Physical Resources of the Humid Tropics and their Relation to Yield Potentials of Food Crops

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Summary

The analysis presented in this contribution has shown that the physical resources of the humid tropics permit high agricultural production levels. However, in extensive areas temporary water shortage presents a serious constraint, so that the potential set by crop characteristics, radiation and temperature is not reached. Development of reliable irrigation facilities could alleviate that problem, as has been shown in various places.

Nutrient shortage to the vegetation forms an even more serious problem, especially oecause many tropical soils are seriously depleted due to their old age. In addition many soils show phosphorus fixing properties limiting the effectiviness of phosphorus fertilizer application. Finally the high temperatures and humidity favour the decomposition of organic material and limit the buffering capacity of the soils for nutrients. However, judicious application of fertilizers could improve that situation.

In any case, sustained high production requires input of materials from outside the agricultural community, at a reasonable cost. In analysing the present situation in many parts of the world, it appears that not so much the physical resources are the limiting factor for agricultural production, but that the economic environment in which the farming community is operating, is a serious limitation to crop production. Such a conclusion may on one hand seem disappointing for agronomists, since it could imply that their possible contribution to alleviation of the problem of hunger and malnutrition is very limited, on the other hand it does require continuous emphasis on the fact that agricultural science can provide solutions, if the economic incentives are strong enough.

1. Introduction

The humid tropical region, as defined by *Blumenstock and Thornthwaite* [1941] comprises about 25% of the land surface of the earth. In terms of total population the humid tropics contain some of the most densely populated areas of the world (the Indonesian island of Java for instance has a population density of over 600 persons per km²), due in part to the favourable environment that ensures a relatively stable food production over the years. The rapidly expanding population of these regions requires, however, a steady expansion of food production to satisfy the requirements also in the future.

In principle, increased food production can be achieved by two means. One is increasing the acreage under food crops, through reclamation of land currently under natural vege-

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tation or not used due to unfavourable environmental conditions, or through transfer of land from cash crops to food crops. The other one is increasing the yield per unit area, either through extension of the period of crop growth, such as multiple cropping, or by increasing the yield per «field day» of the crop.

Reclamation of new land, however, generally meets with difficulties, because the land that could easily be reclaimed is used for cultivation already, thus reclamation in the present situation requires substantial efforts that cannot be provided by individual farmers or local communities, but must be brought about by large-scale government-sponsored operations requiring high investments. In many instances the economics of such operations are doubtful, because price policies for agricultural products are not conducive for production increases. Moreover, transformation of soils presently under natural vegetation into agricultural land often leads to a rapid decline in the nutrient-supplying capacity of the land, through leaching, loss of top soil through erosion and exploitation. This results in disappointingly low yields at relatively short term, that makes the effort of farming hardly worthwhile.

More promising therefore seems the venue of increasing the yield per unit area. In this contribution the physical resources of the humid tropics will be discussed, their relation to the yield potential of some major food crops of the region, and the constraints that may be operative in determining the present yield levels. Some conclusions will be drawn as to the possibilities of alleviating these constraints and increase the yields.

2. The physical resources

2.1 The climatic resource

The geographical zone referred to as the humid tropics is located roughly between 20° north and 20° south of the equator. The climatic environment of the region is in part conditioned by its proximity to the equator, which for instance is responsible for the absence of large temperature fluctuations throughout the year. However, locally, the climate may be modified by the influence of specific topographical and geographical features, such as mountains and proximity to the sea. It is outside the scope of this paper to go into the processes underlying the climatic variation throughout the year, such as the general air circulation over different parts of the world (*Williams and Joseph [1970]*). For the present purpose, only the consequences for the relevant climatic variables will be discussed, and their effects on crop growth and yield.

2.1.1 Radiation

The energy of the sun is a major resource in the agricultural production process in which this energy is converted into edible organic material by means of plants and animals. Outside the atmosphere of the earth, a surface kept at a right angle to the rays of the sun receives energy at an average rate of 1360 W m⁻², a value known as the solar constant. However, the earth's surface is generally not perpendicular to the rays of the sun, and the lower the sun angle, the lower the energy intensity received on a horizontal plane. The variation in this geometrical factor is relatively small in tropical regions, compared to the temperate regions, as illustrated in Figure 1, derived from the *Smithsonian Meteorological Tables (Monteith [1972])*.



Fig. 1 Ratio of radiation received on a horizontal plane outside the atmosphere and the solar constant.

Moreover, in passing through the atmosphere part of the radiation is absorbed and scattered by clouds, by gases and by solid particles in the atmosphere, such as dust and salt. The actual radiation intensity received on a horizontal plane at the earth's surface is thus appreciably lower than the extra-terrestrial radiation intensity. In Figure 2 radiation data from some stations in the humid tropics are given. These data clearly show that considerable differences among the locations exist. In Dacca, the highest value occurs in May at slightly over 2.4×10^7 J m⁻² d⁻¹, dropping to a low of 1.6×10^7 J m⁻² d⁻¹ in January. The pattern for Los Baños, the Philippines is very similar, with the highest value measured in April and the lowest in December, although with about 1.2×10^7 J m⁻² d⁻¹ still 25% lower than in Dacca.

The pattern for San Ramon on the South-American continent is distinctly different, with the maximum occuring in November, but with 1.9×10^7 J m⁻² d⁻¹ substantially lower than in the Southeast Asian region. The amplitude is also lower, as the minimum in June is almost 1.5×10^7 J m⁻² d⁻¹.



Fig. 2 Monthly average total global radiation for five locations in the humid tropics. a) Dacca, 23°43' NL, 90°26' EL; b) Los Baños, 14°25' NL, 121°20' EL; c) San Ramon, 11°08' SL, 75°18' WL; d) Bogor, 6°45' SL, 107°01' EL; e) Lampang, 18°17' NL, 99°31' EL.

The pattern for Bogor, on the island of Java shows about the same fluctuation as San Ramon, the maximum value not exceeding 1.6×10^7 J m⁻² d⁻¹, and the minimum at 1.15×10^7 J m⁻² d⁻¹. The timing is again different however, the maximum being observed in September, and the minimum in January.

