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Jeffrey D. Sachs

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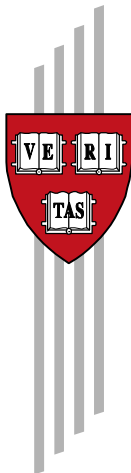
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Abstract

Most recent cross-country analyses of economic growth have neglected physical geography as a determinant of economic growth. This paper reviews the distinctive development challenges faced by economies situated in tropical climates. Using geographic information system (GIS) mapping, the paper presents evidence that production technology in the tropics has lagged behind temperate zone technology in the two critical areas of agriculture and health, and this in turn opened a substantial income gap between climate zones. The difficulty of mobilizing energy resources in tropical economies is emphasized as another significant contributor to the income gap. These factors have been amplified by geopolitical power imbalances and by the difficulty of applying temperate-zone technological advances in the tropical setting. The income gap has also been amplified because poor public health and weak agricultural technology in the tropics have combined to slow the demographic transition from high fertility and mortality rates to low fertility and mortality rates. The analysis suggests that economic development in tropical ecozones would benefit from a concerted international effort to develop health and agricultural technologies specific to the needs of the tropical economies.

Tropical Underdevelopment

Jeffrey D. Sachs

Perhaps the strongest empirical relationship in the wealth and poverty of nations is the one between ecological zones and per capita income. Economies in tropical ecozones are nearly everywhere poor, while those in temperate ecozones are generally rich. And when temperate economies are not rich there is typically a straightforward explanation, such as decades under communism or extreme geographical isolation. Of the thirty economies classified as high-income by the World Bank, only two small economies – Hong Kong and Singapore – are in the geographical tropics, and these two constitute just one percent of the population of the rich economies.[1] Since sea-navigable regions are generally richer than landlocked regions, regions that are both temperate and easily accessible to sea-based trade almost everywhere have achieved a very high measure of economic development. Tropical and landlocked regions, by contrast – such as Bolivia, Chad, Niger, Mali, Burkina Faso, Uganda, Rwanda, Burundi, Central African Republic, Zimbabwe, Zambia, Lesotho, Laos – are among the very poorest in the world. These points can be gleaned from Figure 1, a color-coded map of the world, where national income per capita is indicated by the darker hues. All of the major high-income regions – North America, Western Europe, Northeast Asia, the Southern Cone of Latin America, and Oceania – are outside of the tropics.

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[1] In the *World Development Report 2000/2001* the World Bank defines high income countries as those with Gross National Product (GNP) per capita in $US 1999 of $9,266 or more. The high income countries with populations of more than one million are: Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Hong Kong, Ireland, Israel, Italy, Japan, Korea, Kuwait, Netherlands, New Zealand, Norway, Portugal, Singapore, Slovenia, Spain, Sweden, Switzerland, Taiwan, United Arab Emirates, United Kingdom, United States. The combined population is estimated to be 931 million. Of these countries, only Hong Kong and Singapore, with a combined population of approximately 10 million, are predominantly in the geographical tropics (about 36 percent of Taiwan is in the geographical tropics as well).

The pattern of temperate-zone development and tropical-zone underdevelopment can also be seen within large nations that straddle ecozones, and within highly integrated, multi-national regions such as Western Europe. Thus, the sub-tropical U.S. South lagged behind the temperate U.S. North in industrialization; Brazil's tropical Northeast, though the original site of Europe's colonization of Brazil, has lagged the temperate Southeast for one-and-one-half centuries; temperate Northeast China has long had higher per capita income than the sub-tropical Southeast China; and of course Northern Europe industrialized roughly a half-century or more ahead of Southern Europe.

These geographical correlates of economic development and underdevelopment deserve an explanation, yet have been neglected by academic economists for decades. Until very recently, the outpouring of econometric studies of cross-country economic growth neglected physical geography as a relevant dimension of analysis. Powerful studies from outside of economics, such as Jared Diamond's *Guns, Germs, and Steel,* are helping to bring ecology and physical geography back into economic analysis. Only a few economic historians, such as Stanley Engerman and Kenneth Sokoloff (1997) in a superb essay on economic development in the Americas, and David Landes in Chapter 1 of his *Wealth and Poverty of Nations*, have recently discussed the differences of tropical and temperate-zone production systems. Earlier fine essays, such as Lee (1957) and Kamarck (1976), have suffered an unfortunate and undeserved neglect, and were not updated according to new insights of ecology and economic development. It is time for specialists in economic development, economic growth, and economic history to re-examine the nature of tropical underdevelopment, and to understand its roots in the combination of physical ecology and societal dynamics.

I would like to propose five hypotheses regarding tropical underdevelopment. These are by no means proved, but I think the evidence is in their favor.

(1)   Technologies in critical areas – especially health and agriculture, but also construction, energy use, and some manufacturing processes – are ecologically specific. Such technologies do not easily diffuse across ecological zones. This point is stressed by Diamond in his pithy observation that Eurasia's east-west orientation facilitated a broad diffusion of technologies across a shared ecological space, while Africa and America's north-south orientation frustrated technological diffusion by cutting across a swath of distinct ecological zones;

(2)   By the start of the era of modern economic growth, if not much earlier, temperate-zone technologies were more productive than tropical-zone technologies in crucial areas of health, agriculture, and energy utilization, not to mention military technology. These differences are deeply embedded in ecological characteristics of temperate and tropical zones, and could not be overcome through slight tinkering with existing temperate-zone technologies;

(3)   Technological innovation is an increasing-returns-to-scale-activity, or as Adam Smith would say, one that is limited by the extent of the market. Temperate-zone innovation has been strongly favored by a larger and richer population, which at least since 1800 has been integrated in a global market for innovation. This increasing-returns-to-scale property of technological innovation is probably the main amplifier of the gap between the temperate and tropical zones in the past two hundred years;

(4)   Societal dynamics – especially the processes of urbanization and demographic transition – are two further amplifiers of the development process, by which technologically laggard tropical regions have experienced a widening shortfall vis-a-vis the fast-growing temperate-zone regions;

(5)   Geopolitical factors – such as temperate-zone imperial domination of tropical regions on the basis of superior military technology, and rich-country control of the institutions of globalization – are further amplifiers, but their role is often exaggerated when not considered alongside the underlying technological, demographic, and urbanization processes.

If these hypotheses are broadly correct, then policy solutions for tropical underdevelopment will require a much greater national and international focus on technological innovation directed at the problems of tropical ecology. And since the social institutions that promote technological change are inherently both market and non-market based, the institutional underpinnings of enhanced tropical development will have to extend beyond market liberalization and privatization as now advocated by the international financial institutions, a point that I have stressed in several recent essays (Sachs, 1999, and Sachs, 2000).

I. Some Definitions and Measurements of Tropical Underdevelopment

The tropics may be understood in two main ways: on a geographical basis and on an ecological basis. The geographical tropics are conventionally defined as the region of the Earth in which the sun passes directly overhead at some point during the year. Because of the tilt of the earth's rotation of 23.5 degrees, the geographical tropics include the area between 23.5 degrees North latitude (Tropic of Cancer) and 23.5 degrees South latitude (Tropic of Capricorn). Some recent econometric studies have relied on latitude as a key explanatory variable for economic development, most notably Hall and Jones, 1999. And as we show in Figure 2, there is a systematic gradation of average per capita income, with the high latitudes both North and South showing higher per capita income than the low, tropical latitudes.

It is hard to see why distance from the equator, per se, should be an explanatory variable for economic development, except as latitude impacts economic activity through insolation, precipitation, and other climatic factors. Moreover, countries at the same latitude can have very different climates because of the influence of land masses, wind patterns, and ocean currents. Stockholm, bathed in the Gulf Stream, is at the same latitude as Hudson Bay. Latitude of course will also affect proximity to markets, and therefore transport costs, but in that case it would be distance from major markets rather than distance from the equator that should be the appropriate standard. Northern hemisphere locales would have a distinct advantage relative to the Southern hemisphere locations at comparable distance from the equator.

Hall and Jones make the surprising and untested claim that latitude is really proxying for the penetration of European institutions in various parts of the world, but latitude is an extremely dubious measure of such linkages. Many mid-latitude regions, such as Central Asia, China, Korea, and Japan, have relatively weak links with Europe, while many equatorial regions are former (or current) European colonies with very strong linkages.[2] In any event, such institutional linkages could and should be more directly measured by other means (linguistic, religious, political, trade and financial flows). In fact, when latitude is tested for explanatory power against various direct climate or ecological measures, we find that latitude per se adds little if anything to the explanation of patterns of cross-country development.

