AGROMETEOROLOGICAL MODELING FOR COTTON YIELD ESTIMATION

Leonidas Toulios\(^1\), Alexa Tournaviti\(^2\), Georgia Zerva\(^1\) and Theodore Karacostas\(^2\)
\(^1\)National Agricultural Research Foundation (NAGREF), Larissa, Greece
\(^2\)Aristotle University of Thessaloniki, Department of Meteorology and Climatology, Greece

Abstract

Early estimates of agricultural production are of great importance for agricultural policy and trade. Cotton is a very important crop worldwide and especially in Greece, and there is a great need for good estimates of yield and total biomass production. Agrometeorological models are used worldwide with, unfortunately, in most cases, only local value, and generalization is one of the research issues today.

Relatively simple models using the photosynthetically active range of the solar radiation are available from the literature, although they have not been verified extensively. These models require information about the climatic efficiency and the radiation use efficiency of the crop.

Assuming the above, field studies with cotton were conducted to verify these models under Greek conditions. Based on the linear connection between the interception efficiency of photosynthetically active radiation (PAR) and the normalized difference vegetation index (NDVI), spectral reflectance was measured by means of hand-held radiometer during the whole cultivation season, in a three year experiment in the main cotton zone in Greece, expressed as NDVI. Total dry matter was measured in a weekly basis and it was compared to the findings of the model.

The results show that the estimated dry matter and yield agree well with the field measurements and there is a potential in applying this approach in an operational basis with multitemporal remote sensing data. Limitations concerning the radiation use efficiency (phytomass production per unit of energy received) and the spectral data collection are also discussed.

Introduction

During the last decades, the study of the weather conditions and their connection to the plant growth and the crop yield has been very important in agricultural research. In the same time, remote sensing technology has been developed and its products have many applications in agriculture, especially in crop identification, monitoring of crop growth, land cover estimation and yield prediction.

In most cases, the empirical methods for yield estimation include multiple regression models having the yield as dependent-predictor variable and various meteorological variables as independent-predictant variables. The last ones are selected among others using statistical and physical criteria (Delecalle et al., 1998; Tournaviti et al., 1998). Although this kind of models can often give satisfactory results, they have an intensively local character and it is difficult for them to be generalized. On the other hand, there are more complicated models simulating the physiological processes of the plant growth, taking into account any factor affecting the crop and containing even thousand of equations. In that case, the models are more probable to be used...
efficiently in various environments, but they highly depend on the measurements (Monteith, 2000).

The most important meteorological variables associated with agricultural production are air temperature, its daily minimum and maximum values, solar radiation and precipitation. In second order are soil temperature, relative humidity and wind. Especially, solar radiation provides the energy for the processes that drive photosynthesis, affecting carbohydrate partitioning and biomass growth of the individual plant components (Hoogenboom, 2000). Moreover, there are some weather phenomena, such as hailstorms, that can affect yield, but are difficult to predict. However, weather conditions are not the only affecting the crop growth; nutrients, cultivation methods, soil properties, fertilizers and plant brand are also critical.

Remote sensing is the only tool that can give an exhaustive instantaneous view of large areas, with time repetitivity much better than of any other means of investigation. Many works have revealed the existence of stronger or weaker correlation between the NDVI and the canopy state parameters such as LAI (Holben et al., 1980; Asrar et al., 1984) or aerial biomass (Tucker et al., 1981; Tucker et al., 1985; Diallo et al., 1991; Prince, 1991; Wylie et al., 1991; Toulis 1995; Toulis and Silleos, 1996). All these works tried to establish statistical relationships between the NDVI and the LAI or between the sum of NDVI and the biomass. The regression equation obtained is generally specific to the site or species for which it was established and can hardly be extrapolated. For research and experimental reasons it is convenient to apply spectral data, coming from field radiometers, at plot scale and then to apply at the scale of the pixel. In this case, due to the problem of the representativity of the values, the intra-pixel variation should be taken into consideration.

In the present study, the empirical Monteith ‘s model (Monteith, 1972 and 1977) is used to predict cotton yield in central Greece, a mainly agricultural area. In fact, the model used has been developed for cereals. So, in that study, it is used in two directions: first, to test it in a new environment and second to predict the yield of a non-cereal, cotton. This model is a dynamic spectro-agro-meteorological model estimating the crop dry biomass using plant's spectral responses and solar radiation.

Data and Methodology

The model

The crop growth and yield (cotton fiber for cotton plant, sugar for sugarbeet, grain for cereals) depend on the radiation received by the plant during the various phenological stages and its efficient use by the plants (Harris, 1993 and 1995). These factors in turn, depend on a number of other environmental factors like temperature and the production of plants in fruits. According to Monteith (1977), there is a strong relation between the cumulative radiation quantity absorbed by the foliage during the cultivation period and the biomass production, roots included.

