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TECHNOLOGY AND GLOBAL CHANGE: LAND-USE, PAST AND PRESENT

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1. Introduction

The history of land-use changes is first of all a history of the expansion of arable land areas by large-scale conversion of natural into managed ecosystems. The extent, type and rate of this transformation throughout the world is driven by numerous variables including: population growth, changes in level and structure of food consumption, the productivity of national systems of agriculture, and the international division of agricultural production (e.g., export crop production). Throughout human history population increases could only be sustained by improvements of two factors: namely, enlarging the land areas devoted to agriculture and/or increasing the agricultural productivity per unit land area. Today, the expansion of arable land areas is most visible in some areas of the developing world (see Figure 1 from Marland 1989:205). However, similar patterns of land-use change occurred in the northern hemisphere many decades to centuries ago. Land transformations are therefore not new. What is new however is that the forces of change are far more powerful than in the past, as reflected in the sheer size of increases in the absolute number of people inhabiting planet Earth.

This paper addresses the role of technology (or better: of technological change) in this transformation process. The role of technology in changing land-use patterns is usually associated with images of land areas covered by human artifacts like infrastructures, skylines of city centers and sprawling suburbs. The global quantitative picture however contradicts such conceptions. Although detailed statistics are lacking, the area covered by artifacts of our technological civilization most likely cover less than one percent of the Earth's land area.* In contrast, the areas used for agriculture and pasture cover close to 40 percent of the global land area (FAO 1991:47).

The role of technology has therefore first of all to be discussed in its relationship to agriculture, in particular to increases in the productivity of land and labor. The productivity of land determines the land requirements of a given population.

* We use a value of 250 m^2 per capita for the land devoted to building areas (of course not all of them actually covered by buildings) and infrastructures, a value typical for the most densely populated countries like Japan and the Netherlands. As most regions of the world have a significantly lower population density, the actual percentage of land areas covered by human artifacts will be significantly below one percent of the Earth's land areas.

The productivity of labor determines the percentage of this population that is required to cultivate the land. As we will show later, technological change has dramatically raised agricultural labor productivity and noticeably improved agricultural land productivity. The technologies we use, and the pace by which they change therefore matter. Technology is important not only for affecting the amount of land required to feed people, but even more so for enabling ever increasing fractions of the population to engage in economic activities outside agriculture and living outside rural (i.e., in urban) areas.

1.1. What is Technology?

Before however discussing some quantitative relations between technology and land-use changes we ask the question, *what is technology?* We define technology along a conceptual continuum, in fact, along a hierarchical, i.e., a "boxes-within-boxes" (Simon 1988:10) kind of structure. Moving from single artifacts to more complex systems, technology progressively encompasses, in addition to artifacts, the related knowledge base and organizational and institutional settings which steer the development, widespread diffusion, and different ways of use of artifacts. In this larger sense technology refers to whole *socio-technical systems of production and use* (Kline 1985:2–4) which enable humans to extend their capabilities and to accomplish tasks which they could not perform otherwise.

In the most narrow terms, technology is represented by man-made objects, like manufactured articles, frequently referred to by engineers as "hardware" and by anthropologists as "artifacts". However, this is a limited view. In fact artifacts have to be produced (invented, designed and manufactured). This requires a larger configuration (system): hardware (e.g., machinery, a manufacturing plant), factor inputs (labor, energy, raw materials and other resources) and finally "software" (know-how, human knowledge and skills). The latter term (for which the French use the word *technique*) represents the disembodied nature of technology: the information, skills, procedures (organization) which are required to produce any artifact. In economics this disembodied nature of technology is referred to as knowledge base. Technological change thus not only entails the creation of new artifacts and/or the replacement of old ones, but also involves changes in the related knowledge base. Finally, *technique* is not only required for the production of given artifacts but also for their use (e.g., the *technique* of driving a car or using a bank account), both at the level of the individual and at the level of a whole society. Forms of organization (like the existence of markets), institutions, social attitudes and beliefs are important to understand how systems of production and use of artifacts emerge and function. They are also important determinants for the origin and choice (selection) mechanisms of particular (combinations of) artifacts and the rate by which these become incorporated (or not incorporated) into a given socio-economic system, i.e., the process of their *diffusion*.

Thus, in this paper the term technology is interpreted in a larger context: comprising not only man-made *artifacts*, (scientific) knowledge, know-how, and skills necessary for their inception, production and use (*technical knowledge bases*), but also a larger set of (evolving) *social and organizational know-how and techniques.* It is this larger socio-economic context in which technologies are embedded, and which directs the inception and diffusion of individual or whole clusters of artifacts.

From a historical perspective we can conclude that the process of development, stimulated by changing structures of economic activities and technological change, in particular periods tended to cluster around (interrelated) sets of artifacts, *techniques,* and organizational/institutional configurations. These mutually interdependent and cross-enhancing socio-technical systems of production and use cannot be analyzed from the perspective of single technologies, but have to be considered in relation to many other processes of technological, institutional and social change. Using the concept of "techno-economic paradigms" we will discuss below various clusters of "technologies" (in above larger definition), and their relationship to technological change in agriculture. We then try to relate these technological developments to land-use changes since the beginning of the 18th century.

1.2. Technological Change: Concepts and Theories

There is no universally accepted theory of technological change, and even less so a theory of technology–environment interactions with special reference to land-use changes. On a general level, one might consider that not only type and scale of environmental impacts but also their perception as ultimate constraints for future development and the preparedness and capacity for mitigation measures are not independent from technology. Thus, environmental consciousness itself may grow with higher levels of technological capability and affluence, and the factors that lead to technological sophistication may ultimately also lead to environmental sophistication. The latter is interpreted here not so much as conservation of environmental resources, but as their comprehensive management, extending far beyond traditional end-of-pipe clean-up and repair mechanisms.

A first necessary step to improve the environmental compatibility of human activities is thus the comprehensive accounting of hitherto neglected environmental "externalities". Amongst others, concepts like *industrial metabolism* (Ayres 1989:23–49) have been proposed to comprehensively account the material and energy flows of industrial activities. However, technology–environment interactions should be described as static (e.g., in the frequently used form of fixed emission coefficients associated with particular industrial activities). Environmental impacts may also be alleviated through the deployment of new technologies, the introduction of which depends on both the level of technological competence (research and development capabilities) and appropriate policies for their diffusion. This two-faced aspect of technology-environmental interlinkages has been referred to as the "paradox of technology" (Gray 1989:192–204), which describes technology both as a source and a possibly remedy to environmental disruption. Thus, technology-environment interactions, especially from a historical and long-term perspective, can only be captured once we recognize technology as dynamic, constantly reshaped by a changing economic and social environment into which it is embedded.

Another theoretical approach that may be useful in describing the interface between technology and land-use changes, especially in agriculture, comes from economics. Using a production function approach (i.e., explaining the output of a particular economic activity in terms of required factor inputs such as labor, capital, land, etc.) the impact of technology can be represented in both an indirect and a direct way.

The indirect way would attribute output differentials which cannot be explained by differences in factor inputs (i.e., the unexplained residual of a production function after accounting for traditional factor inputs) to technology (hardware and software). For instance, Gaspari and Millendorfer 1976:175–187 develop a generalized production function explaining different overall macro-economic productivity levels by different endowments and usage of traditional factor inputs. They then attribute remaining productivity differences to variations in technology coefficients (i.e., levels of technological capability), which are found to vary significantly among different socio-cultural settings.

A more direct way to incorporate technology would include technological factors as direct inputs in a more disaggregated production function. Here, in addition to land, labor and capital, also fertilizer, machinery, qualifications of the workforce, etc. are considered to explain agricultural output, or changes in agricultural productivity. Technological change influences (lowers) in such a model either the input coefficients of the production function (i.e., increases factor productivity). Alternatively, technological change could result in a shift of the production function altogether, resulting in a radical new combination of factor inputs, or a "quantum leap" in the output frontier, i.e., the maximum output attainable with optimal use of a given set of available factor inputs. The usefulness of such an approach for the analysis of agricultural productivity changes was demonstrated by Hayami and Ruttan 1985:117–160, although data limitations do not allow use of such a detailed approach over the spatial and temporal coverage considered here. Although this methodological approach allows assessment of the direct impacts of technology on productivity, it is necessarily limited to a more restricted definition of technology. Interdependencies between technologies, and between technologies and *techniques*, (i.e., efficiency in technology application) are difficult to capture in production function models. For instance, the impact of fertilizers on agricultural productivity depends on the availability of high yield crops, availability of transport infrastructures, level of mechanization, etc.

Another aspect of technology is exogenous to production function models: the origin and selection mechanisms of the particular technologies represented. There is a decades long debate on what are the drivers of the inception of technologies, and what are the mechanisms of selection among the usually large number of competing alternatives to fulfill a particular task in the early phases of technology evolution. Theories range at the extreme views that technologies are developed either out of need or out of opportunity (i.e., what in economics is referred to as demand-pull versus technology-push hypothesis), and that the selection mechanisms operate either subject to some optimality criteria or subject to stochastic processes (i.e., emerge out of the cumulativeness of many small random events). Both theoretical and empirical approaches have been developed to corroborate either hypothesis and further discussion of this important aspect is beyond the scope of this paper. What is however important for the present discussion is to emphasize the heterogeneity among technological options, their assessment (criteria) by economic agents, and in their appropriability conditions, which emerges from both theoretical and empirical research streams on this issue. Technologies, their selection criteria and adoption environments thus differ in space and time. This heterogeneity and diversity in the early phases of technology development appears almost as a prerequisite for the longer-term viability of technologies. Limited variance in technological options (and resulting experimentation) can lead to limited success (e.g., nuclear energy) or to complete failure (e.g., zeppelins).

Here we follow a more inductive approach without any particular strong theory bias, concentrating on a quantitative account of changes in agricultural land and labor productivity (without however, attempting a formalization along the lines of a production function approach). These changes in agricultural productivity are then related to a qualitative discussion of important technological transformations. Some illustrative examples of technological change particularly in agriculture will be discussed also in quantitative terms, without however implying that agricultural productivity changes can be reduced to the diffusion of individual technologies in the sense of singular artifacts. Instead, we use these examples rather as indicators of larger systems of technology consisting of whole clusters of interrelated artifacts, and institutional and organizational innovations.

The inductive approach adopted aims in particular to preserve potential "surprises" that the data may contain, as reflected for instance in the long-term stability of some of the structural transition paths identified, their historical path dependency (Arthur 1988:592–599) between different regions as a result of different resource endowments (e.g., the relative availability of land versus labor in agriculture), as well as socio-cultural differences (for instance, dietary differences), and the resulting only conditional convergence at the international level. Such stable transition paths appear sustained rather than broken-up by the succession of various technological clusters over time, but can for the time being not be explained through a formal theoretical model of technological change and its relationship to long-term economic growth and changes in land use.

1.3. Technology and Land-use Changes

How does technological change in form of the succession of various techno-economic clusters identified in our analysis relate to changes in land-use patterns?

First, technological change led to far-reaching transformations in agriculture through increases in land productivity (i.e., "decoupling" the expansion of agricultural areas from population growth) and increases in labor productivity (i.e., freeing people for other economic activities and enabling urbanization).

Second, in particular the successive "transport revolutions" increased the spatial division of labor, enabled the expansion of large-scale export-oriented production and trade and the increasing population concentration in urban areas. Perhaps the most pervasive changes brought about by the Industrial Revolution are a result of the large-scale development of transportation systems of increasing spatial density and productivity allowing to cover ever larger distances (Figure 2) at lower costs.

Third, new transport technologies increased the physical access to land and its use in a geographical sense. Distance can be expressed as physical distance, or measured in hours of travel time (functional distance). New transport technologies *reduced distance* and connected ever larger territories into functionally interconnected systems. This is perhaps best illustrated by the fact that even agriculture today operates as a world-system.

Throughout history, the technological level and the dynamics of its change have and continue to be spatially heterogeneous. In fact, it is only over the last 50 years that technologies have become truly global. And it is also only during this time that agricultural land productivity increases have outpaced the rate of population growth. If the world's population in 1980 would have been supplied by the same productivity levels as prevailed in 1950, the arable land area would have been 500 million ha above the actual value of around 1500 million ha in 1980. It is our contention that the key factor of such developments is technological change. However, the nature of technological change as a process of cumulativeness and historical path dependency requires that we look back to the origins of a series of technological transformations: the Industrial Revolution.

2. Technological Clusters Since the Industrial Revolution

In the 18th century, a series of innovations (most notably the spinning jenny, the flying shuttle and the power loom) transformed the manufacture of cotton in England and gave rise to what eventually became a new mode of production: the factory system. Innovations in the fields of energy (stationary steam engines) and metallurgy (replacement of charcoal by coal in the iron industry) were of a similar revolutionary character, and all these, mutually reinforcing one another, drove an industrial revolution in Britain, making her the world's leading industrial and economic power well into the late 19th century. Technology embodied in machinery, leading to new forms of production, products and markets has been, as Mokyr (1990) says, "the lever of riches".

It is beyond the scope of this paper to list, let alone to discuss, the large number of innovations involved in the take-off of the Industrial Revolution. Landes 1969:41 summarizes them under three principles: the substitution of machines for human effort and skill; the substitution of fossil fuels (coal) for animate power opening for the first time in human history the possibility of unprecedented consumption density and almost unlimited supply of energy; and the use of new (and more abundant) raw materials in manufacturing. These three principles not only apply to the onset of the Industrial Revolution, but also to later stages in the industrialization process. Today, they also apply to the modernization and economic growth in developing countries.

Important technological innovations can also be identified in earlier periods of human history. The special characteristics of the Industrial Revolution is the bundling and mutual cross-enhancing of many individual innovations, and their embedding in profound transformations of the social and organizational fabric of society. The steam engine, the coal industry, railroads, and new steel production processes cannot in fact be considered separately: they depended on each other, enhanced each other and together via a multitude, of what in economics is referred to as forward and backward linkages, contributed to economic growth. The same can be said about the internal combustion engine, the oil and petrochemical industries, synthetic fibers and plastics to name just a few areas associated with the post WW II period of economic growth.

Of equal importance were and are social and organizational changes which span the whole domain from the generation of (scientific) knowledge, its systematic deployment in the innovation process, incentives for innovation diffusion, new modes of production, enterprises, organization of market relations, and so on. In their analysis of "how the West grew rich", Rosenberg and Birdzell (1986) emphasize therefore the decisive role of new institutional arrangements such as the early separation of the political and economic spheres.

Cameron 1989:163–182 cautions against the terminology of an "Industrial Revolution" with its implicit concept of a pronounced discontinuity and emphasis on industrial technology and innovation. He emphasizes that changes were not only industrial, but also social and intellectual, commercial, financial, agricultural and even political. In this "seamless web" of historical change it is difficult to assign relative weights to different factors, or to ignore the importance of earlier developments of proto-industrial economies as driving forces and causes of change. Perhaps the intellectual and institutional/organizational changes were the most fundamental, in that they provided an environment favorable for systematic experimentation (creation) and commercial application (diffusion) of innovations. In this sense, changes in the social context may be seen as the fundamental driving force of change, as permitting and encouraging changes in the fields of industrial technology, products, markets, infrastructures, etc.

From such a perspective, a central characteristic of the period of economic expansion since the 18th century is the "bundling" of whole clusters of technological and organizational innovations. Thus, the impact (e.g., on GDP growth) of any individual technological innovation, as important in its own merits it may be (such as the railways of the 19th century), is necessarily limited. Instead, it is the synergistic interlinkages with other technological and organizational innovations that have resulted in the profound transformations of economic, employment and social structures over the last 300 years.

Freeman and Perez 1988:38–66 refer to such clusters of interrelated technological, institutional and organizational innovations as "techno-economic paradigms". *Table 1* illustrates five such technological clusters. It gives the dominant techno-economic systems for each epoch in the top row, and the emerging ones in the middle row. The last row summarizes the predominant organizational and management models during the respective periods.

Table 1. Clusters of Pervasive Technologies.

1750–1820	1800–1870	1850–1940	1920–2000	1980–
Dominant Systems:				
Water Power, sails, turnpikes, iron castings, textiles	Coal, canals, iron, steam power, mechanical equipment	Railways, steam ships, heavy industry, steel, coal chemicals, telegraph, urban infra.	Electricity, oil, cars,roads telephone, radio, TV, durables, petrochemicals	Gas, nuclear, aircraft, telecomm., information, photo-electronics
Emerging Systems:				
Mechanical equipment, coal, stationary steam canals	Steel, city gas, coal chemicals, telegraph, railways, urban infra.	Electricity, cars, trucks, roads, radio, telephone, oil, petrochemicals	Nuclear power, computers, gas, telecommunication, aircraft	Biotech., artificial intelligence, space industry & transport
Organizational Style:				
Manufacture	Factory system	Standardization	Fordism-Taylorism	Quality control

The list of clusters in *Table 1* is of course not exhaustive, and also the timing is necessarily approximate. However, it provides an account of important clusters of pervasive technologies and infrastructures and their changes, which are to a large extent drivers of the history of economic growth, the spatial division of labor, changes in employment, and to some extent also of the environmental impacts associated with the development of particular technological regimes.

From a historical perspective, we can conclude that the development (diffusion) of such technology clusters is an international phenomenon, but with great spatial disparities. The development of particular systems is initiated in a number of core countries, from which they spread out further via a series of spatial hierarchies to (spatially or economically) peripheral areas (Figure 3). Also adoption starts much later, the latter tend to "catch up" with the core countries, albeit at significantly lower levels of adoption intensity.

For instance, the construction of the railway networks of England and the USA spans a period of 100 years (1830–1930), whereas it took typically only half that time in Scandinavia (1870–1930). Railway networks were also most extensive (in either per capita or unit land area terms) in the countries (England and the USA) that were leading the introduction of this technology than in follower countries (Figure 4). Altogether, the core areas of railway development (England, Europe, and the United States) had constructed about 60 percent of the 1.3 million km railway network worldwide by 1930 (*Table 2*).

Table 2. The Growth of Railway Networks (km).

Country	Introduction Year	Length by 1870 1000 km	Maximum Length Achieved 1000 km	Maximum Length year[1)]	Density[2)] Length in 1923 per 100 km^2	per 10,000 Inhabitants
Austria-Hungary	1837	6.1	23.0*	1913*	8.0	10.2
France	1828	15.5	42.6	1933	9.7	13.7
Germany	1835	21.5	63.4*	1913*	12.2	9.6
Russia	1845	10.7	70.2*	1913*	0.3–1.5	4.8–8.4
USSR	–	–	145.6	1986	0.7	5.5
UK	1825	21.6	32.8	1928	16.0	8.8
USA	1829	85.0	482.7	1929	4.3	38.1
Core Countries	–	160.4	715.0		2.0	16.7
Rest of the World	–	69.5	540.0		0.6	3.7
WORLD	–	221.9	1255.0	1930	1.0	6.7

* Important territorial changes thereafter.

1) Data source: Mitchell 1980:609–616, and Mothes 1950:85–104.

2) Density as calculated by Woytinsky 1927:38–39, except Russia and the USSR (own calculation). Range of figures for Russia corresponds to total density and the European part of the territory respectively. Density figures for USSR are for the 1986 network size.

The length of the world railway network has not increased since. Net additions to the railway network (primarily in developing countries) have been balanced by decommissioning* of railway lines (due to the development of newer transport systems) in the core countries. This implies that the pervasive development of particular infrastructures and technologies is *time dependent*. High application densities as realized in the leading countries are unlikely to be repeated by follower countries at later periods in history. From this perspective, the present different settlement patterns, road densities and high car ownership rates in the USA are not necessarily a guide for future developments in other countries. By 1930, over 20 million cars were registered in the USA (close to 90 percent of the global car population), which corresponds to a car ownership rate of about 200 cars per 1000 inhabitants. This compares to a present value in Japan of 240 cars per 1000.

In dealing with individual countries there is a large heterogeneity in adoption levels of technologies. The leading countries in the introduction of particular systems achieve the highest intensities, while "laggards" often shift to newer "techno-economic paradigms" before high adoption levels are realized. This means that the application of individual technologies has a different history depending on whether leading or lagging countries are considered. At the world level, however,

* Examples of infrastructure decay processes can be found in some sectors such as transport (canals, railways) and telecommunication (telegraph), whereas in other sectors (e.g., urban infrastructures) older system may be continually upgraded and used.

there is a broad succession from older to newer "techno-economic paradigms" as illustrated in *Table 1*.

Let us take the development of transport systems as an example of this historical process of technological transitions: from canals to railways, to roads, and finally to airways (cf. Figure 2 above). The spread of these transport systems was pervasive in the sense that they were and are important to all branches of the economy and to nearly every aspect of daily life. In this sense transport (like energy) systems can serve as an "indicator" of the whole techno-economic cluster they are associated with. Furthermore, one can easily identify the leading countries where the spread of each respective techno-economic cluster was most important, e.g., for the period up to 1820, England (early canal development); for the period 1820–1870, England, France and the USA (pervasive canal construction, and beginning of railway development); for the period 1870–1930, the European countries and the USA (pervasive railway development); and finally for the period up to the present the pervasive spread of road infrastructures and of the internal combustion engine in the OECD countries (cars), and in the USSR and many developing countries (buses). As shown below (Figure 22), the dominance of a particular country or group of countries in the development and resulting application intensity of each of these successive transportation systems is mirrored also in their respective intensity of urbanization.

