop are given, in addition to the dominant season's length, and the percent heat tolerance above the optimal heat units. For example, the tomato crop (*Solanum lycopersicum L.*) has a base temperature of 10 °C, a season length of about 100 days, maximum and minimum tolerable temperatures of 35 °C and 14 °C respectively, and an optimum temperature of 24 °C. The maximum tolerable heat units for tomato was found to be 30% above the optimum.

2.3. Sample climatic data

To test the developed methodology, sample meteorological data were collected for the Kingdom of Saudi Arabia (KSA) on a daily basis. Data were collected for 30 years (since 1980), then summarized as daily averages for calculation purposes. For illustration only, the data were grouped according to season as shown in Table 2. The table shows geographic information (latitude, longitude, and altitude) and seasonal averages for 26 climate stations covering most of the area of the KSA.

2.4. Model development and execution

A computer model was programmed to test the developed algorithm. The model was programmed in the VBA language inside the Microsoft Access environment. This language was selected because of the ease of use especially in I/O operations and for its speed in handling and manipulating large databases.

The model was executed for all 26 climate stations in combination with the 39 vegetable crops. Due to the large amount of data involved, we selected for illustration two stations with all crops, and two crops with all the stations. The selected stations are Wadi Aldawasir in the south and Tabuk in the north, where both stations are known for their intensive agricultural activity. The selected crops were Tomatoes (*Solanum lycopersicum* L.) and Potatoes (*Solanum tuberosum* L.), which were selected for their economic importance to the kingdom, in addition to their good coverage of all conditions to be illustrated.

2.5. Comparison statistics

The output data from the model are qualitative, with yes/no flags for each day in the year measuring the suitability of this day for starting crop cultivation. Thus, to compare suitable dates suggested by the model with those suggested by other sources of information such as the Ministry of Agriculture, we need some inter-rater agreement statistical measures. The most famous inter-rater agreement measures are the κ-statistic (kappa-statistic) from Cohen (1960) and the π-statistic (pi-statistic) from Scott (1955). However, these two measures are unstable and have different interpretations especially when the agreement ratio is far from 50% (Gwet, 2002a). A more sensitive measure called the AC_1 statistic, introduced by Gwet (2002b), overcomes the problems with the κ- and π-statistics. A brief description of the AC_1 statistic is shown below.

Let us consider a case in which we have crop x cultivated under the conditions of station y, shown in Table 3. Considering the results of the model as (A) and the suggestions from the historic data as (B), a subscript of "1" indicates a suitable cultivation day and a subscript of "0" indicates an unsuitable cultivation day. Hence, the number of days for which A and B agree on suitability for cultivation is denoted by the symbol A_1B_1. Similarly, there are A_0B_0 days considered not suitable for cultivation by both methods, A_1B_0 days suggested by the model where the historic data does not agree, and A_0B_1 days suggested by the historic data where the model does not. Notice that none of these categories intersect. Hence the total number of days the model shows as 'suitable' is $A^+ = A_1B_1 + A_1B_0$, and the number of 'unsuitable' days as shown by the model are $A^- = A_0B_1 + A_0B_0$. Similarly, we define $B^+ = A_1B_1 + A_0B_1$, and $B^- = A_1B_0 + A_0B_0$ as the number of days shown by historical data as suitable and unsuitable, respectively. The total number of days 'n', is the length of 1 year, so $n = A^+ + A^- = B^+ + B^- \simeq 366$. To calculate the AC_1 statistic we followed the following steps:

1. Calculate all the variables shown in Table 3 (A_1B_1, A_0B_1, B^+, etc.).
2. Find the overall agreement probability function P_a, where $P_a = (A_1B_1 + A_0B_0)/n$.
3. Find the overall classification probability function P^+, where $P^+ = (A^+ + B^+)/2n$.
4. Find the Gwet measure of the likelihood of agreement by chance $P_e(\lambda)$, where $P_e(\gamma) = 2P^+ \times (1 - P^+)$.
5. Calculate the AC_1 statistic, where $AC_1 = \frac{P_a - P_e(\gamma)}{1 - P_e(\gamma)}$.

This statistic was calculated for each crop-station pair to evaluate the model agreement ratio, the maximum value of the AC_1 statistic is 1.00, which indicates full agreement between model and historical data. The higher the value of the statistic is, the higher the agreement between them.

2.6. Model calibration

After building the model, it has to be tested to ensure suitability for the reason it was constructed. Three operations need to be performed: verification, validation, and evaluation. Wentworth et al. (1997) defined *verification* as the task of determining whether

