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Tropical Soils, Climate and Agriculture: an Ecological Divide?

Pedro A. Sanchez
Director General
International Center for Research in Agroforestry
Nairobi, Kenya
p.sanchez@cgiar.org

I attempt to analyze the central question posed by Jeffrey Sachs (this volume): what is it about the tropics that make it difficult to raise productivity? Is there an ecological divide between tropical and temperate regions? I will do so from the perspective of a tropical soil scientist who spent his childhood and most of his professional life in the tropics.

Empirical evidence suggests that there is something intrinsically tropical that constrains economic growth and human well-being. Most developed countries lie in the temperate regions, with most of their people living at latitudes higher than 23.5 ^{0} north or south (Landes, 1998). Developed countries have used agriculture as its engine of growth, transforming themselves into industrial and information economies only after their agricultural sector was sufficiently developed (Tomich et al., 1995). The exceptions Sachs recognizes are Singapore and Hong Kong, island states that were able to ignore their tropical environment by using their strategic position at the world sea lanes to become major trading enclaves. Other tropical states in similar strategic positions such as Panama and Zanzibar support Sachs' hypothesis.

The main biophysical determinants proposed by Sachs are the greater intensity of human diseases and the poorer soils in the tropics. Masters and Weibe (this volume) further proposed the absence of frost periods as another major determinant why the tropics are behind in terms of economic development. I discuss two key components of the tropical environment, climate and soils, and then relate it to the productivity of annual crops (not pastures or tree crops). The climate section is largely abstracted from my book (Sanchez, 1976) and I rely heavily on my previous writing.

TROPICAL CLIMATES

The tropics are those areas located between 23.5 degrees north and south of the Equator. Because the tilt of the earth's axis has the same angle, this latitude is the limit of the sun's apparent migration to the north or south of the zenith.

Consequently, the tropics are the only part of the world where the sun passes directly overhead.

Temperature

The tropics can be defined as that part of the world where the mean monthly temperature variation is 5°C (9°F) or less between the average of the three warmest and the three coldest months. Daily variation is usually within this range. Mean temperatures in the tropics generally decrease by 6 ^{0}C for every 1000 meters of elevation.

People unfamiliar with the tropics generally consider it oppressively hot and humid. Although this condition certainly exists, it is as broad a generalization as considering the temperate region oppressively cold and dry. I have experienced more intense hot and humid conditions in Washington D.C. during the summer than in the heart of the Amazon Basin, where one can almost always count on cool night breezes. Near the equator tropical climates are hot, averaging 28 ^{0}C at low elevations, pleasantly cool at 1000 - 2000 meters, and positively frigid at elevations above 3000 meters. Travelling in Kenya from hot and humid Mombasa at sea level, through the eternal spring climate of Nairobi (1550 m), and to the top of Mt Kenya with glaciers (5200 m) illustrates this point, as these locations all lie within 4^{0} from the Equator. The main point to remember about temperatures in the tropics is their constancy rather than any absolute value.

Solar Radiation

The tropics receive more solar radiation available for photosynthesis than the temperate region. The tilt of the earth's axis causes more solar radiation to reach the surface in the tropics, because of the more perpendicular angle of the sun's rays. From 56 to 59% of the sun's radiation at the rim of the atmosphere reaches the earth's surface in the tropics; about 46% at 40° latitude (New York City) and only 33% at 60° latitude (Stockholm).

The daily average solar radiation reaching the surface in the tropics is about 400 gram-calories/cm^2/day. In areas with distinct rainy and dry seasons, cloudiness causes considerable seasonality in solar radiation. Table 1 shows some examples, the tropical ones related to rice growing areas. At Los Baños, Philippines, the higher solar radiation during the dry season has a major impact on irrigated rice yields and fertilizer response. Rainy season rice yields are similar in Yurimaguas, Peru and Los Baños, when solar radiation is relatively low and almost identical, due primarily to cloudiness.

In the temperate region, the annual solar radiation averages half of the tropics' (200 gram-calories/cm^2/day), but reaches high levels during the summer months because of longer days, as shown for Ithaca, New York in Table 1. The highest crop yields in the tropics are in arid irrigated valleys where solar radiation is very high. This is shown for Lambayeque, Peru where some of the highest experimental rice yields have been recorded. The situation is similar in other arid, irrigated areas in Mexico, India and elsewhere.

Table 1. Average daily solar radiation reaching the Earth surface during a 4-month growing season at different latitudes. Adapted from Sanchez (1976).

Location	Season	Latitude	g-calories/cm^2/day
Yurimaguas, Peru (humid tropics—Amazon basin)	Sept-Dec	6^0 S	340
Los Baños, Philippines (rainy season-subhumid tropics)	Sept.-Dec	14^0 N	341
Los Baños, Philippines (dry season-subhumid tropics) irrigated crop	Feb.-May	14^0 N	417
Ithaca, New York (humid temperate)	June-Sept.	42^0 N	441
Lambayeque, Peru (tropical arid—sea level) irrigated rice	Sept-Dec	6^0 S	483

The breadbaskets of the temperate region receive more solar radiation during their cropping season than most tropical rainy seasons, giving these temperate regions the advantage on a per-crop basis. But most humid and many subhumid tropical areas can produce more than one crop per year. Overall the tropics have approximately twice the plant production potential per hectare per year on the basis of solar radiation and temperature. Indeed the net primary productivity of tropical rainforests is about twice that of temperate deciduous forests (Sanchez, 1976).

Rainfall

Given the relative uniformity in temperature, rainfall distribution is the main criterion used to classify tropical climates. The seasons in the tropics are rainy or dry, not cold or hot. Annual rainfall varies from zero to over 10,000 mm. The periods of heaviest rainfall occur when the sun is directly overhead. In general, annual rainfall decreases with increasing latitude, but local relief and other conditions limit such a relationship. The length of the dry season also increases with latitude in the tropics. Annual variability in rainfall is high all over the tropics, but generally increases with increasing latitude.

Tropical Climates

Rainfall distribution, rather than the total amount, is the most important rainfall parameter for tropical agriculture. The number of consecutive months when soil moisture is limiting crop growth is used to differentiate tropical climates for agriculture. Four major tropical climates are shown in Table 2. The humid tropics have a short dry season or none at all, and it is possible to grow two or more crops a year without irrigation. At low elevations it is the stereotype tropical climate—hot and humid. The subhumid tropics have distinct seasonality. Close to the equator the subhumid tropics have a bimodal distribution with two rainy seasons and two dry seasons, making it also possible to grow two crops per year. At latitudes higher than 5 ^{0} the subhumid tropics have one long dry season and one long rainy season, permitting one crop a year without irrigation. These are the most productive tropical climates where the breadbaskets of Asia, Latin America and West Africa are located. The dry season breaks many biological cycles, acting in a similar way to the winter in temperate regions.

