CLIMATES OF TROPICAL FORESTS AND SAVANNAS

By

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The problem of protection of already existing forests and of reforestation of regions not covered with forests becomes more and more important in the tropics. Hence it is necessary to review the essential factors determining the possibility of existence of forests in general and of certain types of forests in particular. Such research belongs to the field of ecology, which studies the mutual relations between the vegetation and its environment. Environment is specially defined by soil and climate, but also by animals and man, factors which must not be forgotten.

Studying the relationship between the vegetation and the ecological conditions, one must of course not go too far in generalization. The concept of forest is broad and there are many types of forests; their associations are formed by a smaller or larger number of species, each of which presents different ways of adapting itself to the environment and each of them with specific physiological requirements.

However certain generalizations can be made and are even necessary. The first general statement we can make is that *infertility of the soil does not inhibit growth of forests.* On very sterile, sandy soils, of course, there will be no growth of trees which require a fertile substratum, but, as it also happens with smaller plants, nature produces less exigent species alongside the more exigent ones; the former species content themselves with a

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minimum of plant nutrients and humus and are able to develop well if the other conditions of the environment allow it. This fact which is fundamental for all our coming considerations is usually not stressed in books on ecology because it is so well known in the countries of Central Europe, where modern phytoecology began with the classic works by Warming (36) and Schimper (30). In all Central Europe forests already long ago have been relegated to the non-fertile or inaccessible ranges on which the customary cultures would not pay. With certain exceptions (to be considered later on) the culture or maintenance of forests is always possible, the trees of poor soils naturally being of resistant species or genera, such as Pinus or Betula. Trees with long and sometimes very deep roots are able to draw the last of the plant nutrients from the soil with more facility than the herbaceous plants which generally have fewer and more superficial roots.

Where nature allows formation of forests, these usually will develop under natural conditions as the dominant vegetation because generally the tree defeats its smaller competitors in the struggle for light. We call climax vegetation the plant formation which establishes itself under natural conditions in a given habitat. Regardless of the quality of the soil, this vegetation will be of the forest type, if the climatic conditions are favorable.

Which are these conditions? Let us consider temperature first since there exist polar and alpine timberlines which, due to the cold climate, cannot be trespassed by trees. Careful physiological research shows however that the trees in such regions do not suffer directly from the low temperatures (in the coldest regions on earth, such as Irkutsk in Siberia, where summer presents favorable conditions, there are forests), but from the lack of water. In cold soils absorption by the roots is inhibited while the aereal parts of the plant are exposed to very strong evaporation and transpiration. The limiting factor in the polar and alpine timber lines is therefore lack of water, not due to physical scarcity but to physiological difficulty in absorbing or conducting it (physiological drought). The tree tops with their large number of leaves, distributed in several tiers lose an enormous amount of water by transpiration, more than a free water surface of the same size. (This is the reason why swamps are dried up by planting Eucalyptus or other trees). Not only the number of leaves is important but also the height of the trees which causes the exposure of the foliage to the action of the wind.

Therefore we can establish as a rule—with its exceptions—that wherever the conditions of environment, water supply and evaporation allow tree life, forests will be the natural vegetation. Shortage of water leads to the thinning of the forests; the trees become lower, the tops will not close densely and forests gradually change into savannas, with trees, shrubs or only with herbs.

Such a transition will go through several intermediary stages. In the more humid regions of low latitudes we find the equatorial, hygrophytic forests with large and often thin leaves, with little protection against drought. Where droughts occur accidentally the thin foliage will give place to a hardier and better protected one. Where droughts occur regularly during a certain season of the year, deciduous trees will be found. In the transition zone, as Beard (2) observed in Trinidad, the high trees shed their leaves whereas the trees of the intermediate story and the shrubs protected by the shadow are evergreen.