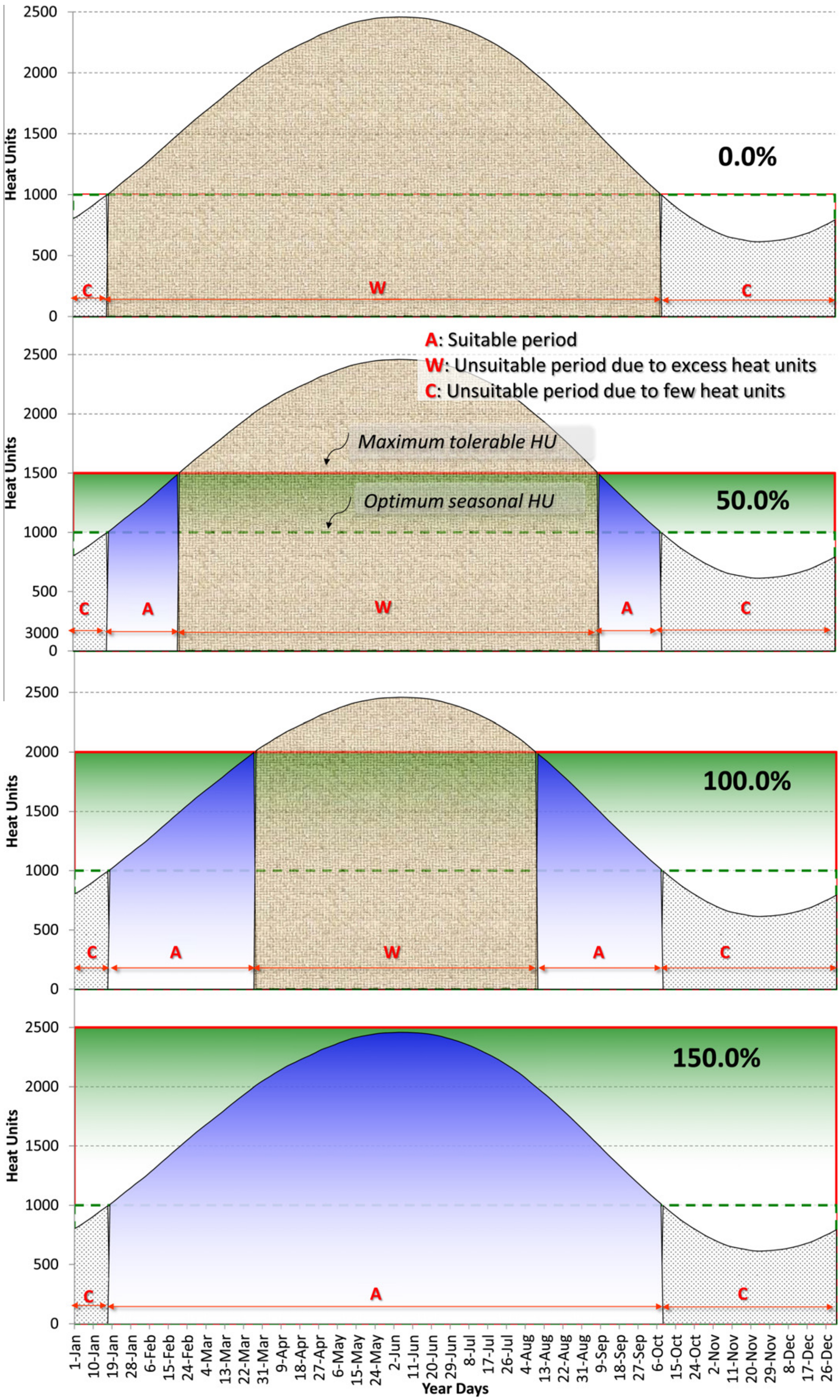

Fig. 1. Planting dates as affected by the selected H_{Tol} percentage.

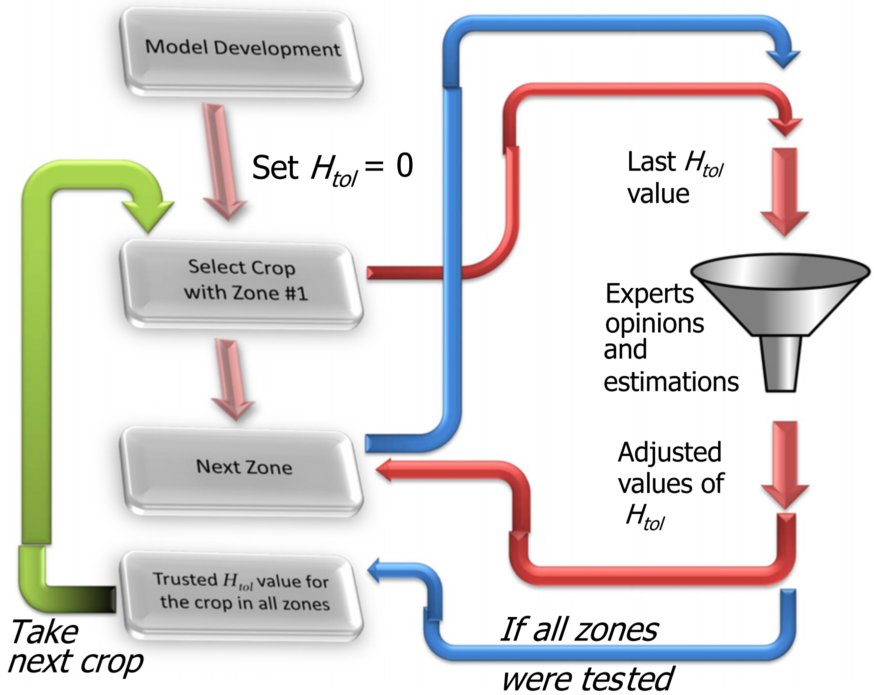

Fig. 2. Validation method for the tolerance heat units.

the system is built according to the specifications, *validation* as the process of determining whether the system fulfills the purpose for which it was intended, and *evaluation* as acceptance of the system by the end users and its performance in the field. In simpler terms, Miskell et al. (1989) summarized the three operations as follows: verify to show the system is built right, validate to show the right system was built, and evaluate to show the usefulness of the system.

Each operation can be performed by several methods. For example, validation could be done by comparison with expert estimation either by simple comparison (Lehmann et al., 1993), by sensitivity analysis (Franklin et al., 1988), or by frequency and distance analysis (Verdaguer et al., 1992). Due to the nature of the output of the model, we validating the results simply by using expert comparisons. Verification can also be performed by several methods depending on the nature of data, for example, by tables

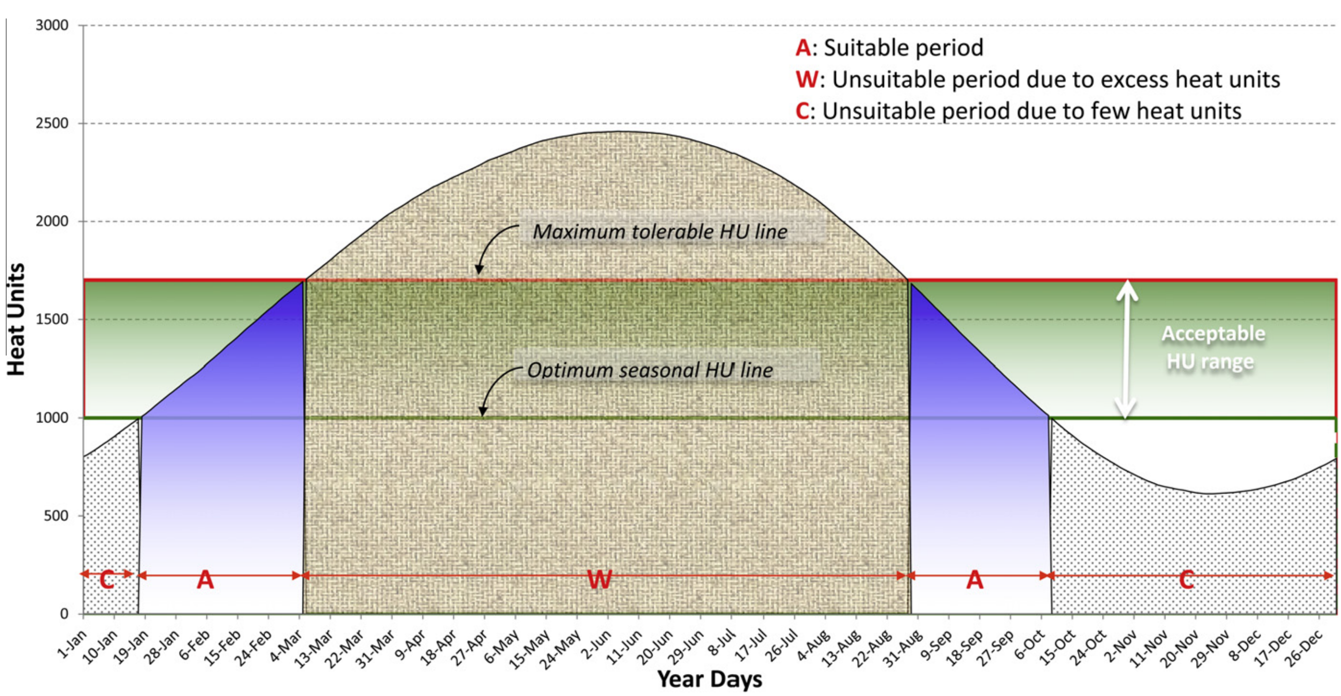

Fig. 3. Planting times suitability chart for Potato crop in the Tabuk area.