More useful definitions of the tropics rely on ecological or climatic characteristics as opposed to latitude. Of course there are a large number of alternative classification systems, based on temperature, precipitation, growing season, natural vegetation cover, and other

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[2] Consider, for example, the latitude band at 45 degrees North. This latitude band passes through the United States, Canada, France, Italy, Croatia, Bosnia, Serbia, Romania, Ukraine, Russia, Kazakhstan, Uzbekistan, China, Mongolia, and Japan. It is clearly unwarranted to suppose that location on this latitude band signifies a relatively

characteristics. In general, tropical zones are defined by high year-round temperatures and the absence of winter frost. Temperature patterns are typically combined with precipitation patterns to distinguish categories such as the humid tropics (or equatorial or rainforest tropics), wet-dry tropics (or savannah and monsoon tropics), and arid tropics (or hot desert regions). Of course specific ecological characteristics of an economy will also depend on topography (slope and elevation); geology including bedrock, mineral deposits, and seismic and volcanic activity; orientation relative to large landmasses, oceans, rivers, lakes, ocean currents, and prevailing winds; proximity to markets; endemic fauna and flora, including pests, parasites and disease vectors; and a myriad of other geographical characteristics, some of which are highlighted and others neglected by any particular classification system. In short, a designation of "tropical" or "temperate" ecozone is only a first and rough categorization of an economy's relevant ecological characteristics.

In our research at the Center for International Development, we have recently used the well-known Koeppen-Geiger (KG) climate classification system. In this system, regions are differentiated mainly by temperature and precipitation. The world according to KG is shown in Figure 3. There are three tropical zones (humid, Af; dry winter, Aw; and monsoon, Am); two arid zones (desert, Bw; and steppe, Bs); three temperate zones (sub-tropical dry winter, Cw; Mediterranean dry summer, Cs; and humid temperate, Cf); two snow zones (humid snow, Df; dry winter, Dw); and high-elevation regions (highland, H).[3] The Cw climate (such as characterizes India's Gangetic valley) is classified as a "mild" climate, cooler than the tropical climates. It is, nonetheless, a low-frost region with warm winter months, and from the point of

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constant (and high) level of European institutional influence. The same is plainly true of other latitude bands as well. If we want to measure European influence, there are many much more convincing ways to proceed.
[3] There is also an E zone, for ice (tundra) regions, with almost no human habitation. We ignore the E zone in our analysis.

view of agriculture and disease ecology it shares important characteristics with the tropical climates. Thus, when we aggregate the detailed climate zones into larger categories – such as tropical and temperate zones -- we include Cw in the tropical zones. Thus tropical climate zones are Aw, Af, Am, and Cw, and the temperate zones are Cf, Cs, Dw, and Df. The non-tropical zones are all zones other than the four tropical zones, thus, Bw, Bs, Cf, Cs, Dw, Df, and H. The non-temperate zones, of course, are Aw, Af, Am, Bw, Bs, Cw, and H.

Using GIS (geographic information system) mapping it is possible to integrate climatic and economic data. We estimate the 1995 average gross national product (GNP) per capita for the various climate zones in the following manner. We first assign a GNP per capita to each individual in the world, by using the finest level of economic disaggregation available for GNP. For most countries, each individual is simply assigned the average GNP per capita of the entire country (using purchasing-power-parity-adjusted GNP). For several large countries and for the European Union, we can assign GNP per capita on a sub-national level (*e.g.,* states in the United States, Brazil, and India, and provinces in China). Individuals are also assigned to KG zones by overlaying the KG climate classification on a digitized map of world population. We also measure whether individuals are within 100 km of an ocean coast or an ocean-navigable river.

The results are shown in Table 1, where we calculate the 1995 GNP per capita of individuals in KG climate-zones, differentiating between "near" (within 100 km of sea navigability) and "far" (more than 100 km away from sea navigability) zones. We see that the highest income per capita in order are the Cf, Cs, and Df zones. The near regions are in all climate zones richer than the far regions. The economic dominance of the Cf-near regions, shown by the colored areas in Figure 4, is truly striking. This small area of the world has approximately 8 percent of the world's inhabited land area, 22 percent of the world's population,

and an astounding 52 percent of the world's GNP as a lower-bound estimate.[4]   Aggregating into

tropical and temperate zones, we see that the average GNP per capita of the temperate zone is 4.5

times that of the tropical zone (4.5 = 1.94/0.43). Note that the near-temperate zone has 6.3 times

the per capita income of the far tropical zone (6.3 = 2.32/0.37).

A low level of per capita income in 1995 signifies slow average economic growth during

the past two centuries, since the inter-regional income differences at the beginning of the 19th

century were much smaller than the differences today. Using the very helpful data of Maddison

(1995) we can estimate, at least crudely, the annual average growth rates of tropical and

temperate regions during the period of modern economic growth. Though Maddison does not

have a comprehensive set of Gross Domestic Product (GDP) accounts by country during the

entire period, he gives estimates of the aggregate GDP and population for major regions from

1820 to 1992. As a rough approximation, we take the temperate zone countries to be Maddison's

categories of Western Europe, Southern Europe, Eastern Europe, European Offshoots (the U.S.,

Canada, Australia, and New Zealand), Japan, and half of China. The remaining regions (Latin

America, Africa, and Asia minus Japan and half of China) are non-temperate. These divisions

are only approximate of course: for example, they put temperate Argentina, Chile and Uruguay

within the "non-temperate" region, and they include Korea within the tropical zone. We simply

lack the data as of 1820 to make a finer categorization.

Based on this split of the data, we find the long-term growth process in Table 2. The

temperate zone began the period of modern economic growth, in 1820, with an estimated per

capita GDP of $794 dollars (in units of 1990 international dollars), compared with $543 dollars

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[4] For economic regions (nations or sub-nations) that cut across climate zones and across the near-far boundary,
we've assumed that per capita income is the same for all individuals within the economic region. If in fact, as is
likely, the individuals living nearer to the coast, and within the Cf zone, have higher average incomes than others

in the non-temperate zone. Thus, the non-temperate zone had a per capita income approximately 68 percent of the temperate zone. During the long period 1820 to 1992, the per capita GDP of the temperate region grew at an annual average rate of 1.4 percent per year, compared with 0.9 percent per year in the non-temperate region. As a result, temperate-zone GDP per capita rose to $10,095 by 1992, while the non-temperate zone GDP per capita rose only to $2,556, or 25 percent of the temperate-zone level.

If we make the calculation with the Maddison data for the period 1960 to 1992, using the same crude classification of countries, we find that both regions grew at a rate of around 2.3 percent per year. This is a reflection of relatively fast growth in non-temperate-zone Asia, around 2.9 percent per year, together with continuing poor performance in Africa and Latin America. It begs the question as to whether the tropical growth deficit has disappeared in recent years.

I believe not. Given the large gap in income between the rich temperate zone and the poorer tropics, we would expect the tropical countries to grow *faster* than the temperate zone countries as a result of various forces of economic convergence, such as technological diffusion from rich to poor countries, and capital flows from rich to poor countries. Barro (1991) and others have repeatedly demonstrated that, all other things equal, poorer countries tend to outpace richer countries in annual growth rates. For tropical countries, however, this tendency towards convergence is muted, if not eliminated altogether.

To examine the effect of climate zone on recent growth controlling for other factors, we use Barro's cross-country growth framework, in which the annual growth rate in GDP per capita over a time interval is regressed on initial ln(GDP per capita), initial years of schooling, and

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living within the same economic region (but farther from the coast or in a non-Cf zone), then our calculation would understate the share of income in the near-Cf zone.

various economic policy and institutional variables. In this now-standard framework, we add in a variable measuring the share of the country's population living in temperate climate zones (Cf, Cs, Dw, Df). Thus, the estimated equation becomes:

$$\text{Annual growth} = a_0 + a_1 \text{ Initial ln(GDP per capita)} + a_2 \text{ Initial Schooling}$$

$$+ \Sigma \ a_i \text{ Policy and Institutional Variables}_i$$

$$+ \ b \ \text{ Share of Population in Temperate Climate Zones}$$

When we estimate this kind of equation for the period 1965 to 1990, using the Summers-Heston (1991) data set, the coefficient   b   on the share of population in the temperate climate zones is consistently positive, statistically significant, and has a magnitude of around 1.6.[5] This implies that a temperate zone economy, all other things equal, would grow at around 1.6 percent per year more rapidly than a comparable non-temperate zone country (either tropical, arid, or highland climate zones).   It also implies that in the long-run, a temperate zone country could expect to have a level of GDP per capita approximately equal to 2.7 times that of an otherwise comparable non-temperate zone country.[6]

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[5] One specific equation is the annual growth of GDP per capita during 1965 to 1990, regressed on ln(per capita GDP in 1965), ln(years of secondary school in 1965), the Sachs – Warner measure of openness for 1965 to 1990, the average budget deficit as a percent of GDP for 1970-90, a measure of the rule of law for 1980, a variable measuring the share of the population in temperate climate zones, and a dummy variable for Hong Kong and Singapore. When this is estimated for 69 countries, the coefficient on the temperate ecozone variable is 1.60 with a t-statistic of 2.8. Similar results may be found in Gallup, Sachs, and Mellinger (1999). Meanwhile, the Hong Kong-Singapore variable has a coefficient of 2.57 with a t-statistic of 2.8. As discussed more below, the strength of this result reflects the fact that, although Hong Kong and Singapore lie in tropical KG climate zones, both benefit from their island geography, which limits the ecological preconditions for disease. Likewise agriculture plays no significant role in these two service- and manufacturing-oriented economies, so the ecological conditions that normally inhibit the development of agricultural technologies in tropical climates have not been relevant.