A more serious shortage of water causes the thinning of forests because the soil moisture supply is too small for a whole system of dense tree crowns. Glades are formed with light enough for herbs and grasses. Thus we have to expect a slow transition into savannas or steppes with trees and shrubs. This transition represents another forest limit brought about this time by a physical lack of water and not by physiological drought.

For a long time geographers and botanists have been trying to determine the amount of annual precipitation necessary for the development of forests. According to Schimper (30) the necessary rainfall to maintain equatorial forests should be at least 1800 mm. "It becomes quite evident that the distribution of high forest—probably always rain forests—and savannas depends in the first place upon the amount of rain. Where the annual precipitation exceeds 2,000 mm. dominance of forests is indisputable. Where rains do not amount to more than 1,700 or 1,800 mm. forests are entirely replaced by savannas. Precipitation under 350 or 300 mm. causes the degeneration of savannas into semi-deserts"(3) (1. c. p. 300)

Beard (2) states that in Trinidad precipitation amounting to 90 inches, that is, 2,250 mm. is sufficient for the development of evergreen seasonal forests, whereas annual rainfall of 70 inches (1,750 mm.) determines another forest type, the so-called semi-evergreen forests. Deciduous forests and finally savannas are to be found in regions with still less rain (l. c. p. 144).

Such figures, however are of limited importance, because there are many factors involved regarding the availability of the precipitation. The first students already noticed that precipitation may have different destinations according to the conditions of environment. A high percentage, about 20% to 25% does not reach the soil at all, it evaporates from the leaves and branches as soon as the rain is over. An unknown amount disappears in the soil without being available to the roots.

But the largest unknown factor is the variable amount of water transpired by the leaves: during the process of photosynthesis stomata have to remain open, hence loss of water by evaporation will be an unavoidable consequence. If so, then, wherever insolation is strong and the daily heat raises the water deficit of the air the loss of water through the cuticle and the stomata must be large, much larger than in conditions of higher relative humidity.

For a long time attempts have been made to evaluate the "humidity" of a region by comparing the precipitation with the evaporating power of given regions, and to this end several formulas

(3) We shall see later that these values are too high. Nevertheless Faber (31) retains this paragraph in the second edition of his book (1935)

have been proposed. Thus Transeau (34) in 1905 introduced a map for the Eastern U.S. based on the relation $\frac{\text{precipitation}}{\text{evaporation}}$ and in which evaporation is measured as the water evaporated by a free water surface. Actually this last value is not as easily obtained as one might think.(4)

Lang's "Regenfactor" (rain coefficient) was applied (1920) in the formula $\frac{\text{precipitation}}{\text{temperature}}$, taking into account the close relationship between evaporation and temperature (14).

De Martonne (17) 1926 used a related formula $\frac{P}{T+10}$; P and T are the annual or monthly averages of precipitation and temperature, a formula which is appelied to compare aridity and humidity during all the months of the year.

Meyer proposed the formula $\frac{\text{precipitation (mm)}}{\text{Saturation deficit of the air(mm Hg)}}$.

For ecological researches none of these formulas is satisfactory.(5)

Thornthwaite (33) introduced a more complex formula in 1948 which also does not solve our problem. He calls the climatologist's attention to the importance of transpiration in plants and speaks of

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(4)- See Lincke (16): " There is no method for measuring the natural evaporation of the earth's surface. This depends upon the existing amount of water; upon the amount of heat available for evaporation (the heat contained in the air plus the direct solar radiation); upon the quality of the soil surface (whether forest, grassland, field, sand, water, etc.) and also of course upon the wind and the existing humidity of the air. Above everything else the influence exerted by the plant cover causes unavoidable difficulties.

Measurements made over lakes and seas are very unreliable; hence computations based upon the amount of heat available for evaporation or based upon the differences between precipitation and drainage in limited areas give better results. " (l.c. p. 169).

(5) See for instance Aubréville (1) : "Toutes les formules proposées sont trop simples, trop incomplètes, trop abstraites et il est difficile de penser qu' elles puissent etre répersentatives de la fonction générale: climat. Celle-ci est trop complexe pour etre susceptible d'une application mathématique (l.c. p. 74).

