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7. A System of Agroclimatic Zoning to Evaluate Climatic Potential for Crop Production

Michel Eldin

INTRODUCTION

Latin America and the Caribbean confront the urgent necessity of significantly raising the production and productivity of the agricultural and livestock sector, and of arresting and reversing the deterioration of renewable natural resources involved in agricultural and livestock production. Without a doubt, a rational and effective agroclimatic zoning system can be an effective tool in overcoming this situation.

This paper proposes, on a continental scale, a zoning methodology related to climatic potentialities of agricultural production. The aim of this zoning is to define and compare agroclimatic conditions for husbandry, to provide a reference outline for studies dealing with selected crops, and to permit a wide and rational extrapolation of the more interesting results of these studies.

The proposed zoning is founded on the computation of an index for potential agricultural production, derived from the integration of a dry matter production function for the period of the year during which both temperature and water availability permit productive growing. This growing period is mainly defined on the basis of a frequency analysis of water deficits for 10-day periods presenting a probability of at least 0.75 (three years out of four) of obtaining rainfall greater than or equal to one-half potential evapotranspiration. The production function is a model of maximum production--without consideration of nonclimatic constraints--based on the action of solar radiation (or sunshine duration) and air temperature on photosynthesis and respiration.

PROBLEMS OF AGROCLIMATIC ZONING

Climatic variables can be associated in innumerable ways to create agroclimatic zoning. A zoning method makes sense only relative to the precise objectives it has. These objectives can be divided into two groups that correspond to two principal types--general and specific--of agroclimatic zoning.

General types of agroclimatic zoning systems often refer to broad geographic regions (country, continent, or the entire world). The object is to identify zones of possible crops as related to the length of the vegetative cycles, the choice of crop and varieties, and the possibility of obtaining satisfactory levels of production. Specific types of agroclimatic zoning studies are done on a more detailed scale and refer to a particular crop. Specific requirements of the particular variety can be compared with existing climate conditions in each zone. Eventually, this type of zoning can narrow down to a single aspect of the crop: disease development, utilization of one cultivation technique, the demands of a particular phenological phase (term or period of photosynthesis, necessity of a dry period for maturation or of intense cold for germination, etc.).

In this chapter, some suggestions for developing a general method of zoning are presented, with these principal objectives:

1. Identification and potential solution of problems of agricultural development linked to the interaction of climatic factors with the systems of production.
2. Definition of a macroclimatic reference framework in which specific crop studies can be situated within a more adequate geographical scale.
3. A well thought-out generalization of the results of agronomic experimentation obtained in a given place for other zones with similar agroclimatic characteristics. The costs of agronomic investigations and tests are high. Thus governments and national and international organizations must use agroclimatic zoning as a tool for extrapolating rationally and in the greatest possible scale the most valuable results obtained in specific places.

In actuality, Latin American and Caribbean countries, which display a wide variety of ecosystems--from deserts to dense and humid forests--have little rational and applicable agroclimatic zoning to facilitate the development of policies that could increase and optimize agricultural and livestock production.

The present ecological zoning systems--such as the division of the American tropics into arid, semiarid, humid, and very humid--are drawn from considerations based mainly on annual averages of precipitation and temperature, or at best are drawn from the duration of the dry season. They do not provide adequate information to guide agricultural and livestock development.

A rational and applicable agroclimatic zoning system specifically oriented to examining and solving agricultural and livestock problems would have to take these facts into consideration:

1. One year is not an adequate time base in agroclimatology. Plant cycles vary according to the crop being considered--whether it is annual or permanent--from a few months to more than 12. Furthermore, there are few regions in Latin America and the Caribbean that have agroclimatic conditions that permit, over the course of the whole year, the assessment of the success of the crops growing there. As a consequence, in most areas dedicated to dryland farming, it is indispensable to take into account the concept of "growing period," defined as the period of the year in which rainfed crops must be established and developed in order to obtain satisfactory yields with adequate margins of security.