[6] The long-run effect on the *level* of GDP per capita of temperate population is found as $\exp(-b/a_1)$, where b is the coefficient on the share of population in the tropical climate zones and a_1 is the coefficient on the initial income. According to the specification in footnote 6, $a_1 = -1.58$ and b = 1.60, so the long-run level of GDP of a temperate zone country would be 2.7 = exp (1.58/1.60), or 2.7 times the GDP per capita of a non-temperate zone country.

Will Masters and Margaret McMillan (2000) have similarly introduced a climate variable in a cross-country growth regression model. Their key variable measures the proportion of a country's land area that is subject to winter frost.[7] This variable takes values from 0 in the tropics to 1 in the higher latitudes.   They find that countries without winter frost (*i.e.*, tropical countries) experienced approximately 1 percent per year slower growth during 1960 to 1990 than did countries with winter frost, controlling for other variables such as initial income and population, trade openness, schooling, investment rates, institutional quality, and other variables.

Of course, a few tropical economies, mainly in East Asia, have achieved rapid growth on a sustained basis in the past three decades, and a couple of economies – Hong Kong and Singapore – have actually become rich. We will re-examine these special cases after we discuss the possible reasons for the more general condition of poor growth and continuing underdevelopment in the tropics.

Note, finally, that instead of running a regression of growth rates on climate, initial income, and other variables, we could alternatively estimate a regression of the level of GDP per capita on a vector of variables.   This is the approach taken by Hall and Jones, in which they find that latitude band is highly predictive of GDP per capita (with higher incomes of course at greatest distances from the equator). We have experimented with similar "level" regressions, and have found that climate and ecology variables (*e.g.,* proportion of population within the tropical climate zones, or proportion of population within a region of malaria transmission) are highly significant explanatory variables for the level of GDP per capita, and that they perform far better than simple geographical variables such as distance from the equator.

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[7] Specifically, they measure the proportion of land area that experiences 5 or more frost days per winter month on average.

II. Explaining Tropical Underdevelopment

Given the varied political, economic, and social histories of regions around the world, it must be more than coincidence that almost all of the tropics remain underdeveloped at the start of the 21st century. For a long time many observers felt that the colonial interlude of the tropical world must be the core explanation, and so they expected that decolonization by itself would end this pattern. Dispassionate observers, though, would have had their doubts. Tropical Africa, the world's poorest region, was colonized only in the 1870s and onward, and yet the pre-colonial period was characterized by the world's lowest living standards. Tropical Latin America had gained independence by the 1820s, without decisive breakthroughs in development as of the late 21st century. A few isolated tropical countries in Africa and Asia had escaped colonial domination altogether without being propelled to high-income status. I have little doubt that the colonial interlude was adverse for economic development in the tropics, but it was the great disappointment of the second half of the twentieth century that decolonization did not break the pattern of tropical underdevelopment. The roots of tropical underdevelopment are deeper. Indeed, one should assume that the vulnerability of the tropics to colonial domination was at least partly a signal of relative tropical underdevelopment. As a very rough guess, the Maddison data suggest that the tropical world had a per capita income equal to around 70 percent of the non-tropical world in 1820, at the start of the period of modern economic growth.

An alternative explanation, introduced for example by Max Weber in his sociological interpretations of capitalist development, is that modern economic growth is inextricably linked to capitalism, and that capitalism is linked to European culture. In this view, the essential source of the temperate-zone advantage is that it is a European advantage, whether directly in Europe or in the "offshoot" settlements of North America and Oceania. This explanation as well cannot

withstand close scrutiny. Most importantly, the rise of temperate-zone East Asia – Japan, Korea, Northeast China, Taiwan – undermined the once-popular case that economic development is a European preserve. Moreover, Europeans established colonies throughout the world – in North and South America, Africa, and Asia – but the levels of income reached by these former colonies is highly dependent on geography. The temperate Southern Cone former colonies of Spain (Argentina, Uruguay, Chile) outperformed the tropical American colonies of Spain. Temperate Southeast Brazil outperformed tropical Northeast Brazil. Temperate Southern and Northern Africa are far richer than tropical Africa though all parts of Africa were colonized by the Europeans. And so forth.

My argument is that the technology for production in the tropics has long lagged behind temperate-zone technology in two critical areas – food production and health – opening a substantial gap in incomes between the two regions. A third gap, the ability to mobilize energy resources, might also have played an important role. This initial gap was then amplified through economic, demographic, and political-military forces. Since technologies in the critical areas of agriculture, health, and related areas could diffuse *within* ecological zones, but not across ecological zones, economic development spread through the temperate zones but not through the tropical regions. The discussion that follows, therefore, first discusses the ecological roots of technological underdevelopment, and then discusses the main hypothesized forces of amplification.

Food production in temperate and tropical zones

For the major staple crops – rice, maize, and wheat – productivity appears to be considerably higher in the temperate zones than in the tropical regions. As a general rule,

temperate zone economies are food exporters, while tropical zone economies are food importers. The world's main grain exporters are the U.S., Canada, Australia, and Argentina. Grain yields per hectare are considerably higher in the temperate regions.[8] If we regress the logarithm of grain output per hectare in 1995 on the logarithm of GDP per capita in 1995 (as a control for overall level of development) and share of population in the temperate climate zones, for 145 countries for 1995 data, we find that productivity per hectare in temperate climate zones was 51 percent higher ($\exp(0.41) = 1.51$) than in non-temperate climate zones on average (t-statistics in parentheses):

$$\ln(\text{Cereal yield per hectare, 1995}) = 7.2 + 0.31 \ln (\text{GDP per capita, 1995})$$
$$(18.1) \quad (6.1)$$

$$+ \; 0.41 \; (\text{Share of population in temperate climate zones, 1995})$$
$$(2.9)$$

$$\text{Adjusted R}^2 = 0.39, \text{N} = 145$$

A recent study by Gallup and Sachs (2000) suggests that this higher productivity per hectare reflects a higher productivity per unit of input, that is, a higher total factor productivity.

Many agronomists, ecologists, biologists, and economists have reflected on the lower levels of food productivity in the tropics, and have identified several possible underlying ecological factors. These include: soil formation and erosion; pests and parasites; effects of ambient temperature on plant respiration on net photosynthesis; and water availability in conditions of high evapo-transpiration. Let me describe these factors briefly.

A. Soil formation and erosion. One of the main themes of tropical agriculture is the fragility of tropical soils. In many tropical settings, soils are weathered by heavy precipitation and by the

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[8] If we divide countries in three categories (tropical, arid, and temperate) depending on where half or more of the country's population lives, the average cereal yield in 1995 was the following: tropical, 18051 kg/ha; arid, 18540 kg/ha; and temperate, 37,288 kg/ha.

rapid mineralization and leaching of organic compounds as a result of high temperatures.[9] In

rainforest ecosystems, most of the nutrients of the forest are actually above ground, in the plant

matter itself. Plant litter that falls to the forest floor is quickly recycled into above-ground

biomass. When the forest is cleared for agriculture, most of the nutrients are removed, and the

nutrients that are deposited on the forest floor tend to be quickly leached by the rainfall. The

soils lose their fertility after a few growing seasons. This is the reason why swidden agriculture

(shifting cultivation with long fallow periods) are prevalent in the humid tropics. Because of the

rapid mineralization of organic compounds, the soil structure is poor, and the cation exchange

capacity (CEC) of the soil is low. Low CEC, in turn, implies that many tropical plants have a

reduced ability to utilize fertilizers on a sustained basis (Weischet and Caviedes, 1993). In

temperate zones, by contrast, the annual winter frost helps to forestall the mineralization of

organic compounds, and thereby results in an actual buildup of deeper and richer top-soils over

time. Thus, while tropical soils are easily depleted of nutrients, the soil base in temperate zones

can become enriched by the natural buildup of soil organic matter (Powelson and Johnston,

1994, and Tiessen, Cuevas, and Salcedo, 1998). This is a kind of biophysical investment that

results in increasing agricultural productivity in temperate agricultural systems, a point recently

stressed by Masters and McMillan (2000).

