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Climate and the Soil

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INTRODUCTION

Soil conditions form only a part of the factors that determine the productivity of a piece of land. Sums of solar energy on days with temperatures high enough to allow plant growth determine potential yields. Soil characteristics, in association with the climate, combine to give land qualities that limit the potential to maximum yields that may be obtained locally. A number of economic, social and political conditions, that direct capital and labour input and knowledge, may further limit the maximum to actual yields. In many cases these limitations are so great that the actual yields are only a small fraction of the maximal yields. Because soil conditions themselves are also closely related to climate, the whole complex of climate, soil and productivity is very complicated.

A number of fundamental requirements that plants, and especially crops, demand from soils, are presented first in order to see which aspects of soils are important. In the second part of the paper, I will discuss the distribution of soils and their characteristics in relation to climate. Finally, I will show why actual yields, maximum land productivity and potential productivity are sometimes similar, but in most cases differ greatly.

THE LAND REQUIREMENTS OF CROPS

Plant growth and productivity are mainly determined by climate, but it is useful to speculate about the role soils play in this context. The whole production of organic matter (OM), which is the primary and secondary source of our food and also provides the soil with organic material, depends upon the assimilation process occurring in the green leaves of plants. A simple equation reads as follows:

CO_2	+	H_2O	+	Small amounts of a variety of major and minor nutrients	+	Radiation energy	→	CHO (OM)	+	O_2
(From the air)		(From the soil)		(From the soil)		(Sunlight)		(Plant material)		(To the air)

When enough nutrients are supplied, living plants may develop in water as is shown by aquatic plants and hydroponics. Although some products of intensive cultivations such as vegetables and flowers are cultivated in nutrient solutions, soils will always be the most economic growing medium for food production.

The *environmental requirements* that both wild and cultivated plants demand from the soil, so that they can realise the above assimilation process, may be summarised in the following general points (Schlichting, 1964):

1. Soils have to act as a medium in which seed may germinate and roots may develop. This means that soils must have structure and porosity, protect against drying out, too high temperatures, etc.
2. Soils must provide the growing plant with an anchorage, to allow it to expose its leaves to sunlight in the most economic way.
3. Soils must be well drained to ensure that the pore system stays partly filled with air to sufficient depths. Roots consume oxygen and produce carbon dioxide and there must be a ready diffusion of gases.
4. Soils have to act as emergency water reservoirs in times of drought or between irrigations. The water storage capacity depends on the soil colloids (clay and humus) and the finer soil pores.
5. Soils must be able to provide the plant with sufficient and well balanced amounts of a number of macro- and micro-nutrients required in biosynthetic processes of plant materials. The soil colloids (clay and humus), the organic matter content, and the amount of weatherable minerals are most important in this respect.

To produce food, plants are cultivated under economic management on defined pieces of land with specific soil conditions. Nobody can produce food continuously if the outputs are lower than the inputs. Outputs are measured in kilograms per hectare, so at this point we have to consider the surface of the soil, which we term 'land'; i.e. a certain piece of the earth's surface that includes not only the soils but also other physiographic characteristics such as slope, climate, groundwater, etc. (Brinkman and Smyth, 1973).

Agricultural land use infers that the land is conditioned for optimal productivity. Every crop or group of crops will make specific demands on the management of the land (Beek, 1978) and certain management requirements have to be added to the environmental ones. In this respect, soils or land must allow:

1. A good seedbed to be prepared and the crop to be sown.
2. Management measures required to safeguard the crop from hazards, pests, diseases and weeds.
3. The possibility that the crop may be harvested, transported and processed even under bad weather conditions.

To facilitate these needs, a certain piece of land should be fairly homogeneous with respect to soil conditions (Pons, 1977).

It is not only economically important to the cultivator but also to the country and possibly to the world that the ability of a certain area of land to produce food is not lost by erosion or other soil degradation. For this reason, conservation requirements may be formulated, to ensure that agricultural or other types of land use do not result in degradation of the land (soil) by (a) erosion; (b) silting up; (c) worsening of drainage; (d) increase in salinity; (e) desertification; etc. Where food production is secondary (i.e. via livestock production), additional land requirements should be listed, but I shall not cover this aspect of food production.

SOME DEFINITIONS OF PRODUCTIVITY

As will be understood from the foregoing, the influence of the climate on production via the intermediary of the soil is very complicated. In an attempt to simplify this complicated subject, some basic terms relating to the principles mentioned earlier may be helpful. The potential productivity (PP) of a certain area is determined by radiation and temperature (independent from the soil), the rainfall and the evaporation. However, actual land and weather conditions are seldom ideal and thus the concept of potential productivity has to be rationalised and the maximum land productivity (MP), a more realistic version of the same concept, is used in practice. In modern land evaluation (Beek, 1978), it is possible to indicate the extent to which crop and other land use requirements are met by the land qualities present and to estimate, at least for some types, how much PP will be limited by the land and weather conditions. Sometimes just one soil quality will depress yields so much that the land is classified as unsuitable for a specific type of land use. Some examples might show how local weather conditions may influence land use and yields.

Frequent high rainfall during harvest time will cause serious difficulties especially if occurring more than 3 years out of 10. Land with heavy textured clay soils will be unsuitable for arable use although all other land qualities may be favourable. On the other hand, on shallow soils with limited amounts of available water, even short periods without rainfall will damage crops, making such land also unsuitable for arable use.

The reductions in PP caused by inadequate land qualities and climate characteristics determine MP: this will be emphasised later in this paper. However, only on relatively small areas will yields actually obtained closely approach the MP. Nearly everywhere, actual yields are far below the MP for economic, social and political reasons. The gravest reason, and direct cause of hunger in developing countries, is the poverty of the majority of the small farmers and the low prices paid for agricultural products even in richer countries (Buringh, 1981).

SOILS AND CLIMATE IN THE TEMPERATE ZONE

It was only in the second half of the 19th century that Russian soil scientists learned that soil formation depends on parent material, climate, topography, drainage, flora and fauna, and time. Dokuchayev (1886) and Sibirtsev (1899) distinguished the genetical horizons of the soil profile: A, B and C. This simple original concept was accepted in nearly every country and rapidly extended, as shown in Fig. 1 (US Department of Agriculture, 1938). Unfortunately adaptions to local conditions are causing more and more deviations from the original concept. Modern soil science has introduced the concept of the soil pedon, defined as the smallest soil volume that can be recognised as a soil individual (Buol *et al.*, 1973). Figure 2 shows how a soil pedon is related to a soil individual forming part of the landscape.

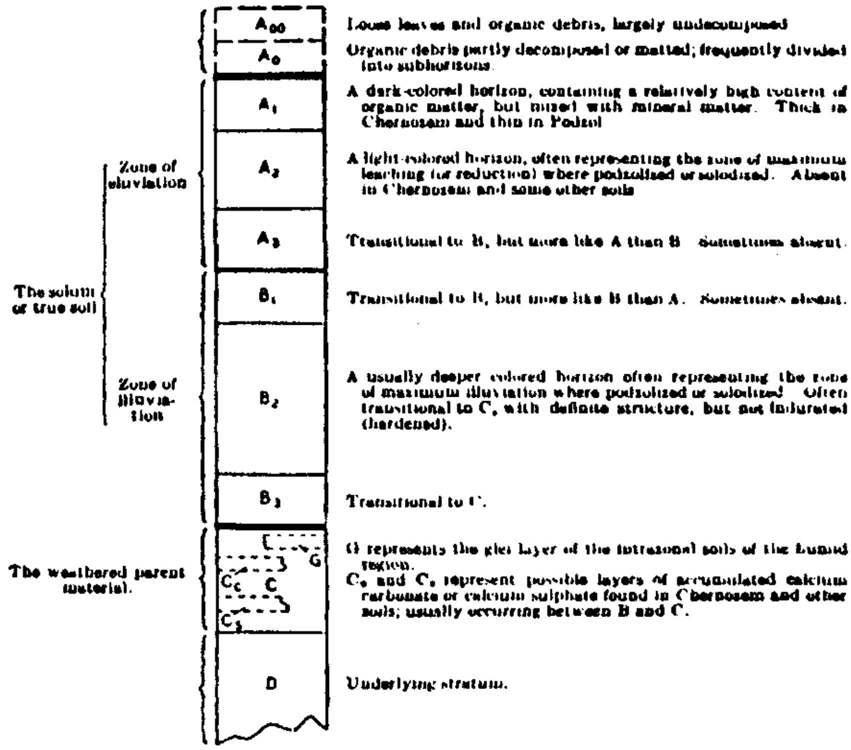


Fig. 1. The subdivision in soil horizons as given in the *Yearbook of Agriculture* (US Dept. of Agriculture, 1938).

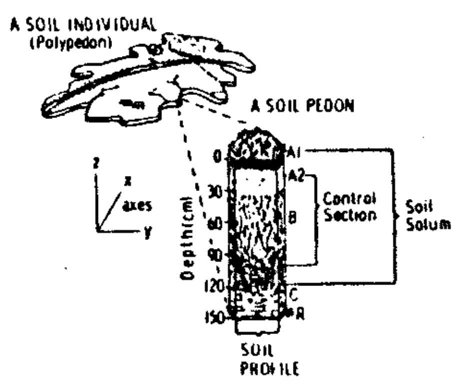


Fig. 2. A soil profile as an aspect of a soil pedon and their relationships with a soil individual (polypedon), forming a natural unit in the landscape (after Buol *et al.*, 1973).

Both Russian pedologists also formulated for the first time soil zonality in comparable parent materials; under the same topographical conditions (flat land) and under free drainage, the soil formation depends only on the climate and the related vegetation and animal life. The zonal soils form the abiotic part of mainly climatically determined ecosystems, and are arranged in climatic zones.

With the birth of the concept of the zonal soil type, soil science was born as a branch of the natural sciences and, at the same time, the foundation was laid for the genetic classification of soils. Parallel to the development in Russia, zonality principles were also formulated in the USA by Hilgard (1833–1906). Zonality as a base for soil classification was introduced in the USA by Marbut (1928). Apart from the class or order of zonal soils, a second class or order of intrazonal soils was introduced, which reflects the dominating influence of local factors of relief, drainage or parent material over the zonal effects of climate and vegetation. The azonal soils, a third order, includes soils too young to reflect soil formation.

