Agroclimatic Mapping of Maize Crop Based on Soil Physical Properties

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INTRODUCTION

With the purpose of estimating water deficit to forecast yield knowing productivity (potential yield), the water balance is useful tool to recommend maize exploration and to define the sowing date. The computation can be done for each region with the objective of mapping maize grain yield based on agroclimatic data and soil physical properties.

AGRICULTURE: THE PROPOSED MODEL TO ESTIMATE YIELD

Based on agroclimatic data, air temperature and solar radiation, a model was built to estimate the corn grain productivity (the energy conversion results in dry mass production). The proposed model is presented in the Figure 2.

Conversion of CO₂ in CH₂O

The carbon dioxide (CO₂) fixation by plants is related to gross carbohydrate (CH₂O) production and solar radiation, according with the following equation:

\[ CO_2 + H_2O + \text{solar energy} \rightarrow CH_2O + O_2 \]  

(1)

The CO₂ assimilation by C₄ plants depends on the photosynthetic active radiation (PAR) and temperature (T) Figure 1. According to the experimental data (Heemst, 1986):

\[ Adc = \frac{a + b.q + c.q^2 + d.q^3 + e.ln(T)}{1 + f.q + g.q^2 + h.ln(T) + i.[ln(T)]^2} \]  

(2)

where Adc is the carbon dioxide assimilation (µL.cm⁻².h⁻¹), q the photosynthetic active radiation (PAR, cal.cm⁻².min⁻¹), T the air temperature (ºC), and a, b, c, d, e, f, g, h and i are the empirical parameters obtained by multiple regression analysis (a = 1.732748682; b = 61.81088751; c = -254.72111; d = 333.7473141; e = -0.54180211; f = -0.19106242; g = 0.29248608; h = -0.5521966; i = 0.080139046).

Knowing the specific mass of CO₂ (44g.mol⁻¹) and CH₂O (30g.mol⁻¹), the carbon dioxide assimilation (Adc, µL.cm⁻².h⁻¹) is converted to carbohydrate mass produced (M(CH₂O), g.h⁻¹.cm⁻² of leaf) as function of leaf area index (IAF), climatic data, air temperature (T, ºC) and PAR (q, cal.cm⁻².min⁻¹).

For the whole crop cycle (C, days), knowing the degrees-day to flowering (GD₆, ºC.day), the reproductive phase duration (D₉₀, days), theoretical photoperiod (H, h.day⁻¹) and mean leaf area index (IAFₘ), the total carbohydrate production (M(CH₂O), kg.ha⁻¹.cycle⁻¹) can be estimated using the following equation:

\[ M_{CH₂O} = \frac{36,585.P.Adc.IAFₘ.C.H}{T + 273} \]  

(3)
where $P$ is the local atmospheric pressure (atm). Solar radiation and theoretical photoperiod values are given in Tables 1 and 3, respectively.

**Grain productivity, maintenance and growth respiration and solar radiation**

To convert the final gross carbohydrate mass ($M_{CH2O}$) in dry mass of different corn organs (grain, stem, root and seeds), to estimate grain yield ($P_{gr}$, kg.ha$^{-1}$), is necessary some corrections. The first correction refers to carbohydrate mass consumption by respiration process (FAO, 1979):

$$CR_{MC} = 0.6 \ (T < 20^\circ C) \quad (4) \quad CR_{MC} = 0.5 \ (T \geq 20^\circ C) \quad (5)$$

where $CR_{MC}$ is the maintenance and growth respiration coefficient and $T$ the air temperature ($^\circ C$). The second correction refers to intercepted solar radiation as function of maximum leaf area index ($IAF_{max}$):

$$CR_s = \frac{1 - e^{-0.75IAF_{max}}}{2} \quad (6)$$

where $CR_s$ is the solar radiation extinction coefficient.

Figure 1. CO$_2$ assimilation by C$_4$ plants as function of PAR and air temperature (Heemst, 1986).
The dry mass of maize grain is a fraction of the total dry mass harvested. According to experimental data (Dourado-Neto, 1999) for maize (grain), the harvest index is around 40% (IC = 0.4). Then, the final grain productivity ($P_{gr}$) can be estimated as follows:

$$P_{gr} = M_{CH2O} \cdot CR_{mc} \cdot CR_s \cdot IC$$  \hspace{1cm} (7)

Table 1. Solar radiation at horizontal surface in the atmosphere (15th day of each month).

