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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 $°\mathrm{C}^{-1}$; γ: psychometric constant, kPa $°\mathrm{C}^{-1}$.

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: