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A spreadsheet model to select vegetables planting dates for maximum yield and water use efficiency

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ABSTRACT

Vegetables planting dates affect yield and water consumption. This study aimed to develop a mathematical model to select the best date/duration to start sowing vegetables to maximize yield and minimize water use which increases the water use efficiency. The model was developed in an easy graphical interface that allows simple selection of the region and crop from dropdown lists, then to display the possible ranges with two degrees of suitability; one based of heat units, and the other avoids heat shocks additionally. The model is packed with a worldwide climatic database for 12,215 climatic stations, in addition to a set of 123 crops with different growing conditions. The model was verified to some published data in Maryland/USA and in Delta of Egypt using an efficiency indicator that considers all the results to reality matching states; like full matching, underestimation, and overestimation. The model's average overall efficiency was 80% and 71% for the two case studies. The model is available for public, and sharing the results of testing is highly appreciated.

1. Introduction

As the world population continues to increase, great responsibility is being placed on the researchers to maximize the crop yields under limited resources of water, arable land, and energy. Scientists suggest some practices that achieve this goal. These practices include selection of better varieties, enhancing soil conditions, improving irrigation systems, in addition to other field management practices (Kretchman, 1988). One of the most important factors affecting the yield quantity and quality is the planting date of the crop (Hershman et al., 1990; Jeavons, 2012; Roberts, 1987; Russo, 1996; Stalham and Allen, 2001; White and Sanderson, 1983). Selecting the proper planting date depends mainly on the temperature profile of the region. The proper planting date is the date that the crop can gain all its heat units without excessive heat- or cold-shocks (Adam and Ageeb, 1994; Alsadon, 2002). However, there are some other considerations such as pests active times, and other marketing considerations (Abdallah, 2012). Specifying the most suitable planting date for each crop varies from region to region, although it depends mainly on climate conditions, but other considerations, like marketing, pest's activities, and crop rotation, may eliminate some durations or append some, which make the operation subject to regional experience and field experiments. Hence, the suggested planting schedules are usually found at the local agricultural extension services and subject to be changed with new varieties or on climate changes. Recently, some research works, Elnesr et al. (2013), attempted to automate this operation to facilitate finding the possible suitable sowing dates. This model depends on calculating the Heat Units, HU, and then to compare the gained amount of HU to the minimum required HU by the crop and the maximum tolerance of it to specify the days that will achieve the conditions. However, this model considered only the HU, and hence it might result in a wide range of suitable planting dates, which need more effort and trials to specify the most suitable date out of them. For example, if the HU concept showed that we could plant a crop at any day in March or April, so, which day is the most suitable? There are some more constraints to be added, the most important constrain in the irrigated regions is to start planting at the time that lead to minimum cumulative evapotranspiration throughout the growing season. Another constrain is the pest activity, if any, which is a serious hazard to most crops. More constraints can be added the same way like marketing prices, etc.

The objective of this work was to develop a model that can specify the most suitable planting dates, for any vegetable crop,

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that maximizes the yield with minimum possible water consumption.

2. Approach and description

2.1. Datasets description

To develop this model, we needed a climatic database and a crop properties dataset. The used climatic database was the FAOCLIM-2 database (FAO, 2001), which provides long-term monthly mean values for 28,100 stations, for up to 14 observed and computed agroclimatic parameters including maximum, minimum, and average temperatures, relative humidity, wind speed, total and effective rainfall, and the Penman–Monteith reference evapotranspiration. In this paper, we used only the temperature and evapotranspiration values. To familiarize the stations' names, we have made a reverse geocoding for all the stations using MapLarge.com online service.

Regarding the crop information, the crop thermal data were obtained from several publications (Alsadon, 2002; Clarke et al., 2001; Elnesr et al., 2013; Maynard and Hochmuth, 2006; Splittstoesser, 1990). The obtained data includes the crop's maximum, minimum, optimum, and base temperatures, along with the prevailing season's length, and the percent heat tolerance above the optimal heat units. To calculate the crop evapotranspiration, we used crop development data from Allen et al. (1998).

2.2. Calculation of heat units

The heat units is calculated in terms of the growing degree-days (GDD) (Akinci and Abak, 1999) as follows:

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

$$\mathrm{GDD} = \mathrm{MAX}\{0, (0.5(T_x + T_n) - T_b)\} \tag{2}$$

where T_x and T_n are the maximum and minimum daily temperatures; T_b: is the crop's base temperature; i: a counter for each growing day in the crop growing duration (season's length) n [Days].

In case of the existence of the average temperature T_a instead of T_x and T_n, Eq. (2) could be simplified to simpler form, Eq. (3), where the difference between $(T_x + T_n)/2$ and T_a was reported as not significant (Dayton, 2003; McMaster and Wilhelm, 1997):

$$\mathrm{GDD} = \mathrm{MAX}\{0, (T_a - T_b)\} \tag{3}$$

However, the formula of the HU is a summation formula, which requires n computer loops to be evaluated, $O(n)$. Recently, a faster, $O(1)$, straightforward method was introduced to calculate HU by an integral form of sinusoidal temperature equation (Elnesr and Alazba, 2016). The method relies on converting the daily or monthly discrete temperature data to continuous form by sinusoidal fitting as in Eq. (4), then to integrate it to find the heat units from average temperature, Eq. (5), where the integration is definite between the Julian date of sowing, j_s, and the Julian date of harvesting, j_h where $j_h = j_s + D_t$; D_t: the total season's length, days. The final formula is Eq. (6)

$$T(j) = a + \rho \sin(\omega j + \varphi) \tag{4}$$

$$\mathrm{HU} = \int_{j_s}^{j_h} (T(j) - T_b) \tag{5}$$

$$\mathrm{HU} = (a - T_b)(j_h - j_s) - \frac{\rho}{\omega}(\cos(\omega j_h + \varphi) - \cos(\omega j_s + \varphi)) \tag{6}$$

where T: the average temperature, °C; j: the Julian day number; a: the mean temperature on the curve, °C; ρ: the amplitude of the sine wave, °C; ω: is the curve's frequency, radians; φ: the curve's phase, radians.

The minimum required and maximum tolerable heat units' values are represented as follows (Elnesr et al., 2013):

$$\mathrm{HU}_{\min} = (T_{op} - T_b) \times D_t \tag{7}$$

$$\mathrm{HU}_{\max} = (1 + H_{tol}/100) \times \mathrm{HU}_{\min} \tag{8}$$

where $\mathrm{HU}_{\min}$: the minimum required heat units; $\mathrm{HU}_{\max}$: the maximum tolerable heat units; T_{op}: the crop's optimum growing temperature, °C; H_{tol}: the heat tolerance above optimal, %.