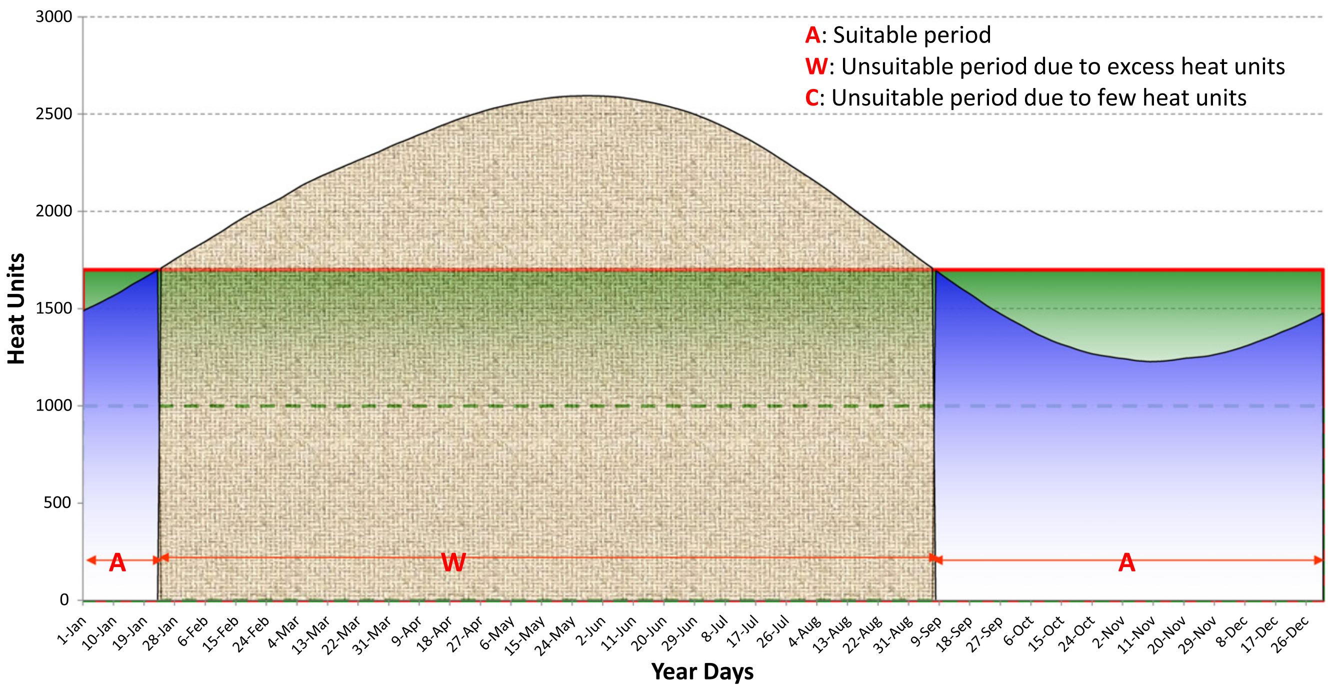

Fig. 4. Planting times suitability chart for Potato crop in the Najran area.

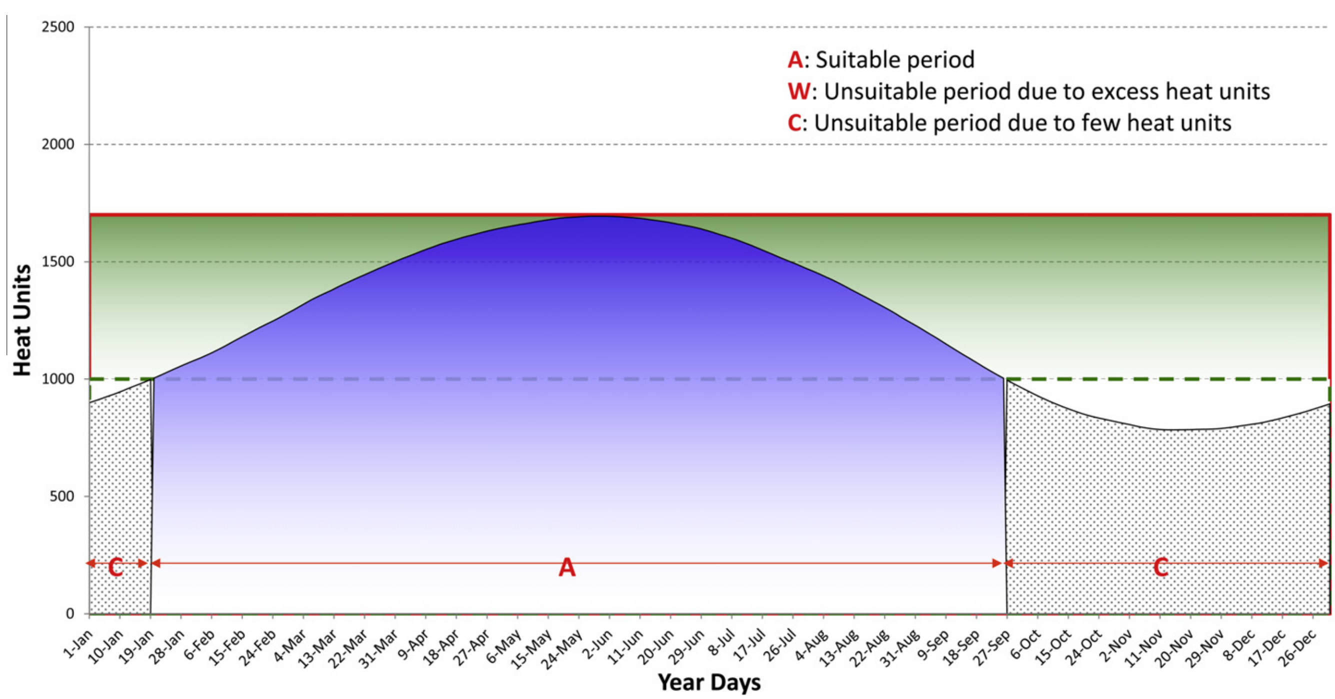

Fig. 5. Planting times suitability chart for Potato crop in the Abha area.

and pairwise rule comparisons (Nguyen et al., 1987), by qualitative statistical measures (Robertson et al., 2003), by graphical methods (Fenton and Kaposi, 1987; Agarwal and Tanniru, 1992; Freeman, 1985), or by several other methods mentioned by Wentworth et al. (1997). Both statistical and graphical methods will be used for verification of the current model.

