AGRO-CLIMATE-BASED LAND EVALUATION SYSTEMS

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Summary

Rainfall, temperature and solar radiation have a direct impact on plant growth either through the uptake of soluble nutrients from the soil and the root zone, the promotion of chemical reactions and photosynthesis in the plant, and the build-up of biomass. Station measurements of these parameters can also be combined into more compound factors of growing period, frost-free period, cumulative degree-days and corn heat units, on the basis of which agro-climatic zones can be delineated.

The classifications of Köppen and Thornthwaite can be considered as early bio-climatic classifications and predecessors of agro-climate-based land evaluation systems. Penman and Monteith have defined in more detail evapotranspiration processes and plant-specific water consumptive use. A number of single-factor and multi-factor agro-climatic assessments are discussed, as well as three representative yield prediction models. The most complete and most innovative agro-climatic classifications are, however, those developed by Papadakis and by FAO for the Agro-ecological zones (AEZ) project.

The Papadakis system is innovative in the sense that it does not use mean climatic data but specific minimum, maximum or hazards that influence more directly crop

development. These parameters permit the more accurate definitions of winter severity, summer heat and moisture regime. Moreover a new method of computing potential evapotranspiration is also introduced, with worldwide validation, based on the mid-day saturation deficit. In the AEZ system the essential elements are: the growing period, temperature regime and soil map unit. The former two define the agro-climatic component. In this respect an agro-ecological zone constitutes a combination of a climatic and soil unit with homogeneous properties that can directly be matched with crop growth requirements.

1. Introduction

The importance of climate in influencing land cover, viz. natural vegetation or land use, requires no emphasis. Climate dictates to a large extent what the natural vegetation is and which crops can be grown; additionally it is mainly responsible - together with soils - for yearly variations in yields. The climate not only affects growth patterns, persistence, quality and yield, but also influences the response of each cultivar to different management practices.

In terms of natural land cover and the evaluation of agricultural potentials at national, continental or world levels climate is the most determining factor, and it defines the limits between which various plants or crops can develop on the basis of differences in soil and terrain composition. For this reason a number of land evaluation methodologies have been developed on the basis of agro-climatic parameters, sometimes in combination with soil factors. The zonation theory that guided Russian geographical research in the beginning of the past century is a typical example of the major emphasis which was given to the links between climate, soils and vegetation distribution over the world.

A good example of this zonation concept is Voloboyev’s classification of geographical zones and soil groups, based on a world zonal pattern determined by moisture and temperature criteria, and technically translated into hydro- and thermo-ranges respectively (see *Land Use, Land Cover and Soil Sciences*). Hydro-ranges are defined on the basis of the ratio between annual rainfall and evapotranspiration, the latter being an expression of plant-available moisture. Thermo-ranges are based on average annual temperatures with a direct impact on photosynthetic activity and related biomass production.

Trewartha’s classification into seven climate/vegetation/soil weathering zones is another example of the diagnostic weight given to climatic parameters. Arctic zones for example have low temperatures and hold water that is chemically not active, in contrast to cold-temperate and temperate zones which have less frost risks and available moisture and where a cryophilous type of vegetation can develop. At the other end, the tropical wet and very wet areas combine high temperatures with alternate dry/wet seasons or with year-round rainfall. The vegetation in these areas is not affected by temperature criteria, but is well differentiated on the basis of its degree of sensitivity to drought.

2. Climatic Factors affecting Land Use and Land Cover

Climate affects plant development and crop production either directly or indirectly. Rainfall, temperature and solar radiation have a direct impact on plant growth either through the uptake of soluble nutrients from the soil and the root zone, the promotion of chemical reactions and photosynthesis in the plant, and the build-up of biomass. The distribution of rain, low and high temperatures and sunshine over the year determine day length, the importance and nature of the growth cycle and the time and the conditions under which vegetative development can take place. Rainwater that infiltrates into the soil emerges as groundwater or as springs. Shortage of water or too low temperature determines what parts of the vegetation can survive or what yield reductions can be expected. Climatic hazards or extreme conditions lead to damage of crops.