The transition from one cluster to the next can be identified through pronounced discontinuities in the social and economic spheres: increased price volatility, mergers and bankruptcies, and the large-scale disinvestment away from old technologies and infrastructures. The transition, although disruptive, becomes necessary when the dominant cluster starts portraying decreasing marginal returns, generally decreasing improvement possibilities and increasing awareness of adverse social and environmental impacts associated with further expansion. Its further intensification in the leading countries and diffusion to peripheral regions becomes blocked. For the latter, opportunities open in such transitional phases for the introduction of new systems and technologies (Grübler and Nowotny, 1990). On the other hand, countries with pervasive adoption of the previous cluster face considerable transition problems due to the heavy commitments of capital stock and human resources in the previous techno-economic cluster. Thus, frequently, the transition from one cluster to another also changes the "club" of leading countries.

3. Impacts on Agriculture and Rural and Urban Populations

3.1. Agricultural Land and Labor Productivity Increases

Let us now examine the impacts of the successive techno-economic clusters on agriculture. Figure 5 presents estimates of agricultural land productivity in terms of the number of the population of a given region divided by the cropland area. The land-use estimates underlying Figure 5 (Richards 1990:164) are only first order approximations. Differences in land productivity reflect different agricultural systems and differences in the stages of agricultural development which can even be observed today. More than 200 million people still apply the simplest mode of agricultural production (shifting cultivation) with land requirements of between 15–20 ha for feeding one person. On the other extreme there are areas where three crops per year are grown and less than one-twentieth of a hectare produces enough food for one person (Buringh and Dudal 1987:12). Therefore, the regional aggregates of Figure 5 mask persistent differences between and within particular regions. For instance, the land productivity figures of Japan* are significantly higher than the Asian average over the whole time period considered. In a similar way, the land productivity figures for France* are below the European average throughout the period considered in Figure 5 (cf. also Figure 7 below). Our crude productivity measure also does not include the recently significant inter-regional trade in agricultural products which would increase the land productivity figures of net export regions (cf. Figure 6 below).

Still, Figure 5 illustrates clearly the spatial heterogeneity in agricultural land productivity and its evolution since the 18th century. Differences in initial conditions, development paths pursued, in the mix of agricultural products produced, and dietary differences explain much of the large discrepancies in agricultural land productivity such as between "rice" and "grain" (and meat) oriented agricultural systems. With the exception of modest productivity increases in Europe and perhaps South America (where data are much less certain), agricultural land productivity did not increase in the 18th and 19th century, which implies that over this time period there is a direct one to one correlation between population increases and land-use changes towards agricultural land. Increases in agricultural land productivity become noticeable in Europe by the second half of the 19th century, and in all other regions by the second half of the 20th century primarily in conjunction with the introduction of man-made fertilizers and the diffusion of high yield crops.

In contrast, agricultural labor productivity measured in total population per head of the agricultural workforce (Figure 6) has increased continuously since the onset of the Industrial Revolution (note in particular the semi-logarithmic scale of Figure 6). These developments took place first in England, but the other industrialized countries (with the exception of France) followed in the 19th century. Considering the significant export of agricultural products, e.g., in the USA, labor productivity is even higher (as indicated by the alternative data series for the USA in Figure 6). Similar more recent transformations in the employment structure in the 20th century such as in the USSR and Japan were achieved at an even faster pace, so the overall trend is one of convergence in the employment structure with only a few percent of the active population employed in the agricultural sector.*

* Land productivity figures for Japan exceeded 8 people per ha arable land already in the 18th and 19th century and currently exceed 20 people/ha (Grigg 1980:265). Values for France did not exceed 1.5 people per ha cultivated land (excluding pastures) throughout the 18th century and well into the 1920s (Grigg 1980:198–203) compared to values between 3 and 4 for England and Wales over the same time period (Grigg 1980:165–177).

* This is of course partly also a definitional question. Many activities, previously performed in the agricultural sector, now employ people in the industrial and service sector. Hence, the percentage of the workforce for all food-related activities (farming, production of tractors, food processing and distribution, etc.) is significantly above the few percent of the workforce that remained on the farms.

In many developing countries such as China and India, about 70 percent of the workforce is still employed in agriculture, but similar structural shifts are very likely to occur in the future. The experience from the developed countries and their temporal variation (i.e., acceleration of rates of change over time) can serve as a guide to derive scenarios about the future pace of this structural transition in developing countries.

Above outlined tendencies in increases in agricultural land and labor productivity since 1700 are corroborated by shorter-term analysis of agricultural productivity increases from Hayami and Ruttan 1985:121–131 (Figure 7). Shorter, linear vectors indicate the changes in agricultural land and labor productivity (constant monetary output per unit factor input) between 1960 and 1980. For the USA, Denmark, France and Japan also longer-term productivity trajectories between 1880 and 1980 are given. Values in parenthesis refer to the percent of the work force employed outside agriculture and thus mirror the impact of improvements in agricultural labor productivity on structural changes in employment. Hayami and Ruttan 1985:124 identify three clusters of productivity increase trajectories: an "Asian", "European" and "New Continental" path respectively which are related to the relative endowment (or scarcity) of land and labor with initial starting values around 1,000, 10,000 and 100,000 ha per agricultural worker respectively. Thus, initial conditions and specific development paths followed as a result of regional variations determine the extent and type of agricultural productivity changes and concomittant changes in land-use patterns. Figure 7 therefore provides yet another illustration of the concept of historical path dependency (Arthur 1988:85–97) developed within the framework of evolutionary models in economics.

3.1.1. The importance of initial conditions

To understand the large differences in agricultural land productivity prevailing prior to the Industrial Revolution between Asia and Europe a longer historical perspective is useful. By 1100, China had an estimated population of about 100 million people, i.e., a population density of about 25 inhabitants per km^2, a value reached in Europe only some 600 years later.

Conversely, Europe's population in the 11th century was about 30 million (McEvedy and Jones 1978:19), or less than 7 people per km^2. Agriculture was practised with long fallow periods and a corresponding low level of agricultural productivity. Typically, fields did not yield more than 3 to 5 (in exceptional harvests 6 to 7) times the seed sown (Slicher van Bath 1963:15).

Europe's population increased by over a factor of 3 to about 100 million with a population density of about 20 inhabitants per km^2 by the end of the 17th century. This expansion of both population and agriculture was however far from a smooth continuous process. Due to plagues and wars fluctuations in population levels resulted in many ups and downs of agricultural output and land use (Abel, 1980). Overall, the population increase, together with the emergence of the medieval city and an urban bourgeoisie was made possible by a large number of innovations in agriculture, transportation and energy.

Although these innovations reduced physical toil and improved labor productivity, yields per unit of arable land remained modest. However, population densities were low and large virgin forest areas constituted *the* resource for increases in agricultural output. Consequently, expanding populations caused large-scale conversion from forests to agricultural areas between the 11th and 15th century in Europe. These were the result of both inward colonization (as the case in France, or England) as well as outwards colonization (as the case in Germany). Figure 8 illustrates this eastward move in the German settlement areas especially between the 11th and the 14th century into low population density areas inhabited by Slavic peoples. Agricultural settlements on cleared forest areas can be recognized even today in many parts of Europe by particular settlement and land-use patterns (for instance by the "Waldhufenflur" in Germany and Austria, cf. Figure 9 below).

The shaded areas in Figure 8 indicate remaining virgin forest areas and swamps by 1400, illustrating that with the exception of the Carpathian and higher altitude alpine areas, the forests in Sweden and Lithuania, and the Pripjet swamps, much of the original European forest cover had already disappeared by that date (cf. Figure 10 below). These large-scale transformations were only temporarily halted or reversed. Depopulated by the *Black Death* or wars large land areas and thousands of villages were abandoned (so-called "Wüstungen") in the Middle Ages (Abel 1956:52), only to be recolonized at later periods. Thus, throughout the Middle Ages and the Renaissance, the Europeans "behaved towards their forests in an eminently parasitic and extremely wasteful way" (Cipolla 1976:112). Many areas in Europe such as the *maquis* of southern France, the barren areas of Central Spain and the eroded coastlines of the Adriatic denuded by the Venetian ship-building industry are testimony of the profound changes brought about by the deforestation of Europe after the 10th century (Figure 10), which preceded similar developments in other parts of the globe at later periods or even at present (cf. Woodwell, 1990).

Despite perennial labor constraints on expansion of agricultural production, labor productivity was such that only between 10 and 20 percent of the 17th century European population could engage in activities outside agriculture. Agricultural land supported just above one person (and two draught animal*) per hectare arable land. The widespread disappearance of forests by the 17th century resulted particularly in England in "timber famines", with rapidly rising energy prices (charcoal prices tripled in the period 1630 to 1690) with many attempts to introduce substitutes (coal). Land became finally the limiting factor to population growth as exemplified in the work of Malthus with his pessimistic vision of the future that agricultural productivity increases would "fall short, beyond all comparisons, of the natural increase of population" (quoted in Glass 1953:140).

By 1600, China had a population of similar order of magnitude to Europe (about 150 million people). However, its agricultural productivity fed 15 people per hectare cultivated land, far exceeding even present European land productivity levels.

*Inventories of the 16th century in England indicate an average farm size of about 30 sown acres and an average population of 27 draught animals per farm (Langdon 1986:208).

For the purpose of analyzing land-use changes the agricultural sector of China is of special interest. Internal colonization, first to the South and later back-migration to the North (Perkins and Yusuf 1984:48) opened up additional land areas for cultivation. Nevertheless, agricultural land availability was *the* principle constraint to increases in agricultural output. As a result China developed a specific agricultural system characterized by labor-intensive, high intensity rice cultivation with corresponding high yields per hectare. In such an agricultural system not only technological innovations are of importance but also social and organizational ones. Wet field rice cultivation required sophisticated civil (terraced fields) and hydraulic engineering (dams, locks, water storages, etc.) allowing the draining and irrigation of lands. Gates, pumps, and water-raising devices (*norias*) controlled the flow of water. The scale of these water control projects required the elaborate organizational skills of a "hydraulic civilization" to use a term of Wittfogel (1957). Perkins 1969:61 reports that more than 50,000 projects can be identified in various government gazetters. Of the 5,000 water control projects, whose construction can be dated, 94 percent were constructed between the 10th and 19th century. Social organization, in conjunction with an elaborate transport system, enabled effective relief of food shortages. The related administrative techniques were written down in legal documents (cf. Yates 1990:164–165).

Agricultural technology was also important. Centuries before Europe the scratch plow was replaced by the iron plow, also adopted for wetfield rice cultivation. Seed drills for sowing and many other tools were introduced after the turn of the millennium. The use of a variety of fertilizers (urban refuse, lime, ash), of insect and pest control (e.g., the use of copper sulfates as insecticides) was widespread. Mokyr 1990:209 highlights yet another feature of Chinese agriculture: the large number of texts and handbooks published dealing with agricultural technology furthering the diffusion of advanced agricultural techniques.

Thus, by contrasting the much longer historical evolution of agricultural systems in Europe and China, their decisive different initial conditions at the onset of the Industrial Revolution can be better understood. These differences in turn determine to a large extent the differences in the development paths followed and the resulting land-use changes that went along with population growth over the last 300 years. Any analysis of the impacts of technological change on agriculture and the resulting land-use changes has therefore to differentiate between broad categories of agricultural starting conditions and subsequent development trajectories followed. "Asian", "European" and "New Continental" development paths have to be considered separately especially with respect to their different land productivity and resulting land-use patterns.

3.1.2. Technology and agricultural productivity increases

What were the technological changes responsible for the changes in agricultural labor and land productivity? We can differentiate three periods of agricultural change, each corresponding to particular combinations of factors responsible for productivity increases and to particular group of countries in which these development took place. Consistent with the larger definition of technology/*technique* introduced above we consider in addition to technological/mechanical innovations (tractors, man-made fertilizers, etc.) also biological (new crops from other continents, new high-yield varieties), and social/organizational innovations (e.g., land reforms) of importance for agricultural productivity growth.

The first phase (*"agricultural innovations"*) lasted until the second half of the 19th century and consisted of the widespread diffusion of new species and agricultural *techniques* in the form of staple foods and crops, crop rotational patterns and a host of institutional innovations affecting operational practices in agriculture. Starting in England, these innovations gradually were adopted in other European countries to a varying degree and with different rates. The second phase (*"mercantilistic agriculture"*) spans approximately the period from the mid-19th century to the 1930s. In this phase the agricultural practices and biological innovations introduced earlier in England and some European countries were introduced in other regions (e.g., in France). Industrial innovations (first mechanization, phosphate fertilizer, etc.) started to be introduced into agriculture. More important, however, were the developments in transportation technologies expanding world trade in agricultural products (food and raw materials) and enabling large-scale export-oriented crop production (grains, cotton, rubber, sugarcane, coffee, tea, etc.) for export to industrialized core regions. Finally, the third phase (*"industrialization of agriculture"*) can be characterized by the widespread application of industrial innovations in agriculture, in particular mechanization, man-made factor inputs (fertilizer), and new high-yield plant varieties developed through agricultural R&D efforts. These developments started around the turn of the century in Europe and North America, and following WW II became global phenomena. Before however discussing in more detail these three phases of technological change in agriculture and its impact on land-use changes, we summarize below some orders of magnitude of land-use and population changes for world regions over the last 300 years.

3.2. Agricultural Land-use Changes

Table 3 summarizes changes in global land use (derived from Richards 1990:164) and population (Demeny 1990:42, and McEvedy and Jones, 1978) since 1700. The data uncertain and more indicative of the direction of change than highly accurate assessments of land-use figures in particular periods.

By 1980 some 5 billion ha (38%) were covered by forests, close to 7 billion ha (51%) by grassland, and 1.5 billion ha (11%) by croplands. This presents a snapshot of a continuing long-term transformation process in land-use patterns that accompanied population growth since 1700: the large-scale conversion of forested areas to cropland. Over this period global forests decreased by close to 1.2 billion ha, with an equal expansion of cropland. Because of the preponderance of developing countries in population growth they dominate land-use transformations both in absolute and in relative (percentage) terms. Current developing countries account for three-quarters of population growth since 1700 and about the same percentage of the area deforested, and for about 60 percent of the increases in cropland area. Asia accounts for over half of the population growth in the 1700–1980 period with the share of other regions ranging between 7 and 10 percent. Deforested areas are largest in Africa and Latin America (–300 million ha) followed by Asia and the USSR & Oceania with –250 and –218 10^6 ha, respectively.

The expansion of cropland is much more evenly distributed among regions. Changes have been largest in Asia (+313 10^6 ha between 1700 and 1980), followed by Africa and the USSR & Oceania with +265 and +253 10^6 ha, respectively. Cropland areas increased by 200 10^6 ha in North America and by 135 10^6 ha in Latin America. Changes in Europe were comparatively small (+70 10^6 ha).

Table 3 illustrates significant differences between regions with respect to the impacts of population growth on agricultural land-use changes. Whereas Asia accounts for 57 percent of the population growth between 1700 to 1980, it accounts for only 25 percent of net additions to cropland areas over the same time period. On the other extreme the USSR and Oceania account for only 7 percent of world population growth but for 20 percent of net additions of cropland. In order to illustrate the different land intensiveness of the "Asian", "European" and "New Continental" development paths we use the data of *Table 3* to calculate marginal land-use changes, i.e., changes in land use per unit change of population for a number of reference periods (*Table 4*). The marginal land-use changes per capita population growth illustrate the differences in the three agricultural development paths discussed above. They serve also as reference points to quantify the impacts of technology (i.e., of agricultural land productivity increases) and the impacts of drawing particular regions into the international division of agricultural production (i.e., land-use changes due to large-scale export-oriented production).

Table 4 shows that for each individual added to the world's population since 1700, on average 3,000 m^2 forests were converted to agricultural land, almost exclusively cropland. However, there exists large temporal and spatial variation. We assume a value of about 2,000 m^2 per additional capita to be a characteristic value for an Asian-type agricultural development path. For a European-type path, we assume a marginal land-use change value of 5,000 m^2 and for a "New Continental" type agriculture a value of between 10,000 and 20,000 m^2 per capita additional population. Above values are only indicative. They serve as a reference point to estimate what the changes in arable land in different regions would have been in the absence of technological change and external trade. Values above the reference marginal land-use change figures indicate that expansion of agricultural land far exceeded population growth. For instance, the expansion of cropland largely exceeded population growth in the USSR & Oceania and in Asia in the period 1850–1920 (cf. Figure 1 above), indicating large-scale land conversion for export crop production. Latin America in the period 1920 to 1950 provides another example. Conversely, values below the reference marginal land-use change values, and especially declining values compared to previous time periods, indicate improving land productivity levels as a result of technological change. Europe since 1850, North America since 1920, and all regions after 1950 illustrate the effects of technology on agricultural land productivity, progressively decoupling land-use

Table 3. Global and Regional Land-use and Population Change (in million ha and million, positive or negative sign indicates direction of change).

	1700–1800	1800–1850	1850–1920	1920–1950	1950–1980	Total 1700–1980	% of Global Change	1980 Land Use & Population	% of World
Europe									
Forests	–15	–10	–5	–1	+13	–18	2	212	4
Grassland	–15	–25	–11	–3	+2	–52	–	138	2
Cropland	+30	+35	+15	+5	–15	+70	6	137	9
Population	+53	+63	+105	+79	+92	+392	10	484	11
N. America									
Forests	–6	–39	–27	–5	+3	–74	6	942	19
Grassland	0	–1	–103	–22	+1	–125	–	790	12
Cropland	+6	+41	+129	+27	–3	+200	16	203	14
Population	+3	+20	+89	+52	+82	+246	7	248	6
USSR & Oceania									
Forests	–29	–42	–86	–38	–23	–218	19	1187	23
Grassland	+2	+7	–12	–9	–22	–34	–	1673	25
Cropland	+27	+35	+97	+47	+47	+253	20	291	19
Population	+19	+30	+62	+50	+95	+256	7	288	7
Africa & Middle East									
Forests	–11	–15	–68	–96	–118	–308	27	1088	22
Grassland	0	+5	+23	+24	–9	+43	–	2218	33
Cropland	+11	+9	+47	+71	+127	+265	21	329	22
Population	0/+1	+4	+39	+70	+250	+364	10	470	11
L. America									
Forests	–6	–19	–51	–96	–122	–294	25	1151	23
Grassland	+2	+11	+25	+54	+67	+159	–	767	11
Cropland	+4	+7	+27	+42	+55	+135	11	142	9
Population	+9	+15	+67	+63	+200	+354	9	364	8
Asia									
Forests	–38	–20	–50	–53	–89	–250	22	473	9
Grassland	–1	–8	–11	–12	–31	–63	–	1202	18
Cropland	+38	+29	+61	+65	+120	+313	25	399	27
Population	+195	+171	+216	+372	+1190	+2144	57	2579	58
World									
Forests	–105	–145	–287	–289	–336	–1162	100	5053	100
Grassland	–12	–11	–89	+32	+8	–72	–	6788	100
Cropland	+116	+156	+376	+257	+331	+1236	100	1501	100
Population	+278	+603	+578	+686	+1909	+3755	100	4433	100

Note: Net land conversion may not add due to rounding errors.

Table 4. Land-use Change Per Capita Population Growth ($\Delta L / \Delta$ POP), ha per head additional population.

	1700–1800	1800–1850	1850–1920	1920–1950	1950–1980	1700–1980
Europe						
Forests	−0.28	−0.16	−0.05	−0.01	+0.14	−0.05
G+C*	+0.28	+0.16	+0.04	+0.03	−0.14	+0.05
Cropland	+0.57	+0.56	+0.14	+0.06	−0.16	+0.18
N. America						
Forests	−2.00	−1.95	−0.30	−0.10	+0.04	−0.30
G+C	+2.00	+2.00	+0.29	+0.10	−0.02	+0.30
Cropland	+2.00	+2.05	+1.45	+0.52	−0.04	+0.81
USSR + Oceania						
Forests	−1.53	−1.40	−1.39	−0.76	−0.24	−0.85
G+C	+1.53	+1.40	+1.37	+0.76	+0.26	+0.85
Cropland	+1.42	+1.17	+1.56	+0.94	+0.49	+0.99
Africa + ME						
Forests	(−11.00)	−3.75	−1.70	−1.37	−0.47	−0.85
G+C	(+11.00)	+3.50	+1.80	+1.36	+0.47	+0.85
Cropland	(+11.00)	+2.25	+1.20	+1.01	+0.51	+0.73
L. America						
Forests	−0.67	−1.27	−0.76	−1.52	−0.61	−0.83
G+C	+0.67	+1.27	+0.78	+1.52	+0.61	+0.83
Cropland	+0.44	+0.53	+0.40	+0.66	+0.27	+0.38
Asia						
Forests	−0.19	−0.12	−0.23	−0.14	−0.07	−0.12
G+C	+0.19	+0.12	+0.23	+0.14	+0.07	+0.12
Cropland	+0.19	+0.17	+0.28	+0.17	+0.10	+0.15
World						
Forests	−0.38	−0.24	−0.50	−0.42	−0.18	−0.31
G+C	+0.37	+0.24	+0.50	+0.42	+0.18	+0.31
Cropland	+0.42	+0.26	+0.65	+0.37	+0.17	+0.33

*Source: Table 3. G+C = grassland and cropland. Note that figures for Africa prior to 1800 are particularly uncertain.

changes from population growth, resulting eventually in back-conversion of cropland areas to grassland and especially forests.