The semiarid tropics are characterized by one short, intense rainy season, where only short-duration, drought-tolerant species like sorghum and millet can be grown with reasonable assurance without irrigation. The land is dry during most of the year. The prevalence of grazing livestock increases as the length of the dry season increases. Finally the arid tropics are where no crops can be reliably grown and nomadic grazing is the main land use. About 25% of the tropics are humid, 50% subhumid, 15% semiarid and 10% arid. Such climates occur at all elevations in the tropics and are interspersed with natural wetlands and irrigated agriculture.

Table 2. Distribution of major tropical climates (Sanchez, 1976).

Tropical climate	Humid months	Natural vegetation	Million hectares	% of tropics
Humid tropics	9.5 - 12	Moist tropical forests	1191	24
Subhumid tropics	4.5 – 9.5	Savannas (continuous grass cover with trees) or woodlands	2430	49
Semiarid tropics	2- 4.5	Shrubs and trees with discontinuous grass cover	771	16
Arid	0 - 2	Desert	558	11
Total			4950	100

Climate change is expected to increase rainfall variability and the number of extreme weather events in the tropics. This is already happening with more frequent El Niño events. Definite changes in climates are predicted for the tropics (Rozenzweig and Hillel, 1998; Rosenzweig, this volume) with less and more variable rainfall expected in Southern Africa, Southeast Asia and parts of India and the Caribbean, and more rainfall predicted for parts of East Africa and the Andean region.

TROPICAL SOILS

Soil science developed first in the temperate region as an outgrowth of geology. Travel of 19th Century soil scientists to the tropics resulted in a misguided view about the uniformity of tropical soils and the presence and importance of hardened layers rich in iron oxides called "laterites." Vast areas of the tropics with soils similar to those found in the temperate region were essentially ignored. Thus the term "tropical soil" developed in the literature to mean red, acid infertile soils that when cleared of vegetation, become worthless brick pavement in a few years and are unsuitable to agriculture. Such laterites exist, but cover less than 7 percent of the tropics, and also occur in the United States (Sanchez and Buol, 1975).

Tropical soils are diverse because of the wide variety of conditions under which they are formed----present and previous climates, vegetation, parent material, geomorphology, and their age. This variability is well described in a book by Drosdoff et al., (1978) and also in mine (Sanchez 1976). The only property common to all tropical soils is lack of seasonal soil temperature variation (Buol et al., 1990). All other generalizations are essentially incorrect. To state that all tropical soils are old and infertile is equivalent to stating that all temperate soils are young and fertile. One cause of confusion stems from the extent of the most recent glaciation (about 10,000 years ago) that produced generally fertile soils in much of Europe, Asia and in North America far south as Pennsylvania. Soils of Southern United States that escaped this glaciation have more in common with the stereotype soils of the humid tropics than with soils of the US Midwest and New England. An entire book has been devoted to explain the myths and realities of soils in the tropics (Lal and Sanchez, 1992).

Soils are classified according to a quantitative soil taxonomy, akin in precision and complexity to plant taxonomy (Buol et al., 1997; Soil Survey Staff, 1998). The distribution of tropical and temperate-region soils is shown in Table 3.

Table 3. Soil distribution by taxonomic orders in tropical (<23.5 ^{0}) and non-tropical regions (>23.5 ^{0}). Adapted from Sanchez and Logan (1992).

Soil Orders	Tropics (<23.5 ^{0})		Temperate and boreal (>23.5 ^{0})	
	Million has	%	Million has	%
Oxisols and Ultisols (red/yellow, acid, low fertility)	1632	36	605	7

Aridisols (desert soils)	685	16	2189	24
Entisols (young soils, many alluvial, high fertility)	574	13	2156	24
Alfisols (high base-status, fertile soils)	559	13	1231	12
Inceptisols (young soils—variable fertility)	532	12	1015	11
Vertisols (cracking clays-fertile)	163	4	148	2
Mollisols (dark brown, very fertile)	74	2	1026	11
Histosols (peat soils-low fertility)	69	2	458	5
Andisols (volcanic soils—high fertility)	43	1	101	1
Spodosols (Podzols, sandy, infertile)	36	1	204	2
Total	4387	100	9133	100

The stereotype tropical soils, classified as Oxisols and Ultisols are generally deep, reddish, acid, with low fertility but not low in soil organic mater (Sanchez, 1976). They cover almost half of the tropical land surface, mainly in the humid tropics, the subhumid savannas of Latin America, upland Southeast Asia, the Congo Basin, the Lake Victoria Basin, the East Coast of Australia, Southeastern United States and Southeastern China. The latter three areas account for their presence in the temperate regions as far as 35 ^{0} N or S latitude.

Entisols are mainly young alluvial soils with high fertility. Together with most Inceptisols of alluvial origin, they constitute the best soils in the tropics and this is where much of the Green Revolution in Asia and Latin America has taken root.

Alfisols look similar to Ultisols but they are high in bases (calcium, magnesium, potassium), not acid and therefore of intermediate to high fertility. Alfisols cover much of subhumid and semiarid tropical Africa, India, the Caribbean and Northeast Brazil. Many Alfisols of tropical Africa suffer from severe soil fertility depletion.

Vertisols have heavy cracking clays with difficult physical properties but with high fertility. They cover vast tropical areas such as Central India, much of tropical Australia, much of the Ethiopian Highlands as well as plains and valley bottoms of subhumid and semiarid tropical Africa.

Mollisols are excellent soils both in terms of fertility and physical properties and are the stereotype temperate-region soils found in Iowa, the Russian steppes and the Pampas of Argentina. They are limited in the tropics but where they occur like in the Cauca Valley of Colombia, they support highly productive agriculture.

Andisols are volcanic soils usually with high soil fertility, and associated with fertile red soils of other orders. They are locally important in both tropical and temperate regions and usually support intensive agriculture in the tropics.

Aridisols are soil of deserts, usually productive if irrigation is possible in river basins. The tropics have large desert areas such as parts of the Sahara, the horn of Africa, the Kalahari, the coastal deserts of South America and Southeast Africa, Northern Mexico and much of inland tropical Australia.