Latitudinal soil zonality is best developed in extended flat areas covered by moraines, loess or other medium textured parent materials, showing gradually changing climates.

Western Russia and eastern and northern North America, where soil formation is only Holocene and young Pleistocene and at most 40 000 years old, provide the classical examples. Knapp (1979) shows the relationship between some major groups and the two major characteristics of the climate, temperature and humidity in a simple theoretical diagram (Fig. 3). Figure 4 presents a comparison of the distribution of very broad climatic zones, the principal vegetative types and the principal zonal soil groups for Europe and North and Central Asia following Strahler (1960). On this very small scale, striking correlations are apparent between climate, vegetation and soils. On a larger scale Fig. 5 compares the Köppen-Geiger climates for North America (Strahler, 1960) with the distribution of the generalised great soil groups in the USA (Knapp, 1979); patterns may also be compared.

The same sequence of zonal soils can occur along mountain slopes, as shown in Fig. 6. This altitude zonality, reported from many mountainous areas, is sometimes of more than local importance.

The process of soil formation involves numerous events, occurring simultaneously or in sequence, which may mutually reinforce or counteract each other. Thus a given process may tend to change the soil or maintain it in its current condition.

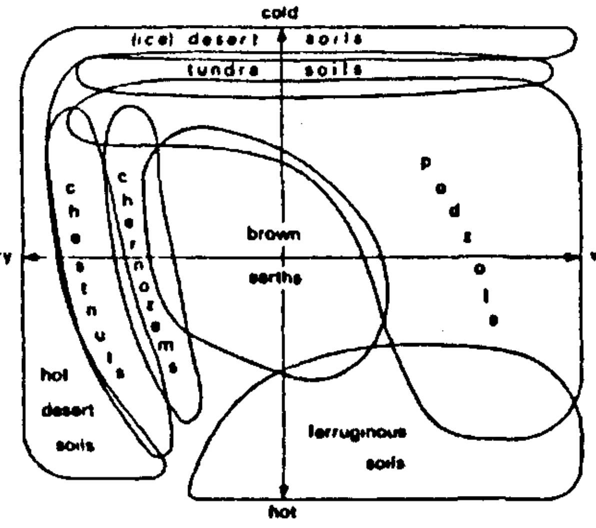


FIG. 3. A simple diagram showing the world distribution of some major soil groups in relation to two aspects of climate: temperature and wetness:humidity (after Knapp, 1979).

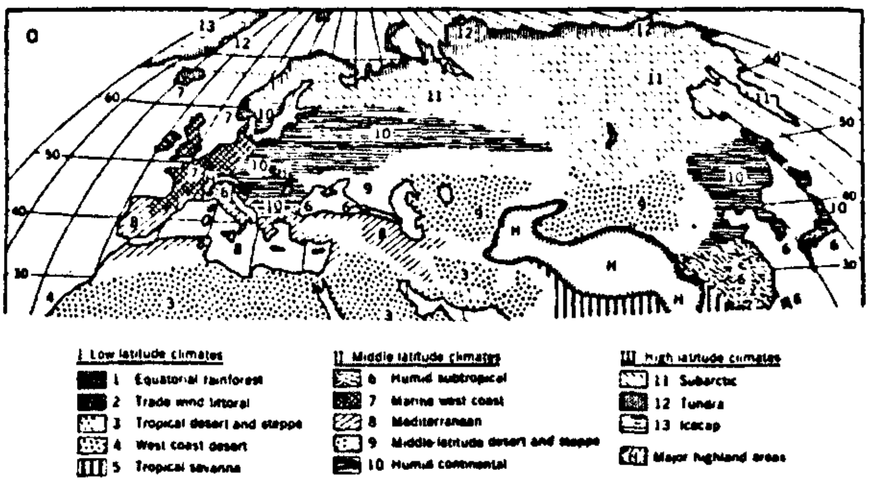
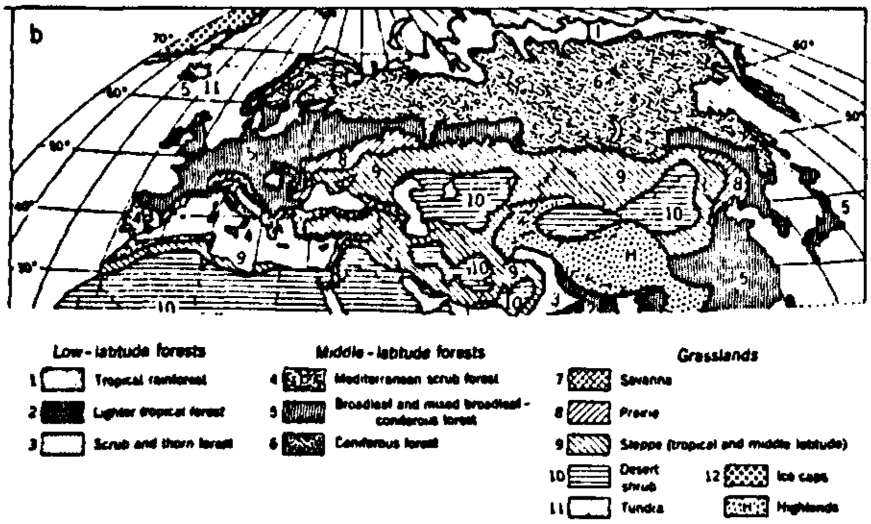


FIG. 4. A comparison of broad climatic zones, the principal vegetative types and the principal zonal soil groups of Europe and northern Asia (after Strahler, 1960).


b
Low-latitude forests
1 Tropical rainforest
2 Lighter tropical forest
3 Scrub and thorn forest
Middle-latitude forests
4 Mediterranean scrub forest
5 Broadleaf and mixed broadleaf-coniferous forest
6 Coniferous forest
Grasslands
7 Savanna
8 Prairie
9 Steppe (tropical and middle latitude)
10 Desert shrub
11 Tundra
12 Ice caps
Highlands

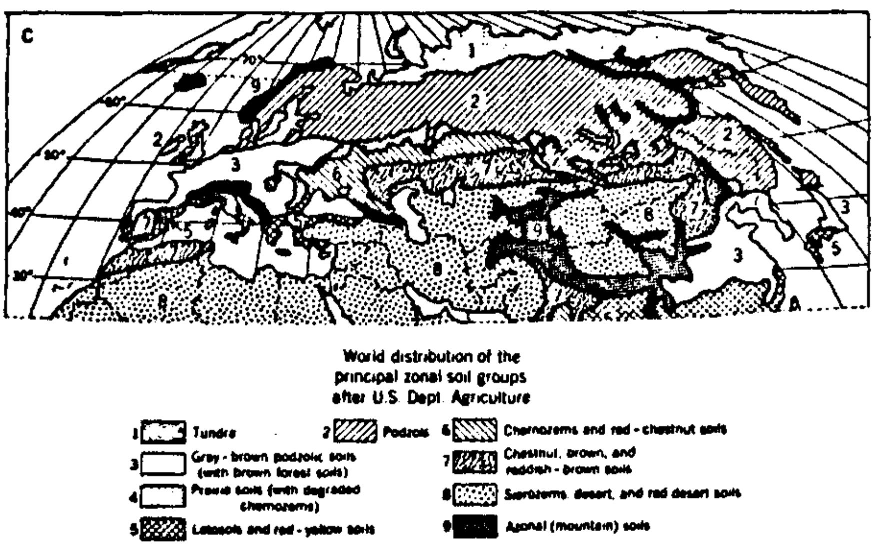

c
World distribution of the principal zonal soil groups after U.S. Dept. Agriculture
1 Tundra
2 Podzols
3 Gray-brown podzolic soils (with brown forest soils)
4 Prairie soils (with degraded chernozems)
5 Latosols and red-yellow soils
6 Chernozems and red-chestnut soils
7 Chestnut, brown, and reddish-brown soils
8 Sierozems, desert, and red desert soils
9 Azonal (mountain) soils

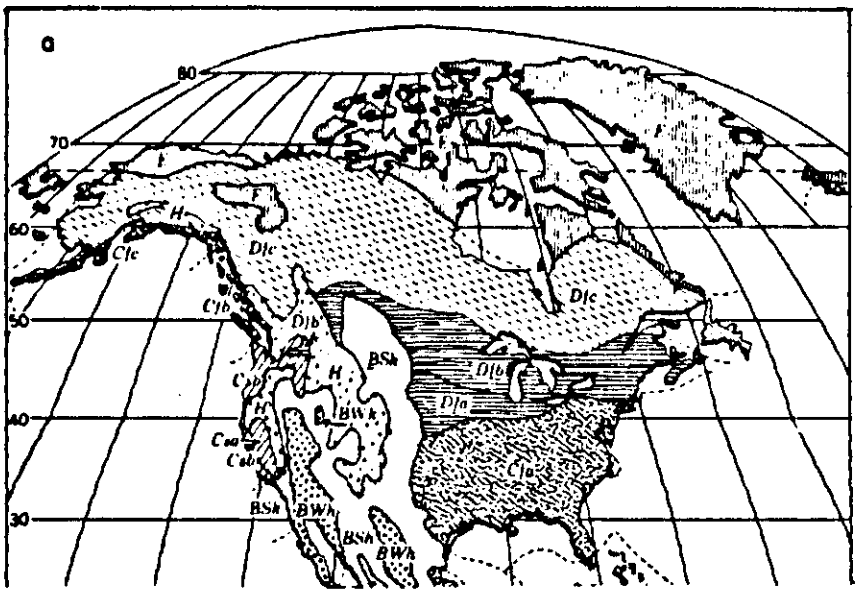
FIG. 4.—*contd.*

In the temperate climatical zone, a number of soil processes are taking place, providing each zonal and intrazonal soil with their typical characteristics. Buol *et al.* (1973) list such pedogenetical processes, and the most important ones acting in temperate climates are given in Table 1. The table also indicates the resulting soil horizons and the soils in which they occur.