2. Crop growth and production demand not only water, but also solar radiation and warmth. Very often, when the water supply for the crops is satisfactory, solar radiation and temperature are limiting factors to agricultural yield, and vice versa. A rational method of agroclimatic zoning must take into account at least these three climatic factors, combining them in a form that emphasizes their influences on the processes of plant growth.

3. Agricultural decision making--such as choice of crops, varieties, techniques of cultivation, and systems of production--is always made in terms of risks, that is, the probability of achieving satisfactory yields. From the exclusively climatic point of view, these probabilities correspond to the occurrence of factors that permit yields. Therefore, the consideration of averages of climatic variables--be those annual, monthly, or for a shorter period--are not very useful in making decisions that should be taken with knowledge of the probabilities of occurrence of the climatic factors needed.

4. Depending on the types of available soils and the possible crops for cultivation, the determination of probabilities of occurrence of climatic factors should be arranged for short periods on the order of 10 days. These periods should correspond to the time during which the total reserve water supply of the soil can assure, in the absence of further rain, a good water supply for the crops. An agroclimatic zoning method should of necessity base itself in the values of the climatic variables that characterize the growing period.

CHARACTERISTICS OF THE METHODOLOGY

To develop a method of agroclimatic zoning that takes into account these considerations and principles, we have developed a unique, computer-processed, computer-calculable index that can be given cartographic expression. The index, which integrates the climatic interactions discussed earlier, permits an estimate of maximum agricultural production, given that the other factors that can limit production (such as soils, drainage, fertilizers, cultural practices, etc.) will not impinge negatively. Thus, we are trying to formulate an index that expresses potential agricultural production as a function of climatic realities of the region under consideration. It is identified as the IPP (index of potential production).

This index is not the result of an arbitrary combination of climatic and biological variables. It is derived by applying the laws of physics to biological processes that govern plant growth: photosynthesis, respiration, evapotranspiration, etc. This process facilitates finding a valid method of ecological zoning.

The creation of the IPP results from the consideration (1) of a function that takes into account, at any given moment, the interaction of climatic variables and of parameters that express the biological behavior of the crops, in order to produce yields; and (2) of a period of integrating this function, corresponding to the number of days during which the crop is actually growing.

Definition of the Function of Production

For the production function, we have chosen a classical model developed by de Wit (1971), which also appears in an excellent work by the Food and Agriculture Organization of the United Nations (FAO 1978). It translates the impact of solar radiation and air temperature upon photosynthesis and respiration in good water supply conditions:

$$NP = \frac{0.36 \times mgb}{1/N + 0.25 \times c_t}$$

where

NP = net production of total dry matter by the crop during N days of its cycle, expressed in tons per hectare
mgb = maximum level of gross biomass production by the crop
c_t = coefficient of respiration of the crop

The coefficient c_t is expressed as a function of the mean temperature t by

$$c_t = c_{30}\ (0.044 + 0.0019t + 0.001t^2)$$

where c_{30} is the coefficient of respiration of the crop for t = 30°C.

The value of mgb depends on the maximum measure (Pm) of photosynthesis of the leaves of the crop in a condition of light saturation and average global solar radiation during the period under consideration (G, expressed in gram calories/cm^{-2}/day^{-1}). G can be approximated based on the relative period of solar insolation: h/H, where H is the duration of the day, from dawn to nightfall.

Figure 7.1 shows the variations of Pm relative to the average (θ) daytime temperature for the different groups of crops: C_3, C_3 special, C_4, and C_4 special. The FAO study (1978) defines these groups, which correspond *to four different types of plant metab*olism.

To keep the study general, avoiding the choice of a particular crop, we choose values for the biological parameters: the coefficient of respiration (C_{30}) and the maximum level of photosynthesis of the leaves (Pm), which lead to the maximum production (NP) in each climatic environment considered. We take the value C_{30} = 0.0108, valid for all the crops except the legumes, which exhibit greater losses of dry matter and therefore less net production. The values of the NP function, and consequently of the IPP, are expressed in tons of total crop dry material at the harvest date. Generally there is a good proportional relationship between the production of usable product (grain, fruit, leaves, roots, etc.) and the total dry matter production.