Using *Table 4* as a yardstick we discuss below three periods of agricultural productivity increases with reference to technological change indicating also some major directions of change of land-use patterns.

3.3. Technology, Agriculture and Land-use Changes

In the following section we give an account of the successive rise of three technological clusters and of important changes in agricultural technologies and *techniques*. They influenced changes in agricultural land productivity and the spatial division of agricultural production and hence land-use patterns in different regions. As approximate timing we examine the period until the middle of the 19th century, the period from 1850–1870 until the 1930s, and finally from the 1930s to the present.

The first period (up to 1850–1870), characterized by an emerging factory system particularly in the textile industries, widespread application of stationary steam power, and the development of canals as new transport infrastructure, featured the diffusion of a host of *agricultural innovations*, mostly of a biological nature in the form of new food crops, and new cropping patterns. Resulting agricultural output and productivity increases sustained rising populations outside agricultural activities and rapid urbanization in the core regions of the industrial take-off, particularly in England.

The second period (~1850–1930) saw the rise of a technology cluster centered around heavy engineering industries (in particular steel) and new transport and communication infrastructures (railways, steam ships, telegraphs) associated with the widespread diffusion of mobile steam engines. Despite first mechanization of agriculture, changes in agricultural systems were mainly characterized by further diffusion of agricultural innovations of the previous period from industrialized core regions to the remainder of Western Europe and North America and biological innovations (new higher yield crops) outside industrialized countries. Most characteristic for this period, however, was the global spread of transport infrastructures and the resulting expansion of world trade in agricultural products both for food and industrial raw materials. Hence we refer to this period as *mercantilistic agriculture.*

Finally, the period from the 1930s until the present has been characterized by a technological cluster centered around petroleum as primary energy carrier and feedstock for industry and transportation (internal combustion engines) along with new communication systems (telephone, radio, TV). Agriculture was revolutionized by the widespread application of industrial innovations: mechanization, man-made factor inputs (fertilizer, pesticides) and resulting unprecedented increases in output and agricultural land and labor productivity. Globally land-use conversions fell significantly behind the rate of population growth and in the most developed regions agricultural land started to be reconverted to forests. This period is referred here as the age of the *industrialization of agriculture.*

3.3.1. The period of agricultural innovations

In the period before the middle of the 19th century, European agriculture was revolutionized by a combination of mostly biological innovations in form of new crops and by new farming practices. None of these innovations were entirely new as they have been used already on a smaller scale in some regions of Europe (such as the Netherlands), or imported from the Americas (corn, potatoes). New farming practices and crops were particularly vigorously introduced in England, raising agricultural labor productivity, which enabled drastic shifts in employment patterns towards newly emerging industries. Particularly important was the widescale introduction of more complex crop rotation patterns in conjunction with new fodder crops (clover, later on also lucerne). This enabled the abandonment of fallow periods and helped to overcome the hitherto limited feed supply for the animal stock (particularly during winter). Typically such a new crop rotation pattern would involve wheat, turnips, barley and clover, but more complex patterns (like the Flemish seven-course rotation) were introduced in some parts of Europe. Better knowledge and practice of animal husbandry increased the stock of animals and availability of fertilizer, later supplemented by imports of guano from Peru (since the 1820s) and later (after the 1840s) of nitrate from Chile. Grigg 1987:100 characterizes the new agricultural system as a greater integration of livestock and arable husbandry. Although the new system did not much improve overall land productivity, it enabled better utilization of fallow lands and grassland areas. Increases in cropland areas could thus draw more on fallow and grasslands. In fact, Europe appears as the only region where such conversions (of some estimated 25 10^6 ha in the period 1800–1850) took place before the middle of the 19th century, resulting also in a slow-down of the rate of deforestation.

Even more important for feeding larger populations was the introduction of new staple food crops from the Americas: corn (maize, the basis of "polenta") and the potato finally put an end to the frequent famines of Ireland, East Prussia, and some parts of southern Germany. From there the new crops spread quickly over the rest of Europe in the 19th century. Additional new crops were tobacco (although of no nutritional value) and the sugar beet. The latter was introduced after the discovery of sugar refining and the opening of the first factory in Silesia in 1801. The sugar beet experienced a particularly strong boost due to the "continental blockade" (i.e., the loss of sugar cane based imports from the Caribbean) during the Napoleonic wars.

However, it was not only the introduction of new crops and cropping patterns which was important in this time period. Organizational and institutional innovations also played a decisive role. First of all we have to mention the abandonment of peasant serfdom in Europe during the 18th century, as well as a number of land reforms (for an account of Sweden, see Anderberg 1991:403–426) and the subsequent concentration of farmlands and resulting economies of scale. New fodder crops and the abandonment of fallow lands (used previously for communal pasture) also implied important institutional changes in patterns of land rights and usage. To keep grazing animals off cropland, farmland was becoming increasingly enclosed. Between 1760 and 1840, over 6 million acres were involved in England in land redistribution in separate holdings by private "Enclosure Acts" with the total area likely being even larger (Fussel 1958:17). The first horse-powered machines (for threshing) were introduced, but faced opposition (as expressed in the violent "Captain Swing" movement in England in 1830–31*) and diffused slowly. Until the mid-19th century, progress in farming techniques took a similar form in many European countries, also with some time lags (being particularly long in France). Yields in England increased slowly from about 16 bushels per acre in the late 16th century to 20–22 bushels 200 years later (Fussel 1958:31).

Although land productivity increases were modest, the new crops and agricultural practices introduced in England progressively diffused throughout Europe and enabled considerable increases in food output that sustained population increases between 1700 and 1850, well before industrialization had much effect upon European farming. Although industrialization of agriculture was modest by the mid-19th century another development deserves particular attention. In all European countries centers of agricultural research and education were established by the mid-19th century. In the USA public sector R&D in agriculture became institutionalized with the founding of the USDA in 1862. Institutions and systematic R&D efforts paved the way for more spectacular future improvements in agriculture through the systematic development of both biological and mechanical agricultural innovations.

The development of textile industries in Europe combined with income increases of a growing population lead to large demand for cotton and wool, satisfied by imports from abroad. Westward expansion of cotton growing in the USA and later more widely in the sub-tropics, however, appeared to have a large-scale impact on land use only after the 1850s. This is indicated by the relatively modest trade figures (compared to the end of the 19th century) in cotton and wool. The much higher than expected land conversion figures in regions outside Europe prior to 1850 (inferred from average land productivity figures) can therefore not be explained by massive land conversions for export crop production, and only partly by population growth. The resulting residuals cast doubts on the estimates of land conversions (and/or population growth estimates) particularly in Africa (and to a smaller extent also in North America) which were presented in *Tables 3* and *4* above.

3.3.2. The period of mercantilistic agriculture

Spanning approximately the period from the mid-19th century to the 1930s, agricultural practices introduced earlier in England and some European countries spread further, increasing agricultural productivity in vast peripheral regions of Europe such as Russia. This phase of agricultural expansion was however not so much characterized by the transmission of agricultural techniques which were in use in the more densely populated areas of Europe, but by new developments in

* For an excellent account of causes, events and consequences of this first manifestation of agricultural "Luddism" see Hobsbawn and Rudé 1968:1–365.

transport, manufacturing, and science which accompanied the process of industrialization (Boserup 1981:116–117). They could spread only after the iron and chemical industries were developed and their products became so cheap as to become economical also in agriculture. Commercial fertilizer and large-scale imports of food and fodder could not be introduced before a railway network was in place and the widespread diffusion of the steam ship. Imports of animal products required refrigeration techniques, increased transport distances for food required new methods of food preservation. Only after these preconditions were fulfilled could new agricultural methods be applied and large-scale trade in agricultural products become possible.

The transport revolution combined tremendous improvements in accessibility with rapidly falling transport costs. This enabled unprecedented regional specialization and the opening of vast new agricultural areas in the Canadian provinces, the American Mid-West, the Argentine pampas, the Russian steppes and the interior of Australia. Thus as the food hinterlands of industrialized core regions shrank these regions relied increasingly on external food sources and diversified diets to include products produced only far away.

The introduction of industrial innovations (mechanization) in agriculture also raised labor productivity, particularly in North America agricultural labor was scarce relative to land. Introduction of mechanical innovations for stationary applications intensified: the mechanical reaper (1831) (see e.g., David, 1975), the transportable threshing machine (1850), and the milking machine (1850) to name a few examples. However, in the absence of a light, high-output movable power source (the 20th century tractor), the impact of these innovations particularly outside North America remained limited.

Especially important for raising land productivity were the discoveries of manmade fertilizers, superphosphates (invented in 1841 and the only chemical fertilizer of the 19th century), nitric fertilizers (1906) and above all of ammonia synthesis for nitrogen fertilizers in 1912 (the Haber-Bosch process). Stimulated by military requirements during WW I, nitrogen fertilizers found widespread application in European agriculture only after the 1920s (cf. Figure 15 below). Fertilizer, the first pesticides and fungicides together with the breeding of new varieties enabled significant expansion of yields per hectare. As a result land conversions in Europe were reduced to half the value (+15 10^6 ha additional cropland area) that prevailed over the previous five decades (cf. *Table 3*) and land-use changes, especially when compared to population growth (*Table 4*), were much smaller than would have been expected in absence of these technological developments.

New plant varieties were also introduced outside Europe, for instance new high-yield rice species were introduced in Japan doubling yields per hectare in the period 1880 to 1930 (Hayami and Ruttan 1985:468). Altogether, however, agricultural land productivity increased most in Europe. This, together with large-scale food imports, minimized further conversion of forests and grasslands to cropland.

Agricultural land productivity outside Europe did not increase noticeably (with the exception of Japan mentioned above). Particularly in North America advances in labor productivity were not accompanied by comparable advances in land productivity. As a result cropland expansion continued vigorously. Wirefencing facilitated conversion from grazing to crop agriculture. An estimated 100 million ha grassland were converted to cropland in North America in the period 1850 to 1920 (cf. *Table 3* above).

Finally, innovations in food preservation also proved important for agriculture during this period: tin cans, concentrated milk, and especially refrigeration (invention of absorption refrigeration in 1850, and of ammonia compression refrigeration in 1876). Refrigeration steam ships enabled the import of meat from as far away as Australia, New Zealand and Argentina. These developments, together with the drastically decreasing transport costs of the railway and steam ship era, enabled an unprecedented expansion of trade in agricultural products. By the 1870s, net imports of agricultural products exceeded the net export value of manufactured goods of the leading economic power, England (Woytinsky 1927:212). Large-scale grain exports from Russia to central Europe and England were carried out by the end of the 19th century. World trade in agricultural products doubled between the 1870s and 1913. Hence we use the term "mercantilistic agriculture" to characterize this development phase of increasing spatial division of labor and food trade on a continental scale, in addition to the first applications of industrial innovations in agriculture.

What was the impact on land-use changes of this large-scale development of trade in agricultural products? Unfortunately statistical records are scarce, but we have tried to assemble in *Table 5* some zero-order estimates of land areas used for export crop production in the mid-1920s. Between ~20 to 50 percent of all cropland areas in regions outside Europe served export crop production. As the trade in agricultural products by the mid-19th century was rather modest* we can infer rather confidently that nearly all these areas represent net land-use changes over the period 1850 to 1925. Our crude estimates indicate that ~20 percent of land-use changes in North America, the USSR and Oceania in the 1850 to 1925 period were related to export crop production. The percentage in Asia (excluding China) is estimated at some 30 percent, whereas in Latin America up to half of land-use changes can be related to export crop production. In absolute terms North America dominates with some 25 million ha converted to cropland for export (cotton and grains), followed by Asia (mostly India) with some 20 million ha, and USSR & Oceania and Latin America with around 15 million ha each. The available trade statistics (Woytinsky 1926:109–220; Mitchell 1982:472–477) indicate that export of food and agricultural raw materials from Africa were comparatively modest. This leaves some doubts about the much larger land conversions estimated to have taken place in Africa over the 1850–1920 time period (cf. *Table 3* above) than could be expected based on the rates of population growth and their additional cropland requirements.

Taking above land-use changes for export oriented production into account, the marginal land-use changes of *Table 4* are reduced to values of about 12,000 m^2 cropland expansion per head additional population in North America, the USSR &

* Exceptions are e.g., cotton exports from the USA and Egypt as well as trade in sugar. Areas producing export crops by the 1850s are subtracted from the land-use change figures of the 1850–1920 period given in *Table 5*.

Table 5. Expansion of Cropland* for Export Crop Production (zero-order estimates) 1850–1925, 10^6 ha

Region	Products				As percent of increase in cropland area 1850–1920 (Table 3)
	Luxury[1]	Grain[2]	Industrial raw materials[3]	Total	
North America	0.2	17.0	7.7	24.9	19%
USSR & Oceania	–	16.3	–	16.3	17%
Africa	0.2	–	>0.8	>>1.0	?
Latin America	3.5	10.7	>0.1	>14.3	53%
Asia (excl. China)	2.5	5.0	>11.8	>19.3	32%
Total (5 regions)	6.4	49.0	20.4	75.8	21%

1 Sugar(cane), tea, coffee, tobacco.

2 Barley, corn, oats, rice, rye, wheat.

3 Cotton, flax, hemp, jute, rubber.

* Cropland areas in proportion of exports in total production of 15 agricultural commodities by mid-1920s. 1850–1925 expansion assumes world agricultural trade in 1850 was negligible. Exports of cotton (USA, Egypt, India), wheat (Russia) and sugar (Caribbean) by 1850 are taken into account in the calculations. Data source: Woytinsky 1926:109–220 and 1926:265–312.

Oceania and to some 2,000 m^2 per additional capita in Asia. These results are in good agreement with the marginal land-use change values adopted above under *ceteris paribus* conditions, i.e., in absence of the impacts of technological change and export crop production.

3.3.3. The period of industrialization of agriculture

Over the 50 years between the 1930s and the present world agriculture was transformed from a resource-based to a technology-based industry. Although technology embodied in new farming techniques, new plant varieties, man-made factor inputs, machinery and equipment is crucial, it is not by itself the primary source of change. Rather, the transformation in agriculture was made possible by a series of institutional innovations furthering the development and *diffusion* of agricultural technology. Examples include the emergence of public and private sector suppliers of new plant varieties and agricultural technology, institutions and services for transfer of technical knowledge to farmers, public and private sector R&D, input supply and marketing organizations, and the development of more efficient labor, credit and commodity markets. Although we focus below on a quantitative account of some of the most important changes of agricultural techniques and artifacts, the importance of institutions and changing attitudes towards modernization and industrialization of agriculture deserve particular attention.

The *industrialization of agriculture* is characterized by three developments: biological innovations; new cheap factor inputs; and finally, mechanization. These three areas, mutually interdependent and reinforcing, have resulted in spectacular increases in agricultural labor productivity but also, for the first time since the Industrial Revolution, have raised agricultural land productivity throughout the world including also developing countries (Figure 11). In highly industrialized countries it has led to reconversion of cropland areas to grassland and forest cover (Figure 12).

Systematic agricultural R&D has resulted in the development of new crops and wide diffusion of new high-yield plant varieties including new hybrid corn and rice varieties. These are perhaps the most important contribution of applied biology in the 20th century. New plant species increased yields, while the further diffusion of crops between continents opened new export markets (e.g., soybeans over the last 30 years in the USA and even more recently in Brazil) or improved and diversified local diets. In the 20th century maize and manioc have become important food supplements in Africa, whereas sweet potatoes, maize and peanuts started to supplement rice and wheat diets in Asia.

Industrialization of factor inputs to agriculture in the form of commercial energy, man-made fertilizers and pest-control substances alleviated most constraints on agricultural output. Fertilizer output was no longer dependent on animal production or naturally occurring deposits. Already prior to WW II, ammonia synthesis based nitrogen fertilizer accounted for over 80 percent of the global fertilizer output and displaced Chilean nitrate and by-product nitrogen from coke production (Figure 13). Nitrogen fertilizer output increased globally to close to 80 million tons (Figure 14), with increasing shares for Eastern Europe, the USSR and especially for developing countries. Total fertilizer application per ha cropland consequently increased throughout the world, and currently shows, with the exception of Europe and Africa (being significantly above and below the world average respectively), comparatively small regional disparities (Figure 15).

Mechanization of agriculture, symbolized by the farm tractor is perhaps the most visible representation of the industrialization of agriculture. The substitution of mechanical power (and fossil energy) for animal and human power (Figure 16*) alleviated yet another constraint on increases in agricultural output: labor.

Mechanization also made available large areas for cropping use, hitherto required to feed working animals. For instance in the USA, the area required for feeding

* Note that Figure 16 just shows fossil energy inputs to agriculture. Taking into account also non-fossil energy consumption (energy from work animals, wind and water power as well as fuelwood) estimated to have peaked around 5 10^{18}J in the 1920s (Fisher 1974:158–159), total energy consumption in US agriculture did not increase significantly (from about 6 10^{18}J in the 1920s to over 8 10^{18}J in the 1970s), whereas total output more than doubled over the same period (Hayami and Ruttan 1985:482). The improvements in total energy consumption per unit of output achieved are the result of better end-use efficiencies of industrial power sources fueled by fossil energy. Recall here that a horse typically converts only 3 percent of the energy embodied in feed to useful work (kinetic energy) compared to a ~30 percent energy efficiency (useful/final energy ratio) of a farm tractor.

farm horses and mules amounted to nearly 40 million ha in the 1920s (US DOC 1975:510), twice as large as the areas devoted to export products and about half of the cropland used for domestic production. The replacement of farm horses and mules by the tractor thus minimized further land conversions.

Because of the scarcity of labor relative to other factor inputs in North America, mechanization started in the USA (where the ground was additionally prepared by the "horse-mechanization" over the previous decades) and in some European countries. Since WW II mechanization has spread to other regions (Figure 17). The mechanization in agriculture is best illustrated by the increasing number of tractors in use worldwide, presently over 26 million (Figure 18). Over the last 20 years, the share of developing countries in the global number of farm tractors has been rising rapidly.

Industrialization not only resulted in new demands for agricultural raw materials but also in substitution of many raw materials produced by agriculture by man-made products. For instance, with the development of the electrical engineering industry and later motor vehicles, rubber moved from a minor curiosity to a major raw material, and in the early 20th century natural rubber production expanded prodigiously in Southeast Asia. After WW II synthetic rubber production increased dramatically worldwide.

Production of natural rubber rose rapidly to about one million tons in the 1930s, with over 90 percent of this production concentrated in Southeastern Asia. Rubber plantations extended over some 5.6 million hectares in Asia in the 1930s, about equally split between large rubber plantation estates and small holdings (Woytinsky and Woytinsky 1953:620). In the late 1980s world rubber production exceeded 14 million tons. It is easy to imagine the land-use impacts of this 14-fold increase in rubber production if it were based only on plantation rubber. Fortunately, such land-use conversions were much smaller due to the introduction of synthetic rubber (yet another outgrowth of the developments in petrochemical industries). Currently two-thirds of the world's rubber output are in form of synthetic rubber with some smaller quantities consisting also of recycled rubber (Figure 19).

As a result of these developments of the industrialization of agriculture, output increases could keep abreast population growth at a global level and productivity in some regions rose to such levels as to enable large-scale reconversion of marginal agricultural lands to forestry (as in Europe and North America, cf. Figure 12 and *Tables 3* and *4*), while maintaining output levels, so high as to yield large and costly agricultural surpluses, with the attendant political embarrassments. Agricultural policies in the OECD countries result in a total subsidy of agricultural production of about 300* billion US$ in 1990 (OECD 1991:5), about equally split between direct producer subsidies and transfers away from consumers (considering that consumers have to pay above world market prices for agricultural products). On the extreme end (Switzerland, Norway and Japan) subsidies to agricultural producers equal about three-quarters of the value of agricultural output.

* Value comparable to the total value of world crude oil trade.

In addition to vastly raised agricultural output western diets have become dominated by the consumption of animal products. In most western countries livestock products account for up to two-thirds of the value of output (Grigg 1987:102).

Agricultural output and land productivity also increased outside OECD countries. Land productivity outside OECD countries increased over the 1950–1980 period at an annual rate of about 1 percent. Although population increased twice as fast (2.1 percent/year), land productivity increases remain a formidable achievement of the "green revolution". Cropland expansion per head additional population dropped to about 1000 m^2 per capita in Asia, 3000 m^2 in Latin America and to some 5000 m^2 in Africa, the USSR and Oceania. Without the productivity increases of an industrializing agriculture, the cropland area outside Europe and North America would have been expanded by close to 400 million ha above the estimated 350 million ha increase between 1950 and 1980.

Table 6 summarizes the current state of agriculture in selected world regions based on FAO data. Despite large regional variations, industrial innovations have diffused into agriculture on a global scale. Land productivity in terms of food calories per arable ha still shows large disparities between regions as a result of differences in climate, soils, output mix, intensity of cultivation, fertilization and mechanization. Still, the picture that emerges from the regional differences is that in many regions food production per ha of arable land could be intensified, producing sufficient food for ever increasing populations.

An open question remains whether in future it will be possible to accelerate agricultural land productivity growth in developing countries to keep pace with population increases. The history of Europe and of North America illustrate the potential that technology holds to fulfill such an objective. However, what kind of technologies will be applied and to what extent, will to a large degree be a function of economic and social policies. These policies will also have to address the issue of how to solve the large number of constraints (most notably capital shortages) and environmental impacts associated with rising agricultural output and increasing further agricultural land productivity. The latter in turn are crucial for sustaining growing populations and minimizing further land-use changes.