The last two soil orders, Histosols (peat soils) and Spodosols (Podzols) represent extreme situations but are both very low in soil fertility.

Putting together reasonably fertile soils with sufficient rainfall in non-arid environments, and subtracting the 1.8 billion hectares of soils with permafrost at high latitudes (Buol et al., 1997) the overall comparison can be summarized in Table 4 below. The proportions of fertile soils with sufficient rainfall and no permafrost are roughly equal in tropical and temperate regions. The broad hypothesis that tropical soils are inferior to soils of the temperate region for agriculture is not supported by this analysis.

Table 4. Tropical vs. non-tropical soils; overall comparison.

	Tropics (<23.5 ^{0})		Non-tropics (>23.5 ^{0})	
	Billion hectares	%	Billion hectares	%
Fertile soils with sufficient rainfall, no permafrost	1.97	45	3.77	41
Poor, low fertility soils, desert soils and those with permafrost	2.42	55	5.36	59

A major misconception about soils is that many of them are fragile. Fragility is an ecological concept-- a system that when severely disturbed will not regain its original state—like breaking a glass goblet and gluing it afterwards. Only soils that are shallow to bedrock can be considered fragile. The rest, including the classic acid, red soils of the tropics are actually resilient—the opposite of fragility—because they have the capacity to recover from severe disturbance. Therefore the term marginal may be more appropriate for what Table 4 describes as poor soils.

SOIL ATTRIBUTES RELEVANT TO AGRICULTURE

Differences in soil taxonomy are important to establish the broad picture, but what does it mean in agronomic and ecological terms? The problem with soil taxonomy is that it quantifies only permanent soil parameters, most of which are located in the subsoil. Soil taxonomy ignores many dynamic parameters crucial to crop productivity, which are mostly in the topsoil where the majority of plant roots are located, both in natural and agricultural systems. The lower levels of soil taxonomy often have specifications that invalidate the generalities described at the order level. For example the great group Eutrustox of the Oxisol order has high base status (lots of available calcium, magnesium and potassium) and hence high fertility, unlike other Oxisols.

To overcome this limitation, a fertility capability soil classification system (FCC) was developed about 25 years ago to interpret soil taxonomy and soil tests in a quantitative manner that is relevant to growing plants (Buol et al., 1975; Sanchez et al., 1982a). It is now widely used and is included in the worldwide FAO soils database (FAO, 1995). Table 5 shows the relative importance of the main biophysical attributes of soils in the tropics that are most relevant to agriculture and the environment according to the FCC system. All of them were originally conceived as soil constraints in the 1970's. However, the current focus on sustainability and natural resource management, as well as new management practices has changed the interpretation of some of them to positive attributes. The term "fertile soil" is used in its broadest sense, encompassing the capability of the soil to supply adequate nutrients, water and aeration to plant roots.

Table 5. Main physical and chemical attributes relevant to agriculture in soils of the tropics. Adapted from Sanchez and Logan (1992) and FAO (1995). The sum of percentages exceeds 100 because a single soil usually has more than one attribute.

Soil attribute	**Million ha.**	**%**
Soil moisture stress (>3 months dry season)	2762	60
Low nutrient reserves (<10% weatherable minerals)	1681	36
High erosion risk	1670	36
Aluminum toxicity (>60% Al saturation)	1493	32
No major limitations (acidity without Al toxicity)	1198	26
High phosphorus fixation (by iron)	1065	23
Waterlogging	898	19
High leaching potential	251	5
Calcareous (micronutrient deficiencies)	152	3
Salinity and alkalinity	117	3
Cracking clays	118	3
High organic content (>30%)	37	1
Total	4639	

Soil Moisture Stress

The presence of dry seasons longer than 3 months is a constraint to year-round crop production in about 60% of soils in the tropics. But it is also a positive attribute, because dry seasons stop many pest and disease life cycles, with drought becoming as effective in the tropics as frosts in the temperate regions. When dry seasons fail to occur, pest attacks can be stronger in the following rainy season. This was the case in Western Kenya in late 1999 when the short dry season failed to materialize. Streak virus essentially wiped out the subsequent short rainy season maize crop because the life cycle of the vector was not interrupted by drought.

Long dry seasons also favor some soil dynamics. They slow down processes such as nitrogen mineralization and leaching and cause the death of many soil microrganisms. When the rains come, there is a flush of nitrogen mineralization as the surviving bacteria involved in mineralizing organic nitrogen find themselves with an ample supply of water and energy from the carbon in the dead microrganisms, producing ammonium and nitrate ions that young plants can readily utilize (Birch and Friend, 1956).

Low Nutrient Capital Reserves

The source of most of the phosphorus, potassium, calcium, magnesium and micronutrients that soils naturally supply to plants comes from the dissolution of primary or weatherable minerals. About 36% of tropical soils have low (less than 10%) reserves of weatherable minerals, which are nutrient capital reserves. Such constraint is most extensive throughout the humid tropics and in the South American savannas, but is locally important in the Sahel and parts of Southern Africa. About 2/3^{rds} of soils in the tropics do have considerable mineral reserves of the above-mentioned nutrients.

The only other source of nutrient capital reserves is soil organic matter, which contains all the nitrogen and much of the phosphorus and sulfur capital of soils. This is independent of weatherable minerals in the soil, although organic phosphorus and sulfur originally come from weatherable minerals. Soil organic matter content is the balance between the rate of organic inputs added to the soil and the rate of soil organic matter decomposition (Sanchez, 1976). Both rates are generally higher in the tropics, the end result being that there are no major differences in soil organic matter content between tropical and temperate-region soils (Sanchez and Buol, 1975; Sanchez et al., 1982b, Coleman et al., 1989; Buol et al, 1990). Soils from both regions exhibit a wide range of organic carbon, organic nitrogen and organic phosphorus contents, depending on the ability of the soil to protect organic inputs from decomposition (Coleman et al., 1989).

The main determinants of soil organic matter content are soil temperature, moisture and clay content. Clayey soils are cooler that sandy soils and have smaller pores where organic matter is better protected from decomposition. Both factors result in higher organic nutrient capital in clayey soils, including red Oxisols and black Mollisols that have similar organic matter contents (Sanchez and Logan, 1992). Soil organic carbon constitutes the largest stocks of carbon in terrestrial ecosystems, and soils can be both a source and a sink of three principal greenhouse gases, carbon dioxide, methane and nitrous oxides (Watson et al., 2000).