The radiation pattern for Lampang in Thailand is again very similar to those for the first two locations, but the maximum is substantially lower (slightly over 2×10^7 J m⁻² d⁻¹), with about a similar minimum.

Such differences are partly related to the geographical position of the locations: Bogor is located 250 m above sea level in a mountainous area, where cloudiness is generally high, whereas Los Baños and Dacca are both located at sea level, with a much longer duration of bright sunshine. San Ramon is located in the Andes at an altitude of 800 m, where cloudiness is also rather high, and the mirrored pattern reflects the position with respect to the thermal equator.

2.1.2 Temperature

A general feature of the humid tropics is, that temperature fluctuations throughout the year are as a rule relatively small. However, temperature is affected by the prevailing air streams, the duration of bright sunshine, and the geographical position in which latitude, altitude and distance to the sea play a role (Figure 3). The «ideal» picture is most closely approached by the temperature regime at Bogor, where average temperature fluctuates only slightly over one °C over the year. The temperature pattern in this case is affected by the altitude of 250 m at which the station is located. The other extreme in the examples is Dacca where the average temperature differs more than 10 °C between winter and summer. Dacca is an inland station, lacking the modifying influence of the sea and located almost at sea level. Los Baños and San Ramon are intermediate cases, with respect to temperature, showing variations of 4 and 2.5 °C, respectively.

There is some danger in considering average air temperature in connection with crop growth, as the same mean temperature may result from different values for minimum and maximum temperature. Especially at higher altitudes the daily amplitude may be considerable. Assimilation is mainly affected by day-time temperature, whereas growth and respiration are much more sensitive to night-time temperatures. Hence, average 24hour temperatures may mask important differences in crop performance.

2.1.3 Air humidity

The major effect of air humidity on crop performance is through its influence on the evaporative demand of the atmosphere, which is one of the main determinants of crop transpiration. In this respect it is not so much the absolute humidity of the air that counts, but rather the difference between the saturated humidity at the prevailing air temperature and the actual humidity. For Dacca (Figure 4a) the vapour pressure varies between about 14 mbar in January and about 34 mbar in June/July. That, however, coincides with a temperature fluctuation between 18.5 °C and 29 °C, corresponding to saturated vapour pressure values of about 21.4 and 40.3 mbar, respectively. The difference in vapour pressure deficit is thus only very small, varying from about 7 mbar in January to about 6 mbar in June/July. The relative humidity, another measure of air humidity fluctuates between 65% in the dry season and 85% in the middle of the wet season. However, in terms of evaporative demand, the absolute difference between saturated vapour pressure and actual vapour pressure is the driving force, hence there is very little variation over the year.



Fig. 3 Monthly mean daily temperature for five locations in the humid tropics (for details see caption Figure 2).



Fig. 4 Monthly mean vapour pressure (--) and monthly mean relative humidity (---) for five locations in the humid tropics (for details see caption Figure 2).

The situation is different in San Ramon, where in the dry season (June/July) the actual vapour pressure is around 15 mbar, at a temperature of 21 °C, corresponding to a saturated vapour pressure of about 25 mbar. Relative humidity is thus about 0.6, and the vapour pressure deficit 10 mbar. In the wet season (January/February) the actual vapour pressure is around 25 mbar, at a temperature of 22.5 °C, hence a saturated vapour pressure of 27.5 mbar. Relative humidity is then 0.9, and the vapour pressure deficit only 2.5 mbar. The contribution of the «drying power» term in the evaporative demand is thus substantially higher in the dry season than in the wet season for this location.

2.1.4 Potential evapotranspiration

In Figure 5 the evaporative demand of the atmosphere, expressed as potential evapotranspiration is shown for the various locations.



Fig. 5 Monthly mean potential evapotranspiration for five locations in the humid tropics. Dotted lines are calculated from class A pan measurements (for details see caption Figure 2).

For Dacca (a), San Ramon (c) and Lampang (e), the values are those calculated according to the method of *Penman*, while for Los Baños and Bogor Class-A pan values are given. It would be possible to devote an entire lecture to the relation between the two values, including a treatise on the question to what extent either of the values is representative for the actual water requirement of a crop surface. There seems to be little point in starting that discussion in the framework of this presentation, hence, as a rule of thumb, a conversion factor of 0.7 has been assumed to convert Class-A pan data into crop water requirements (Figure 5, dotted line).

Comparison of Figure 5 and Figure 2 shows the strong positive correlation between the level of radiation and the evaporative demand for each of the locations. That correlation is of course not surprising because most of the energy absorbed by the vegetation must be dissipated in the form of transpiration, since the photosynthetic process utilizes only a negligible part of that energy. When comparing different locations the correlation is less strong, because other factors such as air humidity and wind speed are co-determining factors for the evaporative demand. Nevertheless, the correlation still holds to a considerable degree as witnessed by the highest value of 8 mm d⁻¹ (Los Baños, April) and the lowest value of 2.6 mm d⁻¹ (Bogor, December), coinciding with practically the highest (2.45×10^7 J m⁻² d⁻¹) and the lowest (1.3×10^7 J m⁻² d⁻¹) average radiation intensity. These values also illustrate the substantial variation in crop water requirements both throughout the year and between various locations in the humid tropical region. These variations are of direct consequence for crop production, because the availability of sufficient moisture to satisfy the demand as dictated by environmental conditions, is a pre-requisite for unrestricted growth of the crop.

2.1.5 Precipitation

The other weather variable that is of importance for the availability of moisture for the vegetation is the amount of precipitation. The designation «humid tropics» could suggest that precipitation is always plentiful, but the data in Figure 6 show that a large variability exists, both within the year and from location to location: monthly rainfall varies from almost 440 mm (Bogor, October) to 5 mm (Dacca and Lampang, January/February). The rainfall amount and rainfall pattern is primarily determined by the general air circulation, but may be modified by the geographical position, including proximity to the sea, and position with respect to nearby mountains, both relative to the main wind direction. Where air streams hit land masses after passing over water bodies for prolonged periods of time, precipitation is generally high, whereas further inland precipitation tends to be lower. Also locations on the windward side of mountains (such as Bogor, Figure 6d) are wet (orographic rains), while locations on the leeward side tend to be much drier. In Southeast Asia (Figures 6a, 6b, 6d and 6e) rainfall is mainly determined by the location of the intertropical convergence zone (ITCZ, Oldeman and Frère [1982]). In the northern hemisphere winter period, the ITCZ is located south of the equator, while high pressure areas are located over the Northasian continent and over the North Pacific, separated by a low pressure area off the coast of Japan. The consequence of this air pressure distribution is that northerly winds prevail in Bangladesh and Thailand, bringing cool and dry air after passing over the Indo-Chinese continent. This period is therefore dry to extremely dry in this region (Figures 6a and 6e). In the Philippines northeasterly winds from the Pacific prevail during this period, but the mountain chain present over most of







Fig. 7 Mean monthly water balance for five locations in the humid tropics (for details see caption Figure 2).

the country prevents far penetration so that Los Baños is very dry during that period (Figure 6b). Indonesia, particularly the southern part is subject to northwesterly winds that bring moist air to the western part of Java, where rainfall is intensified by the east-west chain of volcanoes on the island (Figure 6d).

In the northern hemisphere summer period the situation changes dramatically. The Eurasian continent is heated substantially in this period, creating a cell of low pressure over the Indian subcontinent, accompanied by high pressure regions over the Australian continent, just off the east coast of South Africa, and in the Pacific Ocean on both sides of the equator. The consequence is that in Thailand and Bangladesh southwesterly winds now prevail, bringing air that has picked up moisture passing over the Indian Ocean, so that rainfall is high to very high during that period.

Easterly to northeasterly winds, originating in the Pacific, reach the Philippines bringing also there abundant rainfall. Occasionally these easterly waves develop into cyclonic disturbances that reach the islands in various stages of development, up to tropical typhoons.

Indonesia is during that period subject to southeasterly winds originating from the Australian continent. In the southeastern part of the country that leads to relatively dry periods, but in the western part rainfall is still very substantial, even though relatively it is the driest period (Figure 6d).

In terms of crop production it is the balance between evaporative demand (Figure 5) and precipitation (Figure 6) that determines to what extent unrestricted crop growth can be expected. If the evaporative demand exceeds precipitation for a prolonged period of time, temporary water shortage for a crop may develop, leading to closure of the stomata in an attempt to restrict water loss to the atmosphere with the consequence that exchange of CO_2 is reduced proportionally (*de Wit[1958]*). As a result growth and production will also be reduced. To illustrate that effect more clearly, the data of Figure 5 (on a monthly basis now) and Figure 6 have been combined in Figure 7, according to the method proposed by *Thornthwaite [1948]*.

Figure 7 shows that Bogor (Figure 7d) is the only location where rainfall at all times exceeds potential evapotranspiration, so that continuous cropping is possible without the risk of water shortage. For all other locations there are periods of variable length (3 months for San Ramon, to 7 months for Lampang) where potential evapotranspiration exceeds precipitation to some extent. Especially when the period is prolonged and the deficit substantial, water shortage may easily develop since the capacity of the soil to store such quantities is seldom sufficient.

It appears thus that in the humid tropics extensive areas exist where during part of the year water supply is a serious limitation to crop production.

2.2 The soil resource

In addition to climatic factors, soil properties play an important role in determining the yield capacity of a certain crop in a given environment. On the one hand the physical properties of the soil are of importance, which determine its suitability as a rooting medium, *i.e.* the presence of hardpans, the mechanical resistance to penetration etc., its characteristics with respect to the water balance, such as infiltration capacity, water holding capacity, drainage characteristics. On the other hand the chemical properties of the soil play a role, in which its capacity to retain and supply essential nutrients to the vegetation is of

major concern. In addition, unfavourable characteristics such as high salinity, high concentrations of certain elements, such as aluminium or iron or a low pH may play a role, but such conditions, although sometimes affecting considerable areas, are only of local importance and can be left out of consideration in a generalized treatment.

2.2.1 Soil physical properties

The most important physical characteristics of soils in relation to crop productivity are related to the relative proportion in which the three soil phases: solid material of organic or mineral nature, soil water and soil air occur at a given moment. The distribution of the three phases is to a large extent governed by the particle size distribution of the solid phase. In soil science the particles are generally divided into three classes: those smaller than 0.002 mm, the clay fraction, those between 0.002 mm and 0.05 mm, the silt or loam fraction, and those between 0.05 and 2.0 mm, the sand fraction. Particles exceeding 2.0 mm are called stones and are removed before the particle size distribution is determined. Soils can be classified on the basis of the relative proportion of these three particle size classes and a standardized system has been developed for the nomenclature into clay soils, loam soils, sandy soils and an extensive system of intermediates.

The importance of particle size distribution for the distribution of the three phases can be illustrated by the graphs in Figure 8, giving the relation between the fraction moisture in the soil (on a volumetric basis) and the suction applied to that soil, for three contrasting soil types. The moisture content at zero suction representing the total air space of the soil or the pore volume, is substantially higher for the heavy clay soil than for the sandy soil, with the loam soil having an intermediate position. That value is, however, not very interesting from an agronomic point of view since complete saturation hardly occurs in nature, except of course in bunded rice cultivation where it is a condition aimed for. A more interesting point is that at a suction of about 300 cm of water (at a pF value of about 2.5, pF being defined as the log (suction)), a value commonly referred to as «field capacity». It is rather loosely defined from a pure soil physical point of view as «the moisture content resulting when drainage has virtually ceased after application of excess water». It must be clear that on one hand the «virtually ceased» leaves ample space for subjective interpretation, while on the other hand that phenomenon is affected by the existing boundary conditions, such as the depth of a groundwater table or the presence of a compacted layer. Despite these reservations, however, it has long shown its merits in describing the soil water balance with respect to crop production. It is the moisture content that the soil will attain in an equilibrium situation after excessive rainfall and represents the upper limit of moisture available for uptake by plant roots. The difference among the three soil types is very pronounced here: the heavy clay can store more than $0.5 \text{ cm}^3 \text{ cm}^{-3}$ of water, whereas the sandy soil contains less than 0.05 cm³ cm⁻³. Sandy soils such as some latosols under a heavy rainfall regime are subject therefore to excessive leaching, which is a disadvantage, because with the water also plant nutrients are washed out of the rootable profile. In addition the storage capacity for water is very low so that during a dry spell or a dry season very little moisture is available for plants from such a profile. The lower boundary for plant available water is, in the same terminology, referred to as the «permanent wilting point», defined as that moisture content at which plants do not recover from temporary wilting and eventually die. Differences between species have been established with respect to this characteristic but a generally accepted convention