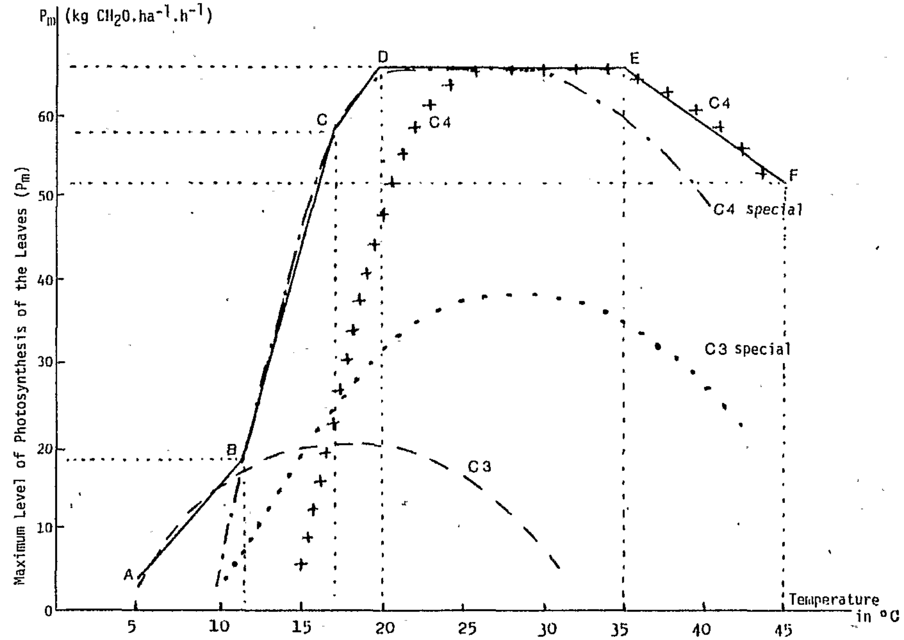

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FIGURE 7.1 Variations of the maximum level of leaf photosynthesis (P_m) relative to average daytime temperature for the different metabolic-type crop groups: C_3, C_3 special, C_4, and C_4 special (*under conditions of light saturation*).

Definition of the Period of Integration of the Function of Production

For a given crop, the logical period of integration* is the duration of the vegetative cycle of the crop. To generalize our study, avoiding the choice of a particular crop, the integration period will be defined as the total duration of the period for any year during which crops can be raised with satisfactory yields. We will call this period the "annual period of cultivation." This can include one or several "elemental periods of cultivation" that will be defined later.

*We use the term "period of integration" because it is easier to use. It would be better to say that we are concerned with the "period of calculating the averages" of the variables and parameters that go into the formula, thereby permitting a calculation of the value of the production function corresponding to this period.

The elemental index of potential production is calculated through integration of the function of production for each of these corresponding elemental periods. The annual index of potential production is attained by adding the elemental indices together. This method can be justified according to the idea that it is always possible to make use of the totality of the elemental periods of cultivation and thus find the maximum possible production. Thus, by choosing variables with cycles of convenient length between 70 and 365 days and by using adequate cultivation techniques (time-spaced plantings, intercropping, or multiple cropping), advantage can be taken of the total duration of any elemental period of production. The production that would have been obtained with just one crop whose vegetative cycle would correspond exactly to the duration of the given elemental period of cultivation can be equaled or surpassed.

Definition of the Elemental Period of Cultivation

This period corresponds to the series of consecutive 10-day periods with conditions of good natural water supply and average temperatures (t) above 6°C.

To understand the concept of "good water supply," we will take into account the wide interannual variation of precipitation, following the methodology initially proposed by Franquin (1973). The crop water requirements will not be expressed in terms of averages that have little relevance to agricultural production; instead, they will be expressed in terms of probabilities of occurrence of a given quantity of precipitation, relative to the potential evapotranspiration (ETP) of the crop for the period under consideration. The ETP--which can be calculated with a climatic formula--gives a good approximation of the maximum water requirements of any crop (Lhomme and Monteny 1980).