Figure 1 illustrates in a schematic way the impact of the different climatic parameters on plant development. The key element in this process is the photosynthesis which produces the source of assimilates that plants use for their development. The rate of photosynthesis is influenced by both radiation and temperature. However, plants have also an obligatory development pattern in time and space which must be met if the photosynthetic assimilates are to be converted into economically useful yields of satisfactory quantity and quality. Details on the developmental sequence of crop growth in relation to crop phenology and C3 or C4 photosynthetic pathways are discussed in more detail in FAO (1978).

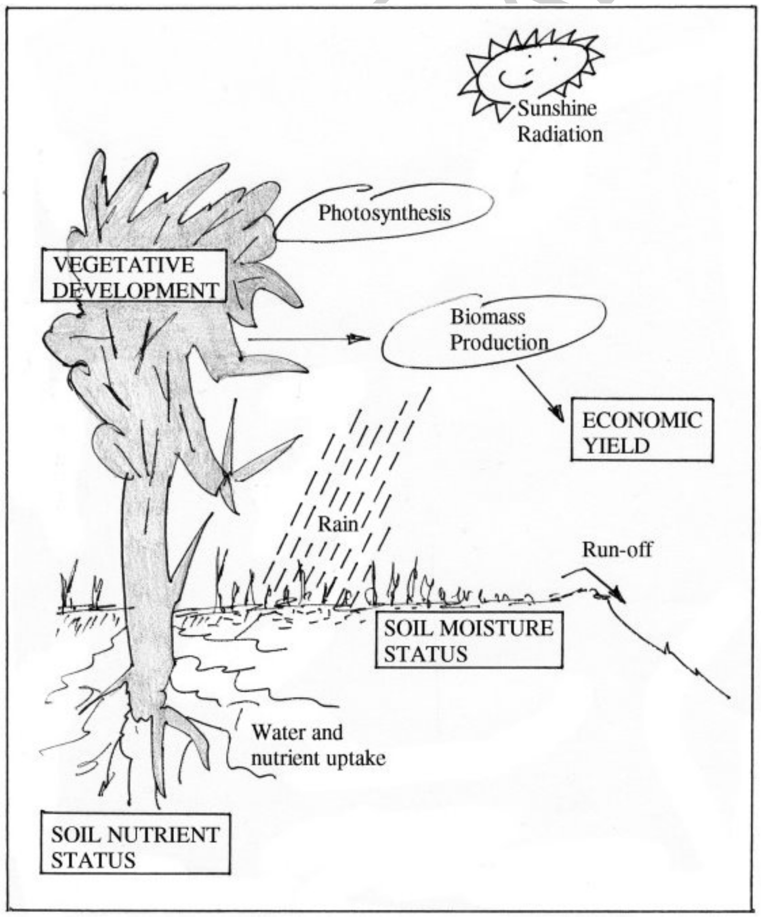

Figure 1. Schematic representation of the different climatic components affecting plant growth and development.

The impact of these factors on land evaluation lies in their relative impact on the specific growth conditions for the different crops. If those factors fit perfectly well with the crop requirements, i.e. if they correspond with optimal growth and production conditions, the given parameters are considered very suitable; the more these conditions depart from the optimum, the less suitable are the parameters. If the relative value of the factors drops beyond the critical level for an economic production, the parameter is considered unsuitable.

2.1. Temperature

Temperature is a major factor in the stimulation of biochemical processes in the plant. It can be expressed through a direct observation or measurement of the average, minimum or maximum temperatures registered over the day, the month or the year. For annual crops which do not stay permanently on the field, only the climatic conditions within the growth cycle are of importance, while annual means or observations outside that growth cycle are of no direct relevance. Hence, the focus should in the first place be on the start, length and end of the frost-free period, the length and quality of the growth cycle, and on the accumulated energy supply over the growing period as a whole.