2.3. The crop water requirement

To determine the amount of water needed by a plant we should calculate the crop evapotranspiration, ET_c, which depends on two factors; one is related to the crop and its growth stage (the crop coefficient, k_c), and the other depends on the weather conditions and the geolocation (the reference evapotranspiration, ET_o). The formula describing the relationship is as follows

$$\mathrm{ET}_c = k_c \cdot \mathrm{ET}_o \tag{9}$$

The ET_o can be calculated by several models, but one of the most accurate estimations of is the Penman–Monteith equation, expressed as follows (Allen et al., 1998):

$$\mathrm{ET}_o = \frac{0.408\Delta(R_n - G) + \frac{900}{T_a+273}\gamma U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \tag{10}$$

where ET_o: reference evapotranspiration, mm day^{-1}; R_n: net radiation at the crop surface, MJ m^{-2} day^{-1}; G: soil heat flux density, MJ m^{-2} day^{-1}; T_a: mean daily air temperature at 2 m height, °C; U_2: wind speed at 2 m height, m s^{-1}; e_s: saturation vapor pressure, kPa; e_a: actual vapor pressure, kPa; $(e_s - e_a)$: vapor pressure deficit, kPa; Δ: slope of vapor pressure curve, kPa °C^{-1}; γ: psychometric constant, kPa °C^{-1}.

To optimize the selection of the planting date, the seasonal crop evapotranspiration, ET_s, (over the whole growing season) should be minimum. ET_s is calculated by the formula:

$$\mathrm{ET}_s = \sum_{j=j_s}^{j=j_h} k_{cj} \cdot \mathrm{ET}_{oj} \tag{11}$$

where k_{cj}, ET_{oj} are the crop coefficient and the reference ET at each day j.

Through the growing season, k_c varies according to the growing stage, where its value is minimum during the initial stage, then increases linearly during the developing stage, until it reaches its maximum value at the mid-season stage, and finally decreases linearly during the late-season stage. To avoid summation formulas, we can use the integral form of the ET, because it's trend is similar to the sinusoidal temperature trend (Elnesr and Alazba, 2016). The sinusoidal form of the ET is similar to Eq. (4), and hence, its integration over the growing season equals

$$\mathrm{ET}_{os} = (a_E - T_b)(j_h - j_s) - \frac{\rho_E}{\omega_E}(\cos(\omega_E j_h + \varphi_E) - \cos(\omega_E j_s + \varphi_E)) \tag{12}$$

where ET_{os}: the seasonal reference evapotranspiration; the subscript E denotes the fitting parameters of evapotranspiration data over the sinusoidal model, the rest of the parameters were defined on Eq. (6).

To convert the summation of the crop coefficient, k_c, to an integral form, we used the following approximation:

$$\sum_{j=j_s}^{j=j_h} k_{cj} \cong k_{ceq} \tag{13}$$

$$k_{ceq} \cong \frac{D_{ini}k_{cini} + 0.5D_{dev}(k_{cini} + k_{cmid}) + D_{mid}k_{cmid} + 0.5D_{late}(k_{cmid} + k_{cend})}{0.25D_{total}} \tag{14}$$

where k_{ceq}: the equivalent seasonal crop coefficient; D: length of growing stage, where the subscripts *ini*, *dev*, *mid*, and *late* denotes the initial, development, mid-season, and late-season's developing stages; the *ini*, *mid*, and *end* subscripts for the k_c represents the crop coefficient values for the initial, mid-season, and end-of-season's stages.

Eq. (11) is now converted to the form:

$$\mathrm{ET}_s = k_{ceq} \times \mathrm{ET}_{os} \tag{15}$$

The water use efficiency (WUE, kg/m^3) is defined as the ratio of the crop yield to the amount of water applied, the WUE is directly proportional to the yield and inversely proportional to the amount of water, hence, maximizing the yield and minimizing the water usage directly maximizes the water use efficiency, which is one of this work's objectives.

2.4. Model development

2.4.1. Basic conditions

The target of the model is to select the best sowing date/duration that passes the following conditions:

1. Fulfils the required heat units of the plant.
2. Avoids heat and cold shocks.
3. Consumes less water (least cumulative evapotranspiration throughout the season).

To meet the first condition, the HU values of each day of the year is calculated using Eq. (6), then each value is checked that $\mathrm{HU}_{\min} \leqslant \mathrm{HU} \leqslant \mathrm{HU}_{\max}$, where $\mathrm{HU}_{\min}$ and $\mathrm{HU}_{\max}$ are calculated by Eqs. (7) and (8) respectively, hence, the date passes this condition, otherwise the date is rejected.

To meet the second condition, the value of T_x of each day of the year is compared to the crop maximum tolerable temperature T_{xc}, and the value of T_n of each day is compared to the crop minimum tolerable temperature T_{nc}. If $T_x \leqslant T_{xc}$ and $T_n \geqslant T_{nc}$ then the tested date passes the condition, otherwise a warning is released, but the date is not rejected.

For the accepted range of dates that fulfill the first condition, the ET_s values are computed by Eq. (15), and the date with minimum value of ET_s is selected.

2.4.2. The optimization index

To help automate the selection operation, we developed an index for each day that combines the three conditions. Due to the difference in units and values of the three conditions (heat units, temperature, and evapotranspiration), the index computed the relative weight of each day for each condition, and then combined the individual weights to a single index. The overall suitability index, I_{ov}, is expressed as follows:

$$I_{ovj} = \beta_j \eta_j (\gamma I_{HUj} + (1-\gamma) I_{ETj}) \tag{16}$$

$$I_{HUj} = 100 \times \frac{\mathrm{HU}_{sj} - \mathrm{HU}_n}{\mathrm{HU}_x - \mathrm{HU}_n} \tag{17}$$

$$I_{ETj} = 100 \times \left(1 - \frac{\mathrm{ET}_{sj} - \mathrm{ET}_n}{\mathrm{ET}_x - \mathrm{ET}_n}\right) \tag{18}$$

where the subscript j denotes the day of the year; γ: a weighing factor represents the contribution of the heat units' index to the overall index, =0.5 by default; I_{HU}: the heat units index; I_{ET}: the evapotranspiration index; HU_n and HU_x are the maximum and minimum values of the calculated heat units through the year, not to be conflicted with $\mathrm{HU}_{\max}$ and $\mathrm{HU}_{\min}$ denoted before; ET_n and ET_x are the maximum and minimum values of the seasonal evapotranspiration through the year; β: the temperature flag, =1 if the condition ($T_{xj} \leqslant T_{xc}$ and $T_{nj} \geqslant T_{nc}$) is true, and = 0 if it is false; η: the heat units flag, =1 if the condition ($\mathrm{HU}_{\min} \leqslant \mathrm{HU}_{sj} \leqslant \mathrm{HU}_{\max}$) is true, and = 0 if it is false. The relationships between the model inputs and outputs are illustrated in Fig. 1.

We can notice that all the indices have values of the range 0–100, the higher the better. For the evapotranspiration index, we added a (1−) operator so that when the ET relative value is high, the index is low, and vice versa, while for the heat units' index, the maximum HU is better (if within the tolerable HU values) because it may lead to earlier harvest and better marketing opportunities. As we mentioned, meeting the heat units is necessary, otherwise the date is rejected, i.e. if η = 0, the calculation stops. On the other hand, if the planting date lead to heat or cold shock, (β = 0), the program continues the calculation with warning.