"evapotranspiration." His empirical formulas do not seem quite satisfactory even to the author himself who in the end states that: "The chief obstacle at present to the development of a rational equation is the lack of understanding of why potential evapotranspiration corresponding to a given temperature is not the same everywhere. Not until this matter is understood will a rational method be possible." (l. c. p. 91). In preceding papers (24,25) it has been shown that mainly two factors obscure the understanding of "why the potential evapotranspiration under a given temperature is not the same everywhere." The first factor has been mentioned already. It is the amount of evaporation due to the transpiration of the leaves. It varies greatly with the conditions of the aperture of the stomata. When stomata are open, a leaf of Cedrela fissilis (a frequent tree of Central and South America) transpires 60 to 70 times more than with closed stomata (25). A leaf is able to change the stomata openings frequently during the day. Under good conditions of saturation and when light allows photosynthesis, the stomata are open during the day, because only then the CO_2 required for photosynthesis can enter the leaf. If, however, the amount of water taken up by the leaf is not sufficient to keep it saturated, the stomata are closed and transpiration decreases very much. There are leaves able to regulate the opening and closing of stomata very rapidly, such as the leaves of Cedrela and Coffea; others as *Kielmeyera coriacea* of the Brasillian savannas react only slightly, keeping their stomata open during the whole day (8).

All these are physiological facts and can not be determined with the aid of formulas. They have to be empirically computed for each habitat by means of observations which, although possible, are very tiresome. Thus far phytoecology has but very few data obtained by such methods.

The second factor is the invisible water reserve in the soil. During the rainy season an excess of precipitation may occur. During such periods this excess may drain into rivers, streams and into the sea; it also may be stored by the soil at certain depths. Very deep soils are able to store large amounts of water, as is generally the case in Brasil. A typical example is that of the "campos cerrados" of Pirassununga (25), where the water table lies at a depth of 17 meters, being supplied by the excessive summer rains.

The 2 or 3 meters of soil just above this water table remain continuously humid and contain in the pores a quantity of water equivalent to the entire average precipitation of 3 years. The upper layers are dry at the end of the dry season. If the thickness of weathered material (soil) would be less and if the bed rock were to be found at only two meters below the suface, there would be no water reserves during the dry season.

In the deep, humid soils, above mentioned, plants with deep roots are able to provide themselves with water during the whole year (even sugar cane with roots reaching a depth of more than 3 meters, is not injured during the dry season). In shallow soils such exigent plants, depending on deep roots, would be eliminated; the remaining vegetation would be xerophytic or constituted by plants which remain dormant during the dry season. In this case the transpiration as well as the "evapotranspiration" of the region would be quite different.

The qualities and behaviour of the soil and the existence and availability of an unknown water reserve are not–and can not be included in the formulas above mentioned [6]

THE WATER CONSUMPTION OF FORESTS

The few reliable data come from two different sources: (1) by determining the transpiration of a tree: then the resulting value is used to calculate the transpiration of a whole hectare covered with forest; (2) when we know the amount of annual rainfall over an area completely covered by trees and also the amount of water flowing from this area into the sea. The difference of the two amounts of water must be that lost by evaporation (supposing that the conditions of the environment are stable, no changes of aridity or humidity taking place in that given region). If the area studied is

6 For another objection to the generalizations regerding climate types see Troll (35).

totally coverd by forests the evaporation represents the transpiration of the vegetation. It is true that from 20 to 25 percent of the rain water is evaporated directly from the leaves and twigs and as soon as the rain is over. This amount therefore must be subtracted if we want to know the real evaporation. Direct evaporation from the soil is insignificant, at least in evergreen forests.