In the temperate climates, the soils are relatively young. Figure 7 shows the maximum spread of the ice sheets in Europe and North America during the Pleistocene. In these areas, all poor, older soil covers are eroded. Fresh parent material was laid down as moraine deposits, most of mixed composition. The same change took place south of the ice sheets in the Pleistocene periglacial zone where river terraces, loess and solifluction layers (also mostly of mixed composition) form the parent materials of the greater part of the land surfaces. Weathering has been mainly physical in type. Minerals are only slightly chemically weathered and new formation of clay minerals has been weak. The relatively low temperatures contribute in part to the weak chemical weathering. Decomposition of organic matter also is depressed, so that relatively high amounts of organic matter and humus are present in the top soils and, because of their youth, many soils are relatively rich in plant nutrients. Mountainous areas and the higher parts of the hills with thin covers of parent material show shallow and mostly stony soils.

Table 2 lists the zonal, intrazonal and azonal soils and shows their most important characteristics in relation to the land qualities necessary for crop growth. From this table and the previous figures, the following summary of the soil conditions of the temperate areas may be given:

The humid temperate areas include very important areas of medium to light textured, well-drained, rather deep to medium-deep soils (grey-brown podzolics, brown podzolics and related soils). Their fertility is medium to rather poor but they respond well to fertilisers. Soil working is not very difficult and the topography is nearly flat to undulating. North of this zone extensive areas of podzols are to be found with mostly light textures and medium root depths. They are rather poor in fertility but in being not stony they are easy to manage. Their response to added fertilisers is good but they tend to have water shortages. The northern part is not suited to crop growth because of the low temperatures.



Key to letter code designating climate regions:

FIRST LETTER

A, C, D Sufficient heat and precipitation for growth of high trunked trees

A Tropical climates. All monthly mean temperatures over 64 4°F (18°C).

B Dry climates. Boundaries determined by formula using mean annual temperature and mean annual precipitation (see graphs).

C Warm temperate climates. Mean temperature of coldest month: 64 4°F (18°C) down to 26 6°F (−3°C).

D Snow climates. Warmest month mean over 50°F (10°C). Coldest month mean under 26.6°F (−3°C).

E Ice climates. Warmest month mean under 50°F (10°C).

SECOND LETTER

S Steppe climate, *W* Desert climate — Boundaries determined by formulas (See graphs).

f Sufficient precipitation in all months

m Rainforest despite a dry season (i.e., monsoon cycle).

s Dry season in summer of the respective hemisphere.

w Dry season in winter of the respective hemisphere.

THIRD LETTER

a Warmest month mean over 71 6°F (22°C).

b Warmest month mean under 71.6°F (22°C) At least 4 months have means over 50°F (10°C.)

c Fewer than 4 months with means over 50°F (10°C).

d Same as *c*, but coldest month mean under −36 4°F (−38°C).

h Dry and hot Mean annual temperature over 64 4°F (18°C)

k Dry and cold. Mean annual temperature under 64 4°F (18°C).

FIG. 5. Comparison between (a) the Köppen–Geiger climates and (b) the generalised major soil groups of North America (Knapp, 1979).

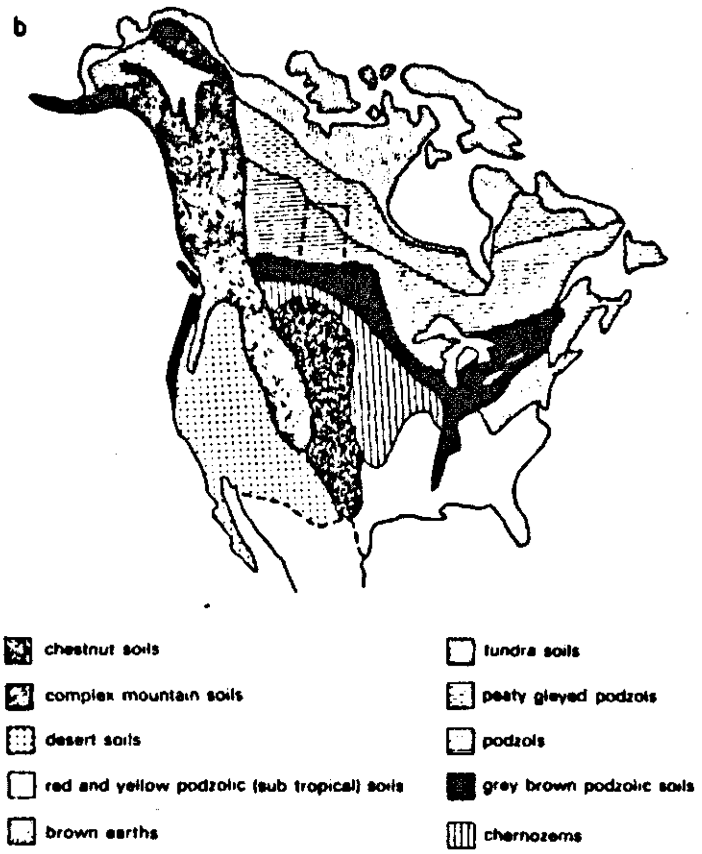


FIG. 5.—*contd.*

In the subhumid to subarid areas of the temperate zone good to excellent quality soils are present. They show well-drained, deep profiles with medium textures, and deep A_1 horizons with very favourable structures. The natural fertility is medium to high and they respond very well to fertilisers. Water shortage is a problem, but the high water storage capacity of the profiles make irrigation economic. Soil labouring and harvesting of root crops do not form limitations.

The lithosols of the mountains and higher hills sometimes occupy important areas as in Europe, middle and eastern Siberia, and western USA and Canada.

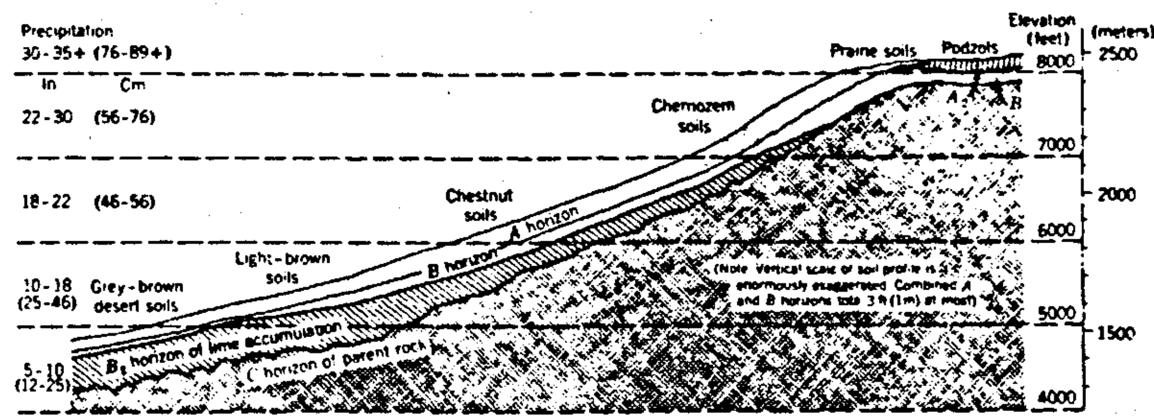


FIG. 6. Diagram showing the altitude zonality along the slopes of the Bighorn Mountains, Wyoming (after Thorpe, 1931).

TABLE 1

THE MOST IMPORTANT PROCESSES OF SOIL FORMATION IN THE TEMPERATE ZONE, THEIR RESULTING HORIZONS AND THE SOILS IN WHICH THEY OCCUR

Process term	*Brief description*	*Horizon*	*Soils*
Littering	The accumulation on the mineral soil surface of organic litter and associated humus to a depth of less than 30 cm	O_l O_f O_h	Tundra soils Podzols Forest soils Gley soils
Humification	The transformation of raw organic material into humus and the incorporation with clay	Mollic A_1 Umbric A_1	Chernozem Prairie soil Chestnut soil Rendzina Gley soil
Decalcification	Reactions that remove $CaCO_3$ from one or more soil horizons	Cambic B	Tundra soils Podzols Grey-brown podzolic soils Prairie soils
Braunification	Release of iron from primary minerals, dispersing of iron oxide in increasing amounts and dehydration, giving the soil mass brownish colours	Cambic B Argillic B	Brown forest soils Grey-brown podzolic soils Chestnut soils
Lessivage	The migration of small mineral particles from the A to the B horizon producing in the B horizon relative enrichment of clay	Argillic B	Grey-brown podzols Planosols
Podzolisation	The formation of chelates and the migration of organo-Al and/or Fe oxides, resulting in the concentration of silica in the eluviated layer	Albic A and part of podzol B	Podzols
Pedoturbation	Biological, physical (freeze–thaw and wet–dry cycles) churning and cycling of soil materials	Cambic B Mollic A	Acid brown soils Brown forest soils Chernozems Chestnut soils Some alluvial soils
Gleysation	The reduction of iron under anaerobic soil conditions (bluish-greenish grey colours) with or without brown and other mottles of ferric concretions	Wet Cambic B Wet Argillic B	Gley soils Pseudo gley soils Planosols
Salinisation and alkalinisation	The accumulation of salinity in soils and/or the accumulation of Na ions on the exchange sites in a soil	Natric B	Solonchak Solonetz