Let us summarize this section on the relationships between technology and agricultural productivity since the onset of the Industrial Revolution. Technological change has been instrumental in raising agricultural productivity. Despite distributional problems, global agricultural production has kept pace with population growth. The productivity of land has increased in many developing countries at a slower rate than population, resulting in net expansion of agricultural land, but without technological change, land-use transformations would have been twice as large over the last 30 years. Above all, technological change has vastly increased agricultural labor productivity, freeing people from the land to pursue other economic activities.

A further consequence of the industrialization of agriculture was that farming has ceased to provide all its own inputs. Farming evolved from a vertically integrated activity (a farmer producing his own inputs like seeds, fertilizer (manure), livestock for traction power, and also storing, conserving and marketing his own production) to horizontal integration with increasing specialization. This shift from

Table 6. Agriculture: Land, People, and Technology, A.D. 1990.

	Europe	USSR	North America	JANZ*	China	Asia	Africa	Latin America	World
Population (10^6)	497.7	288.0	275.7	143.6	1135.5	1855.9	647.5	448.3	5292.2
Arable land (10^6 ha)	140.1	232.4	235.9	52.2	96.6	351.7	186.7	179.8	1475.4
Irrigated area (10^6 ha)	17.3	20.8	18.9	5.0	44.9	94.9	11.2	15.6	228.7
Farm tractors (10^6)	10.3	2.7	5.4	2.4	.9	2.2	.6	1.4	25.9
Fertilizer use (10^6 t)	31.9	26.5	19.9	3.6	18.9	21.4	3.5	8.4	134.1
Food supply (10^9 cal)	1723.9	976.6	994.6	414.3	2946.0	4222.2	1421.0	1204.4	13903.0
Arable land use intensity:									
people/km^2	355	124	117	275	1175	528	347	249	359
fraction irrigated	.12	.09	.08	0.10	0.47	0.27	0.06	0.09	0.16
tractors/km^2	7.4	1.2	2.3	4.6	0.9	0.6	0.3	0.8	1.8
tons fertilizer/km^2	22.8	11.4	8.4	6.9	19.6	6.1	1.9	4.7	9.1
food output 10^6 cal/km^2	1.23	.42	.42	.79	3.05	1.20	.76	.67	.94
10^3 cal per person	3.5	3.4	3.6	2.9	2.6	2.3	2.2	2.7	2.6

* Japan, Australia, New Zealand

Data source: FAO, Production Yearbook

vertical to horizontal integration in agriculture also puts in perspective the dramatic shifts in employment patterns away from agriculture. Many activities which previously were performed within the agricultural sector are now performed in the industry and service sectors. Jobs on the farm have moved to industrial manufacturing plants producing seeds, fertilizer, tractors and other farm machinery, and to food processing industries and to the service sector (e.g., food retail and restaurants).

With these qualifications in mind, Figure 20 summarizes this transformation in the employment structure away from agriculture. Compared to Figure 6 above (using total population per agricultural workforce as a productivity indicator), we analyze the ratio of the non-agricultural to the agricultural workforce. Plotted on a logarithmic scale, the long-term convergence (although with some lagged developments as in the case of France) in the employment structure of industrialized countries becomes apparent. The few long-term data we have been able to assemble for developing countries indicate a similar secular trend.

Technological change has thus raised agricultural productivity and permitted an increasing share of the growing rural population to transfer to urban employment, a development most painfully felt today in many rapidly growing megacities of the developing world.

4. The Urbanization Drive

4.1. Urbanization Trends: Catch-up and Convergence

Figure 20 illustrated the transition from agricultural to non-agricultural employment. Figure 21 illustrates the shift from rural to urban residence. Despite some data consistency problems* the picture is quite consistent and – more noteworthy – also converging in the countries sampled. The similar dynamics in the two structural shift processes (away from agricultural employment, and movement into cities) point to their close relationship and to a clear historical temporal sequence: the shift away from agricultural employment *preceded* the transition to urban populations in all industrialized countries. In countries which are undergoing this transition in this century such as the USSR and Brazil, however, both processes appear synchronized.

The move towards urbanization displays the same dynamic development patterns as discussed above in other technological and economic structural change processes: certain convergence in the dynamics (the rates of change) and spatial heterogeneity as a function of the time since this transition process was initiated. Consequently England (including Wales) has a higher urbanization ratio than Germany (FRG alone after 1945 in Figure 21) or the USA where this process took off later. In industrialized countries the future growth of urban populations will

* The city size limit to define urban populations in Japan is much larger than in other countries due to the absence of more disaggregated statistics. This tends to underestimate the degree of urbanization in Japan compared to other countries, it should however not affect the dynamics of this process as reflected in the slope of the curve in Figure 21.

be comparatively modest as a result of their low overall population growth rates and the fact that already over 80 percent of their population currently live in urban areas. Conversely, developing countries are in the midst of the transition process, where growth rates are highest. This explains the exceptional high population growth rates in urban agglomerations in many developing countries which is the result of a three-fold structural change process: the transition away from agricultural employment, high overall population growth, and increasing urbanization rates. Perhaps this is the biggest challenge for technology in the 21st century: how to provide adequate, housing, sanitation and health, and transportation services in a habitable urban environment for cities in developing countries. The need for improvement is certainly large (6 million people in Mexico City alone), as some estimates of populations in shanty-towns (euphemistically referred to as "informal" settlements) illustrate (*Table 7*).

Table 7. Percentage of Urban Populations in Informal Settlements, 1980.

	Total Population	Population in Informal Settlements	
	(thousands)	(thousands)	Percent
Addis Ababa, Ethiopia	1,668	1,418	85
Luanda, Angola	959	671	70
Dar es Salaam, Tanzania	1,075	645	60
Bogota, Colombia	5,493	3,241	59
Ankara, Turkey	2,164	1,104	51
Lusaka, Zambia	791	396	50
Tunis, Tunisia	1,046	471	45
Manila, Philippines	5,664	2,666	40
Mexico City, Mexico	15,032	6,013	40
Karachi, Pakistan	5,005	1,852	37
Caracas, Venezuela	3,093	1,052	34
Nairobi, Kenya	1,275	421	33
Lima, Peru	4,682	1,545	33
São Paulo, Brazil	13,541	4,333	32

Source: WRI 1991:76.

With respect to the role of technology in urbanization, Berry 1990:103-119 has illustrated anew the linkage between transport infrastructure development cycles and pushes in urbanization in the USA. Increasing the spatial range and accessibility through the development of successive infrastructures (cf. Figure 2 above) can be considered as *the* prerequisite to the spread of urbanization over time, from a few industrializing countries in the northern hemisphere, to a global phenomenon. A few snapshots in time of urbanization ratios are reported in Figure 22 (A-D).* The parallel developments of transport infrastructures will – as treated in detail elsewhere (Grübler, 1990) – not be reported here. However, the close relationship between high rates of urbanization and transport infrastructural development cycles, e.g., in the dominance of railway construction in Europe and North America and their related high urbanization rates by 1930, are apparent. Current high transport intensities either with individual modes of transport (cars) or public ones (buses and aircraft) based on internal combustion engines also correlate highly with urbanization ratios (Figure 22-D), despite wide regional variations. For the purposes of analyzing land-use patterns it is therefore important to note that infrastructural endowments (and hence land requirements) are more a function of population density than of absolute country size, due to the preponderance of short- to medium-distance trips in total travel demand. Total land requirements for transport infrastructures, also small in comparison with agricultural land uses, are significant in relation to other built-up land areas (cf. the following section) and constitute a major human impact on the terrestrial and atmospheric environments. Areas for technological improvements remain vast, either by making current transport technologies more efficient and environmentally benign, or in introducing new high quality transit systems, such as urban metros or high-speed rail or magnetic levitation trains for inter-city transport.

4.2. Urban Land-use

Although land-use patterns and their changes both historically and presently are dominated by agriculture, we will conclude this section by investigating other (i.e., urban) land uses, in particular the ones associated with our technological civilization beyond agriculture (*Table 8*).

Leaving aside small islands and city states (like Hong Kong with 5400 inhabitants per km^2), the countries with the highest population density in the world are (in decreasing order): Bangladesh, South Korea, the Netherlands, Japan and Belgium. All of them have population densities of above 300 inhabitants per km^2. Land-use patterns in these countries are of particular interest either because of their high population pressure (Bangladesh) or because of their high population density in combination with a long history and high degree of industrialization (the Netherlands). Japanese statistics (Japanese Statistics Bureau 1987:7) allow us to investigate the land-use patterns in the prefectures of the three largest metropolitan areas, Tokyo, Osaka and Nagoya. For comparison, *Table 8* also gives land-use patterns in a city (Vienna), where population densities are obviously much higher (around 4000 inhabitants per km^2) than in the larger administrative regional or national divisions on which aggregate land-use statistics are usually available.

* For reasons of data consistency for a worldwide coverage of urbanization trends, we have retained a threshold level value of 25,000 inhabitants to define the residence of urban populations. For 1985, we have retained the UN definition of urban populations, which is however not necessarily consistent between countries and subject to numerous national redefinitions and upward revisions of urban populations (as recently the case in China).

Table 8. Green vs Built-up Land in Densely Populated Areas. Data: Bangladesh: FAO 1991:52; Netherlands: van Lier 1991:386; Japan: Japan Statistics Bureau 1987:7; Vienna: ÖIR 1972:I-XXIII.

	Bangladesh	Netherlands	Japan	Japan: 3 major metropolitan areas	Austria: City of Vienna
Population					
(1) Density, people/km^2	766	388	322	1411	3925
Land use, %					
(2) Rivers & lakes	9.6	9.0	3.5	3.6	3.4
(3) Forests	13.6	9.7	67.0	52.7	24.6
(4) Grassland	4.2	31.2	1.1	0	26.5
(5) Cultivated land	64.4	22.6	14.3	16.0	
(6) Parks & recreational areas	n.a.	6.3	n.a.	n.a.	9.4
(7) Subtotal (4–6)	68.6	60.1	15.4	16.0	35.9
(8) Infrastructures[(a)]	n.a.	1.8[(b)]	0.5	2.8	12.3
(9) Residential buildings	n.a.	7.4	1.9	2.4	14.2[(c)]
(10) Industry & commerce	n.a.	1.3	0.3	0.4	4.3
(11) Office & public buildings	n.a.	n.a.	0.9	1.1	2.1
(12) Subtotal (9–11)	n.a.	8.7	3.1	3.9	20.6[(c)]
(13) Other uses	8.2	10.8	1.1	7.4	3.9
(14) Built-up land (8+12)	n.a.	10.5	3.6	6.7	32.9[(c)]
Per capita land use, m^2/capita					
forests (3)	170	244	2049	373	63
green areas (4–6)	854	1513	471	114	91
infrastructures (8)	n.a.	45[(b)]	86	37	31
building area (12)	n.a.	218	121	211	53

(a) Roads, railways, airports
(b) Only roads
(c) Includes private gardens and parks

Perhaps the most surprising fact emerging from *Table 8* is that even in the most densely populated countries of the world the dominant land-use (typically well above 90 percent) is in form of (semi-) natural (forests) and managed ecosystems (water bodies and agricultural land). Built-up areas (of course not all of them covered with man-made structures) do not account for more than 10 percent of the land use even in the Netherlands, with its high population density, long industrialization history and high levels of economic activities. Even in metropolitan and urban areas with high population densities, between 25 to 50 percent of land is still covered by forests.

Building areas, at higher levels of regional aggregations, range from between 120 to 220 m^2 per capita. The value for the city of Vienna is with 21 m^2 per capita only one-tenth of this value, indicating that the actual ratio of areas covered by man-made structures in the total built-up areas is most likely not exceeding 5 to 10 percent. Of the built-up areas, the land requirements for infrastructures are considerable, ranging between 14 and 17 percent of the national average (Japan and the Netherlands) and between 37 and 42 percent in urban agglomerations (Vienna and the 3 largest metropolitan areas in Japan). Moving people and goods in densely populated areas thus rivals land requirements for housing, and industrial and commercial activities.

Retaining a value of 250 m^2 per capita for built-up areas and 25 m^2 for areas actually covered by man-made structures, the global population of 5.3 billion people is associated with the use of 130 million ha built-up land areas, i.e. only about *one* percent of the land area of this planet. Actual man-made structures –the physical manifestation of our technological age– most likely do not cover more than *0.1* percent of the land areas of planet Earth.

5. Conclusion

Land-use patterns have changed over millennia, but the most dramatic transformations took place over the last 300 years. With increasing population growth, land transformation patterns accelerated. We have shown that agricultural activities dominate both land-use patterns and their dynamic transformations. Conversely, even today the areas covered by artifacts of our technological civilization are small, covering less than one percent of the land area of the Earth.

There are many underlying forces of change in land-use patterns in addition to population growth such as the rise of an urban society, changes in structures of demand brought about by higher incomes and the increasing international division of agricultural production, among many others. In all these long-term transformation processes, technological change has been instrumental. Together with population growth it represents one of the most important agents of change in land-use patterns. Increases in agricultural productivity, spatial division of labor and accessibility of even the most remote geographical areas were made possible by a succession of technological clusters, which spread first to a limited number of countries but presently are global phenomena. We have identified in particular transport technologies and infrastructures as appropriate "metaphors" to represent the spatial diffusion and intensity of development of particular techno-economic clusters. However, their relation to and impact on land-use changes has above all to be analyzed on how they affected agricultural productivity and the spatial division of agricultural production.

Changes in technology enabled the support of ever larger populations at higher levels of affluence and consumption (though extremely unevenly distributed throughout the world). As such, technological change has been instrumental in raising agricultural productivity, pushing further away Malthusian "limits to growth". In turn, demographic and social changes have also induced technological change. Demographics and technology have therefore to be at the core of any analysis of land-use changes, past and future.

Over the 1700–1980 period about 1.2 billion ha forests were converted to arable land globally. This corresponds to about 3000 m^2 per capita additional world population over this time horizon. Large regional variations exist in the relationship between population growth and expansion of arable land due to the specifics of "Asian", "European", and "New Continental" systems of agriculture and their respective paths of agricultural productivity increases. Common to them all is that the rate of land-use change compared to population growth has been significantly reduced due to agricultural (land) productivity increases. In the absence of land productivity increases, the cropland area outside Europe and North America would have expanded about two times the actual value of some 350 million ha over the 1950–1980 period. Technologies have therefore helped to significantly "decouple" the expansion of agricultural land from population growth. In regions such as Europe and North America, the pervasive adoption of mechanization and of high-productivity agricultural techniques enabled the reconversion of agricultural areas to forests, while at the same increasing agricultural production (and surpluses) for a rising number of consumers. About 16 million ha agricultural land have been reconverted to forests since 1950 in Europe and North America, while at the same time population increased by some 170 million people.

A succession of "transport revolutions" has allowed us to overcome ever larger distances at lower costs. Increasing spatial division of agricultural production and worldwide trade in agricultural commodities for food and raw materials have been an additional cause of land-use changes. For instance (crude) estimates indicate that between 20 and 30 percent of the expansion of arable land outside Europe and China between the 1850s and the 1920s was devoted for export crop production. In some regions and countries (e.g., Latin America and India) this value is likely to have been even higher.

Perhaps the most pervasive impact of technology since the onset of the Industrial Revolution was the tremendous increases in agricultural labor productivity. In industrialized countries today only a few percent of the population are required to supply food for all, compared to 70 to 80 percent some 300 years ago. The increases in employment in other sectors of the economy, such as manufacturing and services combined with tremendous productivity increases enabled the expansion of industrial output and increasing levels of personal consumption and affluence. Changes in agriculture, industry as well as in urbanization were enabled by the pervasive adoption of new technologies.

Projections indicate an increase of world population by some additional 5 billion people by the second half of the 21st century, perhaps even more. If this population increase were based on changes in land-use patterns that prevailed in the USSR and Oceania over the period 1700–1980, the agricultural area would have to be expanded by some 5 billion ha, equivalent to the total area covered by forests worldwide in 1980. Fortunately, the extent of land-use changes associated with future population growth will be much smaller. Deforestation and land conversion to agriculture per capita additional population in developing countries dropped to 2000 m^2 per head in the 1950 to 1980 period. Multiplied by 5 billion additional world population, arable land use would increase by 1 billion ha, or 20 percent of the 1980 world forest area. Lowering such figures in the future, minimizing further conversion of natural to managed ecosystems will to a large degree depend on the technologies and agricultural practices adopted to ensure the food supply of future generations.

Malthus considered advances in agricultural productivity unlikely to keep pace with the rate of population growth. Consequently, agriculture and, in particular, land availability would constitute the ultimate constraint to population growth. On the other hand, Boserup (1981) sees increasing population density as a motivation for the development and adoption (diffusion) of more productive technology and social organization, which in turn allow for increased population and/or rising living standards. The long-term history of population and agricultural productivity increases discussed here clearly supports a Boserupian viewpoint rather than a Malthusian. As such it perhaps best illustrates the pervasive impacts of the dynamics of technological change. Therefore, the question of what the ultimate carrying capacity of planet Earth may be (10, 30, or even 1000 billion people as provokingly argued by Marchetti, 1978) is not the issue. The real question is whether humankind disposes and/or will develop appropriate technologies to feed, house and employ whatever level of global population will materialize in the 21st century in an adequate, equitable and environmentally compatible manner.

"Technology" has to be considered in a larger context: comprising not only man-made artifacts, ranging from simple tools to complex technological systems, but also the required knowledge base for the inception, production and use of artifacts. The social, institutional and organizational know-how and *techniques* which steer the inception and diffusion of individual or whole clusters of artifacts is also "technology". Finally, technologies cannot be considered separately: the growth of individual technologies depends on many "enabling" factors. It depends on (and in turn also cross-enhances) many other technological solutions, giving rise to "clusters of technologies". The diffusion of technology also depends on a mediating social and institutional framework, ultimately forming (time specific) regimes of economic expansion which we have referred to as whole "techno-economic paradigms".

Policies, institutions and the economic environment shape to a large extent the inception and selection of technologies. The social and economic environment determines the growth and diffusion (or rejection) of particular (combinations of) technological solutions. However, technology in turn also helps to create and shapes the social and economic context out of which it has evolved. In this intricate interrelationship it appears impossible to conclude with a simple answer what is the primary driving force of environmental change. Perhaps it is best to conceptualize technology as a "mediator" between society at large and its natural environment.

From such a perspective, changes in the technologies we use and in the social and economic context out of which technologies evolve appear necessary. In fact, some* argue that we may be already amidst a transition to a new environmentally more compatible "techno-economic paradigm" and a changing social awareness towards environmental change. Although often disruptive, the succession from one dominant techno-economic cluster to a new one, proved from a historical perspective essential for secular long productivity increases and for mitigation of adverse social and environmental impacts associated with the pervasive adoption of particular technological regimes – objectives that present and future technology should aim to fulfill better than in the past.

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*E.g., Ausubel (1990); Freeman and Perez (1988); Grübler and Nowotny (1990).

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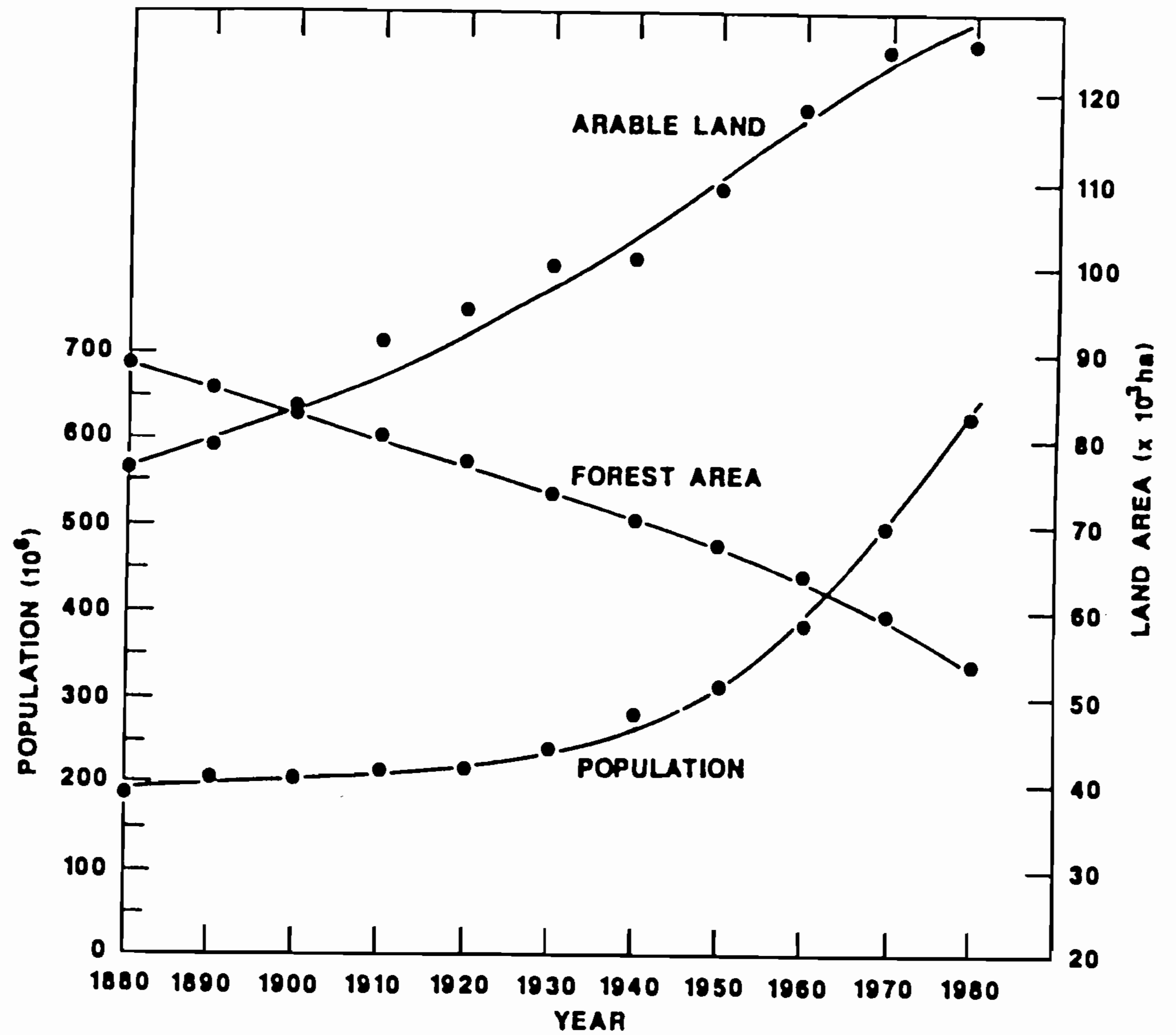

Figure 1. A typical pattern of land-use changes: expansion of arable land at the expense of forested areas. Population and land-use changes in Pakistan, Bangladesh, Burma, Malaysia, Brunei, and Northern India since 1880. Current land-use changes are most pervasive in developing countries, mirroring similar trends in industrialized countries many decades to centuries ago. Note in particular that arable land did not increase at the same rate as population. Prior to 1920 arable land expanded even with a stationary population, mostly for export crop production. Since then population nearly tripled, whereas arable land increased less than one third. Increased agricultural productivity due to improved practices and technologies, especially since the 1950s, helped to "decouple" arable land expansion from population growth. Source: Marland 1989:205.