High Erosion Risk

The third most extensive soil constraint in the tropics is high risk of erosion. About 1/3rd of the soils in the tropics are at a high risk of soil erosion that can negatively affect plant productivity. Included in this category are very steep soils (more than 30% slope) and shallow soils (less than 50 cm deep over rock). Although all soils, including those in flat areas are susceptible to erosion by wind and water anywhere, this table shows that about 2/3rds of the tropics are not highly susceptible to soil erosion. Farmers in many mountainous regions have learned to farm extremely steep slopes sustainably with ingenious soil conservation practices. The key to soil erosion control is to keep the land covered with a plant canopy throughout the year.

Land degradation to many economists equals soil erosion, which is quantified in terms of soil loss. The main parameter used is tons/hectare of soil lost in a year, usually taken from small (4 x 25m) experimental Wischmeier erosion plots (Wischmeier et al., 1958; Lal, 1976). This methodology overestimates erosion losses due to the small size of these plots. What is eroded from one spot is most frequently deposited on another one in the same field, and soil eroded from one field is often deposited on another field, sometimes leading to no losses at the watershed scale. Furthermore soil erosion often has positive effects—the creation of fertile alluvial soils. Erosion risk does not automatically imply crop productivity losses or land degradation, something that is often assumed. The relationship between soil erosion and crop productivity is complex.

Many economists look at data from these erosion plots as representative of real conditions at the field, watershed and even national scales. These data are frequently quoted back and forth in the literature, somehow becoming “common knowledge”. The overall estimates of soil erosion losses and their value have been recently called to question by ecologists (Trimble and Crosson, 2000). Some economists have seen through the “common knowledge” fallacy and are making appropriate adjustments (Stefano Pagiola, World Bank, personal communication). The blame lies squarely with soil scientists who have generally done a poor job in dealing with spatial scales above the plot level, and some have come up with catastrophic predictions that are grossly exaggerated.

Economic assessments of land degradation need to be more rigorously conducted, paying close attention to other constraints in addition to soil erosion.

Aluminum Toxicity

About one-third of the tropics (1.5 billion hectares) have sufficiently strong soil acidity for soluble aluminum to be toxic for most crop species. This constraint is defined as having more than 60% Al saturation in the top 50 cm of soil (Buol et al., 1975). A soil pH value of less than 5.0 usually indicates this problem. Aluminum toxicity is most prevalent in the humid tropics and acid savannas but occurs in large areas of the hillsides of Southeast Asia and Latin America. This constraint is found mainly in soils classified as Oxisols, Ultisols, and closely related Inceptisols and is highly correlated with low nutrient capital reserves. Aluminum toxicity is usually the overwhelming constraint in these soils and must be tackled first, either by modern lime application practices, by using Al-tolerant plant species or by breeding for tolerant varieties (Sanchez and Salinas, 1981). It is relevant to note that aluminum toxicity is rare in most smallholder farming areas of subhumid and semiarid Africa, except for parts of Rwanda, Burundi, Northern Zambia and adjacent areas in the Congo, and some sandy soils of Zimbabwe. Two-thirds of the tropics do not have enough aluminum saturation to worry about liming.

No Major Limitations (Moderate Soil Acidity)

Acid soils with surface pH values between 5.0 and 6.0 but not Al-toxic occupy one-fourth of the tropics (1.1 billion hectares) and are important in all agroecological zones. Although correcting soil acidity by liming might be limited to very Al-sensitive crops such as cotton and alfalfa, this constraint is generally associated with somewhat higher fertilizer requirements for these soils than those with higher pH. Most of the soils where smallholder farmers of subhumid Africa are facing food insecurity due to severe depletion of nitrogen and phosphorus fall into this category. Soils with not even that limitation cover an additional 40 million hectares of the tropics. I have lumped both categories together in this analysis.

High Phosphorus Fixation

Clayey topsoils with more than 20% iron or aluminum oxides in their clay particles “fix” large quantities of added phosphorus fertilizers into slowly soluble iron and aluminum phosphates, which are not immediately available to plants. High P-fixing soils can be identified as those with clayey topsoils having red or yellowish colors indicative of high contents of iron oxides, usually accompanied by a strong granular structure. Since high phosphorus fixation is related to high clay content, most sandy red soils do not fix large quantities of phosphorus. This constraint considered very typical of the tropics, but is only found in 23% (about 1 billion hectares) of the tropics. It is more extensive in the humid tropics and subhumid savannas but is also important in subhumid East Africa.

While these fixed phosphate ions are unavailable to plants in the short run, they are slowly solubilized and made available to plants during a period of several years. Current systems thinking on sustainability, therefore turns phosphorus fixation from a constraint into an asset. Large applications of phosphorus fertilizers in P-fixing soils become a phosphorus capital reserve (Sanchez et al., 1997). Subsequent phosphorus release for several years provides sufficient phosphorus for crop production. Phosphorus recapitalization has been successful in Brazil (Goedert and Lobato, 1980; Goedert, 1985) and also in East Africa (Sanchez and Jama, 2001).

Waterlogging

Poorly drained soils cover 19% of the tropics and are distributed in all climates and geographical regions. Many of them have been converted to rice paddies, supporting intensive agriculture. Others are used intensively during the dry seasons in inland valleys of Africa. Many remain as natural wetlands.

These are the principal soil constraints in the tropics---drought stress, low nutrient capital reserves, high soil erosion risk, aluminum toxicity, phosphorus fixation and waterlogging. The remaining constraints listed in Tables 5 and 6 as well as others in the FCC system do not cover large areas of the tropics but are locally important. They are described elsewhere (Sanchez et al., 1982a; Sanchez and Logan, 1992). It is important to understand that these soil attributes may or may not become actual constraints to crop production; this depends on how the soils are managed.

Regional Differences

There are important differences in soil properties among the major tropical regions (Table 6). Soil constraints are generally less severe in tropical Africa than in tropical Asia or Latin America (Sanchez and Logan, 1992). Tropical America has the most extensive soil chemical limitations, while tropical Asia has the most extensive soil physical limitations (drought, erosion risk). The assumption that soils of tropical Africa are inferior to those of tropical Asia or Latin America is not correct.

Table 6. Main physical and chemical attributes relevant to agriculture in soils of the tropics. Adapted from Sanchez and Logan (1992), and unpublished data.