The prediction model used, based on spectral and radiation data, is the semi-empirical Monteith (1977) model, simplified by Varlet-Grancher et al.(1982):

\[ MST = \int_{t=1}^{n=t} e_b e_{i} PAR dt \]

where: MST: total dry matter on stalk (g/m²).
PAR: the photosynthetically active radiation absorbed by the foliage. PAR can be expressed in terms of the global incident radiation $R_g$ (MJ/m$^2$), i.e. $PAR = \varepsilon_c R_g$, where $\varepsilon_c$ is the climatic efficiency (%) proportion of PAR. The value of $\varepsilon_c$ does not vary a lot whatever the considered place, climatic conditions and the integration time (Cherchali et al., 1995). A mean value of 0.48 is retained for the present study.

$\varepsilon_b$: the conversion efficiency in dry matter, of the photosynthetically active radiation absorbed by the foliage (gr of dry biomass/MegaJoule). The $\varepsilon_b$ values vary among crops and from one experiment to another. According to the literature (Vignolles et al., 1995 and personal communication, Sinclair and Muchow 1999), for wheat it is between 1.2 and 1.4 gr DM/MJ, for corn is $1.6 - 1.7$ gr /MJ, but higher values are also mentioned e.g. 4 (Ruget et al., 1990), while for cotton and sugarbeet it is calculated slightly over the one for wheat. Williams et al. (1965) calculated for corn the produced biomass per unit of absorbed solar radiation in 1.34 g/MJ, while Stewart et al. (1977) have calculated it in $1.31 - 1.35$ g/MJ. Of course, during the last years, with the improvement of the varieties, it is natural to expect higher values of the indicator $\varepsilon_b$. For the present study, $\varepsilon_b$ is taken equal to 1.2 gr DM/MJ.

$\varepsilon_i$: the interception efficiency of the photosynthetically active radiation absorbed by the foliage (non-dimensional). Researchers (Kumar and Monteith, 1981; Asrar et al., 1985) have studied the relation between the vegetation indices and the efficiency of the radiation absorption. The results have shown that there is a linear dependence between $\varepsilon_i$ and NDVI, provided that there is a sufficient supply in water and nutrients: $\varepsilon_i = a\text{NDVI} + b$, where $a=1.25$ and $b$ depends on soil, i.e. $\varepsilon_i = a\left(\text{NDVI}_{\text{crop}} - \text{NDVI}_{\text{soil}}\right)$, with $\text{NDVI}_{\text{soil}}=\text{NDVI}$ for a bare soil.

The integral expresses the cumulative effect of the radiation and plant response on the dry matter production. So, summing from the start of the growth period till its end, that is the harvest day, equation (1) can be written:

$$\text{MST} = \int_{n=1}^{n=t} \varepsilon_c^e \varepsilon_b^e R_g \, dt = a \varepsilon_c \varepsilon_b \sum_{n=1}^{n=t} \left(\text{NDVI}_{\text{crop}} - \text{NDVI}_{\text{soil}}\right) R_g$$

It has to be pointed that the above relation must also contain two other variables. The first one is Stress index (Si), that is an index of the crop growth situation (like water stress, evapotranspiration etc.) and the second one the Harvest index (Hi), that is the amount of fruit that comes from a certain amount of dry biomass divided by the amount of that. According to Loudjani (1995), in similar cases, Si is considered equal to 1, provided that the crop growth conditions are the appropriate. Hi depends on the crop, the variety, the location, the sowing density and the year. For cotton, Hi (lint/total dry matter) varies between 0.08 and 0.12 (FAO, 1979). For the study area, Hi lies near 0.12, since the lint production is the 32% of the harvested cotton (lint + grain) which is the 35-40% of the total dry matter (University of Thessaly and Hellenic Cotton Board, personal communication). In the present study the Harvest index is considered for each year after having estimated the total dry biomass. As the cotton variety of the experimental crop was ZETA-2, Hi (in this study: lint+grain/total dry matter) has been taken equal to 0.36.

**The Data**

The spectral data were taken during the growing seasons of the three-year study period (1997-1999), in an experiment field near the town of Palamas, between the Karditsa and the Larissa district. For that, a portable SPOT Cimel radiometer was used. This radiometer collects
data in three spectral regions - channels, corresponding to those of SPOT satellite (Guyot et al., 1984):

a) 0.50-0.59 µm (visible)
b) 0.61-0.69 µm (visible)
c) 0.79-0.889 µm (near infrared)

Spectral data were taken once a week during the whole cultivation period over a multiple plot experimental field so that measurements are objective. The radiometer was placed at 2m height, in order to cover a field area of 1m². For each plot 5 different measurements were taken each time. The time, weather and field conditions were also recorded.

The plants of each experimental plot were immediately after each spectral measurement collected, dried out and weighed (biomass data).