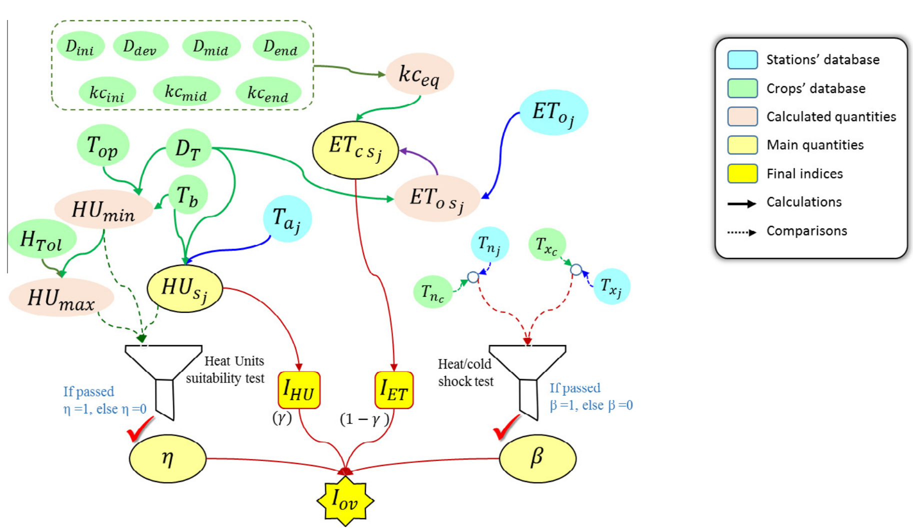


Fig. 1. An illustrative chart representing the main inputs and outputs of the current model. All the symbols are defined in the text.

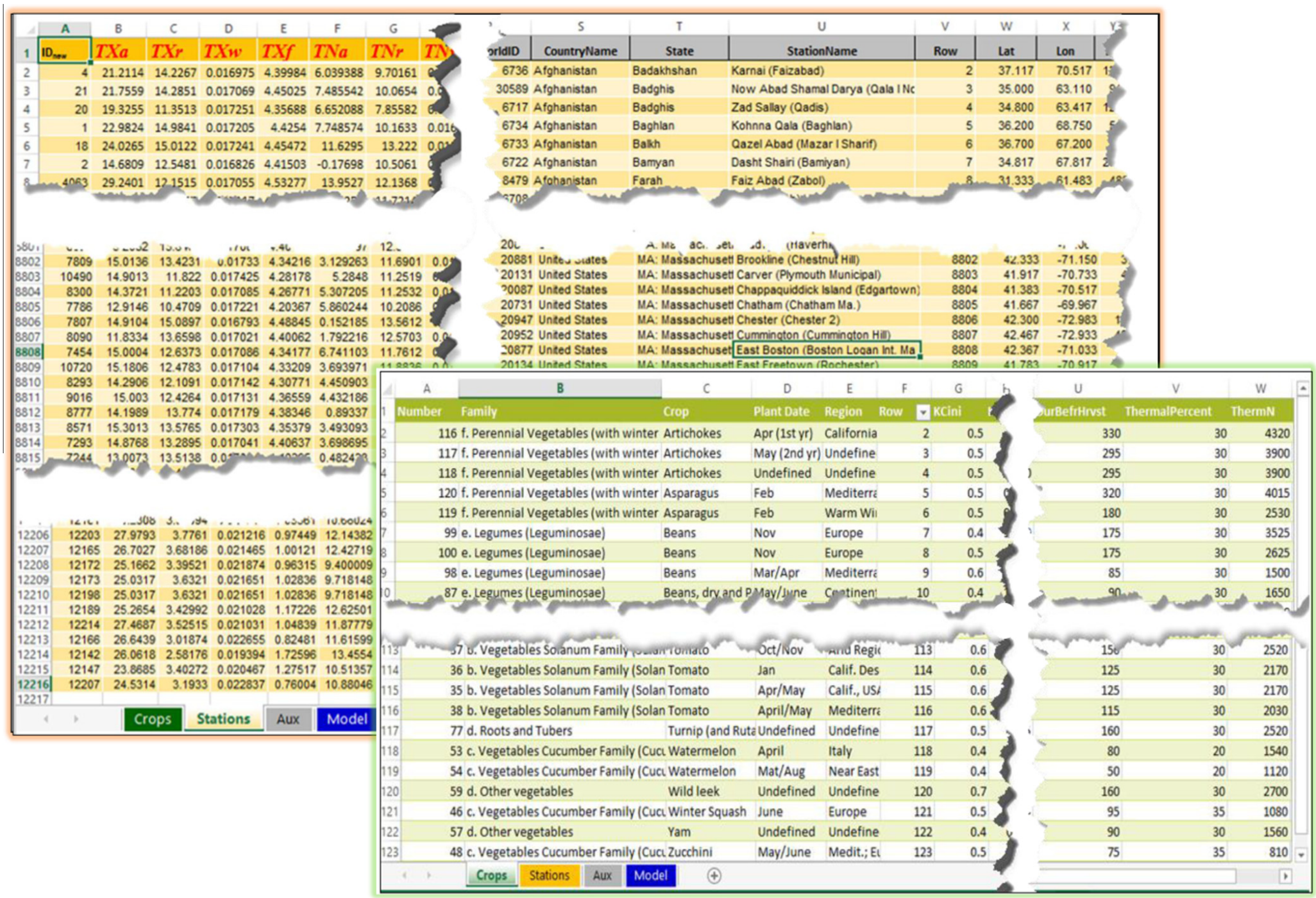


Fig. 2. Crops' and meteorological stations' data tables as appear in the Excel workbook.