Soil attribute	Tropical Africa	Tropical America	Tropical Asia
Chemical:	%	%	%
Aluminum toxicity (>60% Al saturation)	26	43	24
No major limitations (acidity without Al toxicity)	31	18	31
High phosphorus fixation	11	32	20
Low nutrient reserves	31	47	27
High leaching potential	10	4	1
Calcareous (micronutrient deficiencies)	2	1	8
Salinity and alkalinity	2	1	3
High organic content (>30%)	-	-	1
Physical:			
Soil moisture stress (>3 months dry season)	67	45	72
High erosion risk	24	35	53
Waterlogging	22	20	16
Cracking clays	3	1	4
Total of region (million ha.):	1555	1879	1205

SOIL FERTILITY PARADIGMS

Two different approaches to manage tropical soils for crop production are in play now (Sanchez, 1994). The first paradigm basically says, “change the soil to meet the crop’s requirements”, while the more recent second paradigm modifies the crops to tolerate soil constraints and utilizes a more ecologically robust approach to provide nutrients to crops.

The First Paradigm

Major advances have been made in understanding the basic chemical, physical and biological processes as well as the properties, taxonomy and geographical distribution of principal soils around the world. Most of the soil management technologies derived from such understanding have focused on intensive agricultural systems on fertile lands where the working paradigm for years has been:

Overcome soil constraints through the application of fertilizers, soil amendments and irrigation to meet crop requirements

This approach was developed by agronomists in the temperate region and focused on the production function of soils while paying less attention to its ecosystem functions. Fertilizer research concentrated on nutrient uptake by crops and paid little attention to the fate of nutrients that accumulated in the soil or were lost to groundwater or to the atmosphere. Despite its limitations, the bulk of food produced in the tropics as well as the rest of the world is based on the first soil fertility paradigm. In the developing world there is a close correlation between increase in food production and fertilizer use (Mokwunye and Hammond, 1992). Per-capita food production continues to increase in Asia and Latin America, where the first paradigm's application in the Green Revolution responsible for much of its success (Pinstrup-Andersen 1993). About 50% of the yield increases by the Green Revolution in the tropics are attributed to increased fertilizer use. The first paradigm also fosters irrigation to overcome drought stress and conventional tillage practices to overcome soil compaction and facilitate weed control.

The Second Paradigm

Less is known about how to manage marginal soils in a sustainable manner. By “marginal” I mean soils in areas with severe socio-economic constraints that exacerbate biophysical ones such as drought stress, aluminum toxicity, low nutrient capital reserves, high phosphorus fixation or high erosion risk. The intensive use of purchased inputs, mechanization, terracing and irrigation is less feasible in such areas largely because of a lack of a sufficiently enabling policy environment or because of major terrain constraints. For example most of tropical Africa is geomorphologically unsuitable to irrigation. Soil science research to tackle these marginal lands is more recent, and a second paradigm has gradually emerged:

Rely more on biological processes to optimize nutrient cycling, minimize external inputs and maximize the efficiency of their use

Scientific paradigms are different ways of conceptualizing issues in a sufficiently unprecedented manner that captures an enduring group of adherents, and at the same time are sufficiently open-ended to allow scientists many opportunities for improvement. This second paradigm is evolving in such a manner, first with the concept of breeding plants for tolerance to adverse soil factors, such as aluminium toxicity and drought stress. This has been followed by the deliberate incorporation of soil biological processes, and currently with the combined use of organic inputs and mineral fertilizers (Sanchez, 1994, 1997) as well as conservation tillage (Lal, 1989; Blevins and Frye, 1993). Most of the current advances in tropical soil management research are related to this second paradigm.

ANNUAL CROP PRODUCTION IN THE TROPICS: THE NORM AND TWO KEY EXCEPTIONS

This discussion can be put in a somewhat finer analytical perspective by looking at crop productivity at the ecoregional scale (a geographically defined agroecological zone i.e., the humid tropics of Latin America), albeit in a qualitative way. In Table 7 the tropics are subdivided into 18 ecoregions, each defined by its climate, geographical location and general level of soil productivity. Most tropical ecoregions with fertile soils in subhumid and humid climates and those in semiarid climates with irrigation have generally high to medium levels of crop productivity. These are the Green Revolution lands described by Pingali and others in this compendium. Likewise, most tropical ecoregions with marginal soils regardless of climate or location have low to moderate levels of crop productivity. So, soil fertility does matter, particularly since both broad kinds of soils can be found in most tropical countries.

Table 7. Main current agricultural land use and crop productivity levels by climate, geographical region and inherent soil fertility in the tropics.

Tropical Climate	Tropical Region	Fertile Soils		Marginal Soils	
		Main system	Crop Productivity	Main system	Crop Productivity
Humid	Asia	Green Revolution	High	Tree crops/ Slash & burn agriculture	Low
	Africa	Tree crops/ food crops	Moderate	Slash & burn	Low
	Latin America	Tree crops/ sugar cane/pastures/ food crops	High	Pastures, Slash & burn agriculture	Low
Subhumid	Asia	Green Revolution	High	Crops	Moderate
	Africa	Subsistence crops	**Low**	Subsistence crops	Low
	Latin America	Green Revolution	High	Oxisol technology	**High**
Semiarid	Asia	Green Revolution (with irrigation)	High	Crops	Low
	Africa	Pastoral/subsistence crops	Low	Pastoral/subsistence crops	Low
	Latin America	Green Revolution (with irrigation)	High	Pastures	Low

A noteworthy feature of Table 7 is the generally superior crop productivity level of tropical Asia and Latin America over tropical Africa, particularly in areas with fertile soils. This suggests that factors other than soils or climate are limiting agricultural production in tropical Africa, since soil constraints are generally less severe in tropical Africa than in tropical Asia or Latin America, as shown in Table 6.

There are two ecoregions that do not fit the pattern just described: The first one is **high** crop productivity in subhumid tropical Latin America with marginal soils, in sharp contrast with the entire "marginal soils" column. The second one is **low** crop productivity in subhumid tropical Africa with fertile soils. These two cases will be explored in detail.

The Brazilian Cerrado.

The Cerrado of Brazil is a 200 million hectare spread of tropical savanna dominated by Oxisols with low pH, very high Al saturation, low and often undetectable levels of available phosphorus and often high P-fixation (Marchetti and Dantas 1980, Lopes 1983, Goedert; 1985, 1987; Embrapa 1988). In much of the Cerrado annual crops would not grow without phosphorus applications. Prior to the 1970s, the Cerrado was thinly populated and extensive cattle grazing was its main land use.