2.7. Validation procedure

After developing the model, the authors organized several sessions with 4–6 experts per session. The experts' specializations are all in agronomy, with two agronomists, two plant protection specialists, and two irrigation and agro-meteorology specialists.

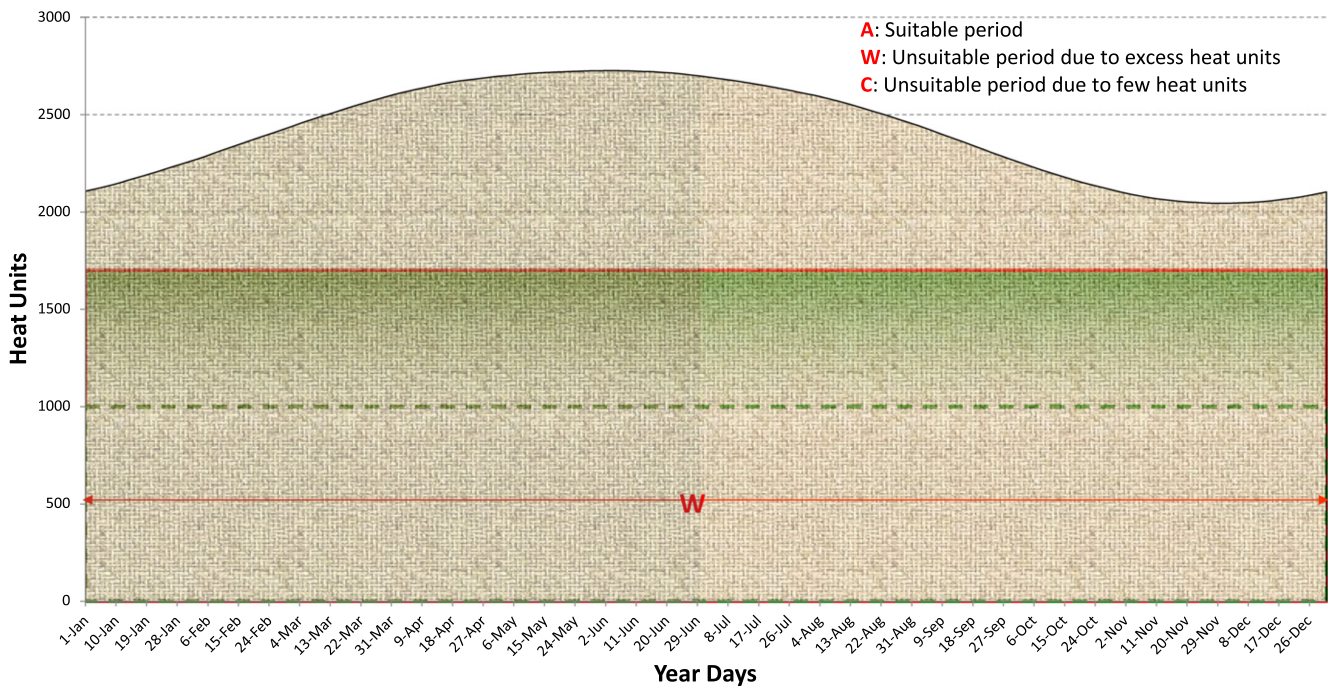

Fig. 6. Planting times suitability chart for Potato crop in the Gizan area.

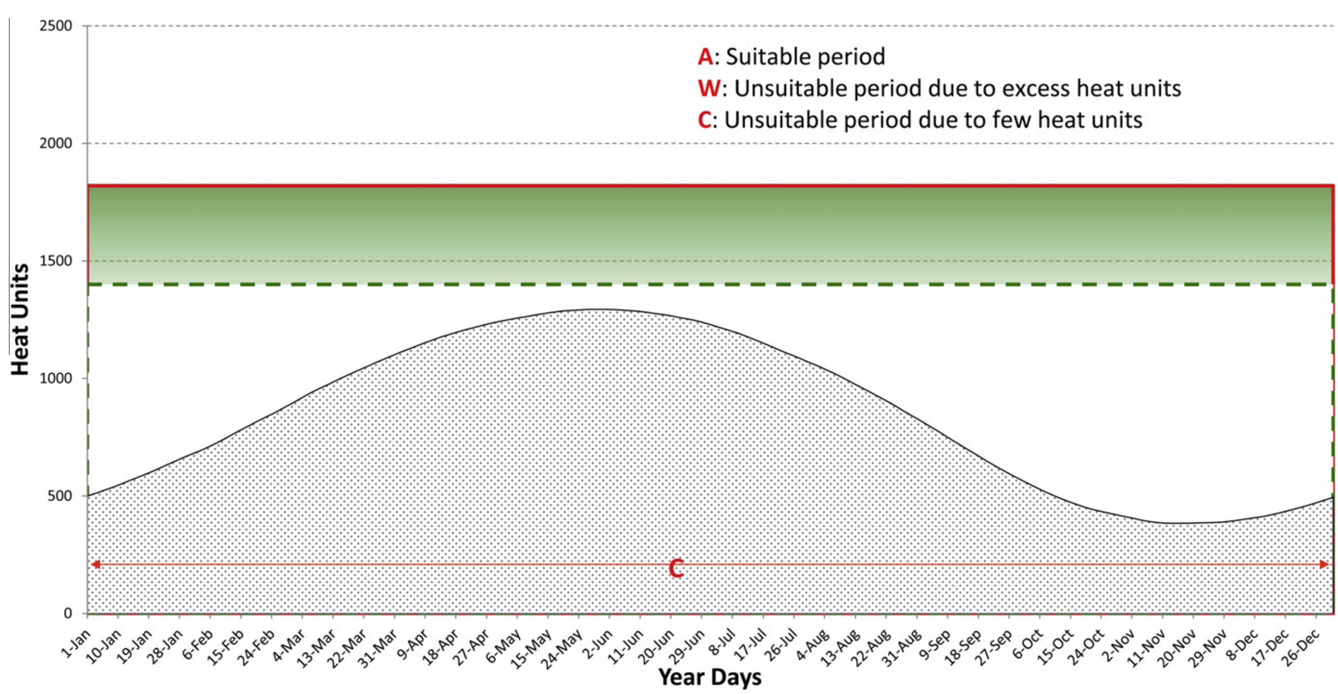

Fig. 7. Planting times suitability chart for Tomato crop in the Abha area.