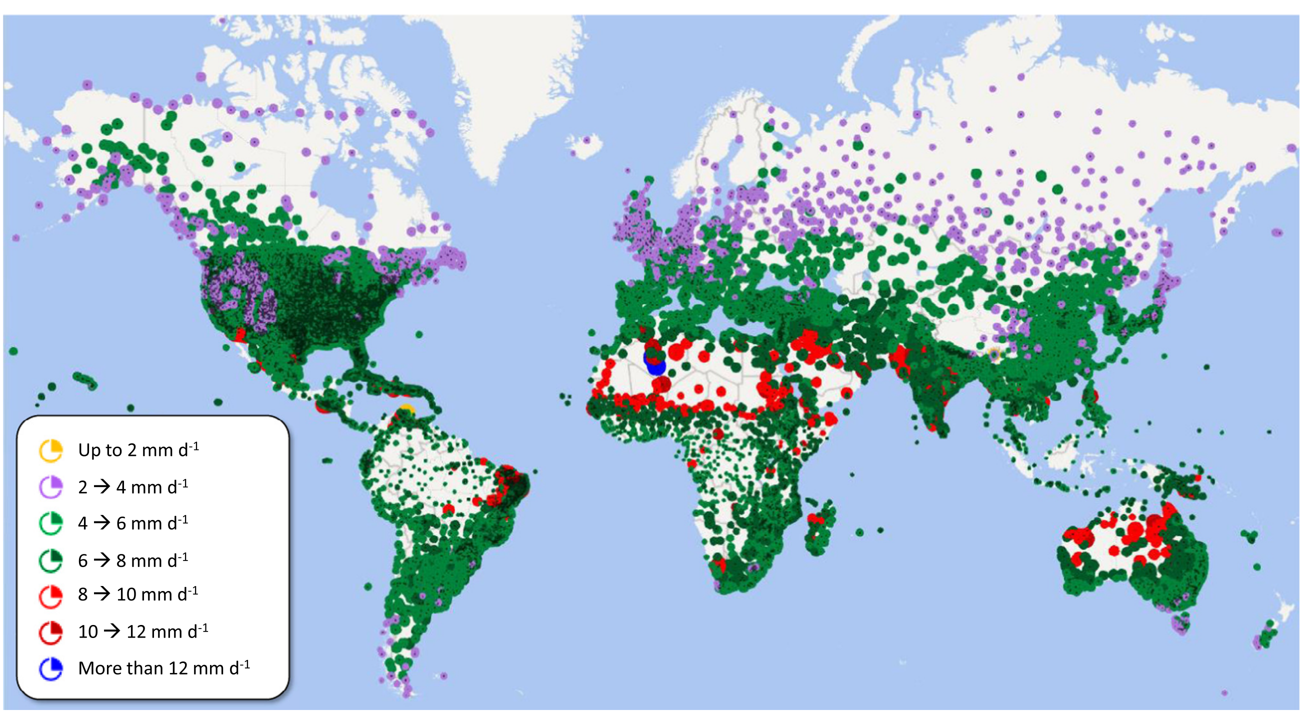


Fig. 3. Bubble distribution of average daily evapotranspiration of the included climatic stations. The color of the bubble refers to the daily mean of the ET throughout the year, while the size of the bubble refers to the amplitude of the ET distribution. Black points refer to the center of the station's location. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.4.3. Modeling environment

This model was developed as a macro-free Microsoft Excel 2013 workbook, to benefit from the database, calculation, and graphing capabilities of Excel, and ensure easy and secure sharing of the model. The workbook comprises four worksheets; 'Crops', 'Stations', 'Aux', and 'Model'. The first two worksheets contain the crops and meteorological stations databases, Fig. 2. The crops' database includes data of 60 vegetable crops as detailed in the "Datasets description" section. The 'Stations' worksheet contains data of 12,215 meteorological stations distributed worldwide, Fig. 3. Each record consists of the sinusoidal fitting parameters for T_x, T_n, T_a, and ET_o (4 parameters each), in addition to the station's name, county/state, country, and the geographic coordinates (latitude, longitude, and altitude). The 'Aux' worksheet consists of three auxiliary tables that summarize some properties of the stations and crops tables in order to speed up database search speed. The 'Model' sheet contains several panes, to select the station and the crop, to view/modify the default properties of either, to perform calculations, and to view a graph showing the results of the model.

2.5. The interval-overlap algorithm

Usually the agricultural extension services suggest potential duration for planting each crop, for example, they may suggest February 15th to March 10th to start sowing Cucumber, this duration of suitability is what we called range of dates. The outputs of the current model also are ranges of dates, so if the outputs of our model are similar to the date-range that was suggested by the extension services, then the model's results are flawless, but what if the model increases the duration end to March 30th, then the model over estimates the suitable duration, still, if the model suggests starting at 25th of February, and ends at March 10th then it underestimates the duration. However, to evaluate the efficiency of the model we should compare the two date-ranges. Although there are several algorithms to compare range overlapping (e.g. Fletcher, 2011; FloatingRock, 2015; Paik et al., 2004; Veeraraghavan et al., 2003; Wheeler et al., 2006), we did not find a way to measure the efficiency of such model's output, hence we developed a simple method to measure the efficiency of range comparison algorithms. The description of the method is as follows.

There are seven possibilities of matching between a modeled and observed date-ranges, Fig. 4, either to correctly estimate, overestimate (in 1 or 2 directions), underestimate (in 1 or 2 directions), both under- and overestimate, or to miss the estimate totally. Let us define the model's output date range as M, and the observed date range as B, where both are set of days. The amount of exact estimation, X, overestimation, V, and underestimation, N, between them are defined as follows:

$$X = M \cap B \tag{19}$$

$$V = M - X \tag{20}$$

$$N = B - M \tag{21}$$

where $\cap$ is the intersection between the two sets, the negative sign denotes the relative complement or the difference, each of the resulted sets X, V, and N either contains positive number of members, or Null, no negatives are allowed.

The model's efficiency can be calculated by first computing the relative size of each set to the observed set B. This can be computed by calculating the quotient of the size of each set (X, V, and N) to the size of B. Notice that the size of a set S is the number of members of it and denoted as $|S|$.

$$X_s = |X|/|B| \tag{22}$$

$$V_s = |V|/|B| \tag{23}$$

$$N_s = |N|/|B| \tag{24}$$

where the subscript s denotes the relative size.

To evaluate the overall efficiency of the model, we should compute the partial efficiency of each property of several cases, as follows:

$$X_{\rho i} = \frac{X_{si}}{X_{sMAX}} \times 100 \tag{25}$$

$$V_{\rho i} = \left(1 - \frac{V_{si}}{V_{sMAX}}\right) \times 100 \tag{26}$$

$$N_{\rho i} = \left(1 - \frac{N_{si}}{N_{sMAX}}\right) \times 100 \tag{27}$$

where the subscripts ρ: indicates the partial efficiency of each property; i: indicates the case number; sMAX: the maximum obtained relative size from all the tested cases. Notice that for V and N we calculated the difference as the increase in their values indicates poor performance.

Finally, the overall efficiency of the model, Ω, is the product of the partial efficiencies.

$$\Omega = X_\rho \times V_\rho \times N_\rho \tag{28}$$

A detailed implementation is given in the verification section below.