Fig. 8 Soil moisture retention curves for three different soil types. FC is field capacity; PWP is permanent wilting point.

places it at a suction of 16000 cm or pF = 4.2 (Figure 8). At that suction value the sandy soil is practically depleted (0.02 cm³ cm⁻³), the loam soil still contains 0.11 cm³ cm⁻³, whereas the clay soil retains still 0.33 cm³ cm⁻³.

The differences among the various soil types can be explained on the basis of the physical laws governing soil moisture dynamics. The pores in the sandy soil, consisting for the larger part of large particles have a much greater diameter than the pores in the clay soil, where the particles are smaller and thence the smaller voids between them.

With respect to crop production, where moisture supply to the crop can be a major determinant for yield, especially during periods of low rainfall, the range between field capacity and permanent wilting point is of importance. In that respect the heavy clay soil presented here and the loamy soil differ very little, the first one having an available moisture range of $0.161 \text{ cm}^3 \text{ cm}^{-3}$ and the latter of $0.166 \text{ cm}^3 \text{ cm}^{-3}$, whereas the sandy soil only has a range of $0.02 \text{ cm}^3 \text{ cm}^{-3}$. As already hinted at earlier, sandy soils are very unfavourable during dry spells, as for instance with a rooting depth of 120 cm, the total soilmoisture store is only 36 mm, hence with an evaporative demand of 3 mm d⁻¹, a very modest value, just enough for 12 days. The loam soil on the other hand contains in the same zone almost 200 mm of available water, which could carry a crop through a rainless period of more than two months. The heavy clay soil in this case can supply practically the same amount of water as the loamy soil, however after a prolonged period of drought in which the soil has dried out to much lower moisture contents due to evaporation from the soil surface, much more water is needed to restore the soil to a moisture content suitable for plant growth.

Moreover, clay soils are much more difficult to work, hence with a given amount of available labour a smaller acreage of a clay soil can be prepared for crop growth than of a loamy soil, reason that loamy soils are much preferred in agricultural practice.

2.2.2 Soil chemical properties

The chemical properties of the soil that are of greatest interest with respect to crop production are those that determine the ability of the soil to supply the crop with the necessary nutrients. That capacity is co-determined by a complex of different factors, that act independently or interact with each other.

Although crops need many elements for unrestricted growth and production, many of these are required in such small quantities that practically always the supply from natural sources is sufficient to reach potential production. However, the macro-elements nitrogen, phosphorus and potassium are required in such large quantities that the actual production level is often determined by the amount of these elements supplied from these natural sources. In tropical soils a number of specific processes is prominent that affect this property.

In general, the warm and humid environment of the humid tropics is conducive to rapid decomposition of organic material. In the natural situation, *i.e.* under tropical forest, or perennial grass, the supply of organic matter to the soil is also high, so that an equilibrium situation at a reasonable level exists. However, under agricultural use, where a major part of the organic matter produced is harvested and removed from the field, the levels of organic matter in the soil decline very rapidly and with it its capacity to supply nitrogen (Nye and Greenland [1960]). After a number of crop cycles the nitrogen-limited yield may therefore reach such low levels that the efforts of farming are hardly worthwhile. Any management or cultural practice that aims at maintaining the level of organic matter in the soil (green manuring, inter-cropping, etc.) is therefore helpful in ensuring a continuous yield at a reasonable level.

Next to nitrogen, phosphorus is the single most important element in plant nutrition in the humid tropical zone. In many cases the level of total phosphorus in the soil is low, and moreover the availability for the vegetation is restricted. That is due to the phenomenon of phosphorus fixation that is widespread in these soils. That phenomenon is characterized by a parallel series of processes of absorption and precipitation in which phosphorus is effectively removed from the soil solution by the formation of insoluble phosphorus compounds such as aluminium and calcium phosphates. The concentration of inorganic phosphorus components, the only ones that can be taken up by the vegetation, remains therefore low in the soil solution and its availability is restricted. Even application of fertilizer phosphorus in such cases is of only limited value, because the recovery is generally low and the residual effects are limited. The exact quantitative relationships that govern these processes are still to a large extent unknown, and even though considerable prog-

ress has been made in recent years, it still appears impossible to predict the supply of phosphorus from natural sources even in well-defined environments, as well as the effects of application of fertilizers.

Also in the phosphorus supplying capacity of the soils, organic matter cycling and decomposition play an important role, as especially in tropical soils, low in total phosphorus, the organic component may constitute a substantial proportion of the total phosphorus supply to the vegetation.

3. Physical resources and crop production

Agriculture was defined earlier as the human activity that transforms the energy of the sun into edible organic material through manipulation of plants and animals. In principle, the number of resources that is needed is only small: a piece of land, some sun and rain, and a little bit of human physical effort. In subsistence farming these limited resources will often suffice to provide a supply of food and shelter to the farmer and his family, without too much inputs from outside. However, an ever increasing proportion of the population lives in such high concentrations that it is impossible to produce the bare necessities for life. That situation puts a heavy burden on the agricultural community that is expected to supply the requirements for living to the urban part of the population. It appears, and will be further elaborated in the remainder of this presentation, that, from a resource point of view, this requirement can only be satisfied, if sufficient means of production are put at the disposal of the farming community. And that at an economic exchange rate, that makes application of these means attractive.