All hold a Ph.D. and have very good field experience in almost all of the tested zones.

Initially, we set the HU tolerance factor, H_{Tol}, to 0%, and run the program to show the selected planting dates. This should not result any dates as shown in Fig. 1, but will show the starting planting date and zones of unsuitability. Next, H_{Tol} is increased to 50% for example, the suitable zone that appears is compared with the experts' view, and if compatible, the next zone is taken to make fine adjustments of this value until we find an approved value for all the zones. If the experts' view does not match with the first value of H_{Tol}, then the value should either be raised or lowered according to their advice, and the entire process repeated. A schematic diagram of the validation process is shown in Fig. 2. After the entire process is finished for all crops and regions the model output was re-examined by the experts, who were very satisfied by the model predictions.

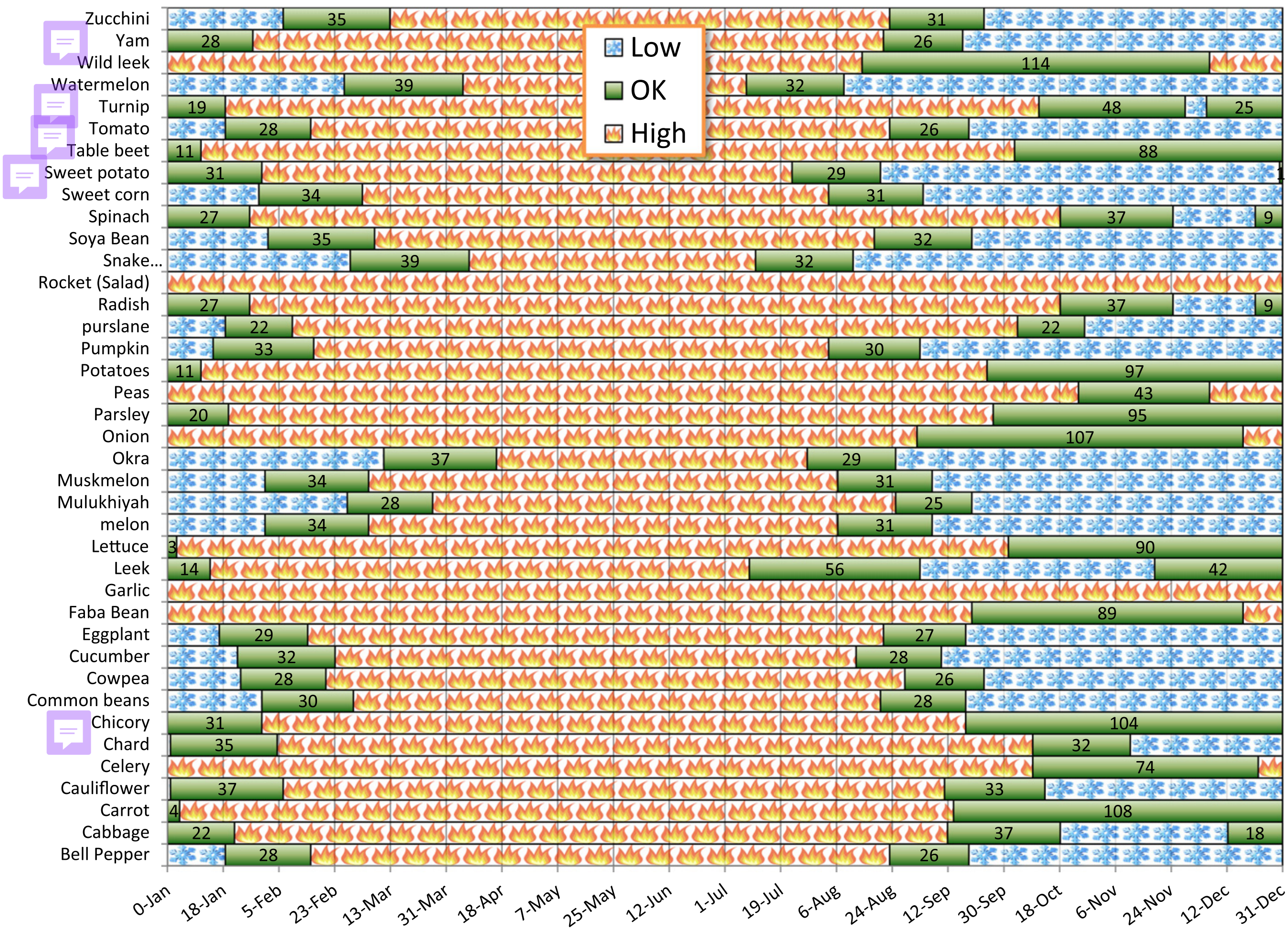

Fig. 8. Planting times suitability chart for all crops in the Wadi Aldawasir area.

3. Results and discussion

3.1. Selected outputs of the model

For each station-crop combination, the model produces a chart, like that in Fig. 3, showing the days of the year on the *X*-axis and the heat units in the *Y*-axis, with the horizontal shaded strip showing the acceptable HU range between HU_{opt} and HU_x. The bell-shaped curve shows the HU that would be collected in cSL_h days in that zone according to the climatic data. According to their suitability, the tested days are combined into vertical strips, and the range resulting from the intersection between the bell curve and the horizontal strip is called the 'acceptable' range or the 'suitable period' as shown in the figure. The range that is higher than the intersection gains too many HUs, and hence is rejected due to overheating. On the other hand, the range that is lower than the 'acceptable strip' is unsuitable due to gaining too few HUs, which may lead to the crop not completing its growing cycle.

The selected case in Fig. 3 shows all three expected ranges: 'suitable', 'unsuitable due to overheat', and 'unsuitable due to too little heat'. These ranges are abbreviated to '*A*', '*W*', and '*C*' ranges respectively. However, in many cases only one or two of these ranges appear. In some relatively hot zones for a specific crop, the '*A*' and '*W*' ranges appear, such as for Potato crop in the Najran area (Fig. 4). On the other hand, in relatively cold zones for a specific crop, the '*A*' and '*C*' ranges appear, such as for Potato crop in the Abha area (Fig. 5). Nonetheless, some zones are totally unsuitable for some crops due to overheating and only the '*W*' range appears, such as for Potato crop in the Gizan area (Fig. 6), while some zones are totally unsuitable for some crops due to few HUs at any time of the year and hence the 'C' range only appears, as in the case of Tomato crop in the Abha area (Fig. 7).