1) *The determination of transpiration by the first method* was already used by von Hoehnel (12) in 1879 who obtained data for forests of Fagus silvatica in Austria. He worked with young potted plants and extrapolated the values to areas covered with adult trees. Although this method seems to be rather uncertain the values obtained by von Hoehnel have been confirmed by recent researches applying the modern method of rapid weighing. The European experts of today agree that the summer transpiration of a beech forest approaches 20,000 liters/hectar/day. To replace this transpired amount a precipitation of 2 mm/day is necessary, or an average rainfall of about 60 mm a month. Pisek and Cartellieri (21) found for beech a daily water consumption of 2 mm; and 3 mm for Corylus avelana, while Hippophae needs approximately 1 mm a day.

These studies apply to the 5 or 6 summer months during which vegetation is active. During the winter water requirements become insignificantly small. Hence the values for the whole year are similar to Engler's (7) data about Switzerland, where the average transpiration amounts to 300 mm a year. Since in these parts of Europe the average precipitation is estimated to be about 700 mm, forests would then consume half of the annual precipitation. But not all of it reaches the soil. The soil also loses some water by direct evaporation, but a great deal more by percolation to streams and rivers. The values for the period of active vegetation show that during the summer months water use is almost as large as precipitation. This at least is true for an exigent plant such as Corylus avellana which in Tirol transpires about 90 mm a month against a monthly precipitation of 96 mm (Pisek and Cartellieri, 21). Burgers (5) shows that plantations of Eucalyptus globulus in Spain need at least 600 mm. of rain per year, which agrees with the other data.

The figures for tropical and subtropical regions are scarce and uncertain. Henrici (11) gives the following provisional data for South Africa:

Types of Vegetation	Yearly transpiration (Ha)	Yearly Precipitation	
		in mm.	per Ha (*)
Grassland Betschuana	2040 m^3	429 mm.	4290 m^3
Caroo-bush	480 ,,	200 mm.	2000 ,,
Natural forest (Pretoria)	1398 ,,	760 mm.	7600 ,,
Eucalyptus (old plantation)	12000 ,,	760 mm.	7600 ,,
Acacia mollissima (,,)	25000 ,,	760 mm.	7600 ,,

(*) — Precipitation quantities are given in mm. and in Ha. for comparison with the transpiration values.

Only a few of these figures are well related to the figures given for precipitation. Wherever transpiration is much lower than precipitation, we have to assume that the prevailing vegetation is not quite natural. Under conditions not changed by man or by animals and fire, vegetation would be more luxuriant so that most of the available water would be used up. Neither the Caroo bush nor the "natural" forest in Pretoria seem to correspond to these conditions. On the other hand we also may find figures for transpiration exceeding those of precipitation (Eucalyptus, Acacia). In this case the plantations must be in areas where besides rains, water is available from rivers or subterranean reserves. It also may happen that such plantations find the necessary amount of water for the first years of growth: but later on the subterranean reserves of once accumulated ground water are gradually used up. In this case, which is not infrequent, it is possible that the plants which at first were developing well, later will suffer or even die. All such figures [see also Coster (6) for Java] ought to be confirmed by more extended and modern studies.

2) *A computation based on the knowledge of the total precipitation and of the draining water of an entire river basin* covered with equatorial forest is given by Bernard (3). This author uses the basic equation P = D + E, P standing for precipitation, D for "débit du fleuve" (the water drained away by the rivers) and E standing for total evaporation. For the entire Congo basin, covered or not by tropical high forest P is 1510 mm, D corresponds to 337 mm. The remaining 1173 mm. represent evaporation or "evapotranspiration" of the region.

Regarding only the forested, equatorial parts of the Congo Basin, Bernard (l. c. p, 188) assumes 1900 to be the average rainfall, 1395 mm. being evaporated. Supposing with Bernard that 20% of the rain water is retained up the leaves and branches, being evaporated without having reached the soil and therefore without having entered the internal supply of the plants, we come to the real stomatal and cuticular transpiration of 1100 mm. These forests transpire during the whole year, and the average daily amount transpired corresponds to 3 mm. of precipitation. These values coincide with those calculated above for Fagus and Corylus avellana in Europe.