TABLE 2

ZONAL, INTRAZONAL AND AZONAL SOILS AND THEIR MOST IMPORTANT SOIL CHARACTERISTICS IN RELATION TO CROP GROWTH

Zonal and intrazonal great soil group	*Native vegetation*	*Drainage*	*Natural kind of A_1*	*Texture*	*Structure*
Tundra soils	Moss, flowering plants	Poor	Peaty	Medium to light	—
Podzols	Coniferous or mixed forests	Good	0 horizon, shallow	Light	Favourable
Brown podzolic soils	Deciduous and mixed forests	Good	0 and A_1 horizons, shallow	Light to medium	Favourable
Grey-brown podzolic soils	Deciduous and mixed forests	Good	A_1 horizon, shallow	Medium to heavy	Favourable
Prairie soils	Tall grass	Good	A_1 thick and well developed	Medium	Very favourable
Chernozems	Tall and mixed grass	Good	A_1 thick and well developed	Medium	Very favourable
Chestnut	Mixed tall and short grass	Good	A_1 thick to medium and well developed	Medium to heavy	Very favourable
Saline and alkaline soils	Halophytic grasses and shrubs, prairie	Poor to imperfect	A_1 very thin	Medium to heavy	Very poor to poor
Rendzinas	Grassland to forest	Good	Well developed, thin	Medium	Very favourable
Lithosols	Grass, shrubs	Good	A_1 thin	Medium to light	Medium
Alluvial soils	Wide range	Poor to good	A_1 thin	Light to heavy	Favourable to medium
Planosols	Grass to forest	Poor to imperfect	A_1 very thin	Light to medium to heavy	Very poor

TABLE 2—*contd.*

Rooting depth	*pH*	*Chemical fertility*	*Other characteristics*	*Present land use*
Shallow	Medium to low	Medium to low	Sometimes strong	Nature or very extensive pastures
Shallow to medium	Low	Low	Sometimes strong	Cropland, grassland, forests
Medium to deep	Low	Low to medium	—	Cropland, grassland, forests
Deep	Medium to low	Medium	—	Crops on small farms
Deep	Medium	Medium to high	—	Crops on medium farms
Deep	High	High	—	Grain crops on large units
Medium to deep	High	High	—	Grain crops, extensive grassland
Shallow	High	Poor	Saline impermeable	Waste to grazing to poor crop land
Shallow	High	Medium	Sometimes strong	Pastures, regional crops
Shallow	Medium	Medium to low	Very strong	Forests, barren, or grazing (extensive)
Medium to deep	Wide range	Medium to high	—	Wide range of land use
Shallow	Medium to low	Very poor	Impermeable	Pasture, some crops, forests

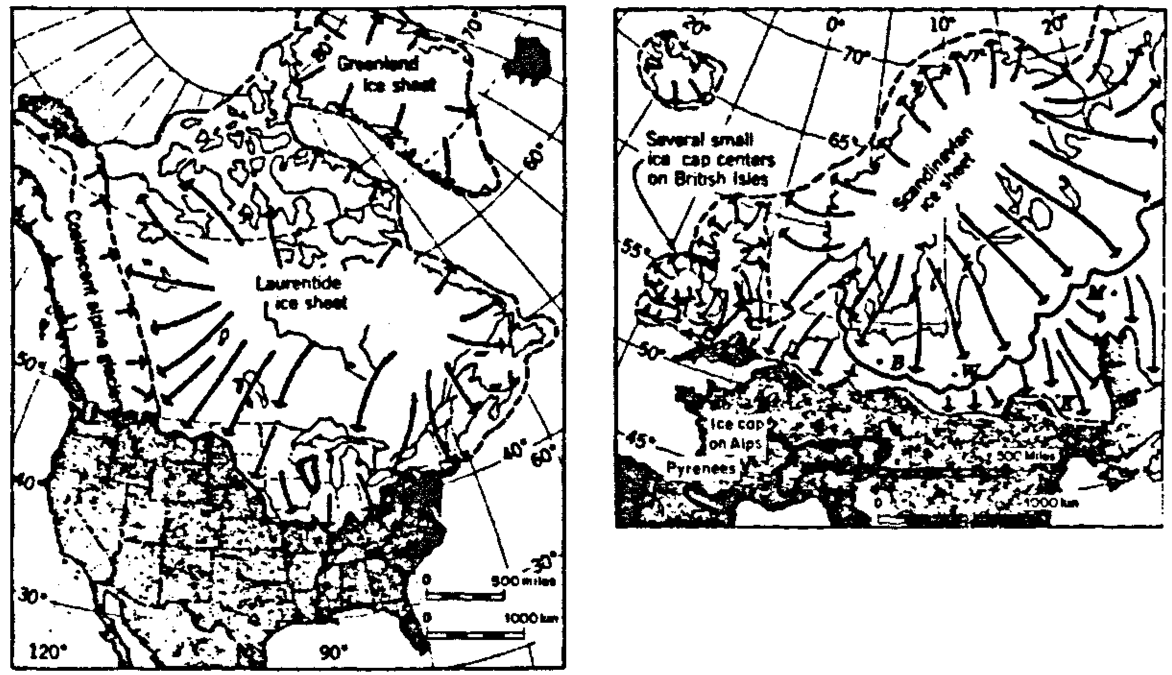


FIG. 7. The Pleistocene ice sheets of North America and Europe at their maximum spread. Solid lines show limits of ice in the last glacial stage; dotted line on land shows maximum extent at any time.

SOILS AND CLIMATES IN THE SUBTROPICAL AND TROPICAL ZONE

Soil classifications founded on zonal concepts are very attractive to soil surveyors, geographers and ecologists and this possibly accounts for their continued use (Fitzpatrick, 1980). In modern classification systems, however, the infallibility of the zonal system has been challenged, for many reasons. The main practical reason is that the system was based largely on environmental factors rather than on intrinsic properties of soils, and in most cases the tendency was to use virgin soils. Other reasons were the impossibility of distinguishing between some zonal and intrazonal soils, e.g. podzols, the relative abundance of intrazonal and azonal soils in some countries, and the strong emphasis placed on colour. Also, for theoretical reasons, the zonal concept must be abandoned as soon as subtropical and tropical soils are incorporated.

Whereas the temperate land areas on which the zonal system was developed are always of young Pleistocene origin and mostly about 10 000 years (maximum 40 000 years) old, the subtropical and tropical land surfaces are 100 000–1 000 000 years and sometimes even older. In fact, the subtropical and tropical soils form at least two other categories of zonality to be added to the zonal, azonal and intrazonal categories of the old system, as shown in Table 3. The terms juvenile, mature and senile (adapted from Carter and Pendleton, 1956) describe the overall development of soils with age.

Although this and other simplifications have to be used with care and in a limited way, because exceptions are numerous, this adapted zonal system does give a clear explanation of the distribution of soils on earth and their important characteristics. The age-differentiated zonality is one of the cornerstones of the morphometric soil classification system developed in *Soil Taxonomy* (US Dept. of Agriculture, 1975) with its 10 Orders.

Whereas the distribution of zonal soils in the northern hemisphere is related to the present climate, the distribution of the juvenile, mature and senile soils on earth has its origin in long-term climatic changes. As already shown (see Fig. 7) the present temperate zones of the earth roughly coincide with zones that were glacial and periglacial during the Pleistocene glacial periods.

Periodically, the vegetation vanished partly or completely, and tremendous erosion occurred. The old, senile soil cover of Tertiary age was eroded and the parent rocks were denuded.

TABLE 3

ZONAL SOILS AND SOIL ORDERS CLASSIFIED IN AN AGE DIFFERENTIATED ZONALITY SYSTEM

Soil category	*Estimated ages (years)*	*Zonal, intrazonal and azonal soils*	*Soil taxonomy, orders and suborders*
Zonal soils	0–±5 000	Alluvial soils, lithosols, peat soils	Entisols, inceptisols, histosols, some aridisols
Juvenile zonal soils	±5 000–±50 000	Tundra podzols, prairie soils, chernozems, G.B. podzolic soils, brown podzolic soils, brown soils, rendzina's, pseudogley, andosols, reddish prairie soil	Inceptisols, spodosols a majority of mollisols, young alfisols, andepts
Mature zonal soils	±50 000–±500 000	Black cotton soils, feriallitic soils, red and yellow podzolic soils, reddish-brown savanna soils, red and brown Mediterranean soils, planosols	Ultisols, vertisols, palaeo-alfisols
Senile zonal soils	±500 000–±5 000 000	Reddish-brown lateritic soils, latosols, laterite soils, ferrallitic soils, white sands	Oxisols

Very strong physical weathering processes, together with transportation of this fresh material by water, wind and gravity provided a totally new and fresh parent material cover over more than 90% of the surface of the temperate areas.

The soils in the present temperate zone are relatively young, rich in chemical components and, depending on their parent materials, of medium texture and physically rather favourable (as shown in Table 2).

South and north of the Sahara in the subtropical and tropical savanna zones climates fluctuated in response to the glacial and interglacial periods in the northern hemisphere. In these areas, however, climates with strong dry seasons alternated with wet climates. Periodically the vegetational cover became sparse and erosion took place, but not on scales comparable with the erosion in the glaciated and periglaciated areas.

The majority of the soils in this area have not been eroded or have only been partly eroded. This means that together with the accelerated soil formation that resulted from the higher temperatures, the soils are much more developed and may be considered as mature soils. The main soil-forming processes are listed and briefly described in Table 4.

TABLE 4

IMPORTANT PROCESSES OF SOIL FORMATION, WORKING OVER LONG PERIODS AND EFFECTIVE IN THE SUBTROPICAL AND TROPICAL ZONES, WITH THEIR RESULTING HORIZONS AND SOME SOILS IN WHICH THEY OCCUR

Process term	*Brief description*	*Horizons*	*Soils*
Chemical weathering	Chemical disintegration and decomposition of rocks and minerals including oxidation, reduction hydration, hydrolysis and solution of the substances formed	Older cambic B, wet cambic B, wet argillic B, red argillic B, oxic B	Planosols, red Mediterranean soils, ultisols, oxisols
Eluviation	Progressive movement of material out of a portion of the soil, or out of the whole soil, causing extreme low plant nutrient contents	Argillic B with low base sat., oxic B	Ultisols, oxisols
Rubification and ferrugination	Continued release of iron from primary minerals, progressive oxidation, dehydration and crystallisation, giving the soil matrix reddish and red colours	Older cambic B, and argillic B, oxic B	Red inceptisols, red altisols, ultisols oxisols
Laterisation (desilication, ferrallitisation)	Chemical migration of silica out of the soil solum and thus concentration of the sesquioxides in the solum	Oxic B, plinthite	Oxisols, white sands

The table also shows the resulting soil horizons and the soils in which they occur. In Table 5 the most important soil characteristics are listed for some mature soils.