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Figure 2. Schematic representation of the model
AGROMETEOROLOGY AND SOIL PHYSICS

Water balance

The water balance can be done with the following variables (Thornthwaite & Mather, 1955; Dourado-Neto, 1999): crop coefficient (Kc) and root effective depth (Ze) for any weather data distribution.

Potential and maximum evapotranspiration

The potential evapotranspiration ($ET_0$, mm.period$^{-1}$) by the Thornthwaite method (Dourado-Neto, 1999) can be estimated as follows:

$$ET_0 = 0.53N_i \left( \frac{H_i}{12} \right) \left( 10 \frac{T_i}{I} \right)^a$$  \hspace{1cm} (8)

$$a = a_0 + a_1I + a_2I^2 + a_3I^3$$  \hspace{1cm} (9)

where $T_i$ is the air temperature (°C), $I$ the thermic index, $a$ the empirical coefficient, $N_i$ the number of days per period and $H_i$ the theoretical photoperiod in the median day of the period $i$, and $a$ the empirical coefficient ($a_0 = 0.49239$, $a_1 = 0.01792$, $a_2 = -0.0000771$ and $a_3 = 0.000000675$).

The thermic index ($I$) and the theoretical photoperiod ($H$) can be calculated as follows:

$$I = 0.08745 \sum_{j=1}^{12} T_j^{1.514}$$  \hspace{1cm} (10)

$$H = \frac{24}{\pi} \cos^{-1}[-\tan(\alpha)\tan(\phi)]$$  \hspace{1cm} (11)

$$\alpha = C_0 + \sum_{i=1}^{3} \left[ C_i \sin(2i\pi d / 365) - D_i \cos(2i\pi d / 365) \right]$$  \hspace{1cm} (12)

where $T_j$ is the air temperature (°C) of the month $j$, $\alpha$ the solar declination (rad) in the median day of the period, $d$ the Julian day ($1 \leq d \leq 365$), $C_0$, $C_i$, and $D_i$ are the empirical parameters ($C_0 = 0.006918$, $C_i = 0.070257$, $C_2 = 0.000907$, $C_3 = 0.00148$, $D_1 = 0.399912$, $D_2 = 0.006758$ and $D_3 = 0.002697$) and $\phi$ the latitude (rad).

The maximum evapotranspiration ($ET_{m}$) corresponds to the maximum crop yield:

$$ET_{m_i} = ET_0 \cdot K_{ci}$$  \hspace{1cm} (13)

where $K_{ci}$ is the crop coefficient (Table 2 and Figure 3).
Table 2. Maize crop coefficient (Kc) for Brazilian weather condition.

<table>
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<tr>
<th>Phenological stage</th>
<th>up to</th>
<th>Kc$^*$</th>
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<tr>
<td>I</td>
<td>10% of vegetative phase</td>
<td>0.20 to 0.40</td>
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<td>II</td>
<td>80% of vegetative phase</td>
<td>Figure 3</td>
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<td>III</td>
<td>Flowering</td>
<td>0.95 to 1.20</td>
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<td>IV</td>
<td>physiological maturity point</td>
<td>Figure 3</td>
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<td>V</td>
<td>harvest</td>
<td>0.3 to 0.5</td>
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1 *Food and Agricultural Organization (1979)*
2 Low values of Kc for relative humidity larger than 70% and wind speed lower than 5 m.s$^{-1}$

$$K_{c_1} = K_{c_1} \left(0 \leq i < t_1\right)$$
$$K_{c_i} = \frac{K_{c_3} - K_{c_1}}{t_2 - t_1}(i-t_1) + K_{c_1} \left(t_1 \leq i < t_2\right)$$
$$K_{c_i} = K_{c_3} \left(t_2 \leq i < t_3\right)$$
$$K_{c_i} = \frac{K_{c_5} - K_{c_3}}{t_4 - t_3}(i-t_3) + K_{c_3} \left(t_3 \leq i < t_4\right)$$
$$K_{c_i} = K_{c_5} \left(t_4 \leq i \leq t_5\right)$$

Figure 3. Temporal variation ($t_1$, $t_2$, $t_3$, $t_4$, and $t_5$: phenological stages duration) of crop coefficient ($K_{c_1}$, $K_{c_3}$ and $K_{c_5}$) (FAO, 1979).
Table 3. Theoretical photoperiod (H, hour.day⁻¹) for different latitudes corresponding to 15th day of each month.