The values mentioned can not yet be regarded as definitive; they were mentioned to show the existence of a method which enables us to determine the amount of water used by forests. We want to stress however, that the transpiration values given do not necessarily represent the amounts of precipitation strictly needed for the development of forests. We have not yet found the minimum of precipitation required to maintain forests of tropical as well as of non tropical areas.

3) A third method of evaluating the precipitation required to maintain tropical forests is of a comparative, statistical character.

This method is the oldest one. Schimper (30) for instance, applied it when assuming an annual precipitation above 1800 mm. in the equatorial rainforest (see p. 96).

Equally of a statistical nature are Koeppen's estimates when he characterizes the savanna climate "Aw" by a "period of true drought and annual precipitation of less than 1000 to 2500 mm. of rain" (l. c. p. 152). Larger amounts of rain would then determine the forest climate.

The great amplitude of these values shows that they are questionable. They are dubious for other reasons too: the climatologic data are used under the assumption that the present limits between forest and savanna also indicate the limit of the ecological conditions necessary for life of both types of vegetation. This would be correct *if* the present distribution of savannas and forests corresponded to the natural ecological conditions.

Today we know that in all the continents the present distribution of vegetation does not reflect the primitive, original conditions. The aspect of the earth's surface has been vastly and profoundly changed by man, and even since prehistoric times. Most important are the cutting of forests, livestock raising, and especially fire. Fire was certainly already employed at the end of the glacial period by the hunting tribes, for only by its use were they able to defy the large mammals of that time (see Sauer, 29).

We may assume that the areas where human culture arose were not densely covered by forests. Hunting as well as cattle breeding and the beginnings of agriculture depended on relatively dry regions where at least glades must have existed in the forest, hence in regions of natural savannas. The origin of most cereals such as wheat and barley can be traced to the Asiatic steppes. In every case regions were involved where fires during the dry season may destroy the bush or the forest. As soon as man learned how to handle fire he certainly burned the woods and enlarged his hunting space by setting fires. Burning must have become more frequent with the appearance of domesticated cattle and of agriculture. Hence the habit of burning had become something almost instinctive in the nature of primitive man – a widespread practice still being followed. Myer's comments (20) on the savannas of British Guiana are expressive: "The scattered aboriginal Indians are inveterate burners. It is almost impossible to prevent one's Indian carriers from setting a light to the dry grass. They do this to signal their approach and for pure fun".

Once the forests disappeared these areas usually did not return to the prior stage. (About the interesting exception of the Maya culture see Gourou, 10). Therefore the present distribution of forests and savannas does not correspond to the ecological conditions which would develop these vegetation types.

All the considerations of classic Ecology must be reconsidered from this viewpoint. Such a revision is now beginning, especially in Africa, which is being studied accurately and methodically by botanists and soil scientists. The best idea of these efforts is given by the three volumes of the "Comptes Rendus de la Conférence Africaine des Sols," a conference held at Goma, Belgian Congo, in November 1948. Very informative too, is the outstanding book by Aubréville (1). According to him all the savannas occurring in tropical Africa are artificial, the result of fire, Lebrun (15), another of the best students of equatorial African vegetation, states "En Afrique tropicale il n' existe pas un pouce de terrian où la végétation de savanne réflète le climax de la région. La végétation présente est faite par l' homme" (l.c. p. 1976).

The senior author has repeatedly stressed the same facts for South America (22, 23, 24, 25, 26). Wherever savannas appear–in the form of "campo cerrado" we do not know whether they represent the natural climax or whether they are due to human interference, especially to the annual burnings.

Nevertheless the formations found in campos cerrados show that they are not entirely of artificial origin In certain regions a similar vegetation must have existed even before human interference was possible. *Anona humilis. Anacardium pumilum, Jacaranda decurrens*, small heliophilous plants with very deep roots must have evolved in non-forested areas where the environment was similar to the conditions of the campos cerrados of the present day.