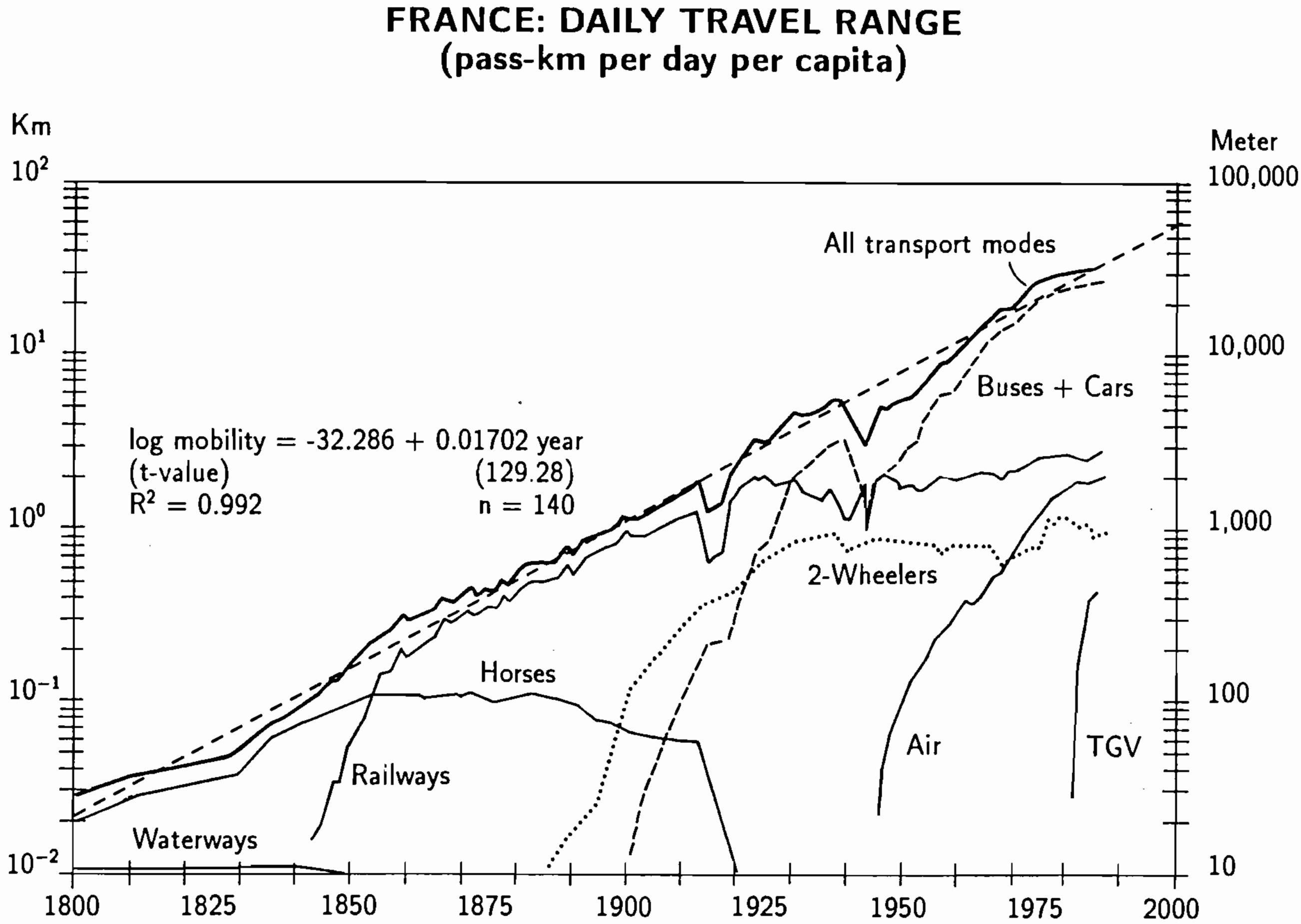

Figure 2. Range covered (average km travelled daily) per capita in France by mode and total since 1800. The succession of transport infrastructures since the onset of the Industrial Revolution expanded the spatial range of human activities by over three orders of magnitude. The current French travel about 35 km per day. New transport technologies also enabled increasing spatial division of labor and trade (also in agricultural products), and the growth of cities. Transport infrastructures are land intensive and account for a significant share of built-up land. Source: Grübler 1990:232.

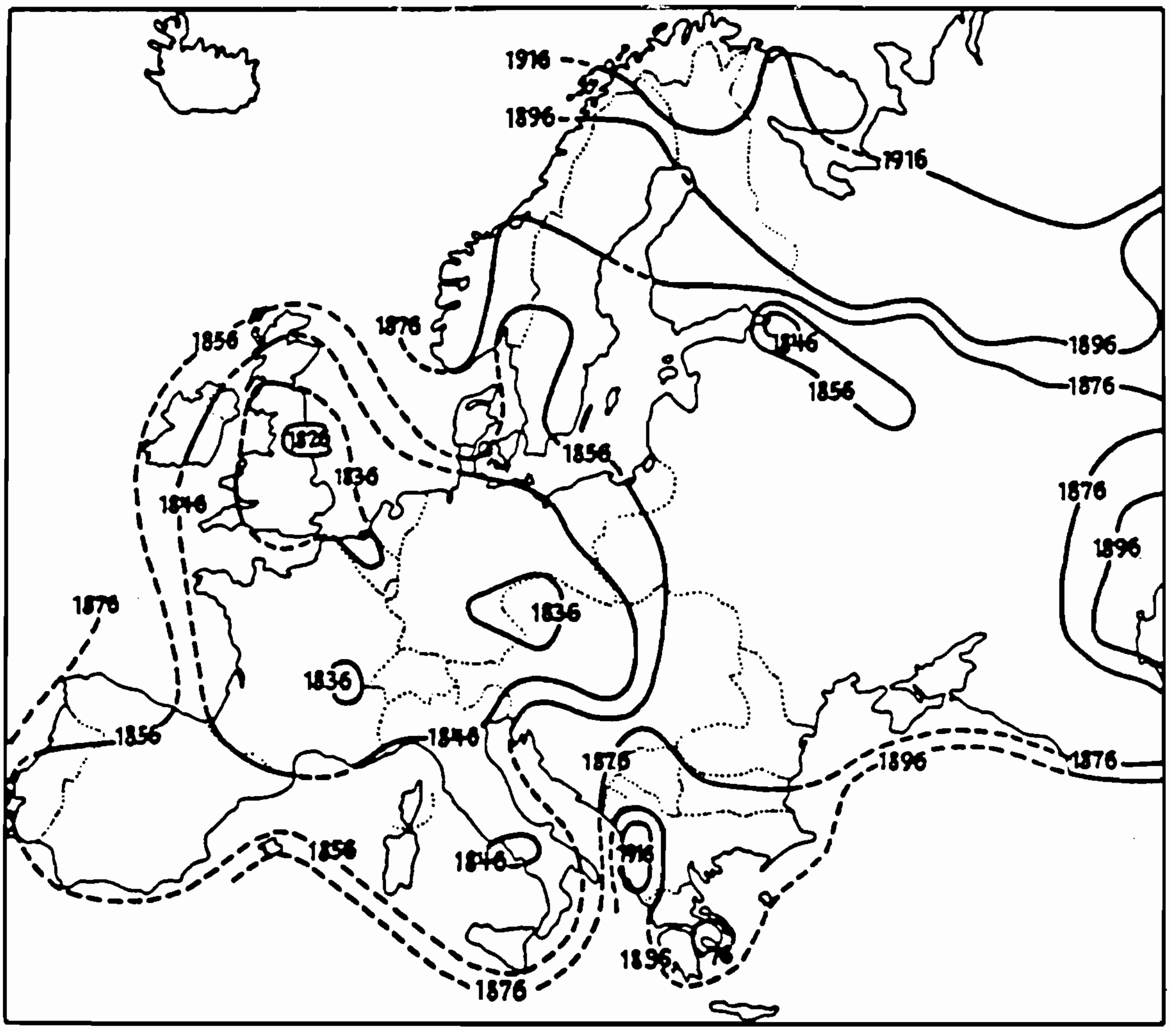

Figure 3. Spatial diffusion of technologies: the case of railways in Europe (in 10-year isolines of areas covered by railway networks). New infrastructures and technological artifacts spread in a particular pattern: first through a hierarchy of innovation centers and from there to their hinterlands. Early starters have long diffusion times and correspondingly high levels of adoption and usage intensity. Peripheral areas adopt later, but at faster rates, i.e. tend to catch up, however at significantly lower adoption levels (cf. Figure 4 below). The resulting spatial heterogeneity precludes normative approaches in inferring from adoption levels of leading countries as likely future potentials of follower countries. Source: Godlund 1952:34.

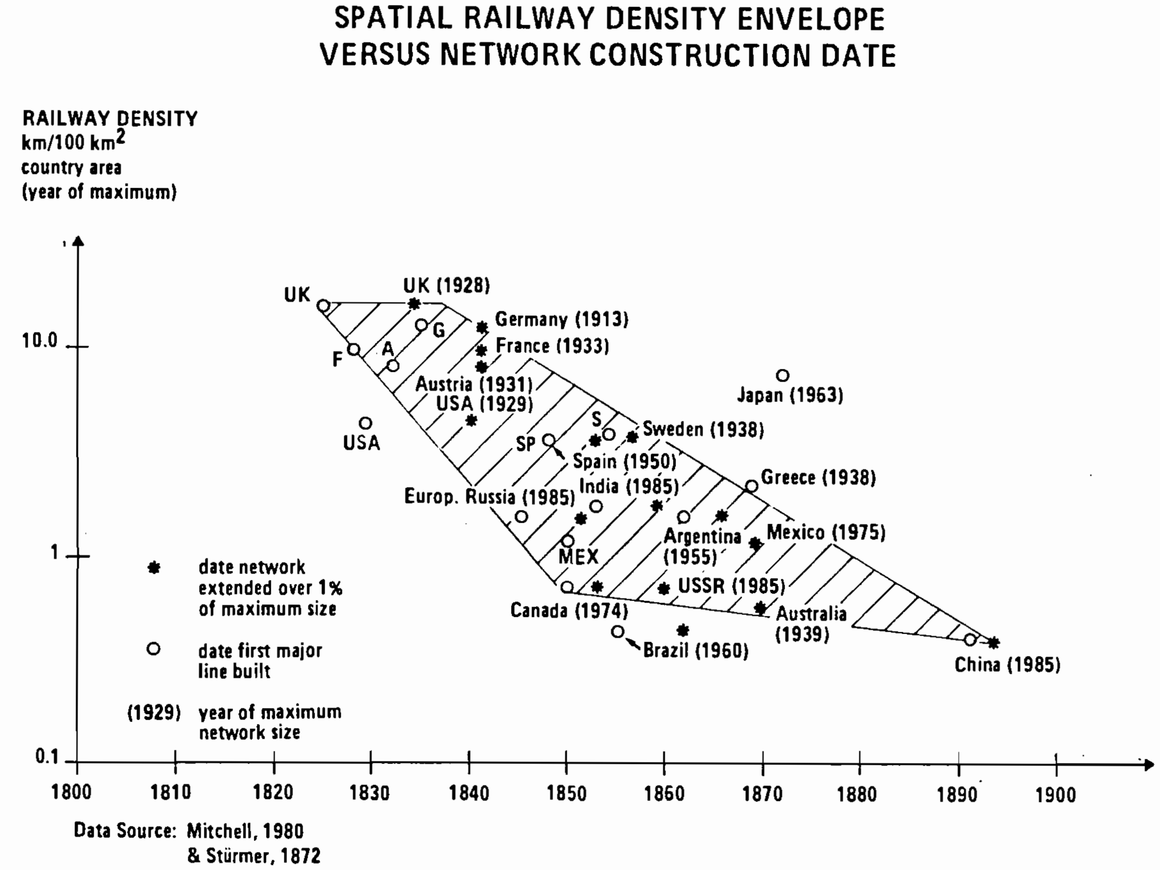

Figure 4. Spatial railway density (railway lines per country area) envelope (at year of maximum network size) as a function of introduction date of the railways. The development of pervasive techno-economic clusters as illustrated by transport infrastructures is time specific. Countries starting the build-up of particular systems at a later date than the leading countries tend to catch up, albeit at significantly lower intensity levels (note the semilogarithmic scale in Figure 4). Particular technological and infrastructural "development trajectories" are not repeated at later time periods, due to the availability of newer systems. Source: Grübler 1990:98.

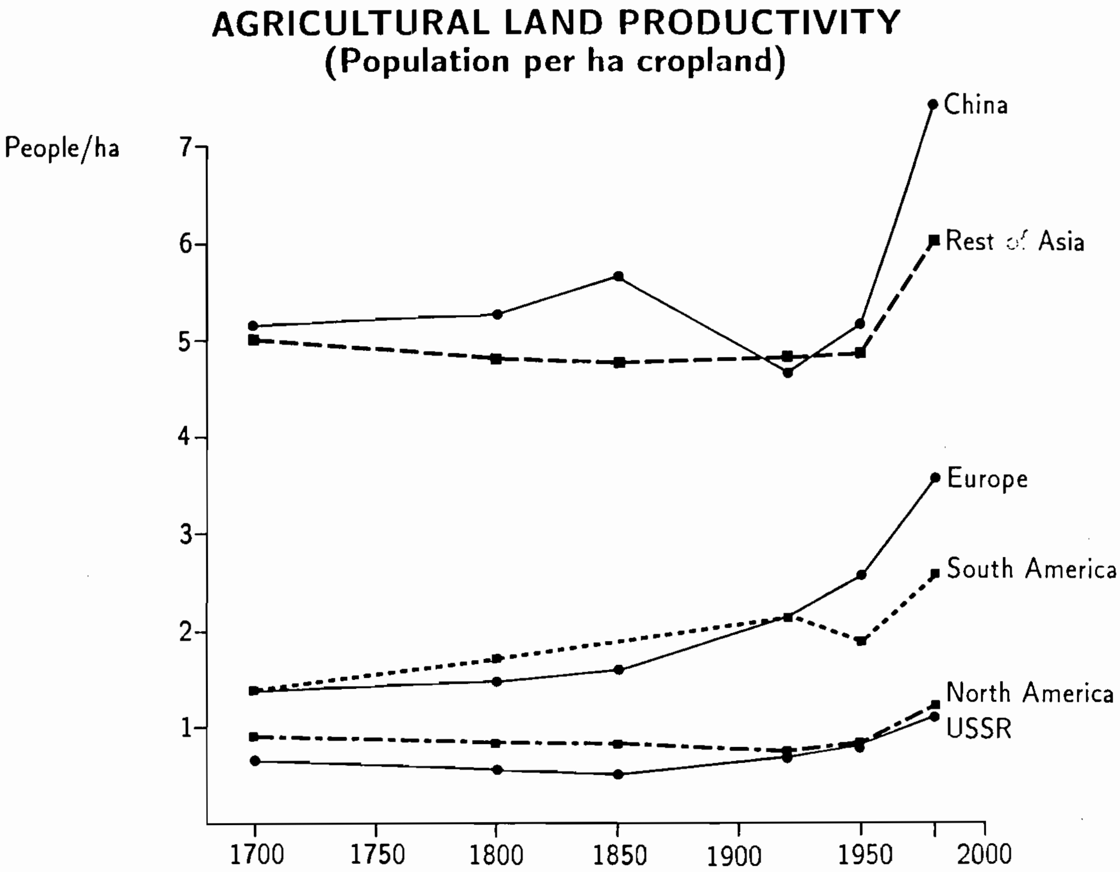

Figure 5. Agricultural land productivity (population per ha cropland). With the exception of Europe, agricultural land productivity did not increase noticeably prior to the 1950s. This implies that population growth resulted in a proportional land-use conversion from forests (and grasslands) to arable land. Rising land productivity is the result of technological change. Note also the large regional differences and path dependency in the evolution of land productivity due to changes in output mix (rice vs grain and meat production), differences in agricultural practices, and level and intensity of technology applied. Source: derived from data in Richards 1990:164, Durand 1967:259, and Demeny 1990:49.

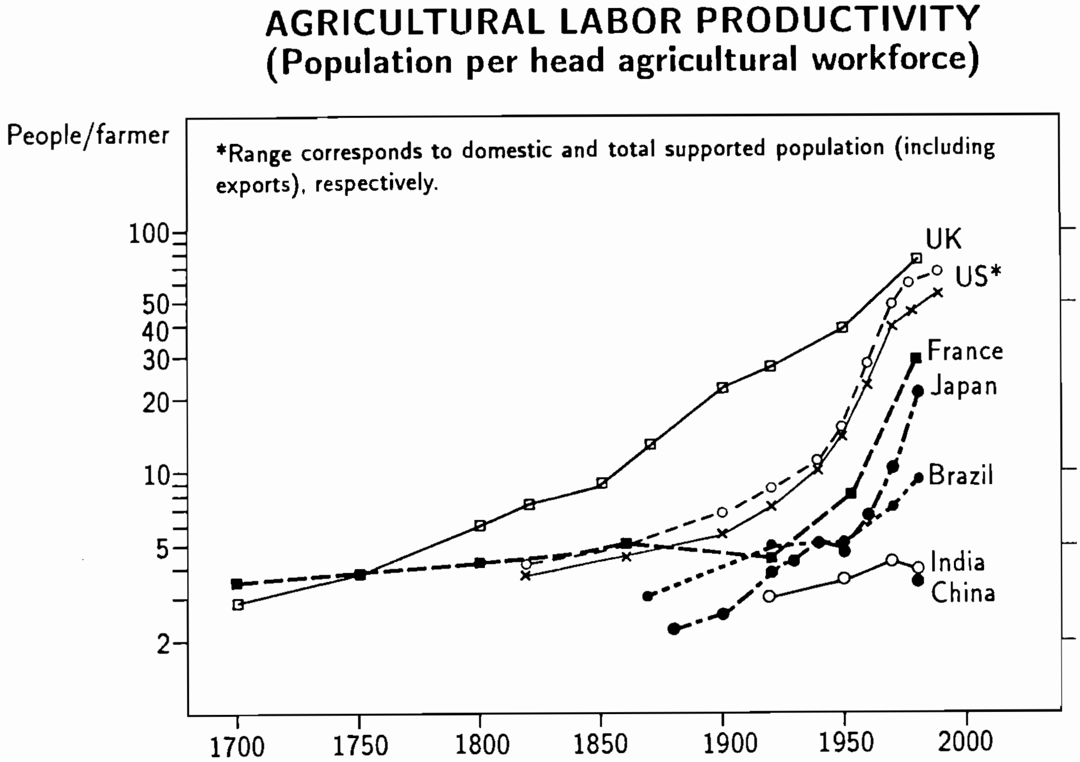

Figure 6. Agricultural labor productivity (population per agricultural worker). The impact of technological change on agriculture is manifest in the rise of agricultural labor productivity. Before the industrial revolution (as is the case today in many developing countries), typically between 70 and 90 percent of the population worked in agriculture (and lived in rural areas). Today, only a few percent of the total workforce is employed in farms, and urbanization rates exceed 80 percent in most industrialized countries. Note that many activities previously performed by the agricultural sector now give employment in industry and services. Note also that agricultural labor productivity is even higher when exports are considered. E.g., the range of values given for the US corresponds to domestic and total supported population (including exports) respectively. Source: derived from data in Durand 1967:259, Demeny 1990:49, and Mitchell 1980:161-173, Mitchell 1982:84-93, and Mitchell 1983:150-160, USA data are from Arnold 1990:72.