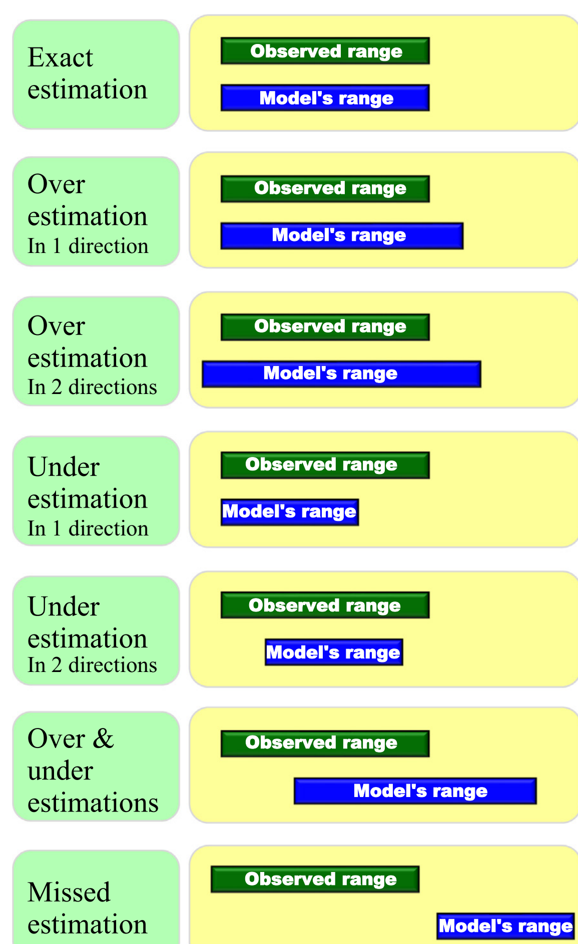
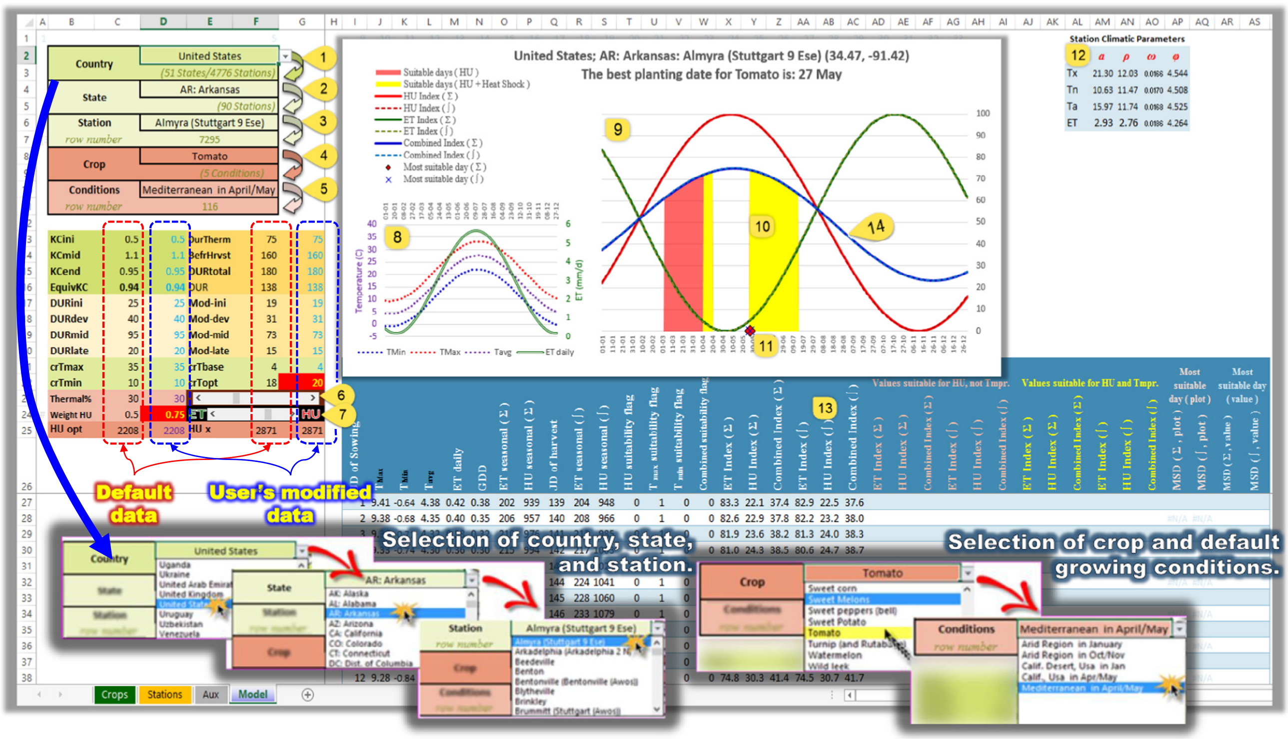


Fig. 4. The seven possibilities of model's estimation of a range.



1. Selection of the country
2. Selection of the state
3. Selection of the station
4. Selection of the crop
5. Selection of the growing conditions
6. Adjusting the thermal tolerance
7. Adjusting the ET/HU weight
8. Display of min., avg., & max. temperatures, and avg. ET
9. Display of the ET, HU, and combined indices
10. Red and yellow bands show degree of possibility of sowing.
11. Points show the best date to start sowing according to selected conditions
12. Table shows the sinusoidal parameters of the selected station.
13. Calculation area.
14. The combined suitability index curve

Fig. 5. The model's main interface and its main components.

3. Model testing and verification

After development, the model was optimized several times to ensure speed and stability. Although the model could perform faster using the VBA modules, we chose to make it macro-free, as this is safer for public sharing. The model's user interface is easy, compact, and quietly simple, Fig. 5. The operation sequence is as follows:

1. Chose the country, state, and station each from corresponding dropdown list (#1, #2, #3 in Fig. 5).
2. Chose the crop and the growing conditions (the nearest to the chosen region's conditions, #4 and #5 in the same figure).
3. Adjust the crop and growing conditions' properties if needed (trough the user's modified data columns as shown in the left of the figure).
4. Adjust the thermal tolerance, and the weight of the ET/HU index (γ) through the sliders #6, #7.
5. Notice the indices curves, #9, the higher, the better, but only within the banded ranges, as described below.

The yellow-band range means the highlighted dates achieved two conditions:

I. The heat units are sufficient (>HU_{min}), and below the critical value HU_{max}.
II. The dates are heat-shock free, i.e. all the temperature values within these dates meet the conditions ($T_{xj} \leqslant T_{xc}$ and $T_{nj} \geqslant T_{nc}$).

While the red-band range means that, the highlighted dates achieved only condition I.

The best date to start sowing (which has the highest index), is marked by a diamond, #11 in the figure. The yellow[1] and red bands appear either together or individually, Fig. 6. Sometimes the suitable ranges are continuous, Fig. 6a and d, or split, Fig. 6b and c.

3.1. The difference between summation and integration methods

Normally, both the HU and the seasonal ET are calculated by summation, Eqs. (1) and (11). However, for speed and stability we applied the integral forms of the equations, Eqs. (6) and (12). We found no difference between the two methods in almost all the tested scenarios, as reported by Elnesr and Alazba (2016). In some scenarios, there were some differences in the HU values calculated by either integration ($HU_{\int}$) or summation (HU_{Σ}). The reason of this is that the integral form may give negative values, which violates the definition of HU, and hence registered as zero. The summation form never rises negative values as the GDD formula, Eq. (2), removes negatives before summation. Furthermore, it worth to tell that this occurs only in the scenarios that T_a is much less than T_b in most of the season. Even if there are differences occur between $HU_{\int}$ and HU_{Σ}, this happens only in a part of the year, but soon the two functions converge to almost equal values, as shown in Fig. 6d.

[1] For interpretation of color in Fig. 6, the reader is referred to the web version of this article.