Soil conditions in the subtropical subhumid to arid climate zones may be summarised based on Tables 4 and 5 as follows:

In the arid tropical areas, azonal soils such as lithosols, sands, etc.

TABLE 5

SOME MATURE AND SENILE ZONAL SOILS AND THEIR MOST IMPORTANT CHARACTERISTICS IN RELATION TO CROP GROWTH

Zonal great soil groups	*Native vegetation*	*Drainage*	A_1	*Texture*	*Rooting depth*	*pH*	*Chemical fertility*	*Other characteristics*	*Present land use*
Red and yellow podzolic soils	Deciduous and some mixed forms	Good to medium	Weak	Medium	Deep	Low	Low	Responsive to fertilisers	Cropland and forests
Reddish-brown savanna soils	Tall grass and shrubs	Good to medium	Weak	Medium (to heavy)	Moderate to deep	Medium	Low	Responds well to irrigation	Grazing in large units
Red and brown Mediterranean soils	Winter green forests	Good to medium	Weak	Heavy	Deep	Medium to low	Medium	—	Cropland, fruits
Black cotton soils	Grass and some shrubs	Poor	Weak	Very heavy	Poor	High to medium	Medium	Responsive to irrigation	Grazing, irrigated crops
Reddish-brown lateritic soils	Tropical rain forest	Good	Weak	Medium to light	Very deep	Very low	Very low	Response low to fertilisation	Fruit plantations, subsistence crops
White sands	Savanna	Good to poor	Weak	Light	Deep to shallow	Very low	Very low	—	Extensive grazing

are covering the major land surfaces. As a result of the shift of the arid zone, fossil well-developed red soils are occurring.

The semi-arid and semi-humid zones include partly reddish soils of heavy textures, and medium to deep root depths. The drainage is good to medium but the poor permeability together with the extreme climatic conditions give major problems in relation to erosion. Relatively high amounts of fertilisers are needed on the chemically poor soils. Other important parts of this zone are occupied by flat land with very heavy textured black cotton soils, now mostly under extensive grazing. Upon irrigation and application of fertilisers, however, these very difficult soils may give reasonable yields, if properly managed (Blokhuis, 1980). The main difficulties in the semi-arid and semi-humid subtropical and tropical areas are unstable climatic conditions, land labouring, erosion hazards, fertility problems and danger of salinity.

On both sides of the equator, in the areas still covered by humid tropical forests, dense vegetation has covered the soils for a very long period. The land surfaces are stable and only slightly eroded and here senile soils are found. They are completely leached and chemically degraded and their clay colloids are broken down or are inactive. Only aluminium and iron oxides are left giving the soils an excellent stable structure (Tables 4 and 5). In this zone senile zonal soils are occurring, indicated as lateritic or latosols and in the modern classifications as oxisols. All are deeply rootable, beautifully structured soils, physically very favourable, but extremely poor from a chemical point of view. A further difficulty arises from their low absorption capacity that, together with the high rainfall, makes the application of fertiliser very uneconomic.

Large land surfaces are occupied by planosols which are mostly used for irrigated crops such as rice. These are also very poor soils, both from a physical and a chemical point of view (Brinkman, 1980).

The best soils in the tropical zones are the azonal soils derived from volcanic materials and from rich alluvium, on which the majority of the population of the tropics depend.

POTENTIAL PRODUCTIVITY

To obtain a clear idea about the maximum land productivity of a certain soil it is necessary to know the local potential level of production. As mentioned earlier, the basis of all crop production is dependent upon radiation from the sun, which provides the energy for photosynthesis. Moving in a northern direction, temperature will progressively limit the length of the growing season, and the total effective amount of radiant energy will also decrease.

The theoretical potential production for the latitude at Wageningen was determined by de Wit (1965) as being about 200 kg dry organic matter per day per hectare. This represents the production of a standard crop, well supplied with nutrients, oxygen and water in a stable soil, under the weather conditions of a sunny summer's day in England and in Holland. Under these conditions the conversion of CO_2 and H_2O into carbohydrates depends only on the number of days of growth of the plant, the day length and the intensity of the light during each day (clear days or overcast days). With the help of the formulas of de Wit (1965) and relatively simple climatical data, the 'mean monthly gross photosynthesis product', expressed in 'kg carbohydrates per hectare per month' can be computed for every place. To calculate the 'amount of plant dry matter with a standard chemical composition' a reduction factor of 0·65 is applied (Penning de Vries, 1973).

Buringh *et al.* (1975) determined the potential production of dry matter (PPDM) for their 'broad soil regions' of the world. PPDM is the sum of the average potential production of each month. Only months with a mean temperature of 10°C or higher during at least 3 months are taken into consideration, because a growing season of less than 3 months does not allow arable farming.

The PPDM of a theoretical standard crop includes roots, stems, leaves, flowers and fruits. To convert PPDM into the potential production in grain equivalents (PPGE), e.g. of wheat or rice, Buringh *et al.* (1975) made assumptions leading to a reduction factor of 0·43. Now, however, this treatment is considered too simple for such a complex situation. In recent literature (Buringh, 1980), this reduction factor is studied in relation to the kind of crop varieties, management practices, finer climatic variations, etc. and is found to vary greatly, but to avoid complications, the factor of 0·43 will be retained.

The value obtained for PPGE is the absolute maximum yield produced by an ideal variety of a theoretical crop, growing during the whole period at temperatures ≥10°C, on an ideal soil, not threatened by adverse weather conditions, diseases or lack of water. In Figs 8, 9, 10 and 11 the PPGE is shown for broad soil regions (see later) in relation to Europe, northern and central America, South America and Asia.

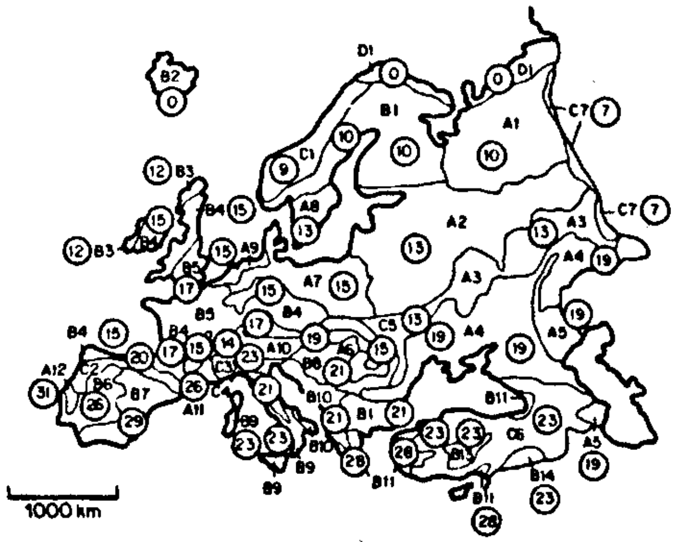


FIG. 8. Europe. Broad soil regions (after Buringh *et al.*, 1975) with potential productivity in grain equivalents per hectare (PPGE).

In Europe (Fig. 8) the PPGE is increasing from 0 in Iceland and the tundras of northern Russia, to 10 t ha^{-1} in Finland and middle Sweden, 12–13 t ha^{-1} in southern Sweden, Scotland, western Ireland and central Russia, 15–17 t ha^{-1} in England, Holland, western and northern France and south-western Germany, 19 t ha^{-1} in southern Russia, and 26–31 t ha^{-1} in the Mediterranean areas of southern Turkey, Greece, Italy, Spain and Portugal.

In North and Central America (Fig. 9) the same tendency is found. The PPGE increases from 9 to 13 t ha^{-1} in Canada, to 19 t ha^{-1} in the northern chernozem area, 23–30 t ha^{-1} in the Gulf Coast States, 26–28 t ha^{-1} in California and 34 t ha^{-1} in central Mexico, the central American countries and the Caribbean Islands. In South America (Fig. 10) the high level of PPGE of 32–34 t ha^{-1} is continued until Uruguay and Argentina, where its value is 24–21 t ha^{-1}. In Africa the PPGE is between 32 and 34 t ha^{-1} over the whole continent.

Asia (Fig. 11) shows wide variations. In this continent the PPGE changes from 0 in northern Siberia and 5–8 t ha^{-1} in western and central Siberia, to 20 and 21–27 t ha^{-1} in Japan and central China respectively, 23 t ha^{-1} in Tibet, and to the same tropical level of

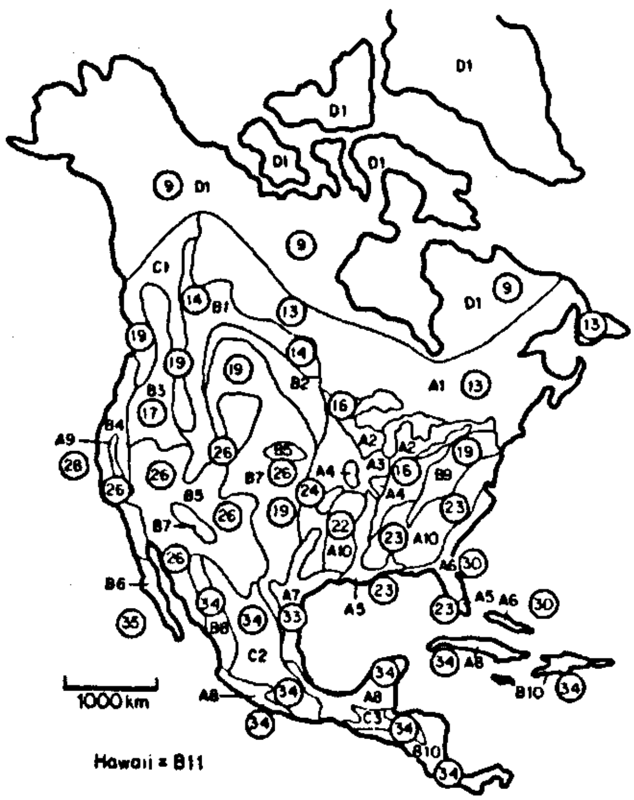


FIG. 9. North and Central America. Broad soil regions (after Buringh *et al.*, 1975) with potential productivity in grain equivalents per hectare (PPGE).