B. Pests and parasites. A second major feature of tropical ecosystems is the high prevalence of

crop pests and parasites. Tropical ecosystems generally are characterized by a high degree of

biodiversity, which in a very general sense resists the monoculture systems that characterize

temperate-zone food production. Monocultures in the tropics are prone to devastation through

plant diseases, pests, and other forms of competition with highly biodiverse ecosystems. Just as

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[9] There are exceptions, of course, such as volcanic soils (*e.g.,* on the island of Java), where a deep nutrient base
supports a highly productive agricultural system without rapid soil depletion, or alluvial and floodplain soils, where

with human diseases, the year-round high temperatures of the tropics, and the absence of freezing winter months to kill parasites and pests, are the root of the high-burden of plant diseases and crop losses due to spoilage. The high prevalence of tropical animal diseases, such as trypanosomiasis, has long hindered animal husbandry and the mixed crop-cattle agricultural systems characteristic of temperate ecozones.

C. Plant respiration and net photosynthesis. Plants use part of their photosynthetic output to support their own metabolic processes. The net photosynthetic output is the gross photosynthetic output minus the plant's own respiration. The rate of plant respiration, in turn, depends on the ambient temperature. Crops in warm climates have higher rates of plant respiration, and warm nights in particular impose a high cost on net photosynthesis. Chang (1968, cited in Bloom and Sachs, 1998, pp. 222-225) has argued that the lower crop yields of grains and cotton in the tropics compared to higher latitudes are an inherent result of the high costs of plant respiration on net photosynthetic potential. In many tropical regions, farmers locate in highland areas, with colder nights, in order to raise crop yields.

D. Water availability and water control. Water control in the tropics poses one of the most difficult problems for crop productivity. Because of high temperatures, evaporation of surface water is very rapid, as is the transpiration of water through plant surfaces. The combined loss of water from these two sources, known as evapo-transpiration, means that water scarcity can be an enormous problem in warm climates even when overall rates of precipitation are high. Almost all of the wet-dry climates (Am and Aw) are subject to severe drought. These climate zones are also characterized by enormous fluctuations in year-to-year precipitation. In the humid tropics, by contrast, water control can be hampered by an excessive amount of precipitation, which

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soil nutrition is replenished annually by the silt brought from the mountains by river flows.

leaches soils, leads to water-logging of fields, and renders difficult the drying and storage of grains.

<u>Health in Temperate and Tropical Climate zones</u>

The burden of disease is considerably higher in the tropics than in the temperate climates. Consider the summary measures of life expectancy and infant mortality. In both cases, the health outcomes are significantly better in the temperate zones even after controlling for the level of GDP per capita (included as a summary measure of overall economic development).

ln(Infant mortality, 1995) = 8.6 - 0.61 ln(GDP per capita, 1995)
　　　　　　　　　　　　　　(29.3) (16.1)

　　　　　　　　　　- 0.74 (% Population in temperate climate zones, 1995)
　　　　　　　　　　(7.1)
　　　　　　　　　　　　　　　　Adjusted R^2 = 0.81, N = 148

ln(Life expectancy, 1995) = 　3.2 + 0.11 ln (GDP per capita, 1995)
　　　　　　　　　　　　　　(38.8) (10.9)

　　　　　　　　　　+0.08 (%Population in temperate climate zones, 1995)
　　　　　　　　　　(2.6)
　　　　　　　　　　　　　　　　Adjusted R^2 = 0.60, N = 148

The first regression implies that infant mortality in the temperate climate zones is 52 percent lower (exp(-0.74)=0.48) than in non-temperate climate zones, controlling for the level of income. The second regression implies that life expectancy in the temperate climate zones is 8 percent higher (exp(0.08)=1.08) than in non-temperate climate zones, again controlling for the GDP per capita of the country. The poorer health outcomes of the tropical regions will impair economic performance in several ways, both direct and indirect. The most direct channels, of course, are through reduced labor productivity as a result of lost workdays, and reduced physical and cognitive capacities as the result of acute and chronic illness. Indirect channels, some of which

are discussed below, include the effects of high burdens of disease on fertility rates, population age structure, and overall population growth rates.

Health outcomes are, of course, a complex mix of ecological, economic, social, historical and genetic characteristics of the population. Ecology affects the transmission of many important infectious diseases (IDs), some of which are inherently restricted to particular climate zones. Economics, of course, affects the ability of households to gain access to medical treatment, and communities to mobilize measures in support of public health. Social factors, such as the status of women, or societal beliefs concerning health, can have important consequences for health status. Historical factors are often crucial, for example whether a given population has had previous exposure to a particular disease. And genetic factors can predispose or protect populations from particular diseases. It is well known that sickle-cell trait in West Africa, a genetic polymorphism in the gene responsible for hemoglobin production, is protective against falciparum malaria in heterozygous carriers of the trait, but results in deadly sickle-cell disease in homozygous carriers of the trait.

Ecology can also affect disease through the interaction of nutrition and infection. It is well known that under-nutrition is immunosuppressive, so that poor nutrition disposes a population to a higher burden of morbidity and mortality from infectious disease. The same disease, say measles, which may result in a relatively minor illness in a well-nourished child can prove deadly in an under-nourished child. Under-nutrition is itself a complex and multidimensional phenomenon that may involve a shortfall in overall energy intake (energy malnutrition), a shortfall in protein content (protein insufficiency), or a variety of micronutrient deficiencies resulting from missing nutrients in the diet.

The tropics are subject to a higher burden of disease for many interacting reasons: a physical ecology that supports a high level of ID transmission; poor nutrition resulting from the low productivity of food production; and the multiple feedbacks through poverty (illiteracy, lack of access to medical care, lack of access to sanitation, and so forth). Let us consider the issue of disease ecology in some more detail.

Infectious diseases display many pathways of transmission between humans. These include: direct transmission (sexual or other contact, aerosol droplets of breath); vector transmission (via mites, ticks, mosquitoes, flies, among other organisms); water-borne transmission (often via a fecal-oral route); soil transmission; and blood borne transmission (via transfusions, sharing of syringes, or blood exchange in sexual contact). A major distinction is between cases in which the infective agent lives part of its lifecycle outside of the human host and those in which the entire life cycle is within humans. When the life cycle is partly outside of the human host, as in the case of vector-borne diseases such as malaria, trypanosomiasis, dracunculiasis, filariasis, or in the case of many water-borne diseases such as helminthic infections, then a sufficiently high ambient temperature is often a crucial requirement for successful transmission between human hosts. For example, malaria transmission generally requires an ambient temperature of 18 degrees centigrade or higher for the anopholene mosquitoes to be infective, and many helminthic infections are warm-weather diseases as well. Many bacterial infections transmitted by a fecal-oral route are also favored by warm, moist environments. Bacteria that contaminate food and induce diarrheal diseases typically reproduce more rapidly in warm temperatures. In temperate zones, such diseases therefore tend to display summer peaks in incidence, while tropical climates support year-round transmission and much higher rates of overall morbidity.

Temperate-zone societies of course have had their share of killer infectious diseases and devastating epidemics. Most of these diseases are of the type directly transmitted between humans (tuberculosis, measles, syphilis, influenza), or transmitted by intermediate hosts that can live in temperate climates (rat-bearing bubonic plague). Some killer epidemic diseases such as measles gradually evolved into less lethal childhood diseases. Measles imposed a major burden on European society in the early stages of urbanization, since growing urban concentrations supported the epidemic transmission of the disease among largely unprotected populations. Over the course of generations, however, the disease lost much of its virulence, as society adjusted to endemic measles infection.[10] Of course, the early urbanization and society adjustment to diseases such as measles gave European colonizers an added biological advantage as they subdued indigenous populations in Latin America, Oceania, and other isolated populations (*e.g.*, the South Pacific Islands).