THREE CLUSTERS OF AGRICULTURAL
PRODUCTIVITY INCREASE TRAJECTORIES

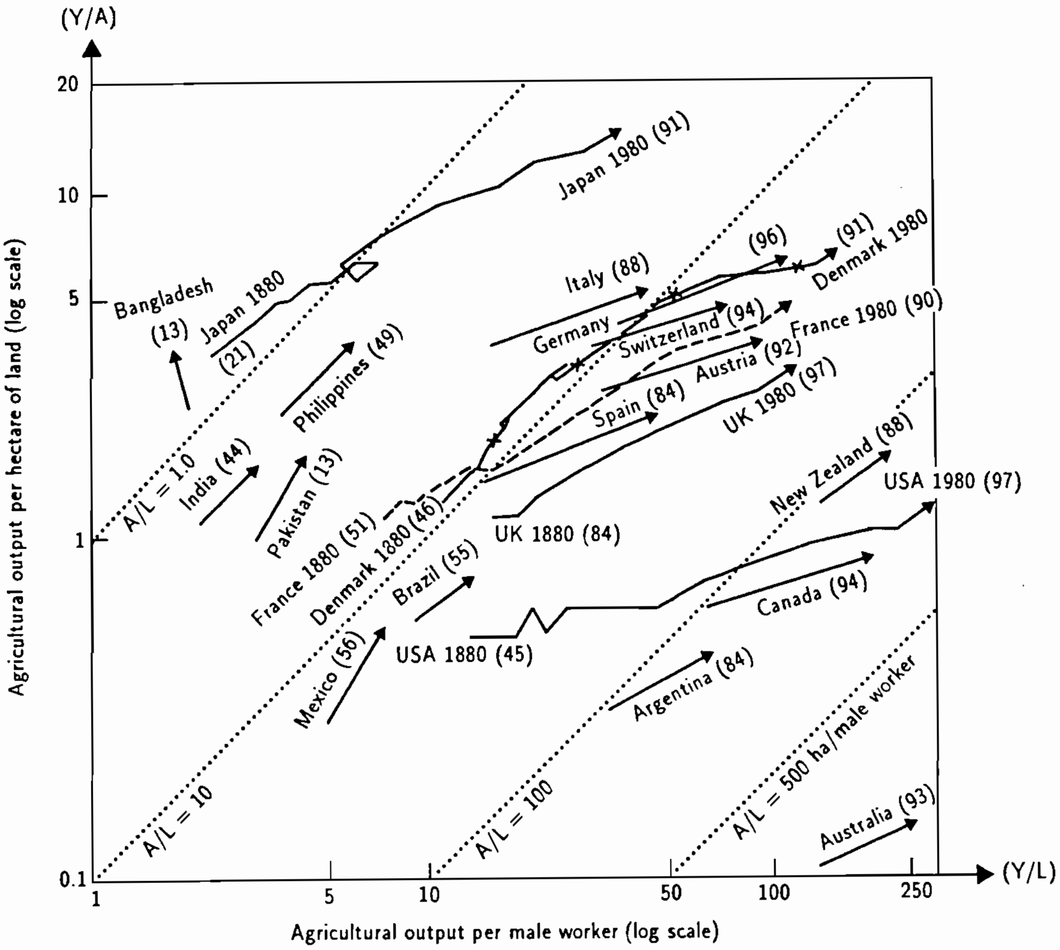

Figure 7. Three clusters of agricultural productivity increases. Agricultural output (constant value) per ha land and per agricultural worker. Linear vectors indicate changes over the period 1960 to 1980. Longer trajectories (Denmark, France, Japan and USA) indicate changes over the period 1880 to 1980. Values in parentheses indicate percent of workforce employed outside agriculture in 1980. Different initial starting conditions as reflected in the relative availability of the factor inputs land and labor (A/L) and specific development paths followed illustrate "Asian", "European" and "New Continental" development paths of agricultural productivity increases. Each path also corresponds to specific ranges of land intensiveness and land productivity increases which have to be considered separately for analyzing agricultural land-use changes. Source: adopted from Hyami and Ruttan 1985:121 and 1985:131.

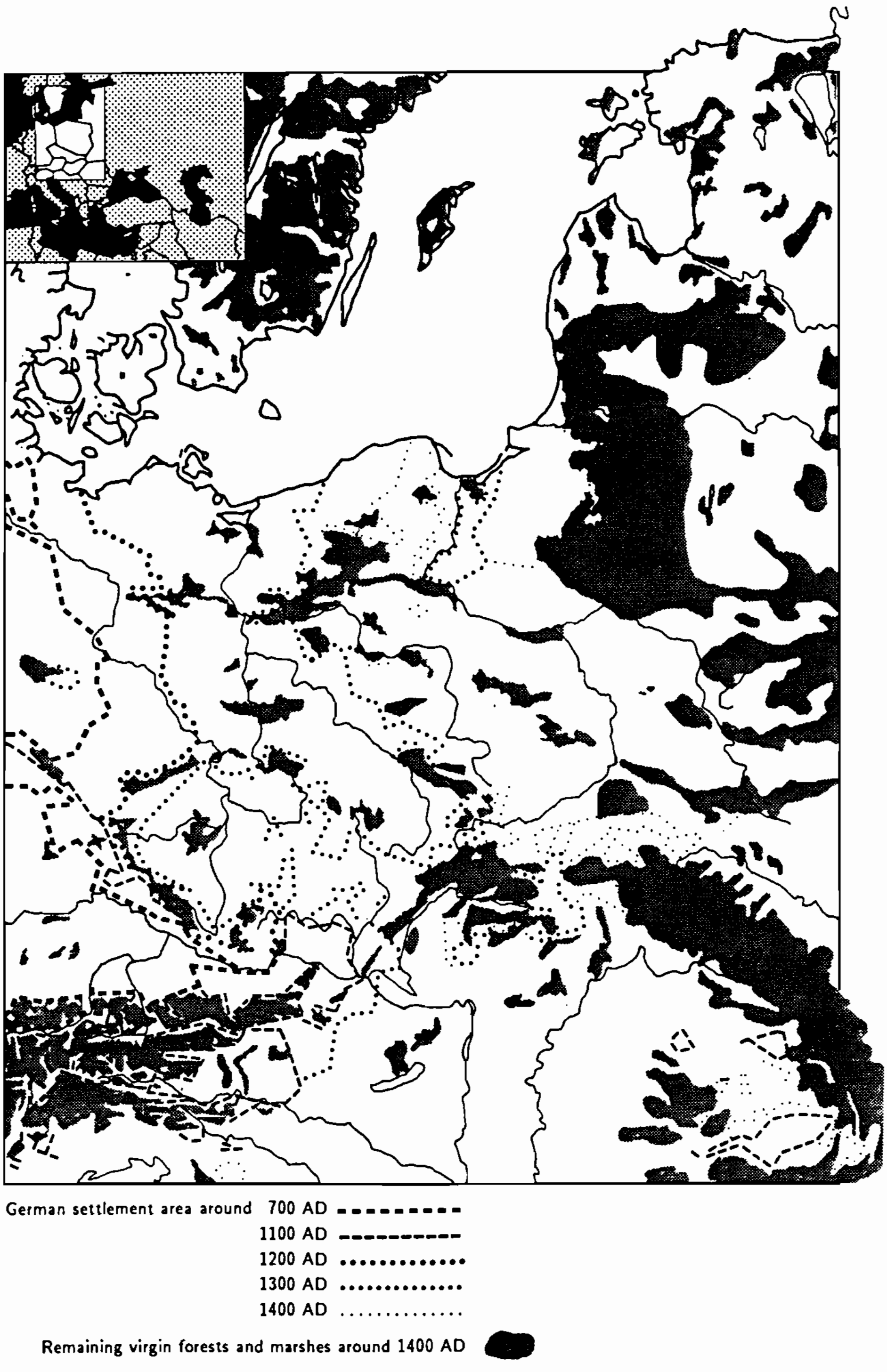

Figure 8. Eastward expansion of German settlement areas, 1100 to 1400. Colonization of sparsely populated areas resulted in significant deforestation in Europe from the 12th to 14th century. By 1400, virgin forests and marshes were confined to remote and mountainous areas. Source: adapted from Putzger 1965:54-55.

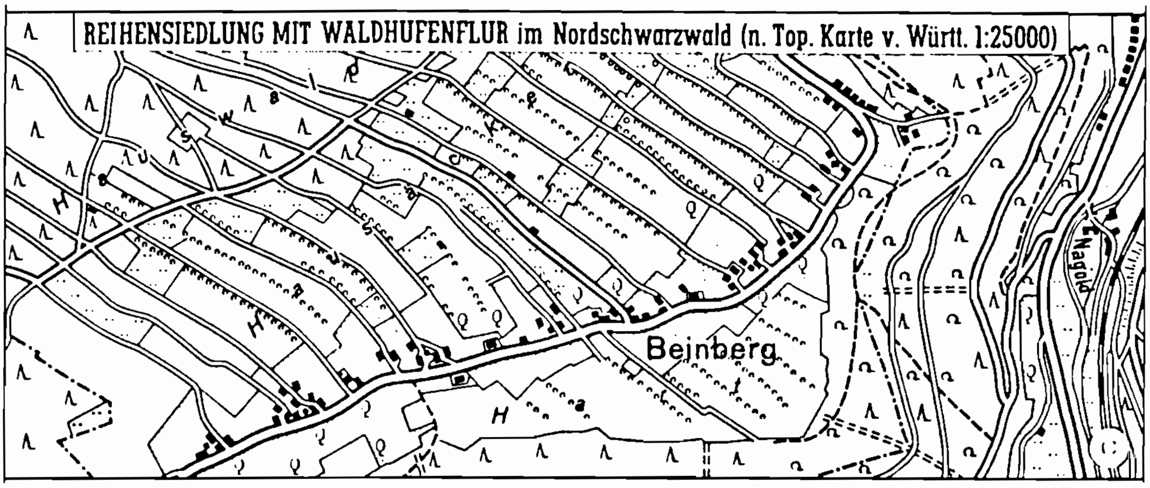

Figure 9. Contemporary evidence of European deforestation: agricultural land and settlement patterns like the "Waldhufen"-form in parts of Austria and Germany bear witness to the impacts of human actions centuries ago. Source: Engel 1979:67.

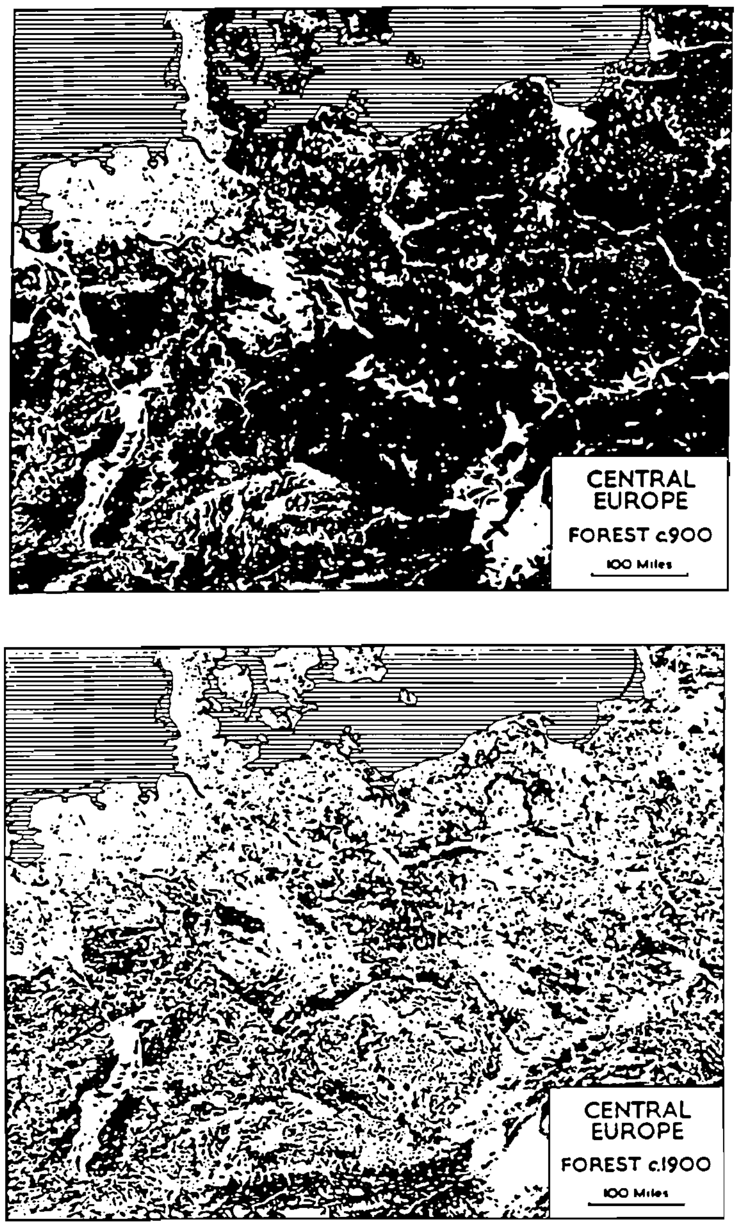

Figure 10. Forests in Europe 900 (top) and 1900 (bottom). The overall European deforestation process (most of it in the 11th to 14th century) is perhaps best visualized by the albedo changes due to large-scale conversion of forests into agricultural land. As such, developments in Europe precede similar transformation processes in other continents of the recent past, even the present. Given low population densities throughout the Middle Ages, European population growth was sustained by drawing on a seemingly unlimited resource: forests. Only after the 1950s do some of these historical transformations begin to be reversed. The application of industrial innovations in agriculture raised productivity to such high levels that some agricultural land was reconverted to forests. During this time period, consistently high output led to agricultural surpluses. Source: Darby 1956:202-203.

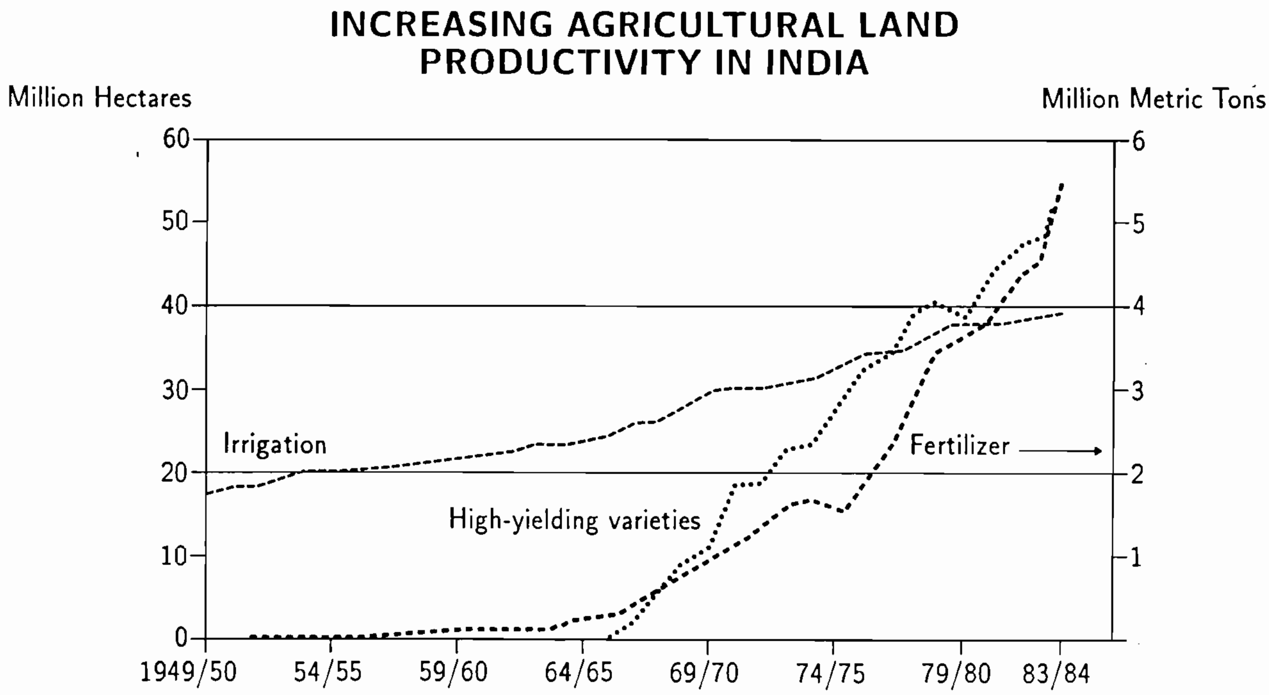

Figure 11. Increasing agricultural land productivity in India since 1950 through the planting of more high yield varieties, the increase in irrigated area and the application of man-made fertilizers. Conversely, increases in the factor input land have been small in the total agricultural productivity growth. Source: Sarma and Gandhi 1990:36.

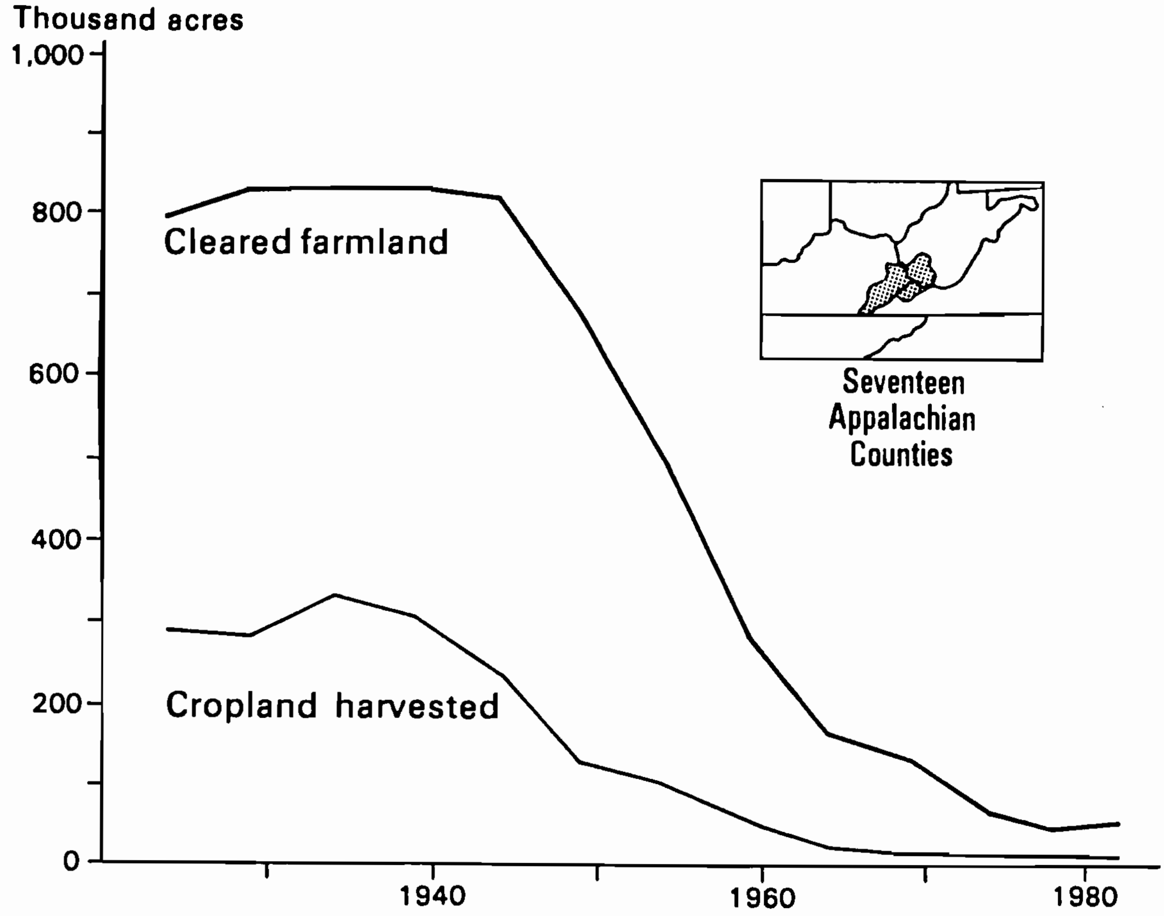

Figure 12. Decrease in cleared farmland and harvested cropland area since the 1930s on the Appalachian Plateau, USA. Agricultural productivity increases have not only vastly raised output (and surpluses) but also resulted in significant reconversion of agricultural land to grassland and forests, particularly in North America and Europe. The ecological and social impacts of this process can be as complex and intricate as the land conversions which previously led to the expansion of arable land. Source: Hart 1991:66.