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Water deficit and grain yield

To estimate water deficit, the rainfall ($C_i$, mm) and the maximum crop evapotranspiration ($ET_{mi}$, mm) must be computed:

$$S_i = C_i - ET_{mi}$$  \hspace{1cm} (14)

If $S_i < 0$:  \hspace{1cm}$$L_i = L_{i-1} + |S_i|$$  \hspace{1cm} (15)

$$Arm_i = CAD_i \cdot e^{\left(\frac{L_i}{CAD_i}\right)}$$  \hspace{1cm} (16)

If $S_i \geq 0$:  \hspace{1cm}$$L_i = -CAD_i \cdot \ln\left(\frac{Arm_i}{CAD_i}\right)$$  \hspace{1cm} (17)

$$Arm_i = Arm_{i-1} + S_i$$  \hspace{1cm} (18)

where $S_i$ and $L_i$ are auxiliary variables (mm), $CAD_i$ the soil water holding capacity (mm), and $Arm_i$ the soil water holding available (mm) in the period $i$.

Thornthwaite & Mather (1955) suggested the following criterion to begin the water balance: $L = 0$ and $Arm = CAD$ in the last period of wet season.
The soil water holding capacity (CAD, mm), the soil water holding available \((Arm, \text{ mm})\), the real evapotranspiration \((ETr, \text{ mm})\) and water deficit \((WDi, \text{ mm})\) are calculated as follows:

\[
CAD_i = 10. (\theta_{cc} - \theta_{pmp}) Ze_i
\]

\[
Arm_i = 10. (\theta_i - \theta_{pmp}) Ze_i
\]

\[
ETr_i = ETm_i \ (C_i \geq ETm_i) \quad (21)
\]

\[
ETr_i = C_i + \left| V_{ai} \right| \ (C_i < ETm_i)
\]

\[
V_{ai} = Arm_i - Arm_{i-1}
\]

\[
WD_i = 0 \ (C_i \geq ETm_i) \quad (24)
\]

\[
WD_i = ETm_i - ETr_i \ (C_i < ETm_i)
\]

where \(Ze_i\) is the effective root depth (cm) in the period \(i\), \(\theta_{cc}\) and \(\theta_{pmp}\) are soil water content corresponding to field capacity and wilting point (cm\(^3\).cm\(^{-3}\)), \(\theta_i\) the actual soil water content, \(Ci\) the rainfall, and \(V_{ai}\) the soil water holding variation in the period \(i\).

The corn grain yield \((R_{gr})\) is calculated as function of grain productivity \((P_{gr})\) and depletion factor \((fd)\):

\[
fd = \prod_{i=1}^{n} \left( \frac{(ETr_i)^{Kc_i}}{ETm_i^{Kc_i}} \right)
\]

\[
R_{gr} = fd.P_{gr}
\]

**AGROCLIMATIC MAPPING OF MAIZE CROP BASED ON SOIL PHYSICAL PROPERTIES**

From agroclimatic data and soil physical properties, a map with region identification can be built for solar radiation (Figure 4), air temperature, rainfall, maize grain productivity and yield, potential and real evapotranspiration and water deficit.

The map allows to identify the agroclimatic and the soil physical restrictions. This procedure can be used in different spatial (farm to State) and temporal (daily to monthly data) scales.

The statistical analysis allows to compare estimated and observed values in different situations to validate the model and to verify which scale is more appropriate.

A software was developed (Visual BASIC for Microsoft Windows environment) to forecast corn productivity.
Figure 4. Annual solar radiation in Brazil.

REFERENCES