3.1 Potential production

Potential production is defined in our context as the production of a certain crop, characterized by its genetic and physiological properties, growing under a given temperature and radiation regime, in a situation where all other constraints, that could feasibly be eliminated, have been removed. Such conditions imply optimum supply of water and nutrients, complete weed control and the absence of pests and diseases.

Under such conditions crop production is determined by the growth rate, *i.e.* the daily rate of dry matter accumulation on the one hand, and the duration of the growth period on the other hand.

The growth rate is determined by the amount of solar energy that can be utilized by the vegetation, which is a function of energy availability (intensity and duration of sunshine) and the capacity of the vegetation to absorb that energy, which is mainly a function of the absorbing green (leaf) area. In general, a crop growing under optimum conditions develops quickly sufficient leaf area to intercept all available energy so that after a short initial period, the crop maintains a radiation-determined linear growth rate. The total amount of dry matter accumulated depends then primarily on the length of the period that this growth rate can be maintained. The length of that period is governed by genetic crop characteristics (short-duration *vs.* long-duration cultivars) and the prevailing temperature. At higher temperatures the phenological development, that is the rate at which a crop goes through the various phenological stages, such as leaf formation, ear initiation, flowering and maturity, proceeds at a higher rate, and consequently the crop cycle shortens, resulting generally in lower total dry matter production. The yield, which only com-

prises the economically relevant plant parts, or the marketable product, and is thus only a fraction of the total dry matter produced, is co-determined by the distribution of dry matter over the various plant parts. Plant breeding over the past decades has for many species resulted in cultivars that invest a higher proportion of their total biomass in the economic plant parts. For such cultivars, the ratio of economic yield to total dry matter production, or the harvest index, is superior to that of the traditional cultivars, hence even with a shorter growth period, yields may be higher. An interesting observation in this respect is, that if traditional cultivars and modern (so called high-yielding) cultivars are grown under the same conditions and present day management techniques their total dry matter yields are very similar. (Of course care should be taken that the traditional cultivars growing under the high nitrogen supply common in modern agriculture, are not lodging). This result illustrates that plant breeding has hardly influenced the basic biochemistry and physiology of the plant.

The effects of environmental conditions (or the physical resources) on crop production and yield have been studied ever since the beginning of agricultural research. However, the variability and unpredictability of especially weather conditions, and the interaction between its various components, make execution and interpretation of field experiments often very difficult. A convenient way to avoid (at least part of) those problems is the use of simulation models, where crop performance is predicted on the basis of knowledge of the basic physical, physiological and biochemical processes relevant for the production process (Penning de Vries /1984); de Wit/1970]). At present many of such models, with different purposes and varying in their degree of detailedness and complexity are available (van Keulen [1983]). In such models crop growth rates are calculated from the assimilation rate, taking into account the respiratory losses involved in maintenance and growth, the distribution of dry matter over the various plant organs, typically in dependence of the phenological state of the crop. The phenological state in turn is determined by genetic factors, and the influence of environmental factors like temperature and daylength. A relatively simple model, containing these elements (van Keulen et al. (1982)) has been used to analyze the effects of physical resources on production and yield of some important food crops grown in the humid tropics.

3.1.1 Radiation

The radiant energy emitted by the sun is in part, *i.e.* the wavelength region of 400-700 nm (visible light) absorbed by the green pigments of the plants and used for the reduction of carbon dioxide. Typically therefore at low levels of irradiance the rate of carbon dioxide reduction is proportional to the level of irradiance *i.e.* energy availability determines the rate of assimilation. At higher levels of irradiance the assimilation rate reaches a constant level irrespective of energy availability (Figure 9), *i.e.* the rate of assimilation is determined by the rate of transport of CO_2 from the ambient air to the active sites. However, especially at higher leaf area indices, part of the green area is in the energy-dependent part of the photosynthesis-light response curve and at the beginning and end of the day all leaves may be at that level. Crop assimilation rate on a daily basis increases therefore with increasing energy availability. The quantitative relations between these variables, in dependence of crop characteristics, geographical position and time of the year have been established with the use of computer models (Goudriaan and van Laar [1978]; de Wit [1965]).



Fig. 9 The relation between absorbed radiation and the assimilation rate for individual leaves of plants of the C_3 and the C_4 type.

The effect of radiation level on the yield potential for a rice crop is illustrated in Table 1, where the calculated yield is given for a non-photosensitive short-duration rice variety. At each location the transplanting date was chosen in such a way, irrespective of other weather characteristics that grain filling took place either in the period with the highest radiation level, or in the period with the lowest radiation level. These results hint already at one of the difficulties involved in the analysis of the effect of one single climatic factor on production and yield. The weather characteristics change simultaneously and therefore interact.

However, as shown in Figure 10, a reasonable correlation exists between absorbed photosynthetically active radiation in the post-anthesis phase and grain yield. The scatter around the regression line may be due to different reasons. For Dacca both crops absorb the same amount of PAR (due to the fact that the crop maturing in the low-radiation period is in the field for two more weeks), but the yield differs 2000 kg ha⁻¹. Two processes contribute to this yield difference. Firstly, witnessed by the harvest index, the crop maturing in the low-radiation period has a higher energy availability in the pre-anthesis period and produced more vegetative material. Secondly, the longer growth duration reflects the lower temperatures during the growing period. As a result of both, the maintenance respiration requirements for the «low-radiation» crop are higher than for the «high-radiation» crop and consequently assimilate availability for grain growth is lower.