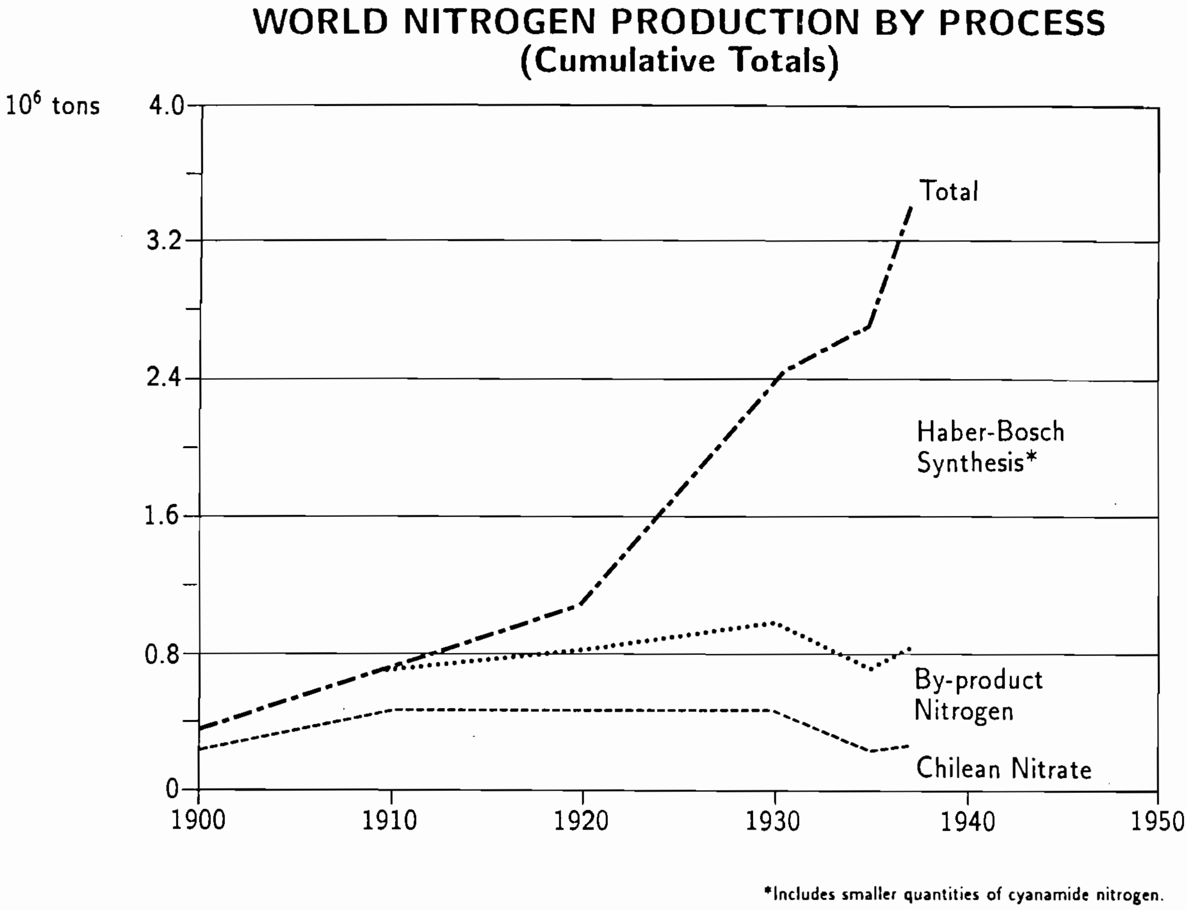

Figure 13. World nitrogen production by process 1900–1938 in million tons (cumulative totals). Ammonia synthesis (by the Haber-Bosch process) was the most important technological innovation for expanding nitrogen fertilizer supply. Already prior to WW II over 80 percent of world nitrogen output was produced using this process. Other nitrogen feedstocks (as a byproduct from coke production and Chilean Nitrate) at peak years did not supply more than one million tons of nitrogen. Current world nitrogen use for fertilizers is close to 80 million tons annually (cf. Figure 14 below). Source: derived from data in Zimmermann 1951:789.

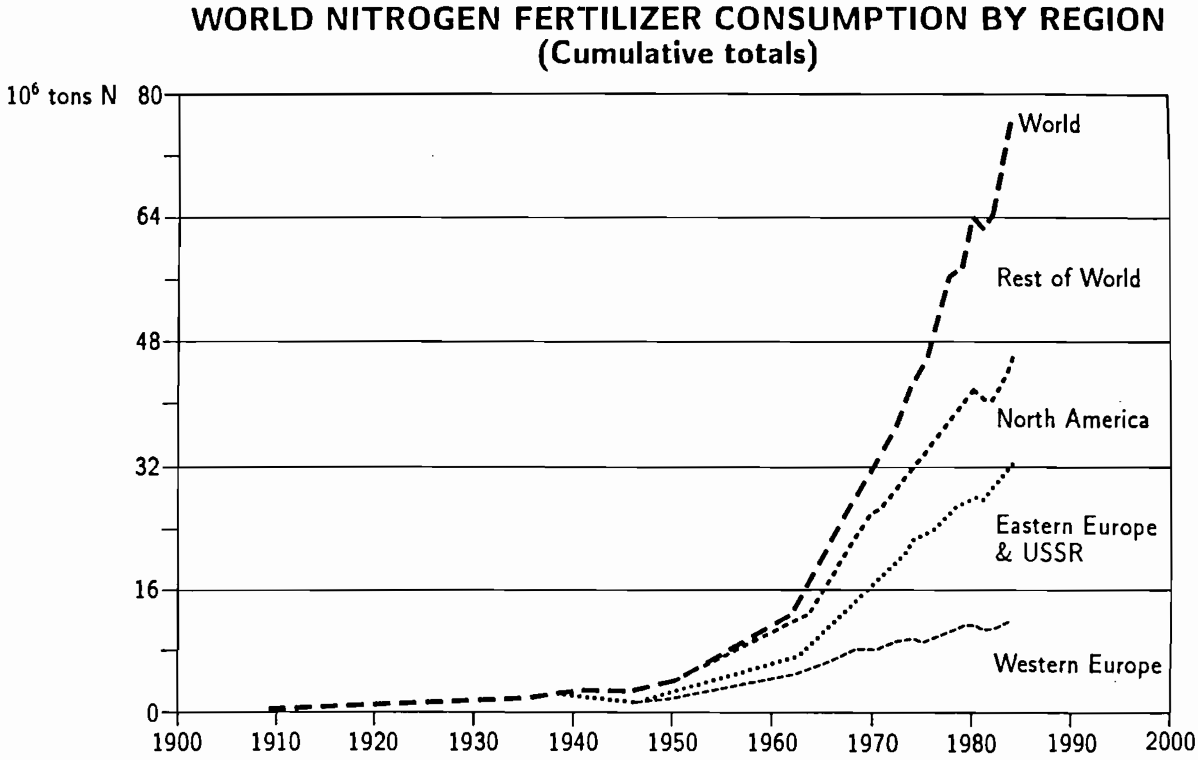

Figure 14. World nitrogen fertilizer consumption (million tons) by region (cumulative totals). Nitrogen fertilizer consumption until around 1970 was mainly confined to industrialized countries. Since 1970 consumption in developing countries has increased rapidly. Currently developing countries consume about 40 percent of the world total, a level which is likely to increase in both percentage and absolute terms. Source: derived from data in Kolmhofer 1987:T3.

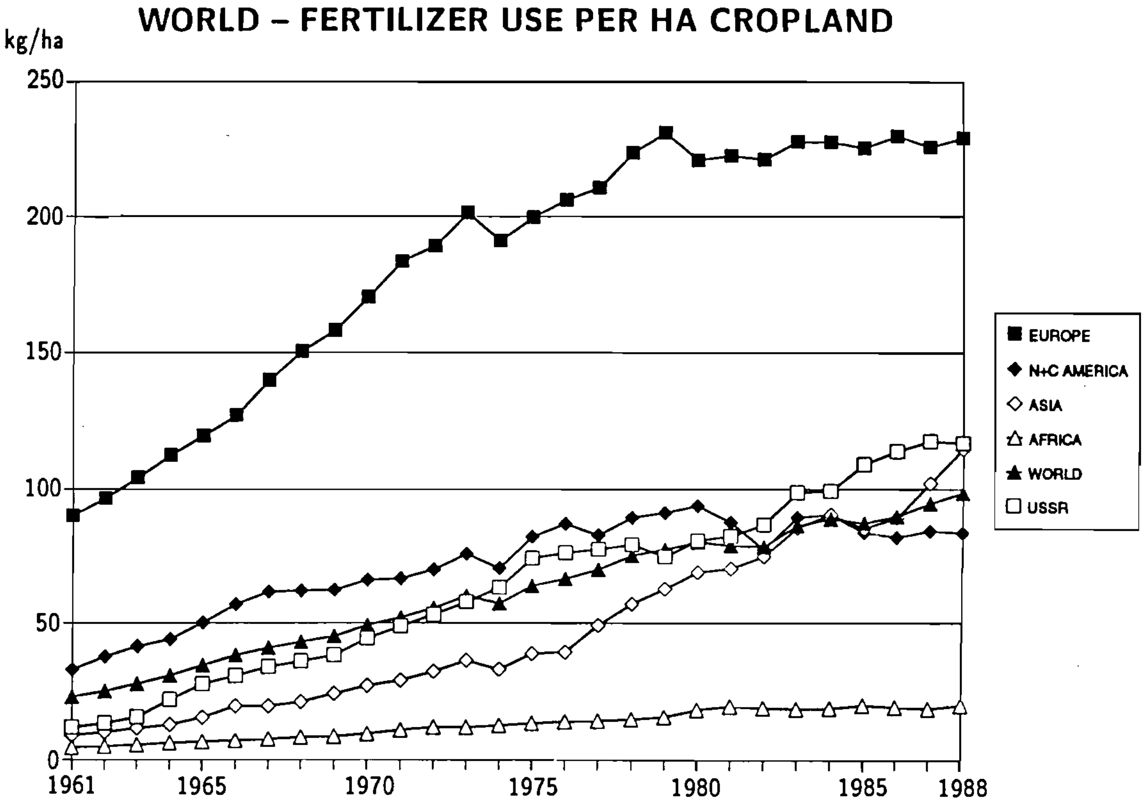

Figure 15. World fertilizer use per ha cropland 1961–1988. Fertilizer application in different world regions (with the exception of Europe and Africa being significantly above and below the world average respectively) has been converging. Current world average is 100 kg of fertilizers per ha. Resulting increases in yields per ha helped to limit even larger scale land-use transformations to arable land for feeding a growing world population. Source: derived from FAO Statistics (var. vols.), Courtesy of G. Heilig, IIASA.

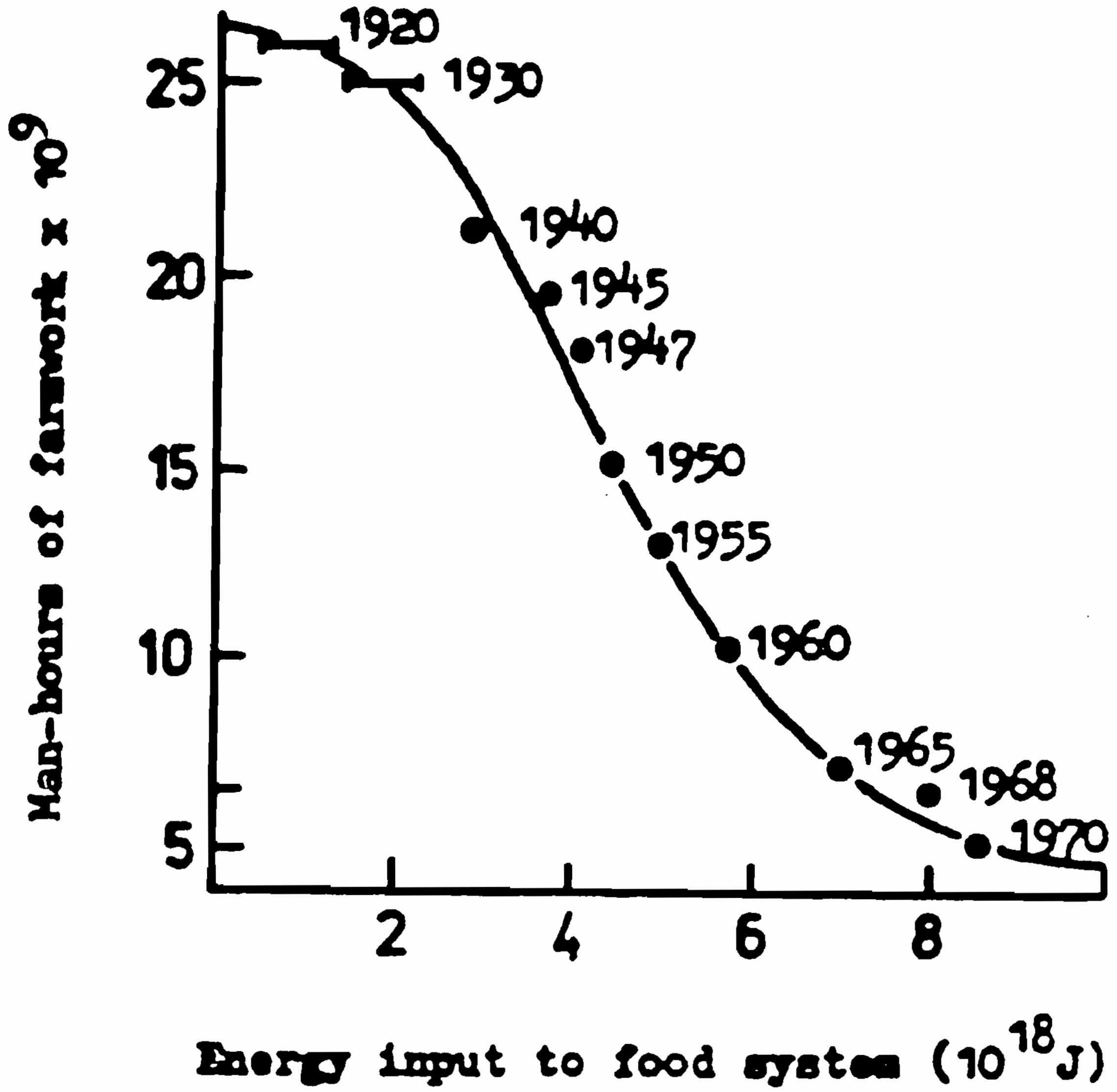

Figure 16. Substitution of human labor in agriculture by mechanization and (fossil) energy inputs, USA 1920-1970. Agricultural labor productivity increases were above all the result of the introduction of mechanization and other industrial innovations. Note that total energy input (including also human and animal energy) to US agriculture increased only slightly over this period despite more than a doubling of output. Mechanization does not necessarily imply increasing energy intensity of agriculture due to the much higher energy conversion of commercial energy applications compared to humans and working animals. Source: Nakićenović *et al.* 1989:29.

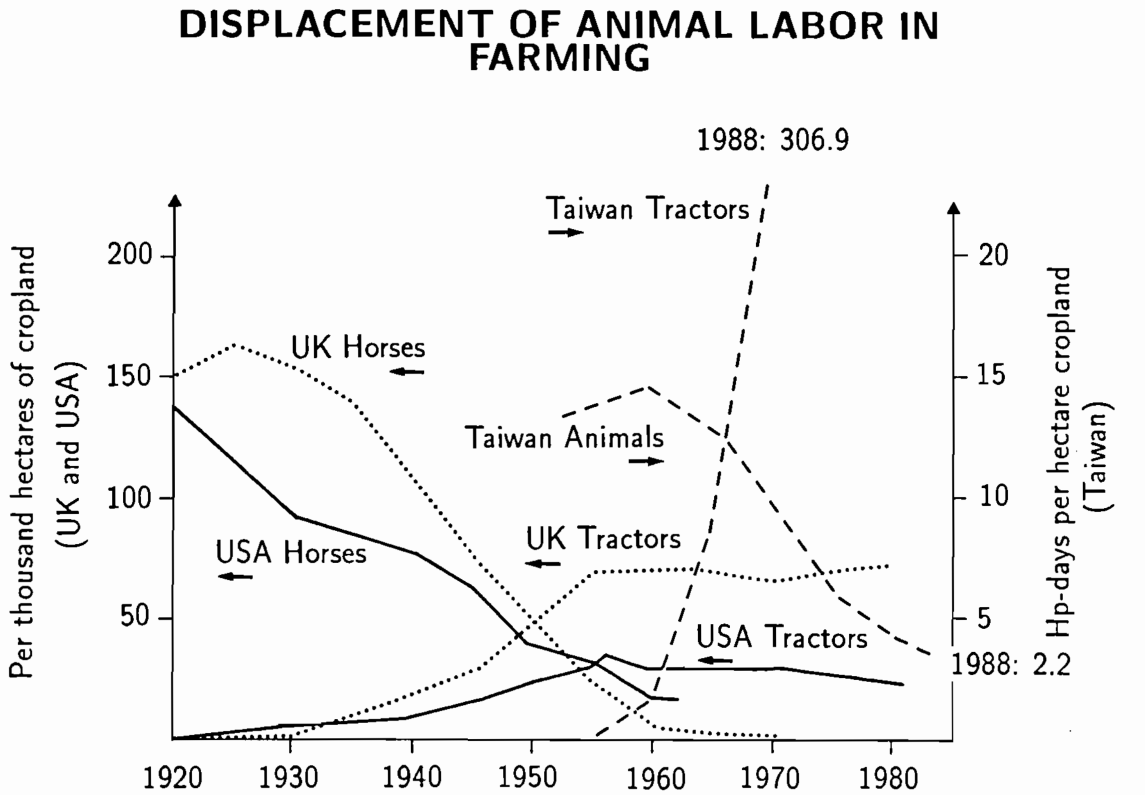

Figure 17. Displacement of animal labor in farming: UK, USA (number of horses and tractors per ha cropland) and Taiwan (hp-days per ha cropland). Mechanization not only vastly increased energy power available on farms but also freed large amounts of land for agricultural production, previously required to feed working animals (about 40 10^6 ha in the USA above). Source: adopted from Grigg 1982:133 and Jones 1991:626.

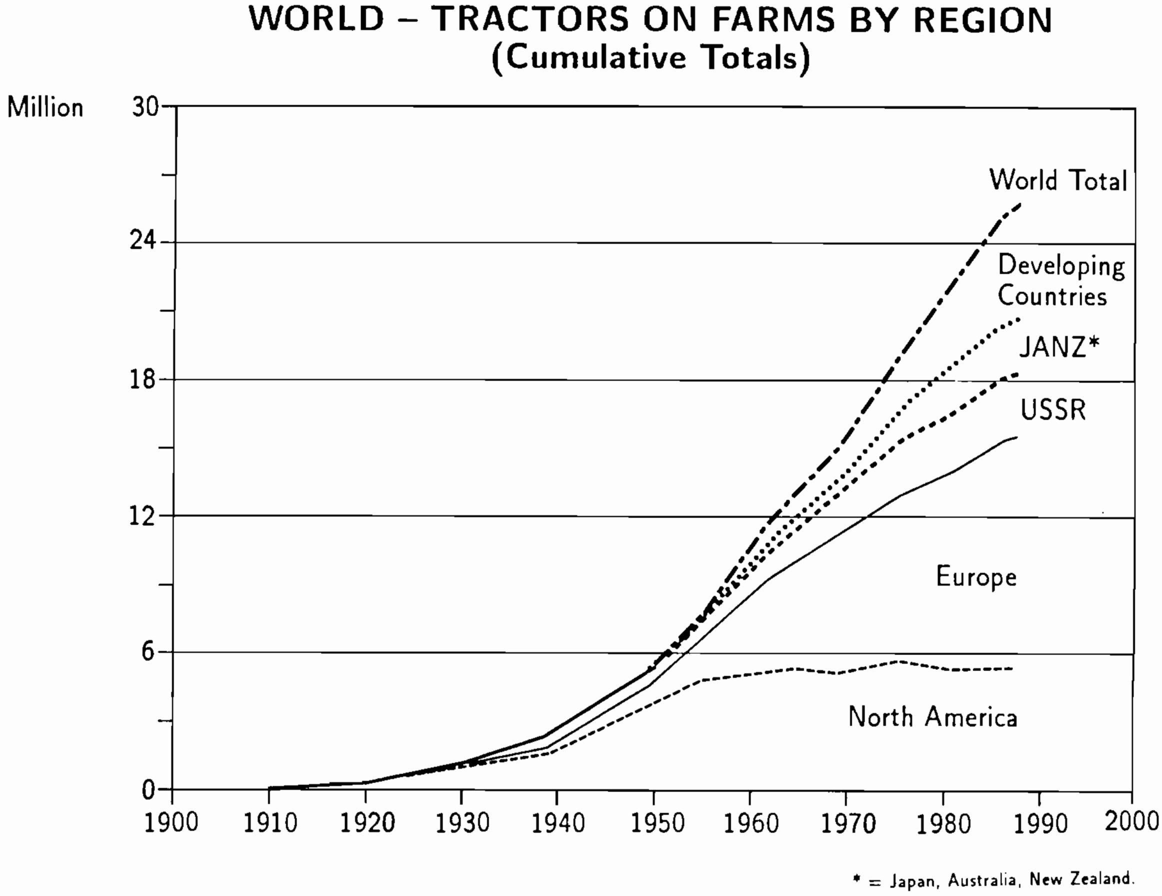

Figure 18. Diffusion of agricultural tractors worldwide and by region (cumulative totals), in millions. Farm mechanization, which started in North America and Europe (cf. Figure 17 above), is becoming an increasingly global phenomenon. The number of farm tractors worldwide had grown to around 26 million in 1988. Source: derived from Woytinsky and Woytinsky 1953:515, and FAO statistics (var. vols).