32–34 t ha^{-1} in Saudi Arabia, Iran, India and the whole of South-east Asia.

Australia also shows a high PPGE value of 32–34 t ha^{-1} except in the south where it drops to 26 t ha^{-1} in Victoria. In New Zealand the value falls from 23 in the northern Island to 16 t ha^{-1} in the south.

Areas with high temperatures and clear skies all the year round exhibit maximum PPGE values of 36–38 t ha^{-1} as a result of maximum radiation. Examples are the desert around the Arab Lake, the West Coast of northern South America, in north-eastern Brazil, the eastern Sahal zone, some East African coastal areas, western Madagascar and central Australia. These values have little practical significance, however, because in these areas the lack of water is also maximal.

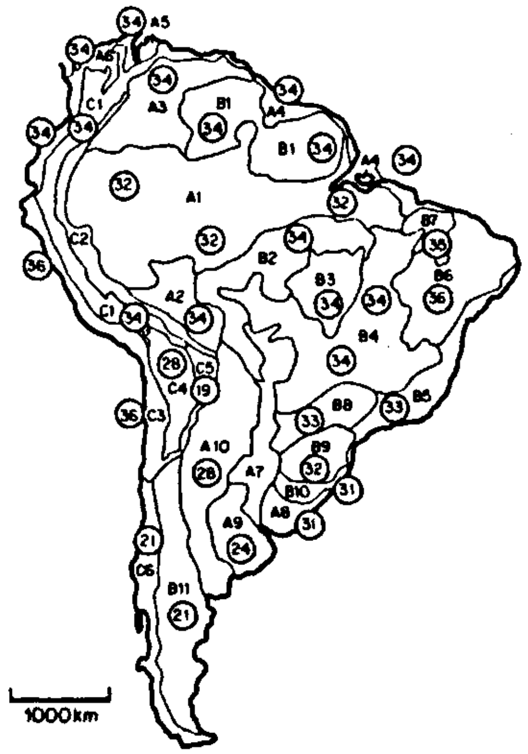


FIG. 10. South America. Broad soil regions (after Buringh *et al.*, 1975) with potential productivity in grain equivalents per hectare (PPGE).

LAND QUALITIES, REQUIREMENTS OF LAND USE TYPES AND BROAD SOIL REGIONS

The potential productivity, both the PPDM as well as the PPGE, although governed by the radiation energy and temperature, is in practice limited by a number of physical factors. These include 'pure' adverse climatical conditions and 'pure' soil conditions, but interacting soil and climatical limitations are more important.

Damage resulting from nightfrost, strong winds, hailstorms, dry winds or heavy rains is due mainly to pure climatical constraints but soils also play some role. On the other hand physical limitations such as poor drainage, impermeable soil layers, stoniness and low chemical fertility are considered pure soil limitations, but climate also has an

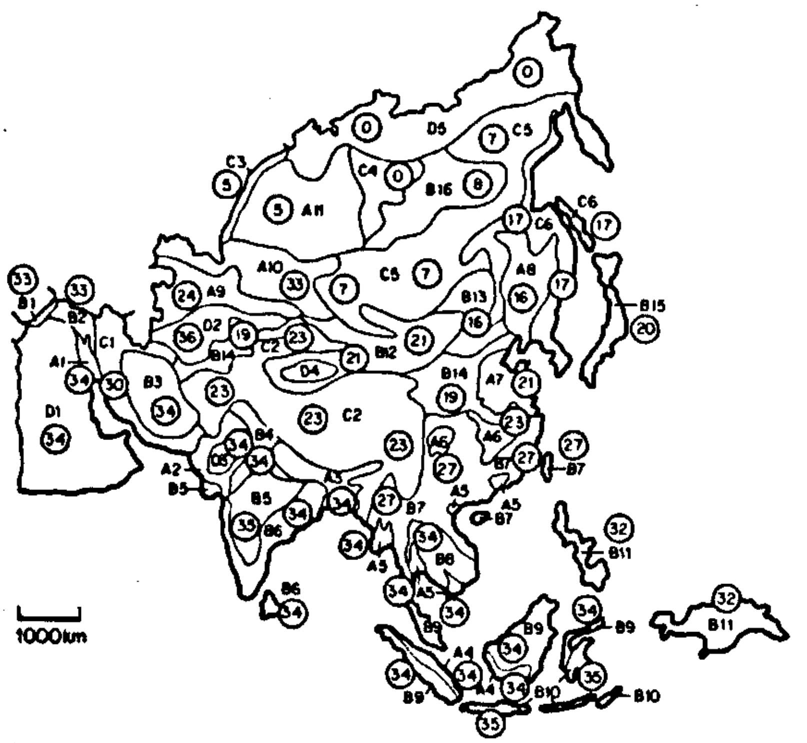


FIG. 11. Asia. Broad soil regions (after Buringh *et al.*, 1975) with potential productivity in grain equivalents per hectare (PPGE).

influence. Normally climate and soils interact in determining the amount of available water, seedbed preparation or the possibility of harvesting root crops mechanically. If a clear idea is to be obtained about the demands which the cultivation of a certain crop puts on the land or of the extent to which land causes limitations for crop growth then account must be taken of the land qualities and the requirements of the land use types. Certain types of land use are determined by basic ecological, management and conservational requirements, which in turn affect land evaluation.

The land qualities required for good crop land may be listed as follows (selected from Beek and Bennema, 1972):

1. Sufficient drainage to allow deep root growth.
2. Enough available water to prevent growth stagnation.
3. Enough available nutrients for the full development of the crop.

4. Suitable conditions for the preparation of a good seedbed.
5. Soil/weather conditions for growth, ripening and harvesting of crops.
6. Trafficability from farm to land and on the land.
7. Suitability for mechanised operations.
8. Resistance to erosion.

In the normal procedure of land evaluation, all qualities of each land unit are analysed, rated and compared with the requirements of land use. For our immediate purpose, however, this is not possible and, in accordance with Buringh (1980), the limitations are combined as (a) soil/land limitations and (b) water deficiency limitations. For the water deficiency limitations, calculations are made on the basis of the ratio between actual transpiration and the potential evapotranspiration, presuming that all soils have a water storage capacity of 150 mm water. This assumption is far from correct but the simplification is necessary in order to avoid complicated calculations.

For land evaluation purposes, Beek (1978) describes land in terms of land (mapping) units (LU) and compares the land qualities of these LUs with the requirements of the land utilisation types (LUTs). For the same reason Buringh distinguished his 222 physiographic broad soil regions, each region being more or less homogeneous in terms of soil and climatic conditions.

Figure 12 shows how these broad soil regions in northern America are related with the soil map. To distinguish the broad soil regions rough topographical characteristics are also taken into account. Lowlands, uplands and high mountains are indicated by A, B and C, respectively. The letter D is used for dry deserts and tundras where crop production is impossible or only possible with irrigation.

It will be clear that the broad soil regions may still include very different soils and climates but that they are homogeneous enough in both aspects on this scale to serve as a basis for calculations of the productivity.

In every broad soil region of the categories A, B and C, part of the soils are unsuitable for crop production as a result of unfavourable land qualities. They may be too steep, too shallow, too stony, too badly drained, too poor, or in permanent use for non-agricultural purposes. The area taken into urbanisation, etc. is rapidly increasing (in the USA by a rate of 1 000 000 ha year^{-1}); nearly always it is the best quality land that is used (Buringh, 1981).

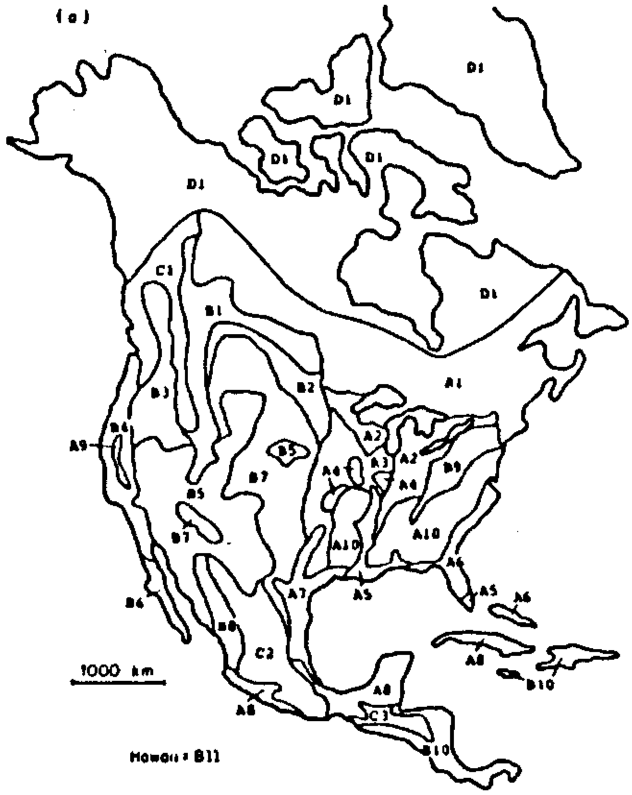


FIG. 12. (a) The broad soil regions of North and Central America (after Buringh *et al.*, 1975) compared with (b) the soil map of a part of northern America.