Average temperature is the most commonly used parameter. It gives a broad response on the question whether a plant or a crop can more or less satisfactorily grow in a given condition. Average temperature is, however, not very significant if the amplitude between minimum and maximum values is not provided. For a number of tropical crops this (daily) **amplitude** is a critical parameter for their development and extension. Coconut *(Cocos nucifera)* for example does not support daily amplitudes of more than 10°C and is therefore most often located near the coastlines and up to a maximum altitude of 200-300m. A similar situation occurs for cloves (*Eugenia caryophyllus*) in Madagascar and Zanzibar; they are only found between sea-level and a maximum altitude of 300m.

Maximum temperatures are rarely a limiting factor to crop growth, unless they are associated with high evaporative demands and moisture stress conditions. The crop damage registered by warm Sahara winds, in particular the *harmattan*, is more the result of low air humidity than of high temperature.

Minimum temperatures are more often a constraint, especially because low temperatures reduce physiological activities and might even become lethal for sensitive crops. Oil palm (*Elaeis guineensis*) is a tropical crop that requires a high average daily temperature (25-28°C) for optimal growth and production, but is seriously damaged when minimum temperatures drop below 18°C and absolute night minima are less than 14°C. At this moment, physiological disorders occur in the plant system, diseases develop and overall oil production decreases. Likewise bananas do not tolerate frost, and most plants die in a temperature of -3°C.

While in tropical countries minimum temperatures are rarely a constraint, the importance of temperature - and in particular the minimum temperature - increases with distance from the Equator. In northern countries, the average May to September or the July temperatures are often considered good indicators for the northerly extension of some heat-sensitive crops. In Canada for example the 70°F/21°C July isotherm - as an expression of mid-summer conditions - has for a long time been regarded as the northern boundary for grain corn and soybean production in the country, and the area south of this line in South-West Ontario still contains the highest concentration of these crops, even though earlier-maturing types are nowadays extending the corn belt further northwards (Chapman and Brown, 1978). Table 1 shows optimal and marginal temperature conditions for some selected crops.

Crop	**Optimal conditions (no growth constraints**	**Medium conditions (moderate growth constraints)**	**Critical value below which production is not economic**
Avocado	18-26	12-18 and 26-30+	<12
Banana	20-30+	8-20	<8
Cocoa	23-28	28-30 and 15-23	<15 and >30
Coffee (Robusta)	22-28	18-22 and >28	<18
Cotton	24-32	20-24	<20
Mango	22-28	15-22 and 28-38	<15 and >38
Oil palm	25-28	18-28	<18
Olives	15-22	13-15 and 22-26	<13 and >26
Pineapple	20-26	16-20 and 26-35	<16 and >35
Potatoes	15-24	8-15 and 24-30	<8 and >30
Swamp Rice	24-32	18-24 and 32-36+	<18
Wheat	12-22	8-12 and 22-30	<8 and >30

Table 1. Temperature requirements, in terms of mean air temperature (°C) in the growing season, for some selected crops.

Frost is a major problem for many crops. At low temperatures most physiological functions are stopped, and in some cases this temperature level is even lethal. Therefore, the **frost-free period** is a common parameter in agro-climatic classifications, especially in high-latitude or high-altitude countries. Frost is a critical factor especially in fruit and vegetable production. The probability of frost injury after a certain date in spring and before a certain date in autumn is obviously of vital concern for many farmers in Europe and North America. Usually, such critical last spring and first fall frosts, as well as the average number of frost-free days, are a critical component in agro-climatic evaluations of these countries.

Frost corresponds generally to a temperature of 0°C (32°F), though for hardy crops a lower temperature would be more applicable. For cereal grains for example the date of the **first killing frost in fall** should be put at the occurrence of a -3°C temperature. On the other hand this average date gives only a 50% chance of avoiding frost damage; for better odds one would point to an earlier date. These two factors tend to balance, so the average date based on 0°C is most often used. In high-latitude countries maps with isolines indicating the occurrence of first frosts in the year are a valuable parameter for agricultural planning. Figure 2 is an example of such map for Eastern Canada.