I vividly recall being asked by a senior official of the Brazilian Ministry of Agriculture in 1972, whether I thought the Cerrado could be good for agriculture now that their new capital, Brasilia, was established in the midst of it. I said yes. Research conducted by Empresa Brasileira de Pesquisa Agropecuária (Embrapa), state research institutions, universities, the private sector and international collaborators got to work on how to transform the Cerrado into an agricultural region.

Several research breakthroughs are largely responsible for making acid Oxisols productive in the tropics. They are based on a better understanding of what these stereotype tropical red soils are, particularly their differences in clay mineralogy as compared with glaciated temperate regions of the US Midwest and Europe that have very different clay minerals. Many of these breakthroughs have taken place not only in Brazil, but also in Southeastern United States, Australia, Hawaii and elsewhere. The key ones are summarized below (Sanchez, 1994; 1997):

- Aluminium toxicity was identified as the principal culprit of soil acidity, leading to the development of practical liming recommendations.
- The development of techniques to ameliorate subsoil acidity expanded the soil volume utilized by roots and decreased drought stress.
- The use of indigenous sources of rock phosphate, coupled with the quantification of residual effects of superphosphate applications provided long-term ways to alleviate phosphorus deficiency in soils with high P-fixation.

- An understanding of the role of variable-charge clay minerals that dominate the chemical dynamics of Oxisols and similar soils led to realistic methods for determining cation-exchange capacity and base saturation.
- The widespread development and use of specific rhizobium strains for inoculating legume species, particularly soybeans, provided major nitrogen inputs to cropping systems.
- The development of laboratory services that use methodologies appropriate to acid soils and the identification of crop-specific critical nutrient levels became the basis for sound fertilizer recommendations.
- A vastly improved database on the geographical distribution of soils, their classification according to quantitative criteria and their interpretation as fertility constraints facilitated the spatial extrapolation of research results.

These technological breakthroughs were accompanied by a strong and sustained political will, as the Brazilian government was determined to “domesticate” the Cerrado as a key part of their expansion into the hinterlands. When the research breakthroughs became clear, the government set policies to promote road building, provide credit and subsidized the use of nearby lime and phosphate rock deposits (Lopes 1983; Goedert 1985, 1987; Abelson and Rowe 1987; Lopes and Guilherme 1994). Federal and state governments invested heavily in the Cerrado for about two decades. This enabling policy environment made the widespread adoption of research results a reality, and is analogous to the strong political will shown by the Indian and Pakistani governments in support of the Green Revolution in the 1960’s and 1970’s.

This combination of technology and policy destroyed the myth that such red, acid soils are unsuitable for agriculture. The results shown in Table 8 indicate that from 1970 to 1990 the land area of under crops more than doubled in the Cerrado, average yields increased by 60% and total grain production more than tripled. Soybean production in the Cerrado became competitive with production in the United States. In addition, the area covered by improved pastures went from a negligible amount to 30 million hectares and the area covered by plantation forests from nil to 3 million hectares. The internal rate of return of these research investments was 32% (Ribeiro, 1979). The first paradigm was successfully applied in the Brazilian Cerrado.

Table 8. Impact of Oxisol management technologies in the Cerrado of Brazil from 1970–90. Sources: Wenceslau Goedert, Embrapa (compiled from Fundacâo Instituto Brasileiro de Geografía e Estatística) and Raul Vera, CIAT.

	1970	1980	1990
Area planted to grain crops*(million hectares)	5	7	11
Average grain yields*(tons/ha)	1.2	1.3	1.9
Grain production* (million metric tons)	6	9	20
Improved pastures (million hectares)	0	16	30
Plantation forests (million hectares)	0	1	3

* Soybean, upland rice, beans, wheat and maize

Soil Fertility Depletion in Subhumid Tropical Africa

The second outlier in Table 7 is the **low** annual crop productivity of fertile soils in subhumid Africa. Many of these soils, particularly in East Africa are very similar to the best soils of Brazil, called Terra Roxa, which are derived from basalt in both continents. They are similar to the Cerrado Oxisols except they are not aluminum toxic and have ample supplies of calcium, so liming is not an issue. What happened is that small-scale African farmers depleted the soils of their two main nutrients, nitrogen and phosphorus by not returning those nutrients removed by crop harvests from the soil over many years (Sanchez et al., 1997).

The current policy environment in subhumid tropical Africa is drastically unlike Brazil's when the Cerrado was "domesticated" in the 1970's and 80's. African governments have paid little attention to the rural sector resulting in poor roads, markets, agricultural research and extension infrastructure. Since fertilizers cost about 2 - 4 times more at the farm gate in Africa than in Europe or the Americas, different approaches had to be developed that combine organic inputs with mineral fertilizers, following the second paradigm.

A robust natural resources management approach has been developed, which fixes nitrogen from the air and brings phosphorus from indigenous phosphate rock deposits, together with biomass transfers of nutrient-accumulating hedge species. Leguminous tree fallows of several species of *Sesbania, Tephrosia, Crotalaria and Cajanus* accumulate 100 – 200 kg N/ha in 6 months to 2 years. The fallow biomass is incorporated to the soil before planting, increasing maize yields 2 – 4 times. These are amounts of nitrogen American farmers apply to their crops, unlike many other organic input approaches, that provide small quantities of nutrients and incur high transportation costs. These fallows also provide multiple benefits such as fuelwood grown *in-situ*, capture of leached nitrates, recycling of other nutrients, control of the parasitic weed striga, improved soil physical properties and carbon sequestration (Sanchez and Jama, 2001).

The concept of building-up phosphorus as an investment in natural capital came straight from the Brazilian experience (Sanchez, 1997). Experiments in Western Kenya show that a single large recapitalization rate of phosphorus or annual additions of Minjingu phosphate rock can double or triple maize yields in phosphorus deficient and high P-fixing soils as efficiently as imported triple superphosphate and at lower cost. *Tithonia diversifolia*, a common hedge species has high nutrient concentration in its leaves (3.5% N, 0.37% P, 4%K) and decomposes rapidly in the soil. Biomass transfer of tithonia at dry mass rates of 2 –5 tons/ha routinely double maize yields without mineral fertilizer additions.