Location	Transplanting date	Absorbed radiation post- anthesis (10 ⁸ J m ⁻²)	Yield (t ha ⁻¹)	Harvest index	Total growth period (d)
Dacca	Sept. 27	3.24	9.3	0.56	105
	Feb. 15	3.24	7.3	0.47	91
Los Baños	Aug. 28	2.05	5.6	0.45	94
	Jan. 15	3.52	8.7	0.52	98
San Ramon	Feb. 25	2.78	7.7	0.47	109
	July 13	3.18	8.5	0.49	106
Bogor	Sept. 27	2.02	6.2	0.48	95
	June 15	2.32	6.5	0.49	94
Lampang	Sept. 12	2.36	6.8	0.51	98
	Jan. 15	2.75	6.4	0.44	94

Table 1. The effect of radiation level on the yield of a short-duration rice cultivar.





A similar situation exists in Lampang, although there the effect is less pronounced. Particularly for Los Baños the difference between the two crops is striking: almost 3 t ha⁻¹ more for the «high-radiation» crop. These results are in good agreement with those presented by *Yoshida and Parao [1976]* from a shading experiment and by *Yoshida et al. [1972]* from a maximum annual production trial. It is interesting to note that simulation of the latter trial, which involved continuous cropping of four rice crops within one year, resulted in a total yield of 33 000 kg ha⁻¹ (*van Keulen [1986]*), illustrating that very high production levels are possible in the humid tropics, provided that possible unfavourable effects of water or nutrient shortage and weeds, pests and diseases can be avoided.

3.1.2 Temperature

Many of the plant physiological processes are enzymatic processes which are temperature-dependent. However, not all processes are affected in the same way, nor with the same intensity, and sometimes the effects work in opposite direction, so that the overall result is very difficult to predict.

Temperature affects the rate of assimilation as witnessed by the results of many experiments. In most cases, however, these results refer to plants grown under controlled conditions (a.o. constant temperature) and subsequently measured at various temperatures. In the field situation plants may adapt to fluctuating and suboptimum temperature conditions (*de Wit et al. [1978]*) so that in fact the temperature effect is much less pronounced and a rather flat optimum exists.

A second process that is affected by temperature is the conversion of primary photosynthetic products into structural plant material, *i.e.* growth. That process takes place especially during the night and is therefore much more affected by minimum temperatures than by the average 24-hour temperature. This phenomenon plays especially a role in situations where low night temperatures coincide with relatively favourable day-time temperatures and high radiation levels. Plant species belonging to the C₄ type are much more sensitive to this phenomenon than species belonging to the C₃ type, because the limiting temperatures for the first group are around 10 °C, in comparison to 3-5 °C for the second group. Especially therefore for crops like maize, sorghum and tropical grasses this process should be taken into account.

A distinction should be made between growth, *i.e.* the increase in size, weight etc. of the biomass and development, the rate and order of appearance of vegetative and reproductive plant organs.

The order of appearance of the organs is species-characteristic, genetically determined and hardly subject to influence of external factors. The rate of development, however, in addition to being genetically determined, is strongly influenced by environmental factors, notably temperature and day length. Within the scope of this contribution the effects of day length will not be discussed, mainly because the quantitative relationships are not very well understood. It should, however, be realized that the choice for a day length intensitive cultivar may carry great risk, because it may result in untimely flowering or maturation of the crop (consider for instance maturity of a cultivar in the middle of the rainy season, when the field cannot be drained and the ears will not dry because of abundant rainfall).

The effect of temperature, however, is well-documented and it appears that the duration of a given phenological period declines with an increase in average temperature (*Robertson [1982]*; van Dobben [1962]). When the inverse of the duration of a certain pheno-

logical period («the development rate») is plotted *versus* average temperature, it appears that in many cases a straight line results, over a wide range of temperatures. This straight line may for some crops (or crop cultivars) cross the temperature axis at a nonzero value, the so-called threshold value below which development comes to a standstill. At high temperatures (above 30° C) the proportionality between development rate and temperature disappears. There is conflicting evidence about the relation above that point, in some cases the development rate appears to remain constant, in others there seems to be again a decline in the development rate. For most practical purposes, however, only the linear part of the relation is of importance. The linearity of the relation between development rate and average temperature is equivalent with the notion that for completion of a phenological phase a constant «heat sum» expressed in d °C is required. The consequences of this property are already visible in Table 1, where it is shown that the growth duration of the same variety that requires 1600 d °C from transplanting to anthesis and an additional 800 d °C from anthesis to maturity varies between 91 and 109 days depending on environmental conditions. The effect of temperature per se on yield is, however, difficult to deduce from these data, because temperature differences interact here with differences in radiation level.



Fig. 11 The effect of temperature on calculated grain yield of a short-duration rice cultivar, standard yields calculated with data of Figure 3, adapted yields by assuming 2.5 °C temperature difference.

A more direct method is therefore applied by assuming that the average temperatures are either 2.5 °C higher or 2.5 °C lower, for both the pre-anthesis and the post-anthesis period. The results, presented in Figure 11 as the relation between the «standard» yield and the «adapted» yield, show that the greatest effects occur from temperature differences during the post-anthesis phase. Temperatures in the pre-anthesis phase also have some effects, but these are smaller and not consistent. Higher temperatures during the postanthesis phase result in shorter periods of grain filling and accelerated senescence of the leaves. Moreover, the maintenance requirement of the existing biomass is higher, hence the overall effect is lower grain yields, as illustrated in Figure 11. Similar observations have been made in temperate regions, showing that bright warm summers generally result in lower grain yields than dull and cooler summers (Monteith [1981]). It may be concluded from the - limited - evidence presented in this subsection that the relatively high temperatures prevailing in the humid tropical region are on the one hand an advantage, because they permit year-round growth of crops. On the other hand they may be disadvantageous, since they induce rapid phenological development of the crop, and hence a limited period of active growth and a restricted time span for growth of the reproductive plant organs.

3.2. Water-limited production

As was shown in Figure 7 there are considerable periods in some regions of the humid tropics where the evaporative demand of the atmosphere exceeds precipitation. Under such conditions it is likely that moisture availability for the crop becomes a factor constraining crop production. If rain does not replenish the moisture withdrawn by the crop from the soil profile, the soil dries out, hence the water remaining in the soil has an ever-decreasing potential, thus hampering uptake by the root system. As a consequence, the vegetation loses turgor, the stomata start to close, thus offering higher resistance to water loss, but at the same time obstructing entrance of CO_2 , hence decreased assimilation rates and lower production. Eventually the plant will shed its leaves, dessicate and ultimately die.