Initial investigations about the frost-free period have rapidly led to the broader concept of the **growing season,** which corresponds to the period in the year that climatic conditions are favorable for crop growth. On average, the start and end of this period corresponds with the time that grass is growing, i.e. when mean soil temperatures are above 5°C (air temperatures above 6.5°C). It may, however, also be adapted to specific crop requirements as argued below.

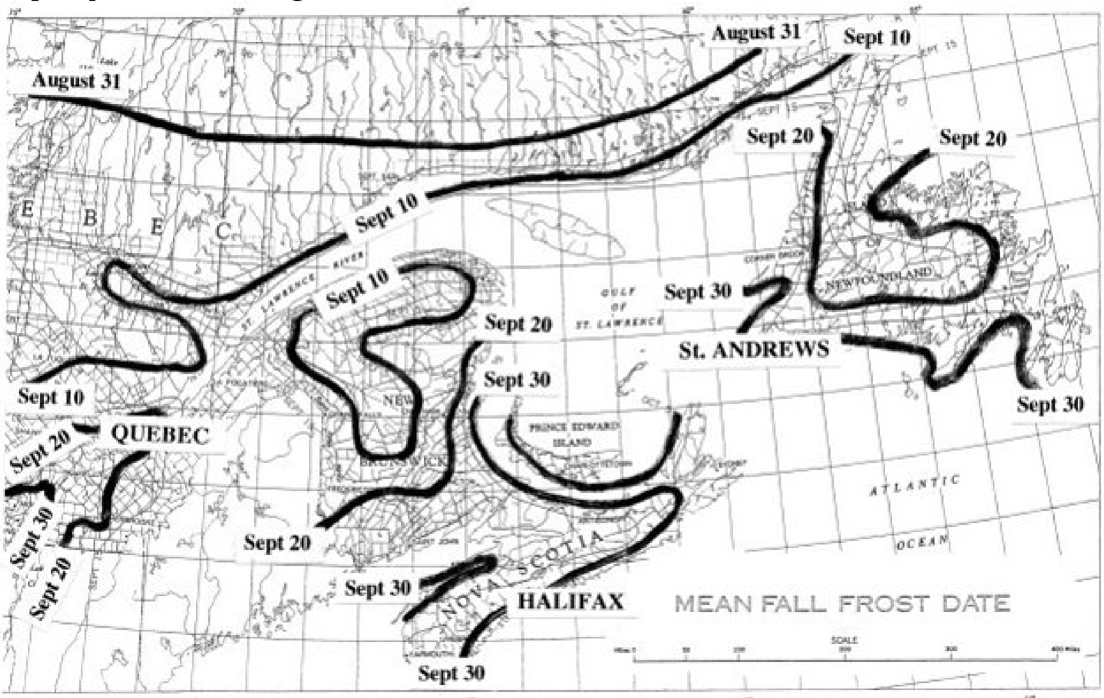

Figure 2. Mean fall frost date in Eastern Canada
(Chapman and Brown, 1978)

Closely related to the definition of temperature conditions in the growing season is the principle of **cumulative degree days** above a critical value. This value combines a time factor (the length of the growing period) with a heat intensity value (mean daily temperatures). The index hereby obtained can then be used as a measure of the total solar energy supplied during the growing period and required to bring a crop/plant to maturity.

In Canada, the critical level above which cumulative degree days are calculated is set at 5.6°C (42°F), which is considered as the limit above which grass and most other higher plants in the Prairie Provinces are activated. In this respect several zones were differentiated in the country (Figure 3):

- Areas with more than 4,000 degree-days (above 5.6°C); this area corresponds with the northern boundary for grain corn, soybean, sugar beets and other cash crops in South-West Ontario;
- Areas with 3,500-4,000 degree-days; this zone includes de production area of grain

corn, soybean and flue-cured tobacco;

- Areas with 3,000-3,500 degree-days; only the earliest corn hybrids can mature here, especially nearby the northern border; silage corn is the main crop of this belt;
- Areas with 2,500-3,000 degree-days; this area includes a broad belt in the Southern part of the Prairie Provinces, and can be associated with a region with a frost-free period of 100 days or more. In terms of agricultural activity this area constitutes a transition zone for wheat growing. For that crop 90 frost-free days is the critical limit and it occurs further north than the 2,500 degree-day line. In fact, the higher temperatures south of the 2,500 degree-day line appear to be a slight disadvantage;
- The area with 2,000-2,500 degree-days; it is rather heterogeneous in terms of frost-free period which extends from 59 to 105 days depending on local conditions; hence wheat production in this zone is only possible along the upper limit of this climatic zone.