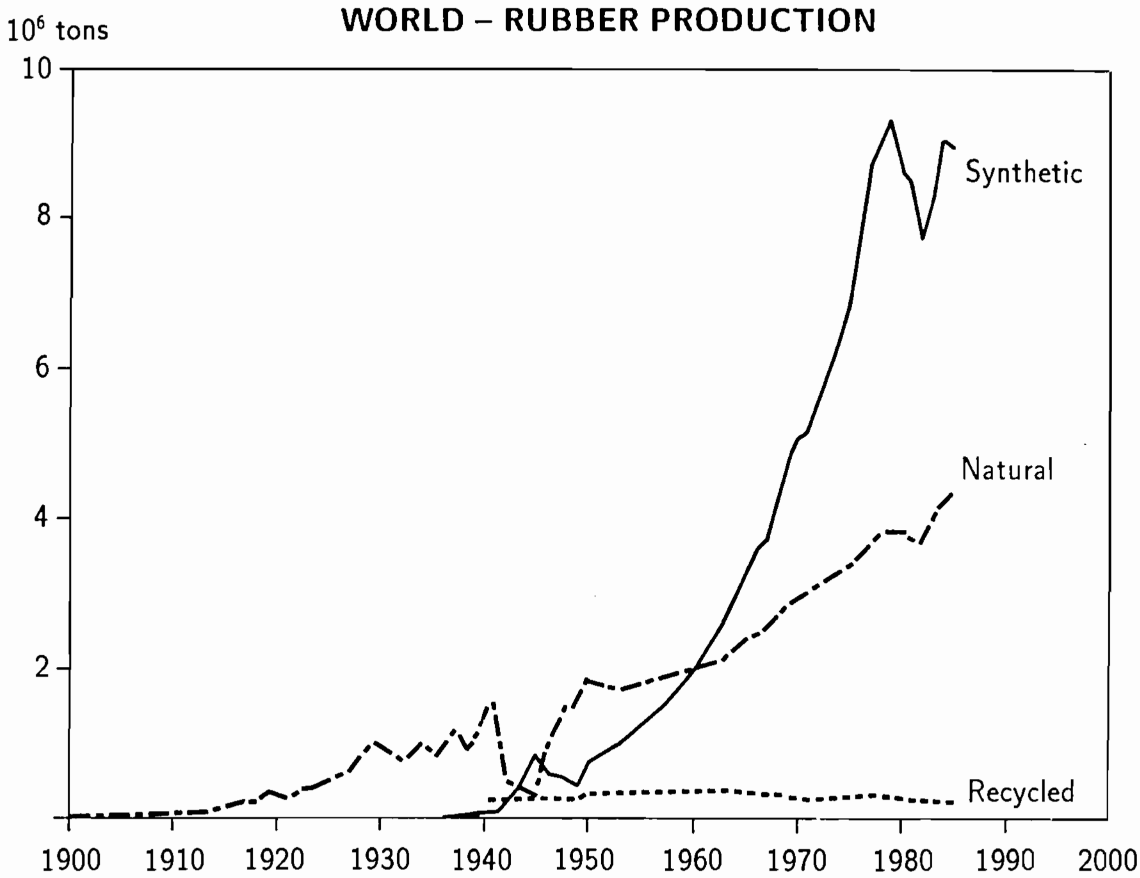

Figure 19. World rubber production: synthetic, recycled and natural, in 10^6 tons. Growing rubber demand from the electrical and automotive industries were first satisfied by large rubber plantations, primarily in Southeastern Asia. After WW II synthetic rubber assumed most of the expansion in rubber demand worldwide, minimizing thus further expansion of plantations. Trends in the production of textile fibers have been similar. Source: derived from data in Woytinsky and Woytinsky 1953:621–623 and UN Statistical Yearbook (var. vols.).

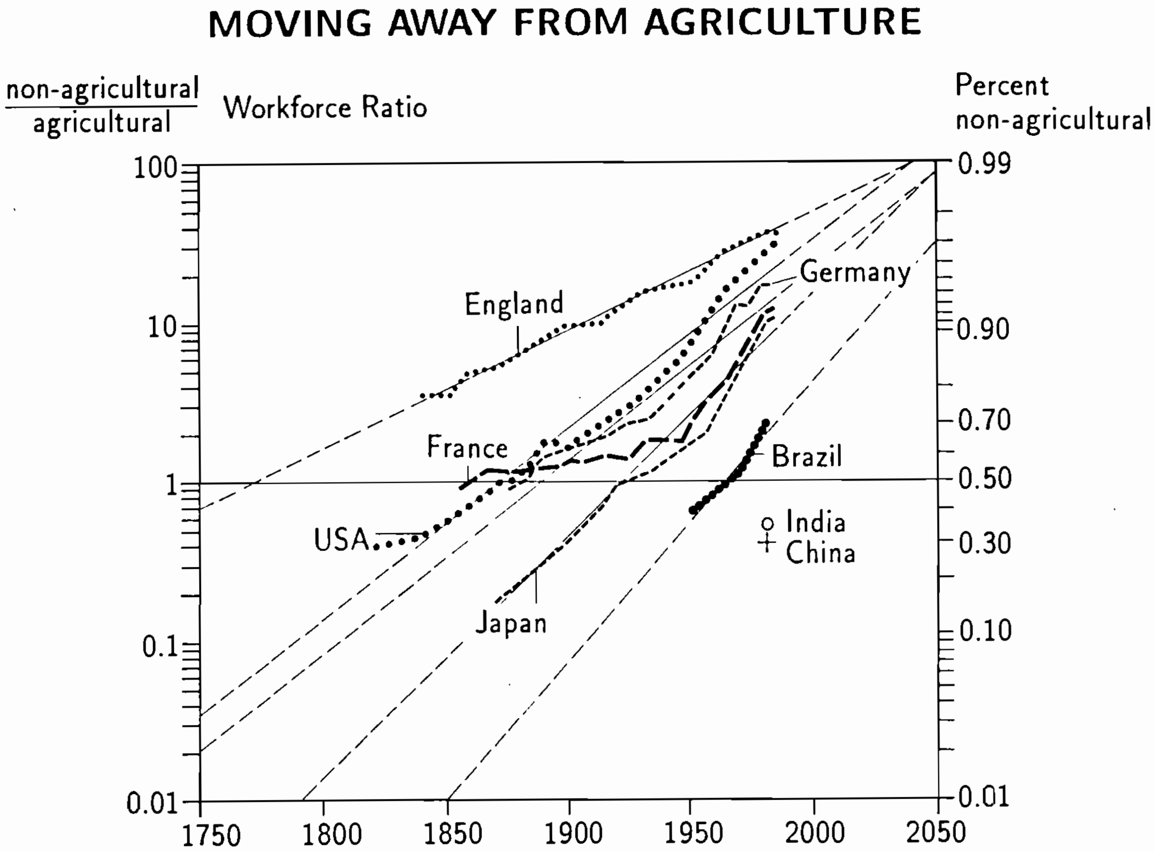

Figure 20. Moving away from agriculture: ratio of non-agricultural to agricultural workforce (logarithmic scale). Productivity increases in agriculture enabled increasing shares of the population to engage in economic activities outside the agricultural sector. Industry and services now provide many functions previously performed by agriculture. This structural transition was initiated in industrialized countries and accelerates over time. Thus, countries are converging towards a level at which only a few percent of the workforce is employed in agriculture. The rise of urbanization (cf. Figure 21 below) is a perfect mirror image of this pervasive structural transformation. Source: derived from data in Mitchell 1980:161–173, Mitchell 1982:84–93, and Mitchell 1983:150–160.

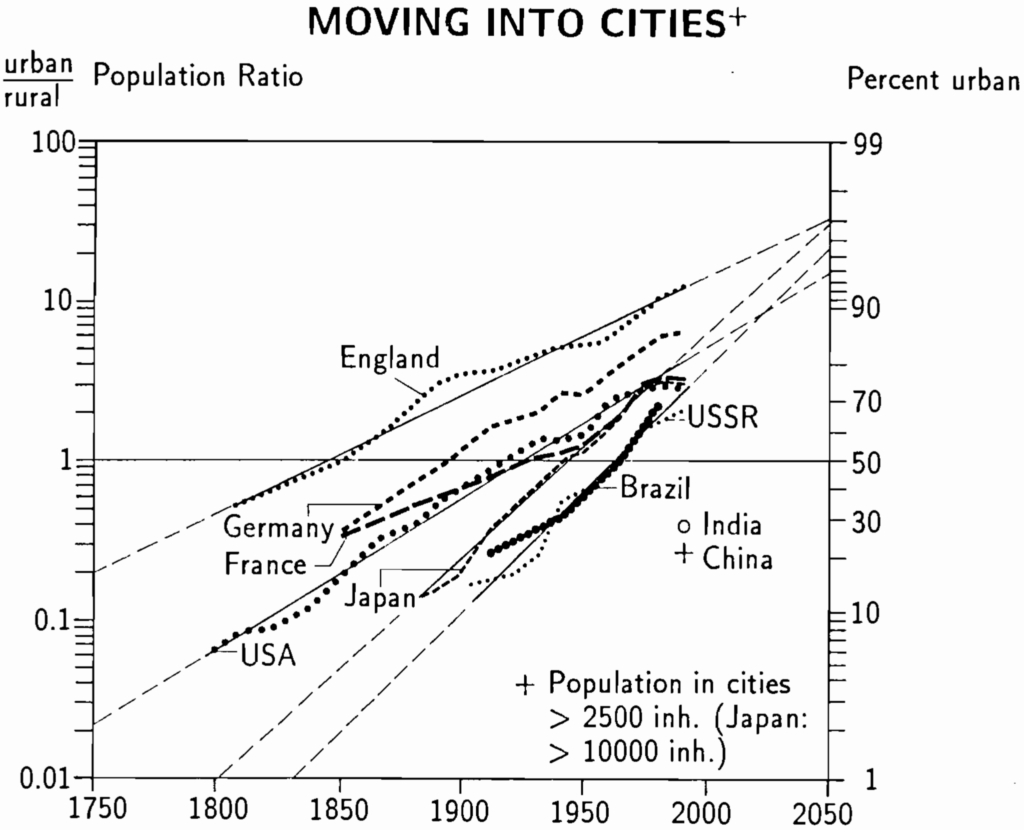

Figure 21. Moving into cities: ratio of urban to rural population (logarithmic scale). Freed from agriculture people seek urban employment and residence. Countries in which urbanization started earlier require long time periods for this structural change and are currently characterized by the highest urbanization ratios. Urbanization trends accelerate over time, so there is overall convergence towards large metropolitan population concentrations. The (painful) growth of many urban centers in the developing world illustrates the combined effects of changes away from agricultural employment, migration from rural to urban areas, and high population growth rates of the urban populace. Source: derived from data in Flora 1975:27–56, and UN Statistical Yearbook (var. vols.).

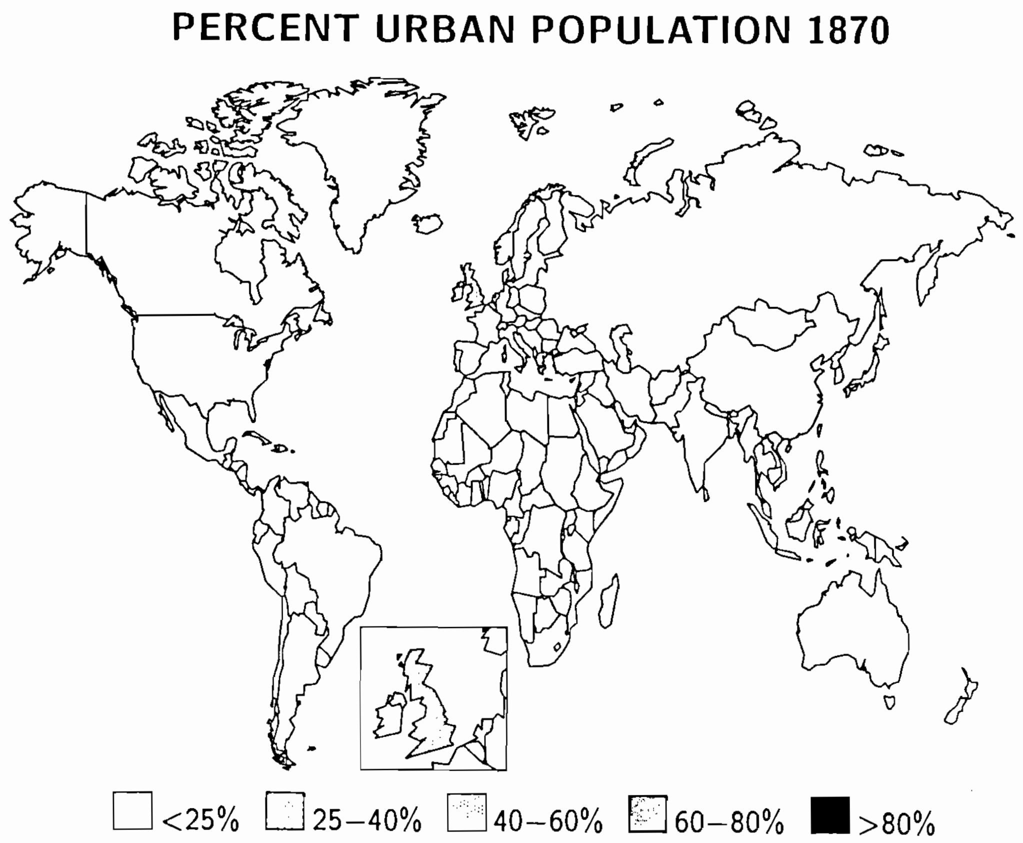

Figure 22 (A). The spread of urbanization as a global phenomenon illustrated by a few snapshots in time: 1870 (A), 1930 (B), 1950 (C), and 1985 (D). Degrees of urbanization correlate with the shift away from agriculture and the pervasive development of high productivity transport systems, canals and railroads in the 19th century and roads (used by cars in OECD and by buses in [former] centrally planned economies and developing countries) in the 20th century.

PERCENT URBAN POPULATION 1930

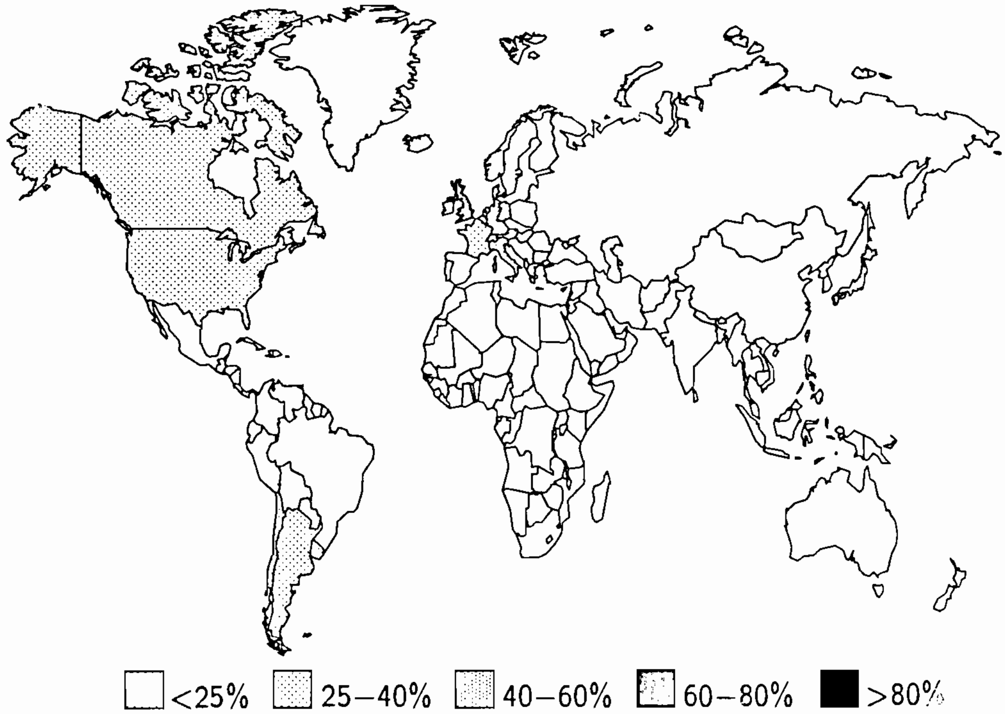

Figure 22 (B).

PERCENT URBAN POPULATION 1950

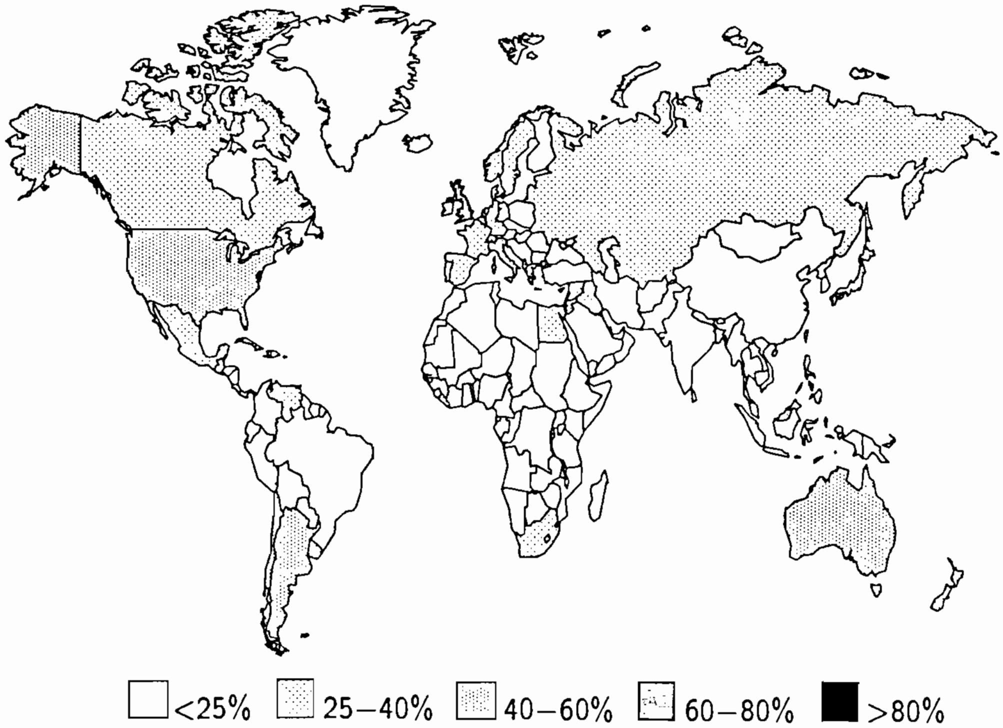

Figure 22 (C).

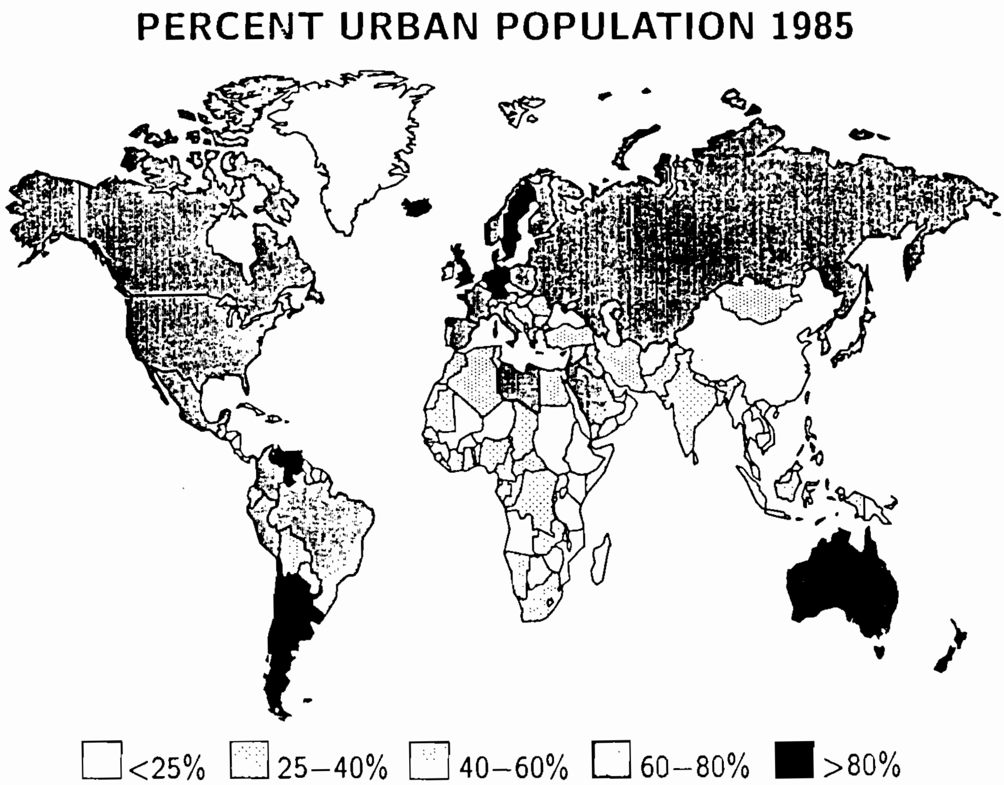

Figure 22 (D).