Tens of thousands of farm families are becoming food secure and no longer suffer from hunger periods because of the tremendous maize grain yield increases attained by these technologies. They also provide higher returns to land and labor than current practices (Sanchez and Jama, 2001) and returns on investment on the order of 90 – 120% (Rommelse and Place, unpublished). Farmers are now taking advantage of improved soils by diversifying and growing higher value crops and trees, and many are beginning to have a dairy cow for the first time, taking the first steps out of poverty. Soil fertility replenishment is a multi-disciplinary issue involving socioeconomic and policy dimensions as well as other biophysical dimensions, such as conservation tillage, improved crop germplasm and integrated pest management. The policy dimension is crucial, to foster a better road infrastructure, access to credit, markets and information by smallholder farmers. The elimination of this root cause of food insecurity in Africa augurs well for turning around the poverty-environmental spiral in this continent.

PERSPECTIVES

The Humid Tropics

The more sustainable and successful systems in the humid tropics are paddy rice in the lowlands and different kinds of agroforestry in the uplands (Hayami, 1998). Rice production has been a great success, often with two or three crops a year with irrigation in generally fertile soils. There is no break in the pest life cycles, but pests are being kept at bay with the steady release of insect and disease tolerant rice varieties as pests mutate, and by the increasingly widespread use of integrated pest management technologies (Herren, this volume; Oka, 1997). The main rice exporters in the world, Thailand and Vietnam grow most of their rice in their humid tropics.

There are problems of yield stagnation and many worry that the rate of yield increases of rice and wheat in Green Revolution lands is flattening. What can we expect, a forever linear increase? Technologies run their course, and the next breakthrough may be possible with new genomic tools that allow scientists to transform plant breeding from a shotgun approach into a quantitative science with a predictive understanding. There are no climatic or soil-related yield ceilings in the humid tropics. After all crops are still utilizing a very small fraction of the photosynthetically active solar radiation available to plants, even in areas with considerable cloudiness.

The humid tropical uplands are where tree plantations and agroforestry have the comparative advantage. Successful agroforestry systems by smallholder farmers in the humid tropical uplands with marginal soils are those supported by appropriate indigenous soil management technologies, well-developed processing and marketing systems and reasonably favorable policies (Garrity and Agustin, 1995; Tomich et al., 1998). This is particularly the case in Southeast Asia, but less so in humid tropical America and Africa where the marketing and road infrastructure is generally less developed, tree crop research has been less intensive and policies have often taxed producers and created perverse incentives.

The tree crops used (rubber, oil palm, coffee, tea, many tropical fruits and timber species) are already aluminum-tolerant, thus taking care of this critical soil constraint (Sanchez et al., 1985). Being trees they grow year-round and tap the full potential of available solar radiation, moisture and high temperatures. Malaysia invested heavily in tree crop research during the 19xx, when other countries were getting out of rubber thinking they could not compete with synthetic rubber (Tomich et al., 1994). Like the Cerrado story, the Rubber Research Institute of Malaysia and allied research centers provided the technological breakthroughs—superior germplasm, understorey agronomy, and industry found how smallholder producers can work in synchrony with large processing facilities handling perishable products like oil palm kernels. The success of tree plantations is one reason why Malaysia can be considered a developed country, located squarely in the humid tropics with almost no fertile soils. They have wisely used tree crops like rubber, oil palm and many tropical fruits to produce enough income to buy rice and other food crops from their neighbors.

The Subhumid Tropics

The two oddball examples in the subhumid tropics show that there is nothing intractable about tropical soils that are originally acid and infertile, like those of the Brazilian Cerrado, or those that were initially fertile but have been depleted of their nutrients, like in East and Southern Africa. Both can be successfully transformed into productive croplands. The Cerrado was handled with first-paradigm technologies and the African case is being handled with second-paradigm technologies as the logical entry point.

The subhumid tropics have probably the best kind of tropical climates for crop production, combining rainy seasons with dry seasons that stop the life cycles of many pests and diseases. The success or failure largely depends on government policies that provide an enabling environment. The Cerrado technology is known to scientists working in other subhumid acid savanna regions such as the Llanos of Colombia and the Miombo of Northern Zambia, but not much has happened in these places in the absence of enabling policies, infrastructure and access to markets. The acid savanna of the subhumid tropics is the only part of the world where the agricultural frontier has expanded in the last decades. The Cerrado, located squarely in the tropics is making Brazil join the ranks of major world food exporters.

The Semiarid Tropics

Biophysically, semiarid tropical areas not suitable for irrigation are the most difficult tropical regions for crop production. They are also the most vulnerable to soil erosion and runoff because unpredictable intense rains often take place when the soil is devoid of plant cover and the soil surface is impermeable to water. Semiarid tropics that is also low in soil fertility, like the Sahel makes crop production even more difficult. Until recently low native soil fertility was essentially ignored in the Sahel, and research priority was given to solving the crop production problem by developing high-yielding varieties, which resulted in little impact. The core problems in the Sahel are soil fertility and the management of rainfed water. Other semiarid regions with fertile soils like the Sudan Gezira, parts of Mexico and India have shown more progress with crop genetic improvement in rainfed areas.

Livestock and trees have the comparative advantage over annual crops in the semi-arid tropics. Integrated approaches need to be vigorously pursued and some are beginning to show incipient success. Since most areas are not suitable for irrigation, “islands” of soil moisture and fertility can be achieved with simple water-harvesting techniques and drip irrigation near homesteads where available nutrient inputs can improve soil fertility, and live fences with trees produce high-value products and separate crops from livestock (ICRISAT, 1989; ICRAF, 1999). In the face of the most severe biophysical constraints, the need for enabling policies in the semiarid tropics is paramount. Such policies have shown success in an almost entirely semiarid tropical country, Botswana (with livestock as the main agricultural activity) and in parts of semiarid Northeast Brazil (with a wide array of options). Both stand in sharp contrast with many Sahelian countries.

A Moving Target

Nothing in this analysis suggests that there is an intractable ecological divide to tropical agricultural productivity in terms of climate and soils. But the fact that the tropics are still lagging behind in agricultural productivity from the temperate regions in indisputable. So, what is the answer to Jeffrey Sachs' question?

There is no one simple answer, but it seems to revolve around this particular time in history. Agriculture probably originated in the temperate region, the Mediterranean climates of Southwest Asia's Fertile Crescent. It then spread to similar climates of southern Europe and North Africa, and eastward to China, across similar latitudes without major physical barriers (Diamond, 1997). In the Americas, agriculture originated in the tropics giving rise to the Mayan, Aztec and Inca empires, using a different suite of domesticated crops and livestock from Eurasia, and including sophisticated irrigation and drainage systems.