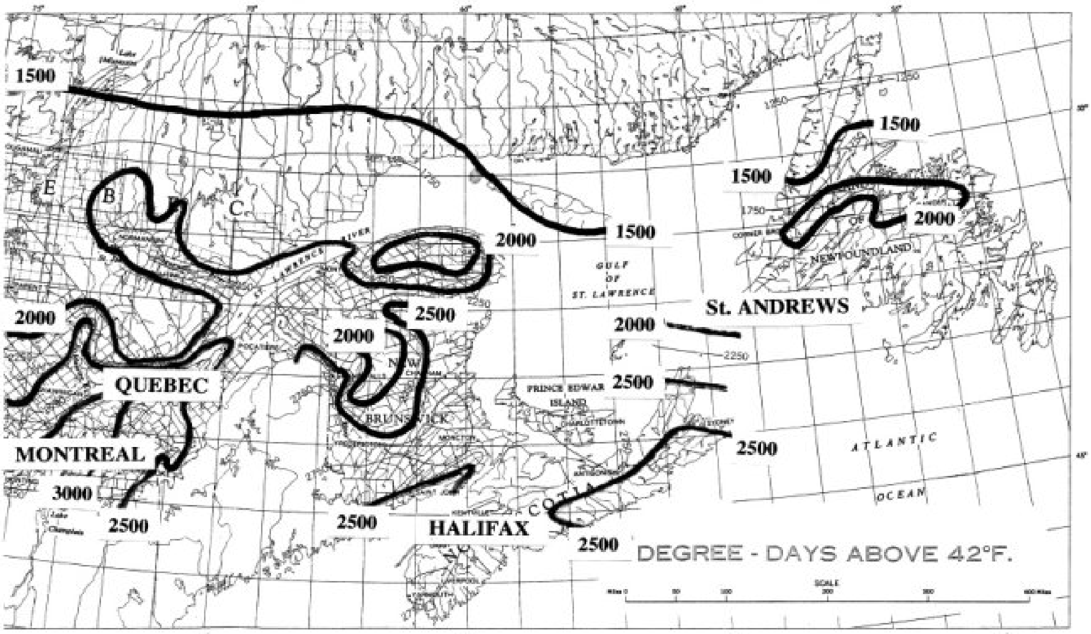

Figure 3. Degree-days above 5.6°C (42° F) in Eastern Canada
(Chapman and Brown, 1978)

Corn heat units (CHU) represent a crop-specific adaptation of the former principle. The concept was developed in Canada where it was used as an expression of maturity ratings of corn hybrids in Ontario. It is based on the principle of cumulative degree-days above a critical value during the growing season for maize. The date coinciding with a mean temperature of 12.8°C (55°F) in spring is used as the planting date. The end of the season was put at the time that the average temperature reaches attends 0°C. Figure 4 displays the corn heat units map for Eastern Canada.

The "corn heat unit" formula makes use of both maximum and minimum daily temperatures. The relationship to maximum temperatures is parabolic, rising from zero at 10° C (50°F) to a peak of 33 at 30° C (86°F), then diminishing. Degrees above 4.5°C (40°F) are computed from daily minimum temperatures. The two are then averaged to give a single figure for each day of the growing season. The formula is expressed as follows:

$$CHU = \sum_{i=1}^{n} \frac{(T_{min} - 40) + 1.85(T_{max} - 50) - 0.26(T_{max} - 50)^2}{2}$$

where T_{min} and T_{max} are the average minimum and maximum temperatures for each day (i).