But we do not dispose of the necessary elements which would enable us to know where such conditions existed originally. We should expect them not to be far from the "caatingas" or deciduous forests of the dry Northeast of Brazil.

Also here the present distribution of campo cerrado and forest does not permit any conclusions about the total annual precipitation required by the existence of forests. Nevertheless we can say that wherever forests persist, depending exclusively upon the rain, and not upon irrigation water from streams and rivers, the precipitation is sufficient for these forests.

In entirely natural conditions we should find a slow transition from evergreen forests into deciduous forests and of these into savannas. It should be sufficient to know the water supply of the transition zones to find the minimum precipitation values characteristic for each one of them. Yet such data are lacking and will be very difficult to obtain.

Considering all the data known up to the present time we are able to make at least some statements for the tropical conditions. We may be certain that evergreen forests can exist where precipitation is not less than 1,200 mm. per year, which is about the total annual rainfall in most of Brazil, except the dry Northeast. Let us compare the African data given by Aubréville for the border lines of the great rain forests of Guiana and Nigeria, starting at the Ivory Coast, and going eastward thru Western Nigeria, and on to Camerun and Ubangi.

Average annual precipitation on the border lines of forests according to Aubréville (1)

Ivory Coast	1250 to 1400 mm.
Gold Coast	1250 ,, 1350 ,,
Togo	1350 ,,
Dahomey	1140 ,, 1300 ,,
Nigeria	1200 ,, 1300 ,,
From Camerun to Ubangui (between Sanaga and Lobaye)	1360 ,, 1400 ,,

Interesting are the author's conclusion: "from these data one can see that many stations of dense forests receive only 1250 to 1450 mm. of rain. Even the region between Parauê and Dahomey has a pluviometric coefficient lower than 1200 mm.". These figures are much lower than those mentioned by Schimper (30). (l. c.p. 209) In a general way we may define with the French authors an equatorial region receiving about 1200 mm. of annual rain as "région de vocation florestale".

Nevertheless it will always be necessary to distinguish between the several types of forest. Aubréville's table regards a type still evergreen but which does not belong to the most hygrophytic ones. The latter would need according to Aubréville and also to Richards (27) 1500 to 1600 mm. of annual rainfall; if less, there would be felt the transition to the deciduous forest, which reminds us of Beard's data for Trinidad. However it becomes very difficult to trace a limit between evergreen forests and the mixed deciduous forests. It has been stressed by MacGregor (18) that according to the environment deciduous trees such as *Tectona grandis* may become evergreen so that the transition of hunid forests into drier ones is hardly noticeable.

That the savannas actually existing are frequently man-made is evidenced by recent experiments dealing with the protection of definite areas of "savannas" against fires. Brynaert and Toussaint (4) report observations for Matadi, on the lower Congo river in equatorial conditions with an yearly average precipitation of 1090 mm. The existing degraded savannas when protected against fire began to change into a forest-like vegetation and the authors conclude that the forest is the climax. Similar studies were made by Germain (9) in the Congo and by Rosayro and others in Ceylon (28). Thus it seems that the 1,200 mm. repeatedly mentioned still does not represent the lower limit between forest savanna.[7]

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(7) Observations and rainfall quantities in the Philippines, in the Chumporn region of peninsular Siam, and in the Nilgiri Hills of South India, also indicate that in all these localities the extensive savannas or down sare anthropomorphic---the result of man's activity.

Besides the average amount of annual precipitation, the distribution and length of the "dry months" may act upon the environment. (19 a). Dry months are considered those during which precipitation is lower than 30, 40 or even 60 mm, the dryness of the month depending also upon its average temperature. A continuous dry season lasting 3 or 4 months constitutes, according to Aubréville, a limiting factor for pluvial forests. Of less influence would be the same total length of the dry season, if divided into two dry periods, separated by a second rainy season, as it is the case in many tropical areas. To these considerations of the French school we should like to add the following: *what really matters is not the strength or the duration of the dry season, but the depth to which dryness penetrates into the soil.* There is no doubt that the decisive question is whether or not the deep roots of the trees still reach available water. Few papers on the water regime of tropical forests adequately consider this problem. Our research in Emas mentioned above, showed how the entire behavior of plants depends on this fact.