Infectious disease burdens were very high in all parts of the world until the 19th century, but then declined markedly in Europe and the European offshoots of North America and Oceania, while not declining in the tropical regions, especially Africa. The temperate-zone infectious diseases were partially brought under control through a combination of improved nutrition, societal adjustment to diseases such as measles, improved public sanitation, and the introduction of immunization, first for smallpox, and then in the late 19th century for diphtheria. The tropical vector-borne diseases, such as malaria, yellow fever, and helminthic infections, proved to be much harder to control. While a yellow fever vaccine was developed in 1937, most of the other tropical diseases lack effective immunizations until today. Controls on intermediate

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[10] The adjustment involved many factors, such as an earlier average age of infection (since measles infections are less lethal at earlier ages); the acquired immunity of parents through exposure to the disease during childhood, thereby allowing healthy parents to tend to sick children during epidemics; and perhaps genetic selection at the

vectors, such as drainage of mosquito breeding sites to control malaria transmission, remain vastly more difficult to accomplish in the tropics than in the temperate zones. (See Hamoudi and Sachs, 1999, for a discussion of malaria control efforts, and why they have been much more successful in temperate climate zones). And the tropical regions had less benefit of improving nutrition and public investments in sanitation and clean water as additional factors in reducing infectious disease.

Energy Resources in Temperate and Tropical Climate Zones

The differences in agriculture and public health are probably the most fundamental sources of economic differentiation of the tropics and temperate climate zones. We should mention, however, the possibility that differences in energy endowments might also have played an important role in the widening income gaps. Industrialization was fueled, quite literally, by coal and then by hydrocarbons. Within the temperate zones, the location of 19th century industrial development depended heavily on the proximity to coal deposits. This is at least one factor in the relative lag of Southern Europe compared to Northern Europe in the pace of industrialization. A relative lack of water power in Southern Europe is also frequently cited as an additional factor. In the twentieth century, access to oil and gas reserves has also contributed to differential performance, though many hydrocarbon-poor economies (Switzerland, Japan) flourished, while many hydrocarbon-rich economies languished.

With regard to coal, deposits are overwhelmingly concentrated in the temperate zone. As of 1998, 10 countries accounted for 90.2 percent of global coal reserves, and of these 10

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population level in favor of reduced vulnerability to measles mortality. Improved nutrition levels also certainly played a role in diminishing the morbidity and mortality of the disease over time.

countries, all but India (with 7.6 percent) are in the temperate zone.[11] These ten countries also accounted for 87.3 percent of global production in 1998, with India's share at 7.6 of the global total. Indonesia also has sizeable coal reserves. With regard to hydrocarbons (oil and gas), global production in 1995 was 210 quadrillion BTUs. Of this amount, 37 quadrillion BTUs (17.5 percent) were in tropical ecozone countries (defined as countries with at least half of the population living in tropical climate zones), while 173 quadrillion BTUs (82.5 percent) were in non-tropical countries. The share of global population in the tropical countries was 43 percent and in the non-tropical countries 57 percent. This implies that the per capita hydrocarbon production in the tropical countries was only 28 percent of the per capita hydrocarbon production in the non-tropical countries.[12]

III. Forces of Amplification of Tropical Underdevelopment

In 1820, the per capita income of non-temperate regions was about 70 percent of the per capita income of the temperate zones. By 1992, as a result of slower economic growth in the non-temperate regions, the per capita income in the non-temperate regions had slipped to around 25 percent of the GDP per capita of the temperate regions. Since the climate itself probably did not change by enough to explain the widening gap, we must surmise that various factors amplified the differences already apparent at the start of the era of modern economic growth. I would surmise that three processes were most important: differential technological advance; differential demographic trends; and the superior economic and military power of the temperate-

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[11] The countries (with their share of global reserves in parentheses) are: USA (25.1), Russia (15.9), China (11.6), Australia (9.2), India (7.6), Germany (6.8), South Africa (5.6), Kazakhstan (3.5), Ukraine (3.5), Poland (1.4).
[12] Tropical production per capita was 37/2427 million BTUs per capita, and in the non-tropical countries 173/3224 million BTUs per capita.

zone countries, especially as manifested through colonialism, but also through the control of international institutions in the post-colonial period.

Technological change in the temperate and tropical climate zones

It is tempting to suppose that the rich got richer out of a generalized tendency towards increasing-returns-to-scale in economic growth. Many models of endogenous growth have the property that larger markets encourage more rapid rates of invention, which in turn spur more rapid economic growth and still larger markets. Increasing-returns-to-scale, in essence, results from the scale-dependence of technological innovation. Since inventions only have to be made once to be applied repeatedly, and since the fixed costs of R&D are easier to amortize when the end-market for innovation is larger, we would expect that innovative activity would rise by more than proportionately with the scope of the market. The rich, broadly speaking, would get richer over time.

This story has merit, but is too simple. It neglects the fact that innovation in one region may diffuse to other regions, thereby speeding the economic growth of the non-innovating (or laggard) regions as well. Indeed, the broad experience of the post-war era is one of conditional convergence, in which poorer countries, all other things equal, tend to grow *more* rapidly, not less rapidly, than the richer countries. Somehow that impulse towards convergence has been extremely weak in the case of the tropical economies.

The relative levels of technology of two regions depends both on technological innovation within each region, and also on the diffusion of technology across the regions. Krugman (1979) offered a neat model of the "North-South" (really temperate-tropical) income gap based on the relative rates of innovation in the North and diffusion of technologies to the

South. To paraphrase Krugman's model, suppose that the technology level of the first economy can be summarized as T_1 and of economy two as T_2. Economy 1 displays endogenous growth, in which technological capacity rises in proportion to the existing level of technology:

$$dT_1 / dt = r \, T_1$$

The parameter r is a measure of the research intensity in the economy (and may therefore depend on market structure, intellectual property law, transactions costs, taxation, and other structural characteristics of the economy). Economy 2 improves its technology only through diffusion of innovations achieved in economy 1. The rate of technological diffusion depends on the gap between technology levels in 1 and 2:

$$DT_2 / dt = f \, (T_1 - T_2)$$

The parameter f is a measure of the rate of diffusion of technologies from 1 to 2.

Now suppose that the relative income of regions 1 and 2, Y_1/Y_2, is simply proportional to the relative levels of technologies, T_1 / T_2. Let $R = T_1 / T_2 = Y_1 / Y_2$. Then, it is simple to see that: $DR / dt = r \, R - f \, (R - 1)$. In the steady state, $R = (r + f)/f$. The income of the laggard country relative to the innovating country is then just $1/R = Y_2 / Y_1 = f / (r + f)$. How far behind is the laggard country? The higher is the rate of diffusion, the higher is the relative income level of the laggard region. The higher is the rate of innovation in the innovating economy, by contrast, the lower is the relative income level of the laggard. Note, incidentally, if the laggard region also innovates, but at a slower rate than economy 1, so that $DT_2 / dt = r_2 \, T_2 + f \, (T_1 - T_2)$, with $r > r_2$, then in the steady state $1/R = f / (r - r_2 + f)$, so that the relative income gap is reduced by innovative activity in economy 2.

My hypothesis is that the rate of technological innovation in the temperate-zone economies was much higher than in the tropical-zone economies in the 19th and 20th centuries,

while the rate of technological diffusion between the two zones was very limited because key technologies could not cross the ecological divide. Temperate-zone countries could more easily partake of technological advances in other temperate zone economies, since they faced similar ecological conditions. This was certainly true of advances in public health and agronomic systems, and was probably true as well of advances in areas such as energy utilization, construction, environmental management, and new materials, to name a few key areas of technological change. Thus, there was a tendency for economic convergence among the temperate zone countries, through rapid diffusion of technology, but a tendency for *divergence* between the temperate and tropical ecozones, because of much higher rates of innovation in the temperate zone combined with low rates of technological diffusion between the two zones.

A number of recent papers have shown that patent citations, one measure of technological diffusion, are greatest in neighboring economies and decline with distance (Jaffee, Trajtenberg, and Henderson, 1993; Jaffee and Trajtenberg, 1999). Using direct measures of economy-wide TFP, Keller (2000) also finds that technological spillovers decline with distance. Johnson and Evenson (2000) specifically address the issue of technological spillovers across ecological zones in agricultural R&D.   They conclude that, "since Africa is far away from countries performing most R&D, it is also clear that Africa will not converge even to other LDC output levels, since they do not benefit from domestic or foreign spillovers." (p. 12).

Table 3 provides one measure of the enormous gap that prevails in the innovative activities of temperate and tropical economies. While the tropical climate zones account for 35.7 percent of global population, and an estimated 17.1 percent of global income, they accounted for only 1.9 percent of utility patents issued in the United States during 1995. The evidence on R&D expenditures as a percent of GDP conveys the same message. The tropical countries not

only lag behind the temperate-zone countries in total R&D expenditures, but also in the share of R&D in GDP.