Key to part (b):

Zonal soils

Pz	Podzol soils
G	Grey wooded soils (Canada)
BP	Brown podzolic soils
GB	Grey-brown podzolic soils
RY	Red and yellow podzolic soils
Pr	Prairie soils
RPr	Reddish prairie soils
Cz	Chernozem soils
Cs	Chestnut soils
RCh	Reddish chestnut soils
Br	Brown soils
RBr	Reddish brown soils
NC	Non-calcic brown (Shantung brown) soils
Sz	Sierozem (grey desert) soils
RD	Red desert soils

Intrazonal soils

Pl	Planosols
Rz	Rendzina soils
So	Solonchak and solonetz soils
W	Wiesenböden, ground-water podzol and half bog soils
Bg	Bog soils

Azonal soils

L	Lithosols and shallow soils, sands, lava bed
A	Alluvial soils

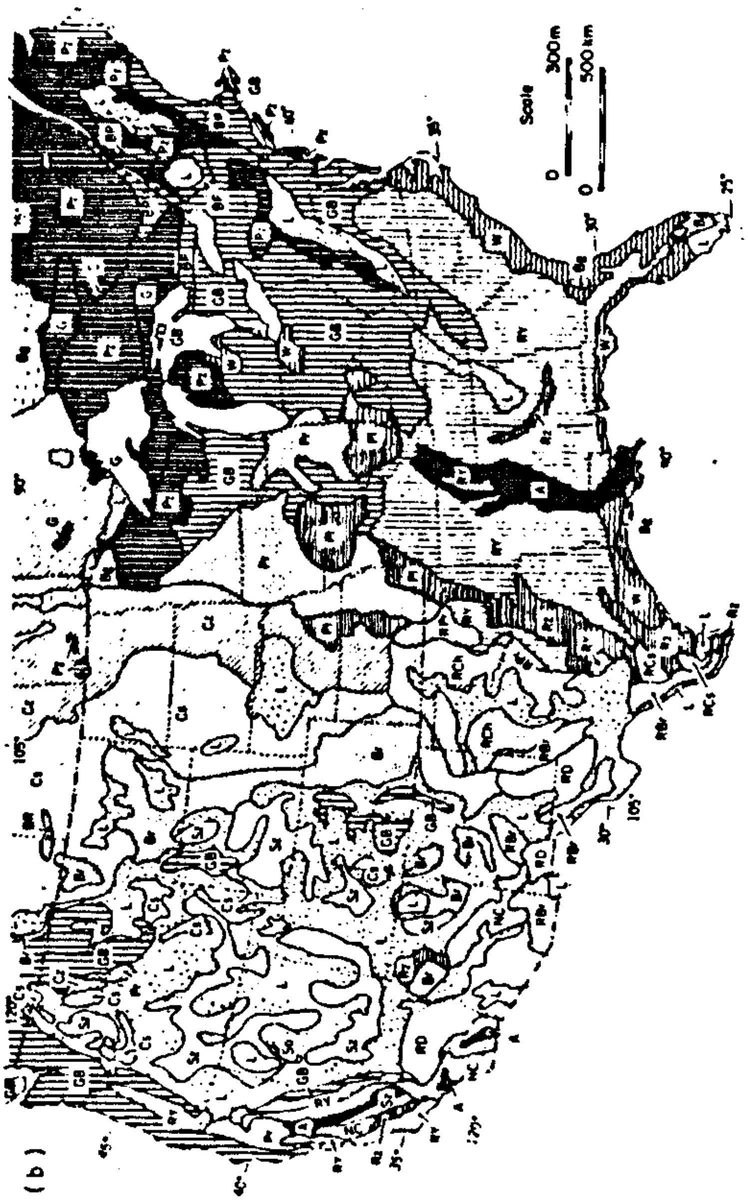


FIG. 12.—*contd.*

The decision as to whether certain land units are suitable for crop production is a very delicate one. Many social and economic factors are involved and the capital input required is also very important in this respect. The danger of erosion or salinisation must be assessed, as must the environmental impact of a changed landscape.

For each broad soil region the land suitable for crop production is roughly appraised and expressed as the fraction of potential agricultural land (FPAL). Very high values of 0·45–0·50, or even greater than 0·5, are sometimes encountered. South-eastern England, Holland, France and southern Germany as well as the Po valley and the chernozem areas of eastern Europe, and southern Russia inclusive of South-west Siberia show FPAL values > 0·45. Much of Ireland, Mid- and West England and southern Sweden exhibit values of 0·25–0·3 but for West Ireland, and northern Scotland the fraction is < 0·15. For Denmark, North Germany and Poland, the value is 0·30–0·35; for mountainous countries such as Spain, the value is 0·20–0·25. In Asia the flood plains of the large Chinese, Indian and Bangladesh rivers have extremely high FPALs of > 0·5. The south-eastern USA shows very high fractions, whilst in South America large areas in Venezuela, Columbia and Uruguay have FPALs of 0·35–0·4. Central and southern Africa are characterised by FPAL values of 0·30–0·35. These last areas contain huge surfaces of potential agricultural land, at present little exploited and so forming important reserves for future crop production. They also have high PPGE values (Figs 10 and 11). It will be of great interest to know the maximum possible yields these areas can sustain in order to judge if it is eventually worthwhile extending crop production.

THE MAXIMUM PRODUCTION (MPGE) OF THE POTENTIAL AGRICULTURAL LAND (PAL)

The potential agricultural land (PAL) area is not always of high quality: in fact, its land qualities in relation to crop production may vary extremely. This is due both to climate as well as to soil conditions. In the study of Buringh *et al.* (1975), reduction factors caused by soil/land conditions (FSC) and by water deficiency (FWD) are appraised for the soils and the climates of the PAL in each broad soil region.

In Table 6 a number of combined reduction factors for FSC and

TABLE 6

THE POTENTIAL PRODUCTIVITY IN GRAIN EQUIVALENTS (PPGE), THE FRACTION OF POTENTIAL AGRICULTURAL LAND (FPAL), THE REDUCTION FACTORS FOR SOIL/LAND CONDITIONS (FSC) AND WATER DEFICIENCIES (FWD) AND THE MAXIMUM LAND PRODUCTIVITY IN GRAIN EQUIVALENTS FOR A NUMBER OF INTERESTING BROAD SOIL REGIONS ACCORDING TO BURINGH *et al.* (1975)

Broad soil regions		*PPGE*	*FPAL*	*FSC*	*FWD*	*FSC + FWD*	*Maximum land productivity, grain equivalents* ($t\ ha^{-1}$)
West Norway	(C1)	9	0·5	0.7	1·0	0·7	6
S.E. Norway	(B1)	10	0·3	0·5	1·0	0·5	5
N. Scotland and W. Ireland	(B3)	12	0·2	0·6	1·0	0·6	7
Central Ireland and Mid Europe	(B4)	15	0·4	0·7	0·9	0·63	9
Denmark, Poland and N. Germany	(A7)	15	0·6	0·7	0·8	0·56	8
Central Russia (most)	A2	13	0·4	0·6	0·9	0·54	7
S.E. England and France	B5	17	0·6	0·8	0·9	0·72	12
Holland	A9	15	0·5	0·9	1·0	0·9	13
Chernozem Russia	A4	19	0·7	0·9	0·5	0·45	9
Po delta	A10	23	0·6	0·9	0·3 (irr.)	0·27	7
Spain	B7	29	0·5	0·6	0·3 (irr.)	0·18	6
S. Italy	B9	23	0·5	0·7	0·3	0·21	4·5
Greece	B11	28	0·2	0·7	0·3	0·21	5
S.E. Canada	A1	13	0·4	0·5	0·9	0·45	6
Chernozem Canada	B1	14	0·5	0·8	0·5	0·4	6
Cornbelt USA	A3	24	0·7	0·9	0·5	0·45	11
Florida USA	A6	30	0·6	0·6	1·0	0·6	18
N. Island	B12	23	0·5	0·7	0·9	0·63	15
Central Congo	B10	33	0·6	0·5	0·5	0·25	8
East Africa	B11	33	0·3	0·6	0·5	0·3	10
Japan	B15	20	0·4	0·7	1·0	0·7	14
Central China	A7	21	0·6	0·9	0·5	0·45	9
S. China	B7	27	0·3	0·5	0·9	0·45	12
Ganges delta	A3	34	0·6	0·9	0·7	0·63	21
Java	B10	35	0·5	0·7	0·8	0·56	20
Low Colombia	A3	34	0·5	0·7	0·7	0·49	17
Amazon area	A1	32	0·5	0·6	0·8	0·48	15
Central Brazil	B4	34	0·5	0·6	0·6	0·36	12
N. Argentine	A9	24	0·5	0·9	0·6	0·54	13

FWD are listed together with PPGE and FPAL values; in the last column the resulting maximum land productivity in grain equivalents (MPGE), calculated from PPGE and the combined reduction factor, are given. In Europe the combined reduction factors (FSC and FWD) differ greatly, as shown by some selected broad soil regions in Table 6 and on the map (Fig. 13), and lead to great differences in MPGE for

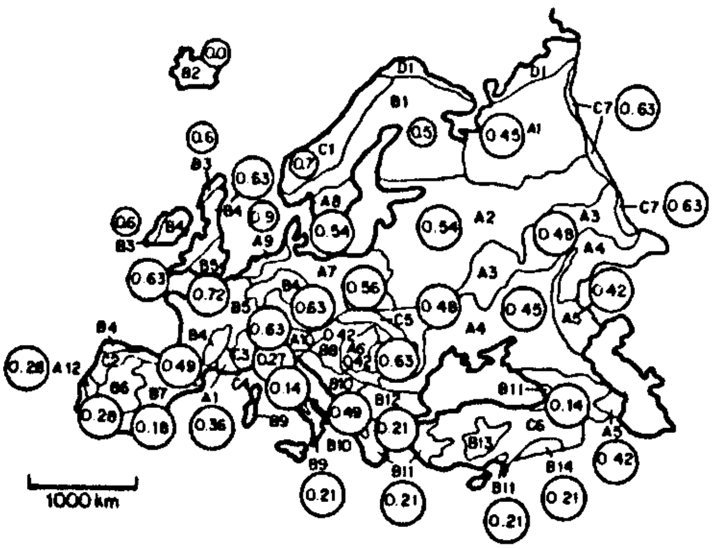


FIG. 13. Europe. The combined reduction factors for limiting soil conditions (FSC) and limiting water deficiencies (FWD) for the calculation of maximum land productivity in grain equivalents (MPGE) and of potential productivity in grain equivalents per hectare (PPGE) shown for the broad soil regions of Europe.

these regions. In south-east England and in France the combined reduction factor is 0·7 giving a MPGE of 12 t ha^{-1}. In Holland this factor is 0·9, which means agricultural land with soils of high quality (FSC = 0·9) and practically no water deficiencies (FWD = 1·0). For this reason the MPGE is 13 t ha^{-1}, somewhat higher than the value for England although the PPGE is lower. In Ireland and the English Midlands only 9 t ha^{-1} is possible, and in Denmark, Poland and northern Germany only 8 t ha^{-1}.