If this were better known perhaps one could explain the so called "abnormalities", mentioned by Aubréville, about certain forests, as' "de la forêt foutanienne en Guinée Française, de celles du Mayumbé, de l' Angola septentrionel, du Moyen Congo, des forêts de l' Ouest et des hauts plâteaux de Madagascar. Nous avons fait valoir pour ces formations l'anomalie de l' existence d' une exceptionelle saison sèche, inconcevable pour des forêts de type humide, comptant 4 mois secs, 5 mois à Madagascar, 6 mois a Kita au Soudan Français . . . . ." (l.c. p. 325).

Richards (27) also finds discordant values for precipitation and limits between pluvial and mixed deciduous forests "and it is therefore possible that the boundary depends primarily not upon the rainfall itself, but on some factor correlated with it . . . ." (l.c. p. 9).

Whenever the dryness reaches the forests' root system, the trees will not find the necessary water to keep their foliage green. This seems to be the case in the northern part of the State of Minas

Gerais, Brazil, where according to Silveira (32) rivers and streams dry up during the dry season, whereas they keep running all year long in areas already deforestated. This means that in this region where precipitation amounts to little more than 1000 mm, we find the limit of the evergreen forest, which under normal conditions would gradually be replaced by deciduous forests.

We do not know how large the water consumption of the deciduous forests is. The figure of 1,750 mm. given by Beard for Trinidad seems to be somewhat high according to everything mentioned about Africa. All depends on the composition of such forests and of the subterranean water supply. Where all the forest components are deciduous, conditions probably would resemble those of the Beech forests where only the months of vegetation count. By and large the water consumption of tropical as well as of temperate climates, during the vegetation period, is of the same order (2 to 3 mm. a day or 60 to 90 mm a month).

Even these values are not minimal; 2 mm a day consumed by a forest as hygrophytic as Fagus forests (during the summer) is probably still above the limit, even in the regions of relatively hot summers such as in Central Europe. The exact minimum values escape our knowledge, more than in tropical regions.

The judgement of annual consumption in the temperate regions is complicated by what happens during the winter. Very often, where soils are shallow, winter rains are not stored. In this case the winter precipitation is only of slight importance for the water regime of the forest. If the precipitation forms a thick covering of snow, it constitutes an important reserve which during the period of melting enters the soil.

Finally the lower summer temperatures near the polar timberline must cause there a decrease of the transpiration values. Exact data concerning all these are lacking and are not discussed here.

We are not surprised that during the hot summer in Central Europe the transpiration of the hygrophytic forests reaches values nearly as high as of the Equatorial forests: the larger amount of transpiration expected for the tropical climate is counterbalanced by the longer duration of the summer days in high latitudes.

And the savanna climate ? As we are not able to define the climate on the boundary of forest with savanna, the case of the savanna climate itself also becomes rather uncertain. Savannas as they are found today can not be considered as ecological formations and in this sense we take the meaning of Aubréville's saying that "savanna climate simply does not exist" (l. c. p. 76). We think however that under truly natural conditions there would be found all the gradual transitions between equatorial rainforest, dry forest, savanna with and without spiny shrubs, semi deserts, deserts, etc.; probably little place would be left to "grasslands".

The practical importance of the foregoing considerations is evident: in the first place, where the actually existing campos and savannas do not correspond to the climax vegetation and where this latter is of a forestal nature, we should be able to reclaim it and to transform the region into one with a more dense and more fertile vegetation. We still can not tell which would be the best way of reclamation. But the first thing to do is to study thoroughly all the possibilities. This is one of the most important conclusions to which the African Congress came and this is exactly the same in the case of South America.