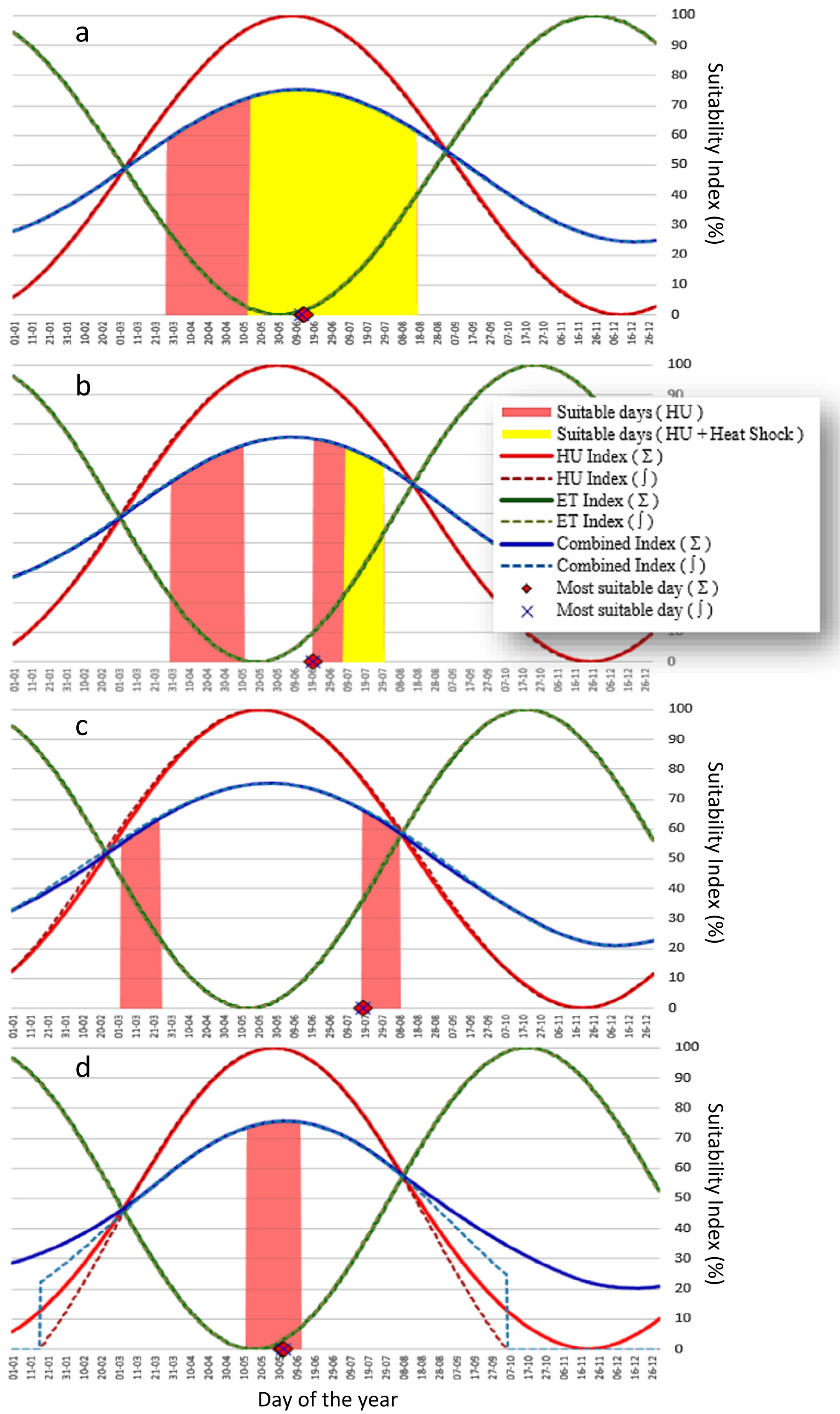


Fig. 6. Sample suitability charts for different scenarios, all scenarios are for planting Tomato in California, USA in different locations (a) Los Angeles, (b) Beaumont, (c) Avenal, (d) Angwin.

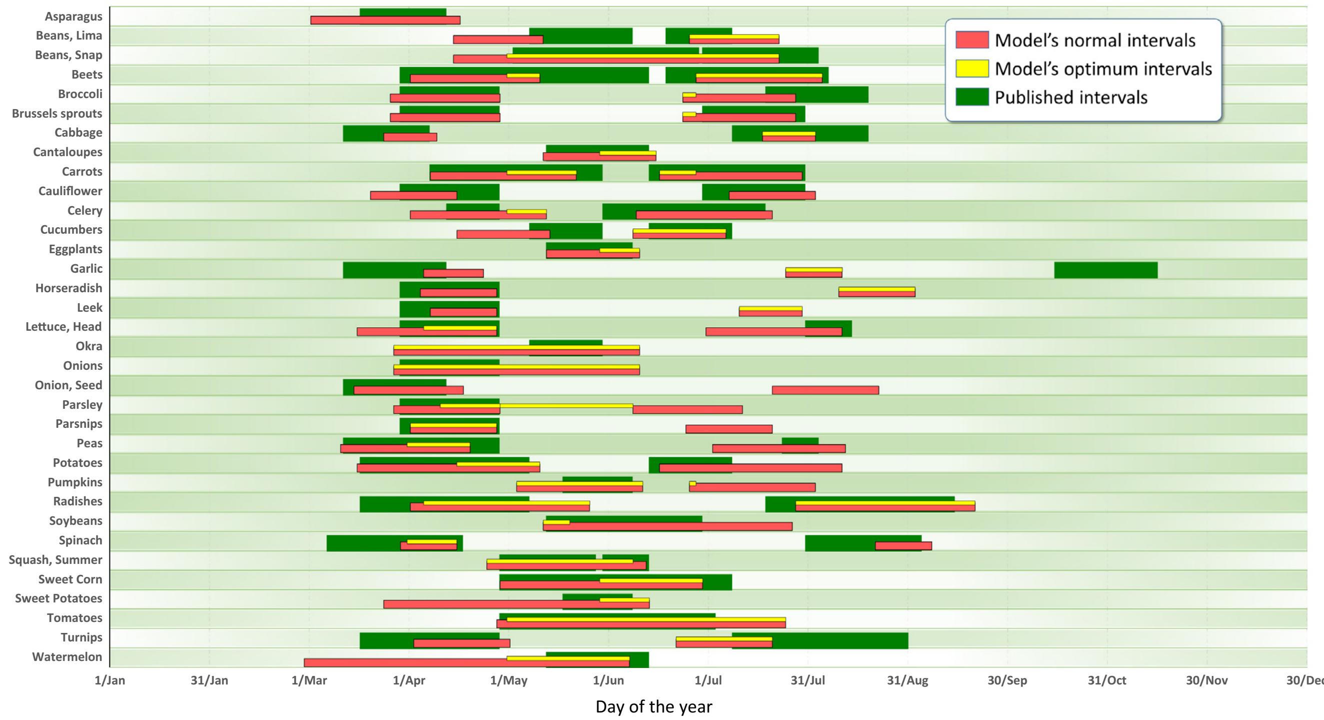


Fig. 7. A case study comparison chart of the recommended planting date intervals observed vs. modeled form Central Maryland.