<u>Demographic transition and tropical underdevelopment</u>

Relatively poor food productivity and poor public health have probably slowed the demographic transition in the tropical countries, which in turn has amplified the difference in per capita income across the ecological divide. The demographic transition, remember, is the transition from a high-fertility, high-mortality society, to a low-fertility, low-mortality society. From the point of view of long-term economic growth, there are several advantages to that transition. Most importantly, investments per child (both at the community and household levels) will tend to be higher in a low-fertility environment. This is the famous "quantity-quality tradeoff" much studied by demographers and economists. Moreover, the transition generally results in slower (or zero or even negative) population growth, and a higher proportion of the population at working age. Slower population growth means less strain on fixed resources (arable land, mineral deposits, soils), and a smaller share of saving that must be devoted to capital widening (equipping the expanding population with the pre-existing level of capital per person) as opposed to capital deepening (increasing the amount of capital per person).   Recent studies have shown that East Asia's rapid demographic transition in the past half century added markedly to the increase in GDP per capita, especially in comparison with regions such as Sub-Saharan Africa where the demographic transition has been delayed. (See Bloom and Williamson, 1998; Bloom and Sachs, 1998; Bloom, Canning and Malaney, 1999.)

Poor food productivity hampers the demographic transition by slowing the shift of population from rural to urban areas.[13] A simple cross-country regression of the percent of population living in urban areas on per capita GDP, proximity to the coast, and climate zone shows that indeed the rate of urbanization in the tropics is lower than in the non-tropics, controlling for income level.[14] Household fertility studies have repeatedly demonstrated that fertility rates are higher in rural areas, and especially in farm households, probably because the net economic cost of child raising is much lower, in view of the positive contributions of children to home production in farm households, and in view of the lower opportunity costs of the mother's time. A high burden of disease directly delays the demographic transition, since households compensate for a high rate of child mortality through a high rate of total fertility. Indeed, given the desire of risk-averse households to raise the likelihood that at least one child will survive until the old age of the parents, it's easy to show that a high rate of childhood mortality is associated with an even higher rate of total fertility, implying (within a reasonable range of parameters) that high fertility rates more than compensate for high mortality rates, leading to high population growth rates in such economies.

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[13] Suppose that food is a non-traded good, consumed with a low income elasticity. A rise in agricultural productivity will result in a decline in the share of the labor force engaged in food production, since the same amount of food can now be produced with fewer workers, and since the income effect of the rise in productivity will not result in any significant increase in the desired amount of food consumption. The result, therefore, of rapidly increased agricultural productivity is a decline in the share of the labor force in farm production, and typically, a rise of the share of the economy in the urban, non-food sector.

[14] The regression estimate is:

%Urbanization, 1995 = -56.52 + 13.41 ln(GDP per capita 1995) + 7.40 (%Pop. within 100km of coast, 1995)
      (5.5)   (10.65)   (1.95)

      -9.25 (%Pop. in tropical climate zones, 1995)   Adjusted R^2 = 0.62, N= 149
      (2.9)

The regression implies that the rate of urbanization is 9 percentage points lower in tropical climate zones than in temperate climate zones for economies at the same level of GDP per capita and with the same proximity to the coast.

The evidence indeed suggests that for a given level of GDP per capita, the total fertility rate (TFR) has been much lower in temperate climate zones than in non-temperate climate zones. The following regression, for example, examines the log-level of total fertility in 1965 as a function of the share of the population in the temperate climate zones, controlling for the log-level of GDP per capita in 1965 (we look at 1965, since it is fertility rates one generation ago which have largely determined the pattern of population growth in the past thirty years):

$$\ln(\text{Total fertility, 1965}) = 2.97 - 0.16 \ln (\text{GDP per capita, 1965})$$
$$(18.0) \quad (6.9)$$

$$- 0.66 \ (\text{Population share in temperate climate zones, 1995})$$
$$(11.1)$$

$$\text{Adjusted } R^2 = 0.80, N = 106$$

The coefficient on the climate variable suggests that, on average, a temperate-zone economy has a TFR that is 52 percent (exp(-0.66)=0.52) of the TFR of a non-temperate zone economy at the same level of income.   For example, for an economy with GDP per capita of $5,000, the temperate-zone economy is predicted to have a TFR of 2.6 births per woman, while the non-temperate zone economy is predicted to have a TFR of 5.0.

Temperate-zone power and tropical underdevelopment

The third great amplifier of tropical underdevelopment is the translation of economic weakness of the tropics into geopolitical weakness. The tropics were subjected to imperial rule by the temperate zone economies in part because the latter economies were economically stronger, and able to translate economic advantage into military advantage. The economic balance sheet of the colonial era is still to be written, in part because this important topic is relatively neglected by economic historians. There is still a raging debate as to whether colonial possessions contributed to economic growth of the metropole or economic stagnation of the

colonized areas. While it is certainly possible that economies might have grown faster as colonies than as independent countries, my own guess, for what it's worth, is that colonial domination frustrated long-term economic growth of the colonized regions through several mechanisms. These include: the relative neglect of key public goods, especially primary education and primary health of the indigenous populations; the suppression of higher education among the colonized population; the creation of oppressive political mechanisms such as forced labor and head taxes to extract resources from the local population; and the active suppression of local industry in favor of cash crops and extractive industry.

One simple way to examine this proposition is to ask whether the level of GDP per capita in 1995 is lower for countries that spent longer under colonial domination. In a regression of level of GDP per capita in 1995 on the share of population near the coast, the share of the population in tropical climate, the proportion of years of open trade policy during 1965-90, hydrocarbon production per capita, and a dummy variable equal to 1 if the country gained independence after 1945, the last variable was highly significant and negative. New states (i.e. those born after 1945) on average showed a level of GDP only 59 percent of old states, holding constant the other variables.[15] While this is a very crude indicator, it does suggest that the colonial interlude may well have been a significant factor in amplifying tropical underdevelopment. (The tropical climate variable has an estimated coefficient of −0.81, suggesting that tropical climate zones showed a GDP per capita equal to 44 percent

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[15] The regression estimate is:

ln(GDP per capita, 1995) = 8.13 + 0.62 (% Pop. within 100 km of coast) - 0.81 (% Pop. living in tropical climate zones)
        (58.0)   (3.3)   (5.5)

        + 1.33 (Sachs-Warner openness measure, 1965-90) + 0.87 (Hydrocarbon production per capita)
        (7.42)   (2.4)

        - 0.52 (Dummy variable for new states)   Adjusted R^2 = 0.64, N=140
        (3.8)

(exp(-0.81)=0.44) of non-tropical climate zones, controlling for the other variables, including the period of colonial rule).

In the post-colonial age, national power is translated into economic gain and loss through the ability to write the rules of the game of international economic life. The rich countries, for example, have often used their majority vote within the International Monetary Fund to impose draconian adjustments on poor debtor countries. For twenty years, many of the poorest tropical countries have had insolvent governments, burdened by un-payable external debts, and yet the international system has delayed or blocked the obvious solution of debt cancellation. The policy has contributed to continuing low growth and instability in the so-called Highly Indebted Poor Countries, a group of 41 extremely poor and highly indebted countries that are the subject of special scrutiny and policies of the international creditor governments.

Tropical success stories

The underperformance of the tropical economies has continued in the past forty years, as shown by the cross-country regression analysis. A few tropical economies, however, were successful in achieving "convergent growth," that is, growth sufficiently rapid to narrow the proportionate gap in incomes with the richest countries. The most notable tropical success stories are Hong Kong, Singapore, Taiwan, Malaysia, and Mauritius. Thailand and Indonesia also grew successfully until the economic crisis of 1997-98. How do these success stories fit into the overall pattern of tropical underdevelopment?

Briefly, the East Asian tropical success stories are all characterized by two main features (see Lee, Radelet, and Sachs, 1997, for further discussion). First, they all achieved notable successes in improved public health in the lead-up to their economic takeoffs. In some cases,

these successes were probably easier than in other tropical environments because of lower rates of transmission of falciparum malaria, and for four of the economies (Hong Kong, Mauritius, Singapore, and Taiwan) because disease control is easier in an island setting compared with a mainland setting. The dramatic improvements in life expectancy and infant mortality achieved by these countries translated, within a generation, to sharply reduced fertility rates as well. Second, these economies took policies to diversify away from primary commodities, and especially tropical agriculture, in favor of export-oriented manufacturing activities. The governments introduced special economic institutions – such as export processing zones – in order to attract multinational firms to undertake export-oriented production in their economies. The result was that these economies were able to establish new productive sectors (*e.g.*, textiles, electronic machinery, semiconductors and electronic components) where tropical production was not burdened by climatic or ecological factors.