Although soil conditions in the chernozem areas of Russia have satisfactory FSC (i.e. 0·9) and PPGE values are not very low, water deficiencies (FWD = 0·5) reduce the combined reduction factor to

0·45, and so the MPGE is only 9 t ha^{-1}. Marked water deficiencies are also responsible for the very low reduction factors in the Po delta (0·27), Spain (0·18), southern Italy (0·21) and Greece (0·21) and result in extremely low MPGE values of 7, 6, 4·5 and 5 t ha^{-1}, respectively, unless the land is irrigated. Even in Norway, with much lower PPGEs, the MPGE is still about 5–6 t ha^{-1} due to the high rainfall.

Table 6 also shows some other important broad soil regions of the world. In Canada the MPGEs are only 6 t ha^{-1}, partly because of water deficiency (the chernozem area) and partly as a result of poor soil conditions (South-east Canada). The USA cornbelt shows a MPGE of 11 t ha^{-1} because of a higher PPGE. Values in Florida are highest (18 t ha^{-1}) because there is no lack of water and the PPGE is high. New Zealand's North Island has a relatively high MPGE (15 t ha^{-1}) due to high soil quality and favourable rainfall. In Africa, although the PPGE is high, the combined reduction factor is extremely low (0·25–0·3), resulting in MPGEs of 8 and 10 t ha^{-1} for the Congo and East Africa, respectively. The FPAL, however, is relatively high (0·5 and 0·6, respectively), which suggests that an extension of production may be readily possible in these areas.

Japan shows a high reduction factor of 0·7 and relatively high MPGEs. Central and southern China, in contrast, exhibit lower values of 9 and 12 t ha^{-1}, respectively, attributable to water deficiencies in central China and poor soil conditions in South China. Moreover, in South China the FPAL is also very low. Very high MPGEs are found for the Ganges–Brahmaputa flood-plain and delta and for Java (21 and 20 t ha^{-1}, respectively). Both broad soil regions show excellent soil conditions and relatively low water deficiencies (reduction factors of 0·63 and 0·56, respectively). Since FPALs are also relatively high in both areas (0·6 and 0·5), these factors together explain the ability of these regions to feed an enormous population.

In the tropical parts of South America, the MPGEs are considerable, e.g. 17, 15 and 12 t ha^{-1} for Lower Columbia, the Amazon area and central Brazil, respectively. Because of the rather high FPALs, the enormous land areas and the low number of inhabitants, some of the most important land reserves for agricultural production are present in these regions. Northern Argentina, which also has a high reduction factor (0·54), shows a high MPGE.

In conclusion, the foregoing account has shown how the MPGE can be estimated for each broad soil region. More detailed work which is being performed in some research centres will provide more detailed forecasts, as soon as more information on soils, climates, crops, etc. is available. It will be especially important for land qualities to be determined more precisely. Such additional information will also clarify why actual productivities fall so far behind the maximal land productivities in many cases.

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Discussion

Professor Buringh pointed out that the information which Professor Pons had given relating to potential productivity which was based on his work was now somewhat outdated. The earlier figures and diagrams had related to calculations from radiation input and temperature and attempted to predict what maximum photosynthetic yield would be if the canopy of the crop was closed throughout the whole growing season. This was clearly a wrong interpretation of data which gave an over-estimate because, even theoretically, crop yield cannot be simply the product of radiation input and growing season length. The old and more recent figures suggested that maximal productivity would be considerably lower. The interesting thing, however, was that in Holland average farm production was already approaching these revised estimates of average maximal productivity. *Professor Pons* agreed that the figures of Professor Buringh which he had quoted did imply a closed canopy. They had value for reasons of comparison, not only between different climates, but also to get an equal theoretical maximum level to start from. Potential productivity is a theoretical, but simple, level of reference on which all kinds of reduction factors may be applied to get maximum productivity for certain crops, soils and climates. *Professor Bushuk* asked whether, on the basis of current knowledge, we could begin to make decisions about certain husbandry practices which would be compatible with the long-term maintenance of soil fertility. He was thinking particularly about minimal or zero tillage. The same general point was elaborated on later in the discussion by *Dr Lake*. He drew attention to the marked changes which could take place in the ecology of the soil if inversion of the soil by the time-honoured methods of ploughing were discontinued and so-called minimal cultivation adopted. He pointed out that because of the advent of herbicides it was no longer necessary to cultivate land deeply to control weeds and that in some countries like Bangladesh, where intensive hand-weeding of crops was practised, non-inversion of the soil was a practical reality. He made a plea for the preparation of maps similar to those prepared in the UK indicating on what soils non-inversion processes could be adopted. *Professor Pons*, in reply to these questions, emphasised the weather-dependent nature of seedbed preparation which must take place whether there was soil inversion or not and additionally drew attention to work in progress in Holland relating to the effect of traffic on the soil. Experiments were not complete, but should provide interesting data related to soil compaction. Generally, however, *Professor Pons* thought that not enough knowledge was really available on this point. Probably for some soils this would already be possible. But the problem was so complicated that, at the moment, no overall models for different soils could be constructed.

A general discussion took place relating to other aspects of the calculation of potential productivity. *Professor Jarvis* asked about the derivation of the grain equivalent yield and whether the factor 0·43 was based on the harvest index, to which *Professor Pons* replied that this was an average factor equal to the ratio of grain dry weight to total dry weight and had been used simply to obtain the potential productivity in grain equivalents. The factor was roughly estimated from very general data, indicating the ratio between grains and roots, stems, leaves and flowers. *Dr Landsberg* asked whether the various modification factors used in the estimation of potential production in grain equivalents had been tested against actual determinations in the field and made a plea for this. *Professor Pons* stated that virtually all the reduction factors applied related to soil conditions as affected by climatical zones. These were very difficult to estimate precisely in an independent fashion and they had associative effects on crop growth. Although rough estimates, they were of considerable importance in the evaluation of land capability. In his opinion it would never be possible to give exact values of these factors. *Professor Buringh* then mentioned the work that he is doing on the building of mathematical models based on available water, nutrient and organic matter for a specific crop growing at a specific site. These were being tested by appeal to experimentation and such work should do much to clarify the factors involved. The problem is now, however, to simplify the obtained data to make the results clear. *Sir Kenneth Blaxter* asked whether the soils of the northern temperate region would eventually mature to become senile in the same way that the soils of the subtropics and tropics had matured and what the implications of this would be in terms of their fertility. Despite the long time scales, can we envisage that the basic fertility of soils in northern Europe and the United States would slowly decline? *Professor Pons* stated that while looked at in the short-term, one could state that the northern soils were in a quasi-equilibrium state, nevertheless they were changing and deteriorating. This was already evident for some soils in the temperate areas developed on poor parent materials. These already showed very poor nutrient status, but man had also contributed to the degradation. The yearly loss, however, was so small that only minimal applications of fertilisers might counteract it. In this respect, it was doubtful whether in recent times, with all kinds of polluted rains, the leaching was yet continuing. Rubification would certainly also spread over temperate soils if the soils were given enough time (>40 000 years) to develop. *Professor Truszczynski* asked whether there were any close links between soil type, the zonal distribution of soils and soil classification with the health and well-being of animals and man and with the quality of produce. *Dr Fowden*, in reply, stated that perhaps this aspect would be dealt with later in the Symposium and that perhaps the question could be considered later during the course of discussions. *Professor Pons* commented that the quality of wheat was certainly partly associated with climatic factors and particularly with the water supply at different tension levels in the soil.

Professor MacKey pointed out that man had in fact tried to find solutions to problems of difficult climate and difficult soil in particular regions. He instanced the work on the Negev where there is but 50 mm of rain per annum. The soils here characteristically form a crust which gives a water run-off with little penetration, allowing water to be accumulated in depressions. Since biblical times the populations there have found this to be a solution in a difficult agricultural situation and at present Israeli practices in that line appear to be highly successful. Similarly, there are problems arising with regard to agricultural practices leading to the misuse of soil and the emergence of problems such as aluminium toxicity. Here breeding of plants tolerant to adverse conditions could be highly successful and he instanced the International Rice Research Institute programmes where some success had been obtained. He pointed out that in fact man's activities can result in a movement against the general rule of decline in soil fertility with time.

Mr Wilkinson of ADAS stated that while it was interesting to look at land capability on a global scale, the local problem is usually far more important. He instanced the blueprint approach to crop production which had resulted in considerable increases in yield through activities of those farmers who practised this approach. Here, cognisance was taken of soil and cultural factors required to overcome the known physical limitations. However, economic factors became overriding in deciding what was possible. Land capability maps are based upon a physical classification which must be dynamic and not static and climatic change or extreme variability could well result in an alteration in the capability of the land resources within a country. *Professor Pons* replied that he had chosen this small scale of generalisation in relation to the targets of the Symposium. For this reason, the land qualities could not be dealt with in detail. For greater scale problems, land qualities could be calculated in more detail, but he had always taken into account that land qualities which might limit the crop growth were nearly always dynamic combinations of climate and soil characteristics. Changes in climate may also change the characteristics of the soil, but only in the long-term. Changes in water regime however may induce short-term changes. Chernozems in eastern Europe, for example, were after 10 years of irrigation already showing marked decreases in the organic matter contents of the A_1 horizon because of accelerated microbiological decomposition under longer humid conditions when irrigated. Erosion and salinisation may also change the soil rapidly. Changes of climate will, however, change land qualities and for this reason will also change crop production. *Dr Gormley* raised questions related to elevated carbon dioxide levels in peat soils and how this influenced the growth of leafy crops but the Chairman decided that this was better left until later in the Symposium when these specific aspects would be dealt with.