The model was run on 26 stations and 39 crops (1014 cases). We chose to show two of the stations with all crops, Wadi Aldawasir (Fig. 8), and Tabuk (Fig. 9). The results show that the cultivation times for vegetables are concentrated in the cold seasons (autumn and winter) in Wadi Aldawasir, while active cultivation in Tabuk is mostly from February to the third week of April and from the last week of July to the end of September, with exception of sweet corn and melons, which are cultivated from the first of April to the end of July. However, the information from the model is very useful for farmers and landowners, especially since most of the vegetables included are not listed in the Ministry of Agriculture's brochure giving suitable cultivation dates.

3.2. Model verification

The outputs of the model were verified by both statistical and graphical method as mentioned. The results were compared to the planting dates published in the yearly statistical book from the Ministry of Agriculture (MOA, 2011). Sample comparison charts for the crop-station combinations are found in Figs. 10 and 11. Graphically, the model seems to give an acceptable representation of the planting dates with few exceptions. One can

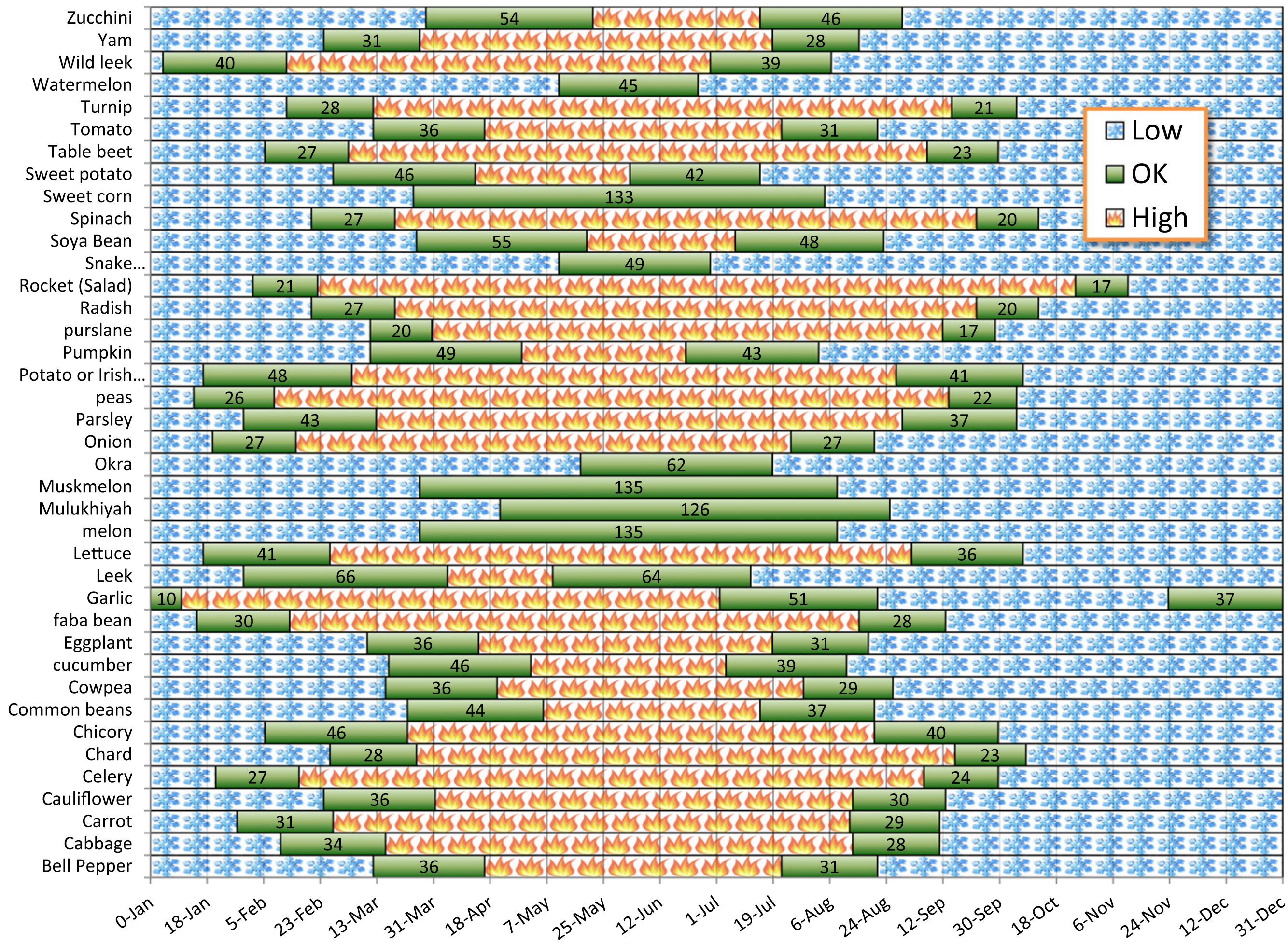

Fig. 9. Planting times suitability chart for all crops in the Tabuk area.

understand these mismatches after considering the following realities:

The yearly statistical book deals only with whole months rather than weeks or days. That is, it talks about 'January', 'May', or 'August', not 'the last week of January' or 'the first 2 weeks of August'.

The Kingdom of Saudi Arabia is vast in area, so there is not a single species of tomato or potato cultivated everywhere. Hence the yearly book speaks about tomatoes and potatoes in general, thus when it mentions that tomatoes are cultivated in Riyadh from January to April, this accounts for several species and several places in Riyadh (the Riyadh region covers 380,000 km^2, 17% of the kingdom's area).

The current model shows the results for specific species when cultivated in a specific location near a meteorological station.

3.3. Statistical verification

The inter-rater statistics confirm the suitability of the current model for predicting planting times. As seen in Table 4, we found for potatoes that out of 26 stations, 15 stations resulted in an AC_1 statistic greater than 0.7, 9 stations had $0.7 > AC_1 > 0.5$, and 2 stations had $AC_1 > 0.3$. For tomatoes, 6 stations had $AC_1 > 0.7$, 11 stations had $0.7 > AC_1 > 0.5$, 5 stations had $0.5 > AC_1 > 0.3$ and the other 4 had $AC_1 < 0.3$.