In principle this kind of strategy of public-health led development, combined with a conscious policy push away from tropical agriculture and towards export-oriented manufactures (and now services) is more generally available to tropical countries. However, in Sub-Saharan Africa, the disease and agricultural conditions are so adverse that it is unlikely that most Sub-Saharan countries could replicate the East Asian successes without a substantial increase of external assistance (such as greatly increased funding for disease control activities).

IV. Some Closing Thoughts

The most notable feature of global economic development – the continuing impoverishment of the tropics – remains to be explained. I have offered some hypotheses that attempt to link underlying ecological forces with societal dynamics – economic, demographic,

and technological. There is much work to be done to test these hypotheses. We at the Center for International Development are hard at work on these issues, and I hope that others here will become similarly interested.

At the core of long-term economic growth has been the continued development of technology, a complex social activity that has benefited the temperate zones much more than the tropics. Policymakers in the years ahead should surely pay far more attention to technological change, and to the supporting social institutions that foster discovery and innovation, if they are to successfully address the special problems that face the tropical world. Rather than continuing to put all of the international energies into market reforms – as if markets alone could address the special ecological and technological needs of the underdeveloped tropical world – it will be necessary for the global community to find new ways to harness global science to meet the challenges of tropical health, agriculture, and environmental management. This is the theme of Sachs (1999, 2000).

More generally, for the economics profession, the need to integrate ecological and economic perspectives will only grow in the future. As everyone increasingly appreciates, the very success of economic development and the attendant growth in the human population, are now putting unprecedented stress on the ecosystem at all scales – local, regional, continental, and global. Some of the greatest challenges in the future will involve a reorganization of economic activities to support ecological functions, whether that is replenishment of soil nutrients and water aquifers, or reforestation of watersheds now afflicted by massive erosion and flooding; or protection of disappearing species; or adjustments to and mitigation of anthropogenic climate change. Many studies, moreover, suggest that it is precisely the poorest countries – with the largest populations living off the land, with the most rapid rates of population growth, and with

the special vulnerabilities of tropical ecosystems – that are the most vulnerable to environmental degradation and long-term climate change. I hope that our profession can join hands with the ecologists, demographers, and geographers, to enrich our understanding of these critical issues.

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Table 1: 1995 GNP per capita

Climate zone	GNP per capita		
	Near	Far	Total
Af	0.66	0.54	0.64
Am	0.41	0.30	0.41
Aw	0.39	0.36	0.38
Cw	0.54	0.37	0.44
BS	0.80	0.49	0.55
BW	0.65	0.54	0.58
H	1.01	0.75	0.78
Cf	2.42	1.63	2.24
Cs	2.22	1.51	2.10
Df	2.67	1.22	1.90
DW	0.92	0.53	0.64
Tropical[1]	0.48	0.37	0.43
Non-temperate[2]	0.54	0.48	0.50
Temperate[3]	2.32	1.18	1.94
Total	1.35	0.65	

1) Tropical = Af, Am, Aw, and Cw
2) Non-temperate = Tropical + BS, BW, H and E
3) Temperate = Cf,Cs, Df, & DW

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Table 2. Long-term Growth of Temperate and Non-Temperate Regions, Maddison Data

GDP per capita, 1990 International Dollars

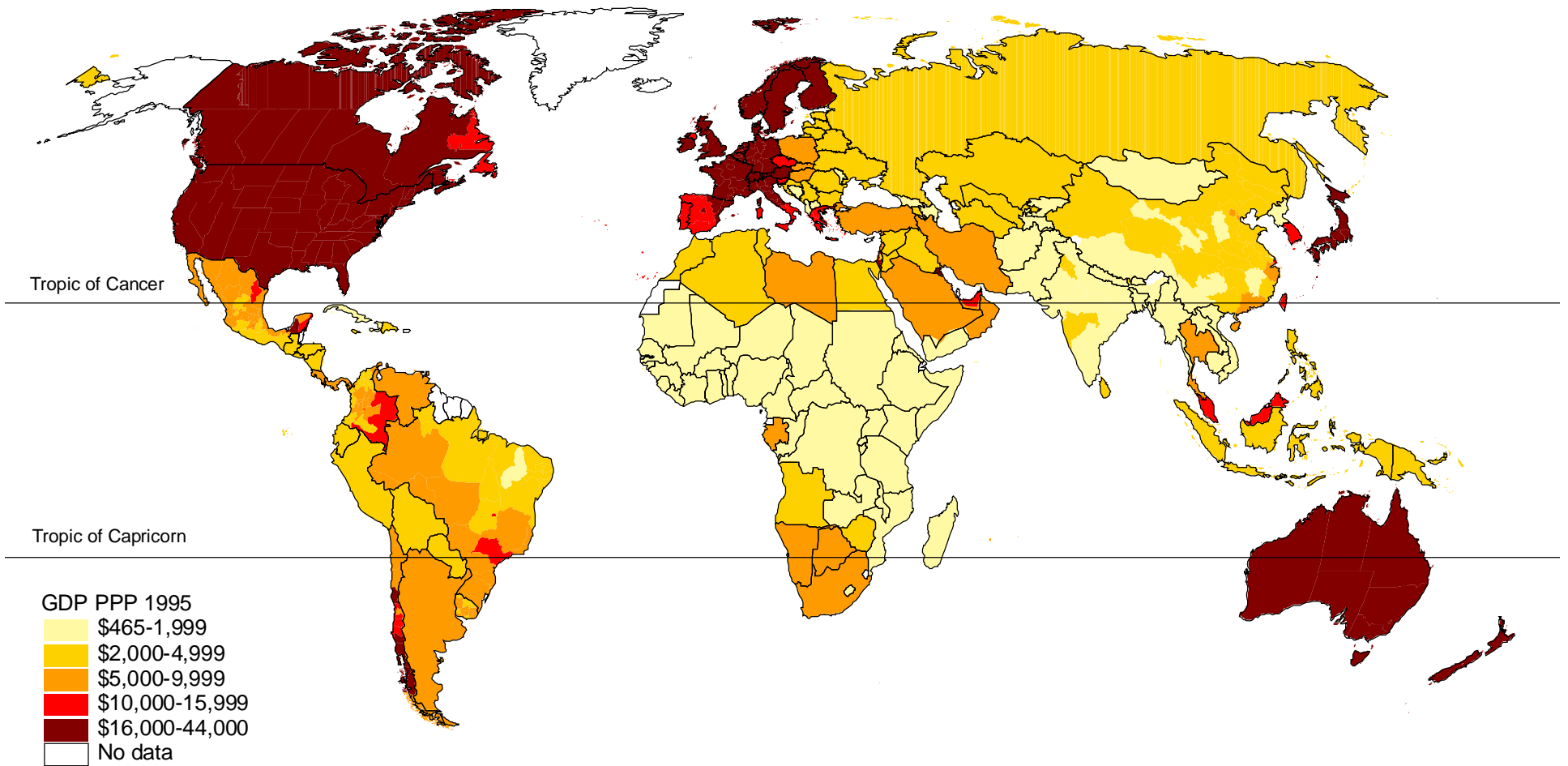|	1820	1992	Average Annual Growth, 1820-1992 (%)
Temperate	794	10,095	1.4
Non-Temperate	543	2,556	0.9
Ratio of Temperate/Non-Temperate	0.68	0.25	

Source: Based on Maddison (1995). The Temperate Region is taken to be Western Europe, the Western Offshoots, Southern Europe, Eastern Europe, Japan and half of China. The Non-Temperate Region is the rest of the world. We assume that half of China's population is in the temperate zone both in 1820 and 1992, and that the per capita income in both zones of China are equal to the overall country average. Data are from Tables G-1, G-2, and G-3 for Europe, Western Offshoots and the World; and A-3a, C-16a, and D-1a for Japan; and A-3e, C-16e, and D-1e for China.