For each period of 10 days of the year, the probability is calculated as to whether precipitation (P) will be equal to or greater than one fraction of ETP. We consider that during one 10-day period, a good water supply is attained for any crop if precipitation brings a quantity of water equal to ETP/2 with a probability equal to or greater than 0.75 (three years out of four). Figure 7.2 illustrates this definition.

It is estimated that the 0.25 probability (one year out of four) of not having sufficient water supply for 10 consecutive days of the crop cycle constitutes an acceptable risk for the farmer. We also estimate that a quantity of water equal to ETP/2 permits a good supply for the crop over the length of its vegetative cycle (except during phenological phases that are very sensitive to lack of water, such as the blossoming phase). This is the reason why only elemental periods of cultivation are taken into account: besides exhibiting a probability equal to or greater than 0.75 of having $P > ETP/2$ for each of their 10-day periods, they also exhibit a probability equal to or greater than 0.75 of having $P > ETP$ during at least one 20-day period. It is considered that 20 days is more or less the duration of the phase most sensitive to water supply for the majority of crops.

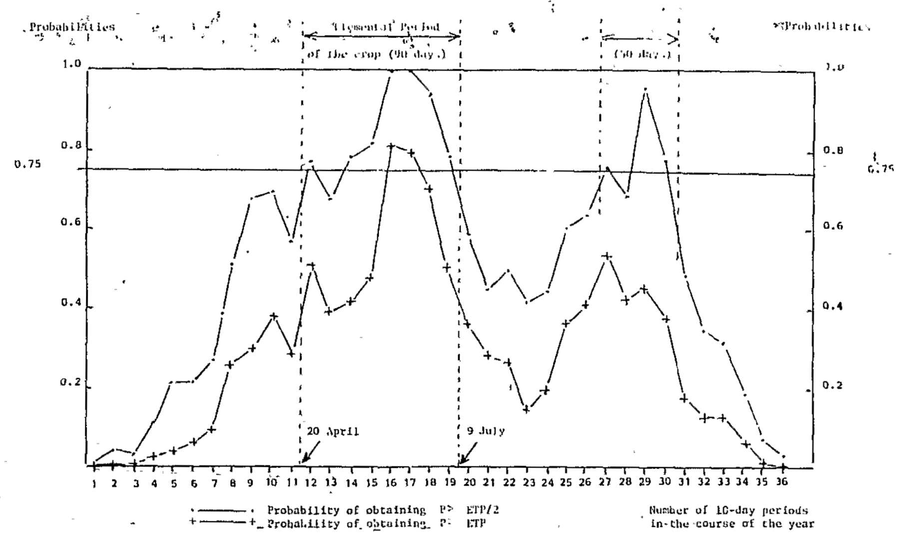


FIGURE 7.2 Probability of obtaining a good water supply during each 10-day period of the year.

The choice of 10 days as a time base for analyzing water balance derives from the ability of a soil with average characteristics to hold rainwater and to have that water available to the crop. In practice, this means that if all the precipitation for a 10-day period falls at the beginning of the period, the quantity of water retained in the soil should assure a good water supply for the crop throughout the 10-day period and for part of the following one.

Ten-day periods with an average air temperature of less than 6°C are eliminated. Such low temperatures during the growth period of a crop are not considered compatible with profitable agriculture. It is permitted that a 10-day period with a probability of having $P \geq ETP/2$ less than 0.75 form part of an elemental period of cultivation if it is preceded or followed by 10-day periods with probabilities of having $P > ETP/2$ equal to or greater than 0.75.

Finally, the succession of 10-day periods that fulfill all the preceding requirements constitutes an elemental period of cultivation only if it has a minimum duration of 60 days.