One can interpret these results that potatoes are more compatible with the model than tomatoes, but this is not the case, as there are many more tomato varieties than potatoes varieties in the local markets. Furthermore, as we explained in point three above, there are some varieties that are cultivated in times that are not mentioned by the model, such as at the Bisha and Hail stations, where farmers cultivate different species over the year to guarantee continuous yield supply, see Fig. 11, but our model tests only one species at a time, and the tested species here was a cold season species. So the inter-rater statistics is too low as $AC_1 = -0.07$ for Bisha and 0.19 for Hail. The MOA lists the ability to cultivate tomatoes, but it is mentioned that there are different species in the market according to region and season. However, the model agrees with the MOA that Tomatoes are not suitable in ABHA and in Khamis-Mushait. The tomatoes results are good in all northern and southern regions like Nejran, Tabuk, Baha, Taif, etc, while low results appear mostly in the regions in the middle of the country like W-Dawaser, Yenbo, and Gassim, in addition to Bisha and Hail. The same discussion of Bisha and Hail applies here too.

The results for potatoes are very good, as seen in Fig. 10 and Table 4, with the AC_1 statistic showing very good matching between the model and the MOA suggestions. The model predicted the planting dates excellently for most stations. Note that underestimation by the model can probably been attributed to point 1 above. Potato crops are not suitable for cultivation in the Gizan region because of overheating, according to both the model and the MOA yearly book. Underestimation by the model for the Gassim and Riyadh areas may be due to points 1 and 3. Some regions such as Taif, Turaif, Tabuk, Khamis-Mushait, and Abha show overestimation by the model. The model shows that

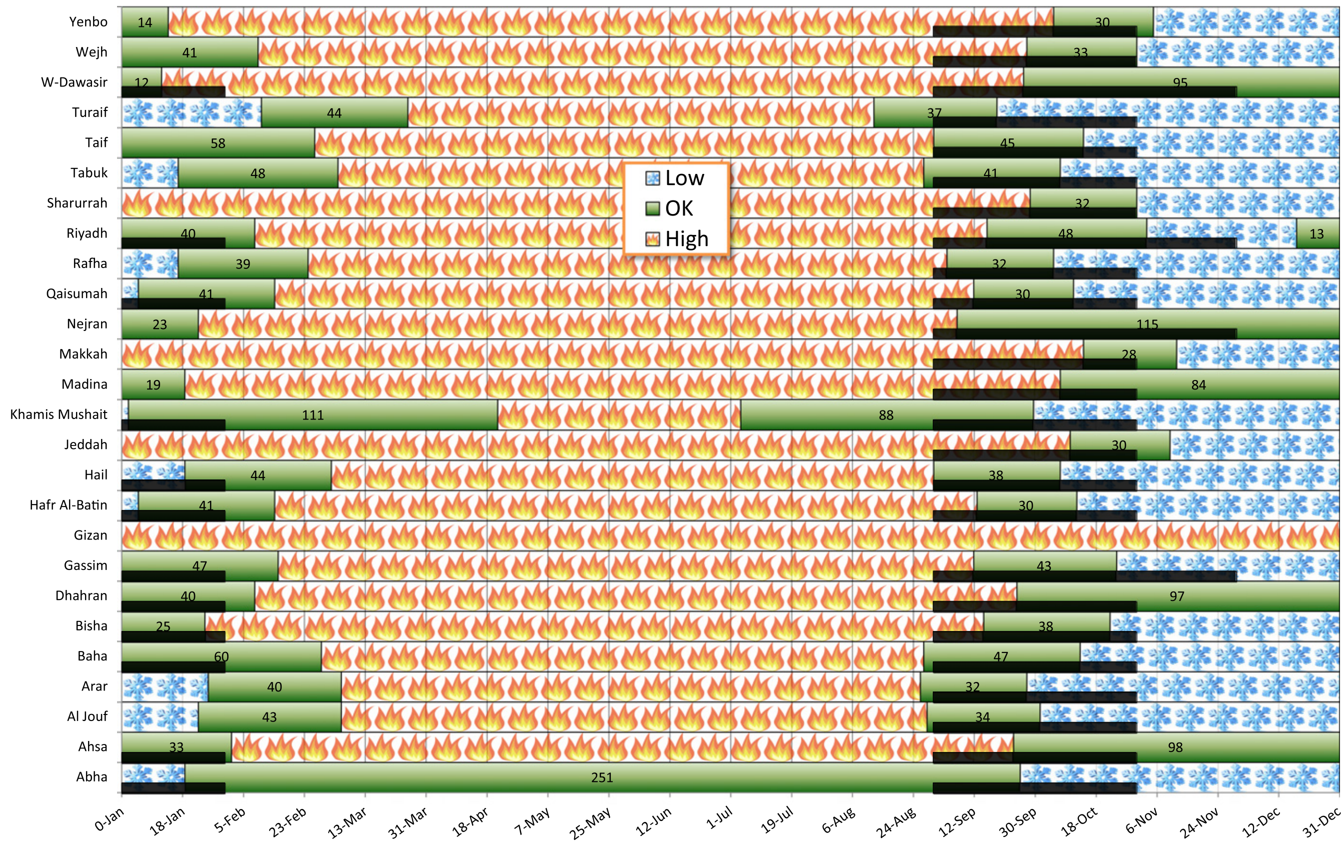

Fig. 10. Planting dates of Potatoes in 26 zones in the KSA, showing times that the crop takes fewer/more HUs than it needs, as well as the perfect HU range and the suggested times by the MOA.

Table 4
Inter-rater statistics of the model results.