Table 3. Shares of Tropics in World Population, GDP, and U.S. Patents in 1995

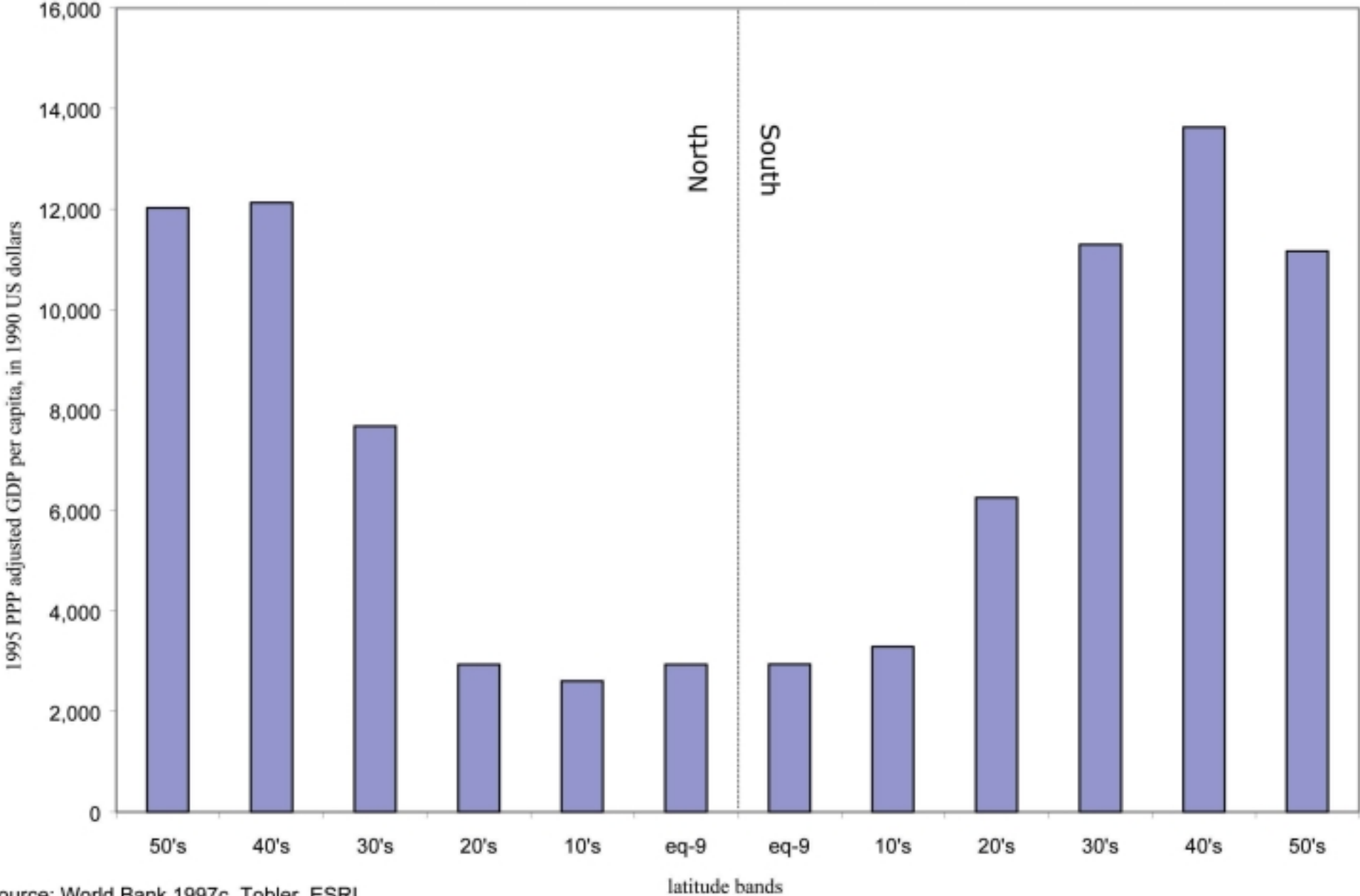|	Population (millions)	GDP (billions)	Patents issued, 1995
Tropics	2,019	5,893	1,880
World	5,653	34,519	101,330
Tropics (% of world)	35.7%	17.1%	1.9%

Source: Tropical population is the number of individuals living with the tropical climate zones. GDP is allocated to climate zones by assuming that GDP per capita is identical for all individuals within a country. Thus, the "Tropical GDP" of a country is calculated as the proportion of the population within the tropical climate zones in the country, multiplied by the aggregate GDP of the country in 1995 (PPP adjusted). "Tropical patents" are calculated as follows. The U.S. Patent Office reports patents by country according to the residence of the lead inventor. I then count as "tropical patents" in a country as the number of patents of the country multiplied by the proportion of the population within the country living in tropical climate zones.

Figure 1. Income per person, 1995 (with sub-national data for 19 countries)

Tropic of Cancer

Tropic of Capricorn

GDP PPP 1995

	$465-1,999
	$2,000-4,999
	$5,000-9,999
	$10,000-15,999
	$16,000-44,000
	No data

Note: GDP PPP = 1995 Gross Domestic Product per person in purchasing power parity international dollars.

Figure 2. GDP per capita by Latitude

Source: World Bank 1997c, Tobler, ESRI

Figure 3. Koeppen-Geiger climate zones

Tropic of Cancer

Tropic of Capricorn

Climate zones
- Tropical-subtropical (Af, Am, Aw and Cw)
- Desert-steppe (BS and BW)
- Highland (H)
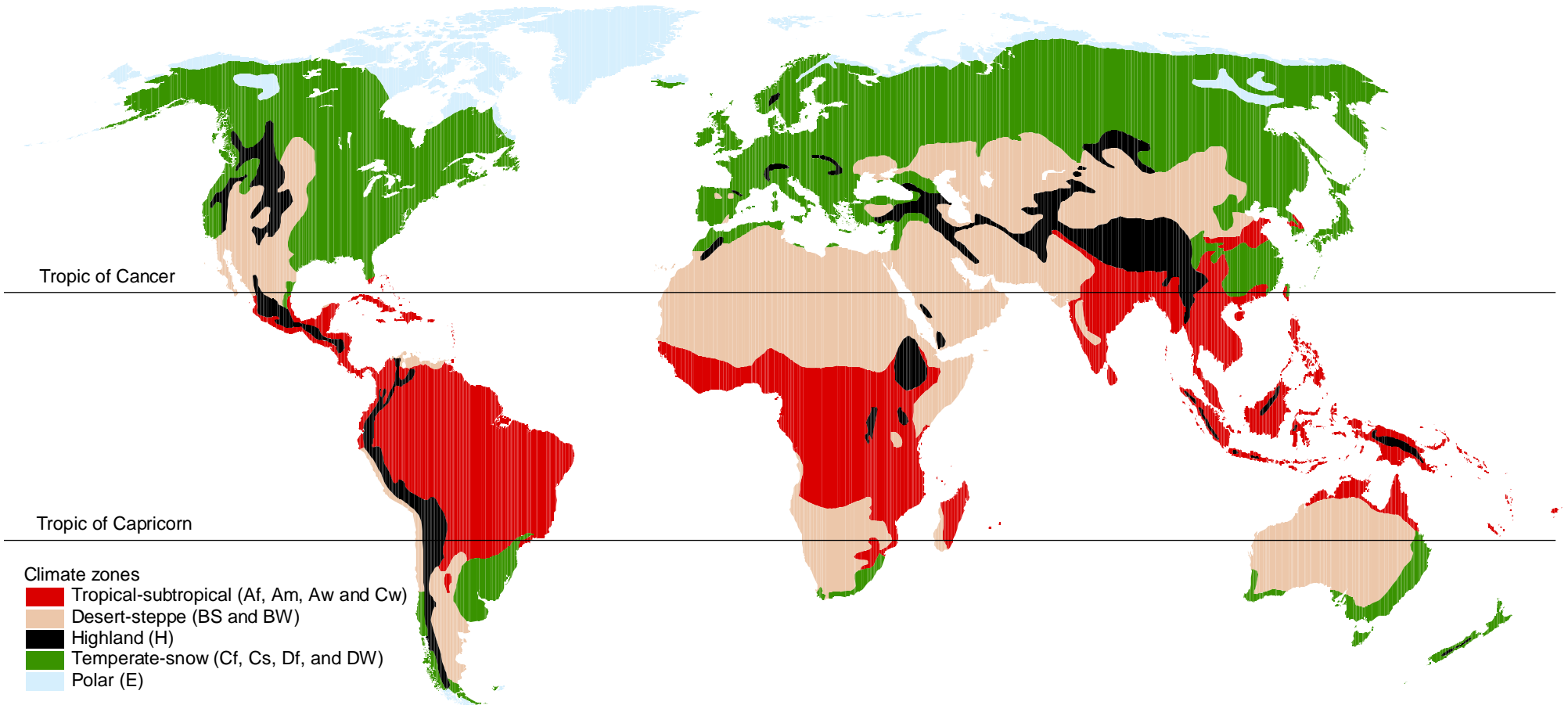- Temperate-snow (Cf, Cs, Df, and DW)
- Polar (E)

Figure 4. GDP-PPP 1995 in temperate climate zones 0-100 km from the coast and sea-navigable rivers

Tropic of Cancer

Tropic of Capricorn

GDP per sq km
- $ 0~8,099
- $ 8,100~59,999
- $ 60,000~162,999
- $ 163,000~441,999
- $ 442,000~546,000,000