DATA PROCESSING

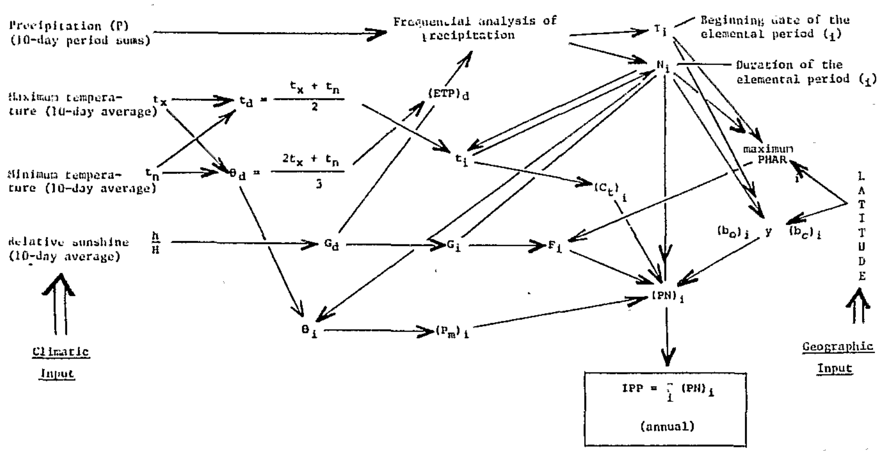
The cartographic expression of the IPP is related to two main problems: (1) having a sufficient density of stations where available climate data permit calculating the IPP; and (2) defining a method of interpolation between the exact values of the data required for calculating the IPP, thereby facilitating drawing the isovalue curves of this index.

The basic idea is to divide the territory under study into zones that present a certain homogeneous morphology (slope, plateau, altiplano, savannah, etc.) and that experience the same macroclimatic influences (air masses, orientation of the principal winds, presence of ocean currents), processing the information for each one of these zones in this way:

1. Using the frequency analysis described earlier, the duration (N_i) and the beginning date (τ_i) of each elemental period of cultivation are determined.
2. For each 10-day period of the year, multivariable regressions are sought from the duration (N_i) and the beginning date (τ_i) of the elemental periods of cultivation, from the maximum air temperature (t_x), the minimum air temperature (t_n), and the absolute sunshine duration (h) in function of the three following variables: altitude (ALT), latitude (LAT), and longitude (LONG) of the stations under consideration. These regressions permit calculating the net potential production of total dry matter (NP_i) of each elemental period of cultivation and then the annual climatic index of potential production (IPP) for any location, knowing only its altitude, latitude, and longitude. (See earlier discussions and figure 7.3.)

This process permits easy cartographic expression of the IPPs. It is sufficient to program a computer to make the necessary calculations for each point of intersection of a geographic grid whose density will depend on the heterogeneity of the region under study. The only preliminary work to be done is pinpointing--with a relief map, for example--the altitudes of each point of the grid.

In regions with scarce climatic data, it may be possible to use images of the vegetative ground cover obtained by remote sensing to check the completed agroclimatic zoning system. The basic idea is that natural vegetation is a good integrator of climatic factors, and that a certain correspondence can be expected between the



NOTE: The inferior index ($_i$) identifies the averages calculated by the duration (N_i) of the elemental cultivation period ($_i$); the inferior index ($_d$) identifies those averages calculated by 10-day periods.

FIGURE 7.3 Calculation of the index of potential production (IPP).

presence of large expanses of vegetation and the characteristics of the principal agroclimatic zones.

COMMENTARY

The index of potential production (IPP) is expressed in terms of tons of total dry matter per hectare per year and represents the approximate annual production that could be achieved under the following conditions: no nonclimatic interference, crop(s) functioning during all the elemental periods of cultivation, and crop(s) displaying the highest level of gross photosynthesis and the least coefficient of respiration compatible with the environmental temperature. It is necessary to remember that this index has above all a relative value. Its principal purpose is to permit the definition and comparison of different geographical zones from the point of view of the climatic potential for agricultural production.

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