Table 1
Calculating model's efficiency for the Central Maryland case study.

Crop	Observed from Traunfeld (2001)		Model's recommendations		Size of sets			Relative sizes			Partial and overall efficiencies				Changed properties		
	B	|*B*|	*M*	|*M*|	|*X*|	|*V*|	|*N*|	*Xs*	*Vs*	*Ns*	*Xρ* (%)	*Vρ* (%)	*Nρ* (%)	*Ω* (%)	T_{op}	H_{tol}	T_b
Asparagus	3/20–4/15	27	3/5–4/19	46	27	19	0	1.0	.70	0	100	74	100	91	18		
Beans, Lima	5/10–6/10; 6/20–7/10	53	4/17–5/14; 6/27–7/24	56	19	37	0	.36	.70	0	36	74	100	70	20		
Beans, Snap	5/5–6/30; 7/1–8/5	93	4/17–7/24	99	81	18	0	.87	.19	0	87	93	100	93	20		
Beets	4/1–6/15; 6/20–8/8	126	4/4–5/13; 6/29–8/6	79	79	0	47	.63	.00	0.37	63	100	31	64		35	
Broccoli	4/1–5/1; 7/20–8/20	63	3/29–5/1; 6/25–7/29	69	41	28	0	.65	.44	0	65	83	100	83	18		
Brussels sprouts	4/1–5/1; 7/1–8/1	63	3/29–5/1; 6/25–7/29	69	60	9	0	.95	.14	0	95	95	100	97	18		
Cabbage	3/15–4/10; 7/10–8/20	69	3/27–4/12; 7/19–8/4	34	32	2	35	.46	.03	0.51	46	99	6	50	19	50	
Cantaloupes	5/15–6/15	32	5/14–6/17	35	32	3	0	1.0	.09	0	100	97	100	99	23		
Carrots	4/10–6/1; 6/15–8/1	101	4/10–5/24; 6/18–7/31	89	89	0	12	.88	.00	0.12	88	100	78	89	19		
Cauliflower	4/1–5/1; 7/1–8/1	63	3/23–4/18; 7/9–8/4	54	42	12	9	.67	.19	0.14	67	93	73	78			
Celery	4/15–5/1; 6/1–7/20	67	4/4–5/15; 6/11–7/22	84	57	27	0	.85	.40	0	85	85	100	90	19	27	
Cucumbers	5/10–6/1; 6/15–7/10	49	4/18–5/16; 6/10–7/8	58	31	27	0	.63	.55	0	63	79	100	81	21	35	15
Eggplants	5/15–6/10	27	5/15–6/12	29	27	2	0	1.0	.07	0	100	97	100	99	23		
Garlic	3/15–4/15; 10/15–11/15	64	4/8–4/26; 7/26–8/12	37	8	29	27	.13	.45	0.42	13	83	22	39	18	35	
Horseradish	4/1–5/1	31	4/7–4/30; 8/11–9/3	48	24	24	0	.77	.77	0	77	71	100	83	16	35	
Leek	4/1–5/1	31	4/10–4/30; 7/12–7/31	41	21	20	0	.68	.65	0	68	76	100	81	19		
Lettuce, Head	4/1–5/1; 8/1–8/15	46	3/19–4/30; 7/2–8/12	85	42	43	0	.91	.93	0	91	65	100	85			
Okra	5/10–6/1	23	3/30–6/12	75	23	52	0	1.0	2.26	0	100	16	100	72			
Onions	4/1–5/1	31	3/30–6/12	75	31	44	0	1.0	1.42	0	100	47	100	82			
Onion, seed	3/15–4/15	32	3/18–4/20; 7/22–8/23	67	29	38	0	.91	1.19	0	91	56	100	82	15	50	
Parsley	4/1–5/1	31	3/30–5/1; 6/10–7/13	67	31	36	0	1.0	1.16	0	100	57	100	86		22	
Parsnips	4/1–5/1	31	4/4–4/30; 6/26–7/22	54	27	27	0	.87	.87	0	87	68	100	85	19	35	
Peas	3/15–5/1; 7/25–8/5	60	3/14–4/22; 7/4–8/13	81	51	30	0	.85	.50	0	85	81	100	89		90	
Potatoes	3/20–5/10; 6/15–7/10	78	3/19–5/13; 6/18–8/12	112	75	37	0	.96	.47	0	96	82	100	93			
Pumpkins	5/20–6/10	22	5/6–6/13; 6/27–8/4	78	22	56	0	1.0	2.55	0	100	5	100	68			
Radishes	3/20–5/10; 7/20–9/15	110	4/4–5/28; 7/29–9/21	110	86	24	0	.78	.22	0	78	92	100	90		90	
Soybeans	5/15–6/15; 6/15–7/1	49	5/14–7/28	76	48	28	0	.98	.57	0	98	79	100	92	22	30	
Spinach	3/10–4/20; 8/1–9/5	78	4/1–4/18; 8/22–9/8	36	33	3	42	.42	.04	0.54	42	99	0	47	15		
Squash	5/1–5/30; 6/1–6/15	45	4/27–6/14	49	44	5	0	.98	.11	0	98	96	100	98	22	30	
Sweet corn	5/1–6/15; 6/15–7/10	72	5/1–7/1	62	62	0	10	.86	.00	0.14	86	100	74	87	22		
Sweet potatoes	5/20–6/10	22	3/27–6/15	81	22	59	0	1.0	2.68	0	100	0	100	67	20		
Tomatoes	5/1–6/15; 6/15–7/5	67	4/30–7/26	88	66	22	0	.99	.33	0	99	88	100	95	21		
Turnips	3/20–5/1; 7/10–9/1	97	4/5–5/4; 6/23–7/22	60	40	20	37	.41	.21	0.38	41	92	29	54	20	60	
Watermelon	5/15–6/15	32	3/3–6/9	99	26	73	0	.81	2.28	0	81	15	100	65	18	30	
					Maximum			1.00	2.68	0.54	100	100	100	99			
					Minimum			0.13	0.00	0.00	13	0	0	39			
					Average			0.80	0.68	0.08	80	75	86	80			

Table 2
Calculating model's efficiency for delta of Egypt case study.