To estimate the quantitative consequences of a certain rainfall pattern on crop production the soil-water balance must be considered. As discussed in Section 2.2 considerable differences exist among soil types with respect to soil physical characteristics associated with the water balance, such as infiltration capacity, storage capacity, etc. Moreover, geomorphological characteristics play a role such as the vicinity of a river and height above sea level. Water-limited production should therefore always be considered by combining climatic resources with soil resources.

That point is illustrated in Figure 12, where calculated grain yields for Dacca are presented for a medium duration maize cultivar, requiring 850 d °C above a treshold value of 10 °C from emergence to silking and 650 d °C from silking to maturity. Three situations are considered: first potential production as a reference point, varying between 7.5 t h⁻¹ for crops emerging in the middle of the year (June/July) and 10.5 t ha⁻¹ for a crop emerging in the middle of October. These differences are due to the combined effect of radiation and temperature as outlined in the previous section. The crops emerging in the middle of the year grow in a period with relatively high temperatures (the total post-silking period for instance is only about 40 days) and low radiation, whereas the crop emerging in October is subject to the reverse conditions (the post-silking period is more than 60 days in that case).



Fig. 12 Calculated potential grain yield (----), and water-limited grain yield on a loam soil (x-x) or a clay soil (....) for a maize crop sown at twelve dates throughout the year in Dacca.

In the context of this section, however, the other two lines in Figure 12 are of more interest: under rainfed conditions, the yield potential is only fully expressed for crops emerging in the period mid-May till mid-September. Crops emerging outside that period suffer from water stress during some stage in the growing season, which results in lower yields, or even complete crop failure, *i.e.* for crops emerging between the middle of November and the middle of December, if grown on a clay soil. It is clear that the sandy loam soil is more favourable in terms of water supply for the crop than the clay soil. For instance the crop emerging in the middle of February still yields 4 t ha⁻¹ of grain when grown on a loamy soil and only 750 kg ha⁻¹ when grown on the clay soil. This difference is related to the much higher storage capacity of the loamy soil, *i.e.* the difference between field capacity and permanent wilting point: 0.11 cm³ cm⁻³ for the clay soil versus 0.18 cm³ cm⁻³ for the loamy soil. Of course, in discussing such yields in general terms there is always a certain degree of arbitrariness involved, because the moisture conditions in the soil at the time of emergence have to be specified. And these conditions depend on the preceding use of the field and the boundary conditions. For the data presented in Figure 12 it was assumed that at emergence the profile was at field capacity in all cases, irrespective of preceding weather or other conditions. Such a situation would presumably only be commensurate with reality if the field had been fallow for some time preceding the assumed seeding date, and rainfall in that period was abundant. It is, however, difficult to treat this point in more detail in a general way.

Another aspect of the water-limited production is illustrated in Figure 13a, where the relation is given between calculated grain yield and total crop transpiration. Obviously a positive correlation exists, but the variability is quite high. Part of the reason for this variability is the fact that the harvest index, *i.e.* the ratio between grain weight and total dry weight depends to a large extent on the distribution of moisture availability. For the twelve emergence dates illustrated in Figure 12, the harvest index varies between 0.4 (emergence on day 319, *i.e.* the middle of November) and 0.5 (emergence on day 258, the middle of September). Obviously for the first emergence date, moisture availability during the pre-silking period was still reasonable, whereas after silking rainfall is very low and hence moisture supply to the crop is seriously limiting. On the other hand, the crop emerging in mid-September has a sufficient water supply throughout the growing cycle, and matures during a period of high energy availability.

When total dry matter production is related to total transpiration, the variability decreases markedly (Figure 13b). This illustrates that the processes of CO_2 exchange and water vapour exchange are closely related, because they are governed by the same physical principles. Thus a reduction in transpiration, due to insufficient moisture availability in the soil is accompanied by an approximately proportional reduction in dry matter production. Three points clearly deviate form the eye-fitted line in Figure 13b, which is due to the fact that the three crops concerned are growing in a period where the evaporative demand of the atmosphere is low compared to the remainder of the year. For the three encircled points the average *«Penman»* evaporation over the growing period is 2.7, 3.1 and 3.2 mm d⁻¹, respectively, compared to an average of 4.6 mm d⁻¹, for the other simulated crops.

The slope of the line in Figure 13b is 0.0054 kg dry matter per kg water or equivalent to a transpiration coefficient *(Tanner and Sinclair [1983]; de Wit [1958])* of 185 kg water transpired per kg of dry matter produced, which is a very reasonable value for a C₄ crop growing under intermediate evaporative demand. Of course, the overall water use efficiency expressed as kg dry matter produced per unit of moisture input in the system is much lower, because part of the rainfall evaporates directly from the soil surface and does not contribute to production, whereas amother part, especially in the rainy season is lost through drainage beyond the potential rooting zone.



Fig. 13 The relation between grain yield and total transpiration (a) and that between total dry matter production and total transpiration (b) for a maize crop sown at twelve dates throughout the year in Dacca.