This leads us to the final very important question: the present African and Asian savannas as well as the South American campos cerrados are usually found on deteriorated soils, such deterioration being extremly rapid in tropical regions. What are the reasons for this ? We know by now that this deterioration is often caused by the use of agricultural methods introduced from Europe or North America. The culture of annual crop plants, including corn, wheat and cotton is dangerous in tropical humid regions where the surface erosion and still more the internal lixiviation impoverish the soil.

This leaching out of plant nutrients is counteracted by the forests, the great transpiration of which diminishes the quantity of rain water that percolates downwards to great depths in the tropical soils. This gravitational water will always carry dissolved salts which the tropical soils do not well retain because of their generally low adsorptive power. In humid regions, even when forested, a loss of salts is unavoidable, but this loss will be counterbalanced by the deeper roots of the trees which are still able to make the contact with the underlying bed rock. This equilibrium which maintains a certain fertility in the forest soils is disturbed by the felling of the trees. It can not be restored by annual crop plants with shallow roots, and which give little and temporary protection to the soils. In tropical conditions lixiviation is so strong that inorganic and organic fertilizers may be of little utility, or at least are too expensive. The Belgian researchers in the Congo have not yet come to any better conclusion than the adaptation of the ancient methods already in use by the Africans, and which consist in the return of the fields to a forest cover crop after a few years of cultivation. Thus far the use of a forest cover crop seems to be the only practicable method of maintaining or restoring the fertility.

Since we have been speaking of the dangers inherent in the cultivation of annual plants in the tropics, it becomes necessary to stress that the foregoing considerations do not all apply to the alluvial river plains, especially where lowland rice (padi) can be grown. It is here where much of the material eroded and lixiviated from the higher lands accumulates. Here the land can be cropped continuously to rice, providing that water for flooding the fields is available at the proper times and that the weeds are kept under control. Lowland rice will always be the cereal most adapted to humid tropical lowland climates, especially where grown in the alluvial soils in the river valleys and on the deltas. Rice is the main food in the Asiatic tropics and in Eastern Asia, as has already been pointed out by Gourou (10) in his outstanding book. As he further states, lowland rice will occupy an increasingly important place as a food for more and more of the world's rapidly increasing population.

SUMMARY

Under natural conditions the boundaries between tropical forests and savannas depend, generally speaking, upon the humidity factor. An exact determination, however, of the amount of rain necessary for the existence of forests is very difficult. The general considerations which lead to the establishment of rainfactors, aridity coefficients, climatic types or formulas do not include the important physiological facts of plant transpiration nor the existence of subterranean water reserves which may be stored in the great depths of the tropical soils.

The data on water requirements of forests from classical plant ecology are based upon the assumption that the present distribution of tropical forests and savannas corresponds to the ecological conditions of their environment. Today we know, especially from researches in central equatorial Africa, that a very great area of savannas occupies areas of deteriorated soils, which in ancient times were forested.

More reliable data are obtained from the direct determination of transpiration values, which are scarce because difficult to obtain, or from a computation based on the knowledge of the total precipitation and of the drainage water of an entire river basin, covered by equatorial forest.

A comparison of the actually known facts leads to the conclusion that the water requirements during the vegetation time in temperate as in tropical climates approximates 3 mm. of rain a day or 90 mm. a month; tropical, evergreen forests seem to need 1000 to 1200 mm. a year.

Finally, the practical importance of such data is emphasized. We can distinguish which savannas can be reclaimed; and a consideration of all the facts involved will in the future teach us how this reclamation can best be done. To this last point we can only add that it is now clear that the agricultural methods of temperate

regions are inappropriate, when not destructive of the crop producing power of the soil, when applied to tropical lowland soils. Such practices disturb the water balance, favour serious surface erosion, and the internal leaching of the tropical soils; there is evidence that they cause an irreversible degradation of the fertility.

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