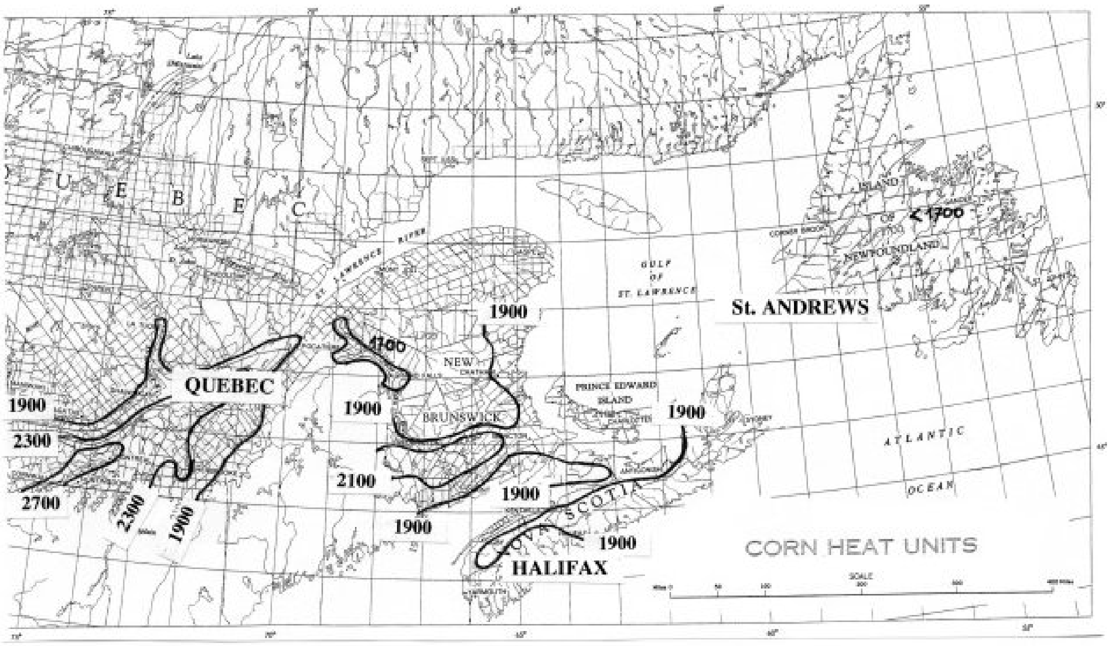

Figure 4. Corn heat units map for Eastern Canada
(Chapman and Brown, 1978)

The system has been applied only in the warmer areas of Canada, where corn production is possible, i.e. in Ontario where grain corn is grown in areas with 2,500 CHU and above, and in other southern areas where silage corn is produced in areas with CHU between 2,000 and 2,500.

Grain corn, oats and barley are used mainly for energy in livestock feed. In areas where the growing season is ample, corn is a more efficient producer of energy than barley. However, the advantage that corn has over barley decreases as the growing season shortens and cuts off with our present hybrids at about the 2,300 CHU line. The development of new earlier hybrids would push the northern fringe of corn production towards the 1,900 CHU line.

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Biographical Sketch

Willy Verheye is An Emeritus Research Director at the National Science Foundation, Flanders, and a former Professor in the Geography Department, University of Ghent, Belgium. He holds an M.Sc. degree in Physical Geography (1961), a Ph.D. in soil science (1970) and a Post-Doctoral Degree in soil science and land use planning (1980).

He has been active for more than thirty-five years, both in the academic world, as a professor/ research director in soil science, land evaluation, and land use planning, and as a technical and scientific advisor for rural development projects, especially in developing countries. His research has mainly focused on the field characterization of soils and soil potentials, and on the integration of socio-economic and environmental aspects in rural land use planning. He was a technical and scientific advisor in more than 100 development projects for international (UNDP, FAO, World Bank, African and Asian Development Banks, etc.) and national agencies, as well as for development companies and NGOs active in inter-tropical regions.