The meteorological data were taken from the self-operating automatic meteorological station of the Ministry of Agriculture, located near the experimental field. The daily values of solar radiation were used.

**Data processing**

For each day the mean value of the spectral measurements has been calculated for each channel. Next, the Normalized Difference Vegetation Index has been calculated based on the above mean values, according to the relation:

\[
NDVI = \frac{\text{nearInfraRed} - \text{Visible}}{\text{nearInfraRed} + \text{Visible}}
\]  
(3)

So, naming the three radiometer channels Ch1, Ch2 and Ch3 respectively, it becomes:

\[
NDVI = \frac{Ch3 - Ch2}{Ch3 + Ch2}
\]  
(4)

or alternatively:

\[
NDVI = \frac{Ch3 - Ch1}{Ch3 + Ch1}
\]  
(5)

Usually, the expression (4) is used, because the difference between channels 2 and 3 is more intense. However, the use of channel 1, instead of channel 2, is recommended by some researchers (Frederic Baret, personal communication). In the present study the relation (5) has been used for the calculation of NDVI, since channel 2 has presented some problems, giving thus non-accurate measurements.

From the mean values of the above channels for each experiment day the NDVI has been calculated for the cotton crop and the bare soil. The evolution of NDVI for both crop and soil for 1998 is given in Figure 1.

The solar radiation, available in W/m² has been converted to MJ/m² to take the total daily value.

To calculate the predicted value of dry biomass, the \( a_0 e_{0g}(NDVI_{crop} - NDVI_{soil})R_g \) product has to be calculated for every day of the growing season and then all these values have to be summed. Since it was impossible to take measurements every day, the whole period has been divided into smaller ones, of the range of a week. For each such period, starting from a measurement day and ending one day before the next measurement day, the NDVI has been considered the same, since no great changes can be observed in such a short time.
Results and Discussion

The model results are given in Table 1, along with the measured values for the total dry biomass production as well as for the cotton staple (lint+grain) production. From the measured values the Hi value can be extracted, and it is, for the three experiment years equal to 0.36. This value has been used to predict cotton production from the model predicted dry biomass.

Table 1. Measured and model predicted values of cotton dry biomass and yield for the study years.

<table>
<thead>
<tr>
<th>Year</th>
<th>Measured values</th>
<th>Model predicted values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry biomass (kgr/hectare)</td>
<td>Cotton (kgr/hectare)</td>
</tr>
<tr>
<td>1997</td>
<td>8510</td>
<td>3030</td>
</tr>
<tr>
<td>1998</td>
<td>8250</td>
<td>2970</td>
</tr>
<tr>
<td>1999</td>
<td>8500</td>
<td>3060</td>
</tr>
</tbody>
</table>

As it can be seen, prediction is very satisfactory for both dry biomass and fiber production. The deviation from the measured values is greater for 1998. The prediction error for all cases is given in the following Table 2, where the comparison between the measured and the predicted values is clearer.

Table 2. The prediction error (measured-modeled/measured) for cotton dry biomass and yield for the three study years.

<table>
<thead>
<tr>
<th>Year</th>
<th>Dry biomass (kgr/hectare)</th>
<th>Cotton(kgr/hectare)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1997</td>
<td>3%</td>
<td>4%</td>
</tr>
<tr>
<td>1998</td>
<td>11%</td>
<td>11%</td>
</tr>
<tr>
<td>1999</td>
<td>0.4%</td>
<td>0.3%</td>
</tr>
</tbody>
</table>
Obviously the prediction error varies among the three years of the study. This error can be due, not only to the simplifications of the model, but also to the experiment which concerns a very limited field. In addition, the study period is really small - only three years - and a more extended period could give a better image of the stability or not of the model.

Conclusions

In the present study the Monteith 's model has been used to predict cotton yield in central Greece, based on solar radiation data and canopy spectral data taken from field experiments conducted with the use of a hand-held radiometer.

From the results, it is concluded that the dry matter production as well as the cotton (lint+grain) production is well predicted from the model, even if the model seems to be simplified, since cotton production also depends on other external factors.

Undoubtedly, more experiments and measurements are required for more accurate results. Additionally, as the experiment in this study was conducted in a certain area and field, the generalization of the results could be untrustworthy. However, spatial differentiation of spectral and meteorological parameters has to be taken into account, and this can be easier by using satellite images. Real and detailed data concerning crop production, sowing dates and phenological stages for the extended area will also improve the accuracy of the model results. The photosynthetically active radiation, absorbed by the foliage and its conversion efficiency ($\varepsilon_b$) in dry matter, has to be tested and improved every time, according to the region and crop concerned. The Harvest index has to be carefully considered for every year, region and variety.

These preliminary results show that combining meteorological and spectral data cotton yield can be satisfactorily predicted and the proposed improvements will give more stable and accurate results in order to take the right decisions, apply the appropriate cultivation methods and exercise the national agricultural policy better and in time.

References