As indicate before, the initial conditions, that is the situation at the start of crop growth has a marked influence on crop performance, but also the boundary conditions. Taking again Dacca as an example, two contrasting situations are considered: one a sandy loam located in a river valley, where the groundwater table is at a depth of about 2 m below soil surface, and the other where the same soil type is situated at a much more elevated location, with a water table at a depth of at least 10 m. The initial conditions in both cases are the equilibrium moisture profiles associated with the assumed depth of the groundwater table. The crop in this case emerged on November 14th and, as shown in Figure 14, took 132 days to maturity. The crop growing in the low-lying area produces 20000 kg ha⁻¹ of dry matter and yields 5500 kg ha⁻¹ of grain (The potential production for this situation was calculated as 9300 kg ha⁻¹). The harvest index of this crop is 0.27 which is very unfavourable for a maize crop, but that is due to the fact that moisture shortage occurs from about day 105 onwards, i.e. during the grain filling stage. Hence, stover vield is virtually unaffected by drought, but grain yield suffers dramatically. This effect is even much stronger if the crop is cultivated at a site without influence of a groundwater table (Figure 14). Under those conditions production virtually ceases after silking and just enough moisture is available to allow assimilation at a rate equal to the maintenance requirements of the vegetation. With the groundwater table at 2 m depth, 137 mm of water is supplied by capillary rise out of a total transpiration requirement of 325 mm over the total growth cycle. Hence, the presence of a real, or a pseudo-groundwater table originating from an impervious layer somewhere in the profile, may be of crucial importance for crop production during a period of low rainfall.



Fig. 14 Calculated growth curve for a maize crop emerging on November 14 in Dacca in either a low-lying or an elevated location.

In the situation with the groundwater table at a depth of 2 m the total transpiration deficit, *i.e.* the difference between actual transpiration and potential transpiration is about 50 mm over a period of a month. To achieve potential production under these conditions it would thus be necessary to ensure availability of that amount to the crop during the grain filling phase. If that would be supplied by irrigation, it is to be expected that losses will be incurred, their magnitude depending on the mode of irrigation and the quality of the irrigation system. Moreover, some irrigation applications will increase soil surface evaporation, which must be compensated also. A reasonable estimate would therefore be that 100 mm or 1000 m³ ha⁻¹ of water would have to be available to reach potential production.

From the five situations given as examples of the humid tropics in Figures 2-7, Dacca occupies an intermediate position in terms of moisture availability for crop production. Rainfall in Bogor is so high throughout the year that continuous cropping is possible without the risk of moisture shortage, *i.e.* moisture determined production equals potential production for any sowing date. On the other side of the spectrum is Lampang where only crops emerging between the middle of April and the middle of August attain potential yield under rainfed conditions. Crops emerging outside that period suffer from water shortage during part of their growth cycle, resulting in yield reductions. For twelve emergence dates, each time in the middle of a month, the relative transpiration, *i.e.* the ratio of actual transpiration to potential transpiration varies between 0.23, for the crop emerging in the middle of December, and 1.0 for the crops emerging in the middle of the year. In line with those observations is the fact that also the harvest index varies dramatically. It is about 0.01 for the crops emerging at the end of the year so that with a growth period of about 115 days grain filling takes place in the months January through March, by far the driest period of the year. On the other hand, the crop emerging mid-March suffers from water shortage at the beginning of the growth cycle, but is exposed to gradually improving conditions during the grain filling stage, which results in a harvest index of



Fig. 15 Calculated potential grain yield (· --- ·) and water-limited grain yield (x-x) for a maize crop sown at twelve dates throughout the year in Lampang.

0.58, even though the yield falls considerably short of the potential, set by radiation and temperature.

Considering the results presented in this section, it may thus be concluded that watere shortage is a serious limitation for crop production in considerable parts of the humid tropics. The somewhat ironical situation exists, that the yield potential set by genetic crop properties, radiation and temperature is generally highest in the period that water supply is low and uncertain (Figure 15). Development of reliable and efficient irrigation systems could therefore provide a substantial contribution to increased food production in the humid tropics.

3.3 Nutrient-limited production

The subject of nutrient limitation and nutrient requirements will be treated in detail in another presentation in this colloquium, so there is no need to discuss it here extensively. However, in discussing the physical resources of the humid tropics, the impact of soil fertility cannot be completely neglected. As explained in the preceding section, the supply of nutrients from natural sources is relatively low in many soils in the humid tropics. Exceptions do exist, for instance in places where the soil originates from relatively young volcanic material, that due to continued weathering still supplies reasonable amounts of nutrients.

However, the more common situation is that, where the «base uptake», that is the uptake of nutrients in the absence of fertilizer application, is low. Under such conditions, where nutrient supply is the constraining factor for crop production, plants will tend to maximize the efficiency of utilization of the limiting element by diluting its concentration in the tissue to a minimum value. For cereals like maize and rice those values are around $0.01 \text{ kg N kg}^{-1}$ dry matter and $0.001 \text{ kg P kg}^{-1}$ dry matter in the grains, and $0.004 \text{ kg N kg}^{-1}$ dry matter and $0.0005 \text{ kg P kg}^{-1}$ dry matter in the straw or stover, respectively (*van Keulen and van Heemst [1982]; van Keulen [1977]*). If a harvest index of 0.5 is assumed, that means that about 70 kg of grain can be produced for each kg of N taken up by the crop, and about 625 kg grain per kg P absorbed. This implies that under natural conditions in countries like Thailand and Bangladesh, where typically 15-20 kg N ha⁻¹ is supplied from natural sources, the yield varies between 1000 and 1500 kg ha⁻¹ for cereals (*Wolf et al. [1983]*). On the island of Java in Indonesia, consisting for a large part of more fertile soils, the N supply is of the order of 30 kg ha⁻¹ during a rice growing cycle and yields reach values of about 2000 kg ha⁻¹.

The associated P requirements are of the order of 2-4 kg ha⁻¹, which is generally available from natural sources, However, the moment that nitrogenous fertilizers are introduced in the system and the N determined yields increase, P soon becomes a limiting factor and application of phosphorus fertilizers should be considered.

In the Southamerican part of the humid tropics often phosphorus is the most limiting element, as the soils have strongly phosphorus fixing properties. P-limited grain yields are often of the order of 600-1000 kg ha⁻¹. Improvement of that situation, however, requires in general application of substantial quantities of phosphorus fertilizers, as the recovery, again due to to fixation, is extremely low.

It must thus be concluded that in addition to water, soil fertility is a constraint for crop production in the humid tropics, and that application of fertilizer is a prerequisite for attaining yield potentials, set by the inherent physiological and biochemical properties of the plants.

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