Crop	Observed from Morsi and Elmoraba (1960)		Model's recommendations		Size of sets			Relative sizes			Partial and overall efficiencies				Changed	
properties	B	$\lvert B\rvert$	M	$\lvert M\rvert$	$\lvert X\rvert$	$\lvert V\rvert$	$\lvert N\rvert$	Xs	Vs	Ns	$X\rho$ (%)	$V\rho$ (%)	$N\rho$ (%)	Ω (%)	T_{opt}	H_{tol}
Asparagus	1/1–2/28	59	1/6–7/7	184	54	130	0	.92	2.20	.00	92	0	100	64	20	
Beans, Lima	3/1–6/30	122	4/3–8/28	148	89	59	0	.73	.48	.00	73	78	100	84	21	
Beans, Snap	1/15–2/29; 8/15–9/15	78	3/24–5/7; 7/25–9/6	89	23	66	0	.29	.85	.00	29	62	100	64	21	
Beets	1/1–2/28; 8/15–12/31	198	1/1–2/28; 9/2–12/31	180	180	0	18	.91	.00	.09	91	100	85	92	14	
Cabbage	2/1–9/1	214	4/22–7/30	100	100	0	114	.47	.00	.53	47	100	14	54	24	
Cantaloupes	3/1–6/30; 10/1–11/1	154	5/7–7/15	70	55	15	84	.36	.10	.55	36	96	12	48		
Carrots	1/1–2/1; 9/1–10/15	77	1/1–2/27; 9/2–11/1	119	76	43	0	.99	.56	.00	99	75	100	91	15	45
Cauliflower	2/1–9/1	214	1/1–3/3; 7/10–9/16	132	32	100	82	.15	.47	.38	15	79	38	44		40
Celery	8/1–9/30	61	3/24–4/29; 8/2–9/6	73	0	73	0	.00	1.20	.00	0	46	100	49		
Cucumbers	2/1–7/30	181	3/17–8/5	142	136	6	39	.75	.03	.22	75	98	65	80		
Garlic	8/15–10/30	77	3/5–5/7; 7/25–9/26	128	0	128	0	.00	1.66	.00	0	25	100	42		
Leek	1/1–12/31	366	1/1–12/31	366	366	0	0	1.0	.00	.00	100	100	100	100		
Lettuce	9/1–11/30	91	2/2–4/2; 8/29–10/27	121	0	121	0	.00	1.33	.00	0	40	100	47		
Onion, Seed	9/23–11/7	46	9/15–10/27	43	35	8	3	.76	.17	.07	76	92	89	86		
Parsley	1/1–2/28; 8/15–12/31	198	1/1–2/28; 9/2–12/31	180	180	0	18	.91	.00	.09	91	100	85	92	14	60
Peas	9/15–11/30	77	1/1–2/17; 10/13–11/29	96	0	96	0	.00	1.25	.00	0	43	100	48		
Potatoes	1/1–3/7; 9/1–10/7	104	1/1–3/21; 9/9–11/29	163	96	67	0	.92	.64	.00	92	71	100	88	14	85
Pumpkins	2/15–4/15	61	3/11–4/16; 9/14–10/19	73	36	37	0	.59	.61	.00	59	72	100	77	18	50
Radishes	1/1–2/28; 9/1–12/31	181	1/1–3/14; 11/1–12/31	135	120	15	46	.66	.08	.25	66	96	59	74	13	50
Spinach	2/1–3/30; 9/1–11/30	150	3/12–4/9; 9/6–10/3	57	47	10	93	.31	.07	.62	31	97	0	43		
Squash	2/1–5/21	111	2/28–5/20; 6/12–9/1	165	83	82	0	.75	.74	.00	75	66	100	80		35
Sweet Pot.	4/1–7/7	98	3/22–7/11	112	98	14	0	1.0	.14	.00	100	94	100	98	23	
Tomatoes	2/1–5/7; 7/1–10/31	220	2/8–5/1; 6/30–9/22	169	168	1	51	.76	.00	.23	76	100	63	80		
Turnips	2/28–4/30	126	3/28–5/9; 7/7–8/19	87	40	47	39	.32	.37	.31	32	83	50	55		
Watermelon	2/1–6/1	122	1/30–8/2	186	122	64	0	1.0	.52	.00	100	76	100	92		
					Maximum			1.0	2.20	0.62	100	100	100	100		
					Minimum			0.0	0.0	0.0	0	0	0	42		
					Average			0.58	0.54	0.13	58	76	78	71		

3.2. Case studies

To evaluate the current model, we compared its results to two published planting dates, one for small scale open field agriculture (gardens), and for large scale open field agriculture (farms).

3.2.1. Case #1

The first case study is the comparison to the published planting dates of the University of Maryland Extension service (www.extension.umd.edu) in the USA. Traunfeld (2001), reported the recommended planting dates for 48 types of vegetables, from which we selected the mutual types in our database, that were 34 types. We selected each type from the dropdown list after selecting the station that is close to Central Maryland to match the report. For some vegetables, we changed one or more of the given growth properties to match the species or natural conditions in the selected zone. The possible changed properties were HU_{tol}, T_{op}, and T_b. The crops, their published durations, and the model results are sketched in Fig. 7, while the calculations of the properties and efficiencies are shown in Table 1.

The results show that the average overall performance for all cases was 80%, where $\Omega > 90\%$ for 11 cases, $90\% > \Omega > 80\%$ for 12 cases, Table 1. The table also shows that the average overestimation efficiency is less than the other efficiencies, this shows that the model slightly overestimates the possible planting dates, which can be attributed to the other properties that are omitted in this model like insects' activities and marketing conditions.

3.2.2. Case #2

The second case study is to compare the published planting dates of farm-scale recommendations for the delta of Egypt, as reported by Morsi and Elmoraba (1960) and updated by Green Pages (2015). We selected 25 vegetable crops, and performed the same comparison procedure as described above. The results, Table 2, show that for 10 cases out of 25 the value of Ω was > 80%, while $80\% > \Omega > 50\%$ for 8 cases, with overall average performance of 71%.

In general, we noticed that the most important factor that should be adapted is the T_{op} as we changed it for 24/34 crops in case study #1 and for 11/25 crops in case study #2. The second factor that should be adapted is the HU_{tol} that were changed for 15, and 7 crops in cases #1 and #2. while we changed the T_b for only 1 case (from 16 °C to 15 °C) in case study #1. This, however, shows the importance of selecting the optimum temperature and the heat units' tolerance, which both are species-dependent (Welbaum, 2015; Yamori et al., 2010). The graphical output of the model shows clearly the recommended intervals (either for HU only or for both HU and heat shock), and the suitability-index curve, Fig. 5 #14, shows clearly the trend of highest HU and least water consumption.

3.3. Limitations and risks

The current model is designed for open-field agriculture, including farms and gardens, however, it is not suitable for determining planting dates for mulched agriculture or greenhouses. The model takes into account all the temperature-related risks including frosts and heat shocks, however, the recommendations of the model depend on historic climatic data that are included in its database, hence these recommendations remain applicable as long as the region's temperature averages still within the range in this database. In case of using the model's recommendations with incorrect climatic data or crop properties, severe crop loss may occur.

4. Conclusions

The model for specifying the most suitable period for planting vegetables was developed in an easy graphical interface. The model includes meteorological data from the FAO for 12,215 stations worldwide that covers almost all the inhabited areas in the world. It also includes data for 123 crops with the corresponding growing conditions. The model was validated by comparing its results to some published data as a case study with 34 crops. The average overall efficiency of the model was 80% for this case study, and we found that the most important factors to alter are the crop's optimum temperature and tolerance of heat units. The base of the model is ready for orchards, but not tested yet. The authors recommend testing this model in different regions and for different crops, and they welcome receiving the testing results at the corresponding author's email.

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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.2016.03.029.

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