	Potatoes							Tomatoes						
	Number of days				Statistics			Number of days				Statistics		
	A_1B_1	A_1B_0	A_0B_1	A_0B_0	P_a	P_e (γ)	AC_1	A_1B_1	A_1B_0	A_0B_1	A_0B_0	P_a	P_e (γ)	AC_1
ABHA	39	53	212	62	0.28	0.50	−0.44	0	0	0	366	1.00	0.00	1.00
AHSA	60	32	71	203	0.72	0.42	0.51	24	68	24	250	0.75	0.31	0.64
AL JOUF	32	29	45	260	0.80	0.31	0.71	34	58	19	255	0.79	0.32	0.69
ARAR	28	33	44	261	0.79	0.30	0.70	31	61	18	256	0.78	0.31	0.69
BAHA	75	17	32	242	0.87	0.40	0.78	82	10	29	245	0.89	0.40	0.82
BISHA	63	29	0	274	0.92	0.33	0.88	60	183	16	107	0.46	0.49	−0.07
DHAHRAN	68	24	69	205	0.75	0.43	0.55	27	65	26	248	0.75	0.32	0.64
GASSIM	74	48	16	228	0.83	0.41	0.70	29	123	18	196	0.61	0.40	0.36
GIZAN	0	0	0	366	1.00	0.00	1.00	85	37	24	220	0.83	0.43	0.71
HAFR	56	36	15	259	0.86	0.35	0.79	20	72	23	251	0.74	0.30	0.63
HAIL	51	41	31	243	0.80	0.36	0.69	55	158	0	153	0.57	0.46	0.19
JEDDAH	20	41	10	295	0.86	0.22	0.82	27	96	63	180	0.57	0.41	0.26
KHAMIS	60	32	139	135	0.53	0.48	0.10	0	0	0	366	1.00	0.00	1.00
MADINA	23	38	80	225	0.68	0.35	0.51	26	66	30	244	0.74	0.32	0.61
MAKKAH	17	44	11	294	0.85	0.21	0.81	18	105	33	210	0.62	0.36	0.41
NEJRAN	83	8	55	220	0.83	0.43	0.70	74	47	3	242	0.86	0.39	0.77
QAISUMAH	56	36	15	259	0.86	0.35	0.79	20	72	23	251	0.74	0.30	0.63
RAFHA	32	29	39	266	0.81	0.30	0.74	21	71	26	248	0.73	0.31	0.62
RIYADH	79	43	22	222	0.82	0.42	0.69	39	83	9	235	0.75	0.36	0.61
SHARURRAH	32	29	0	305	0.92	0.22	0.90	43	109	21	193	0.64	0.42	0.39
TABUK	38	23	51	254	0.80	0.33	0.70	22	40	45	259	0.77	0.29	0.67
TAIF	45	16	58	247	0.80	0.35	0.69	58	4	48	256	0.86	0.35	0.78
TURAIF	19	42	62	243	0.72	0.31	0.59	51	41	33	241	0.80	0.37	0.68
W-DAWASIR	76	46	31	213	0.79	0.43	0.63	28	123	26	189	0.59	0.40	0.32
WEJH	33	28	41	264	0.81	0.30	0.73	53	40	64	209	0.72	0.41	0.52
YENBO	25	36	19	286	0.85	0.25	0.80	29	93	44	200	0.63	0.39	0.39

there is a winter season for potatoes in the first three regions, which is not mentioned in the yearbook. This may be due to some winter diseases that harm the crop and cannot be predicted by the model right now.

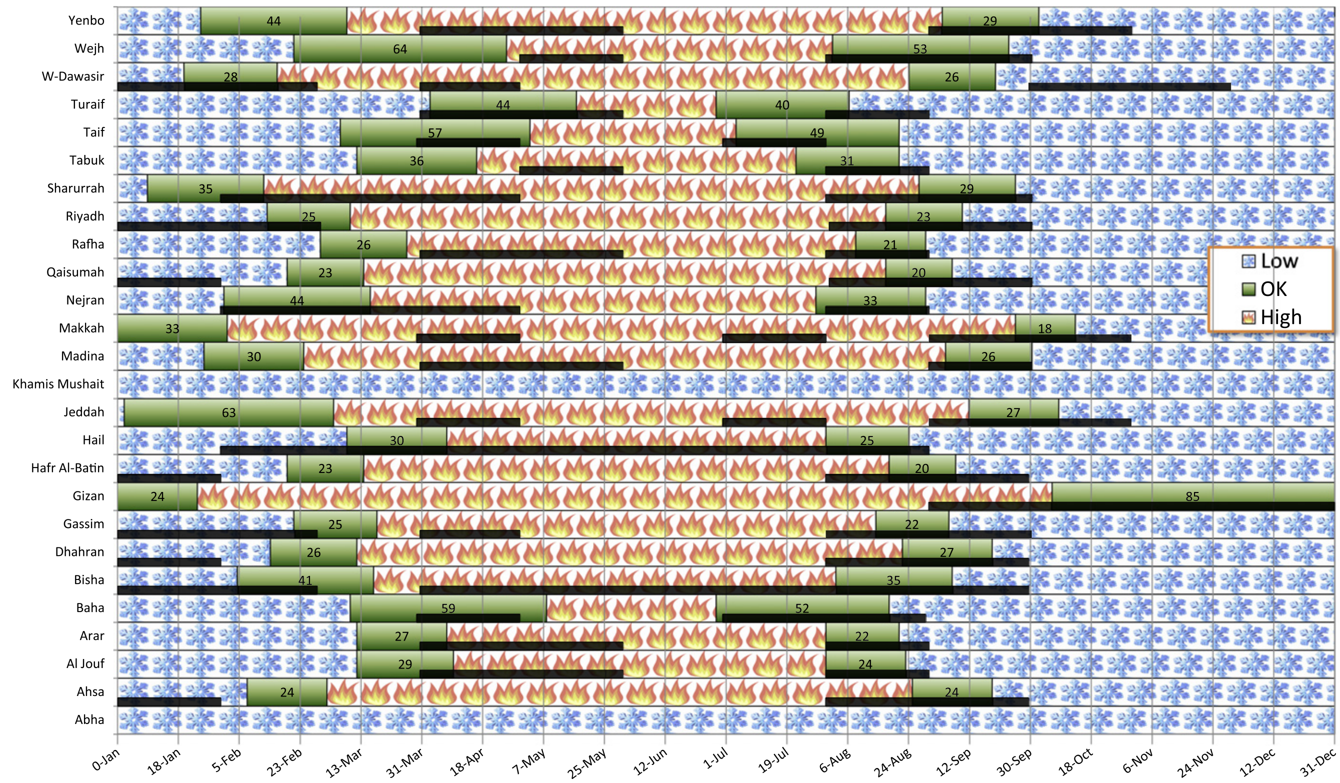

Fig. 11. Planting dates of Tomatoes in 26 zones in the KSA, showing times that the crop takes fewer/more HUs than it needs, as well as the perfect HU range and the suggested times by the MOA.

3.4. Final verification and evaluation

In addition to the statistical verification above, the results of this model and a previous version (Alsadon, 2002) were evaluated by displaying the results to many farmers, landowners, and field agronomists in 13 different zones of the kingdom. The results of the model were widely accepted and said to be close to the real conditions. Furthermore, some of the farmers were cultivating some crops only in the autumn, but when shown that the model also identifies some suitable dates in late winter they were impressed and intended to cultivate it the following year.

4. Conclusion

The heat unit concept was shown to be suitable for determining proper planting dates for vegetables. The developed model uses thermal properties of the crops as well as some basic meteorological data for the region. Some thermal properties of the crops are mentioned in this paper, but these may need to be adjusted for different species and different climatic areas. The main property that should be adjusted for different zones is heat tolerance. Although the temperature is very important for identifying planting times, several other parameters should also be considered, such as rainfall amounts and times, marketing considerations, pest activity, and so on. This study introduces a simple method for determining thermally-suitable planting times, while the other parameters should also be considered. Further studies on this model are needed to identify the thermal properties of vegetable crops in different climatic regions.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.compag.2012.09.010.

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