Crop yields in all these regions were uniformly low by present standards with the low population densities of cities that consumed much of the products (Diamond, 1997; Landes, 1988). There does not seem to be any temperate region advantage in crop productivity prior to the European colonizations. Crop productivity in the most technologically advanced areas was probably similar in tropical vs. temperate regions (Landes, 1988). Certainly tropical America was way ahead of temperate America prior to the arrival of Europeans.

The European colonizations in the 16^{th} to 19^{th} centuries globalized agriculture, mixing domesticated crops and livestock species from all over the world. Crop yields and livestock productivity were probably similar worldwide, and increasing populations were fed by increasing the area under cultivation around settlements, largely in some form of shifting cultivation systems into the 19^{th} century.

The 19^{th} century's industrialization of agriculture (internal combustion engines, chemical fertilizers) produced another agricultural revolution, permitting the transformation of shifting cultivation systems into permanent cropping in temperate-region family farming as well as in tropical areas that had access to such technologies (Landes, 1998). Agricultural research, initially in Europe began to produce major technological advances in all fields, and finally gave rise to what we call mainstream, mechanized modern agriculture in Eurasia and temperate America. This resulted in the temperate region clearly surpassing the tropics in agricultural productivity, probably for the first time.

Major research advances in the first 6 decades of the 20^{th} century further increased crop productivity so much in North America and Europe that land began to revert back to other uses, and yields continued to increase with maximum use of fossil fuels. Temperate region yields exceeded those of the same crops grown in the tropics (rice, maize, wheat) by a wide margin.

But the tropics began to strike back. The agricultural performance of the world's tropical regions has been outstanding in the last 40 years of the 20th century. Against Malthusian predictions of worldwide starvation during the 1950's and 1960's, farmers in tropical countries have tripled cereal production, keeping food production ahead of population growth, and decreasing the real prices of rice, wheat and maize by 76% in the last four decades (Pingali, this volume). The Green Revolution is one of the main achievements of humankind in the past century, and was due to a successful combination of scientific research, political will and effective farmers in developing countries. The example of the Brazilian Cerrado shows that success is not limited to areas with fertile soils and irrigation. It also happened in rainfed, acid infertile soils at the scale of millions of hectares.

Countries with sustained political will that have given priority to agriculture as the engine of growth have been the most successful in raising crop productivity. They include India, Indonesia, Malaysia, Thailand, Colombia, Brazil, Mexico, Costa Rica and two non-tropical but closely related countries China and Pakistan. Tropical countries with little investment and no real commitment to the rural sector, including weak agricultural research systems, have not been part of this success story. Although poor governance is an easy scapegoat for all ills, there is no denying its importance in terms of agricultural growth.

The literature shows often a "temperate bias" when dealing with tropical agriculture. Not all tropical countries develop their agriculture in ways equivalent to the temperate regions. Some crop production areas, particularly in subhumid regions like the Cerrado or irrigated areas of the semiarid regions of the Indo-Gangetic plain look familiar to a temperate region farmer. Even paddy rice production in the humid tropics looks familiar to a Japanese or a California rice farmer.

But the diverse intercropping and agroforestry systems in much of the tropics often looks untidy and complex, with many crop and tree species and complicated planting and harvesting sequences. Many of them are highly productive, but there is no denying that the high spatial variation typical of these complex systems makes the spread of innovations more difficult than in monocropping systems in irrigated valleys. Pasture-based cattle production systems without feedlots are now basically extinct in the temperate region, but still common throughout the tropics. Such systems are more ecologically sound and make use of the advantage of the ruminant animal—the ability to eat plants that humans cannot. Fast-growing trees that are harvested in about 5 years in the tropics baffle foresters from temperate regions that have to wait 20 to 70 years for trees to be ready to harvest.

Therefore the relative productivity of tropical vs. temperate agriculture has not been constant through time. In addition most comparisons are based on cereal crops that can be grown in both regions. Such comparisons ignore the contribution of complex systems where tree crops have the definite advantage.

Limitation of Correlations

Attempts to correlate specific climatic characteristics with the current inferiority of the tropics must be carefully examined. That correlation does not prove causality is a well-known fact. Correlations can suggest profitable avenues for exploring causality, but will only do so reliably in a so-called 'stationary' system, one that has reached equilibrium. If the factors in the system are changing over time at different rates or in the presence of non-linearities (i.e., if there are any time lags, as there clearly are in the case of technology diffusion), then the correlation structure will also change, and spurious correlations are likely to emerge. For instance, this occurs when correlating the number of Olympic gold-medal winners in running sports with the latitude of origin of the winner. If one attempted this correlation in 1900, one would find that the best runners came from Europe, but if you looked at them now, you would find they come from Kenya. The answer one gets is purely dependent on the time window, because the Olympic movement started in Europe, and diffused southward.

CONCLUSIONS

- Overall the tropics have approximately twice the plant production potential per hectare per year (net primary productivity) on the basis of solar radiation and temperature.

- The stereotype tropical soils, red, acid, of low fertility (Oxisols and Ultisols) cover almost half of the tropical land surface, the other half has soils common to the temperate region.

- The proportions of fertile soils with sufficient rainfall and no permafrost are roughly equal in tropical and temperate regions (45% vs. 41%). The broad hypothesis that tropical soils are inferior to soils of the temperate region for agriculture is not supported by this analysis.

- Tropical Asia and Latin America show superior crop productivity over tropical Africa, particularly in areas with fertile soils. Factors other than soils or climate are limiting agricultural production in tropical Africa, since soil constraints are generally less severe in tropical Africa than in tropical Asia or Latin America.

- The current superiority in crop yields in temperate over tropical regions reflects one point in history, and not a long-term historical trend.

- Tropical soils and climates are often problematic but not more so than temperate climates and soils. The big difference is the scientific research capital and the priority given by governments the rural sector. When those two conditions are met like in Malaysia or in the Cerrado of Brazil, the ecological divide is overcome.

Consequently I strongly support Sachs's call for drastically increasing investments in tropical agriculture to strengthen the technological base, provide supportive policies and galvanize political will. This probably also applies to tropical public health for similar reasons—the historical record of epidemics in both temperate and tropical regions, the investments in technology and the policy environment. In the long run, the biophysical superiority of tropical climates will be reflected in a superior tropical agriculture, just as it is now reflected in the net primary productivity of natural systems.

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