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Anthropogenic Albedo Changes and the Earth's Climate

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Summary. The human species has been altering the environment over large geographic areas since the domestication of fire, plants, and animals. The progression from hunter to farmer to technologist has increased the variety and pace more than the geographic extent of human impact on the environment. A number of regions of the earth have experienced significant climatic changes closely related in time to anthropogenic environmental changes. Plausible physical models suggest a causal connection. The magnitudes of probable anthropogenic global albedo changes over the past millennia (and particularly over the past 25 years) are estimated. The results suggest that humans have made substantial contributions to global climate changes during the past several millennia, and perhaps over the past million years; further such changes are now under way.

Alterations of the terrestrial environment by *Homo sapiens* are geographically widespread and encompass nearly every aspect of the natural world. The water we drink, the food we eat, the air we breathe, the microenvironments in which we live have all been anthropogenically altered on a global scale. During the past two decades, concern has been expressed that current human impact on our environment may be large enough to induce climatic changes which might in turn have significant agricultural and other consequences (*1*, *2*). A preoccupation with the climates of the present and the future and a widespread view that only modern technologists are effective in assailing the environment have led most investigators to dismiss the possibility of climatic variation induced by previous anthropogenic changes in the environment.

In contrast, there is excellent evidence that humans long have held rapacious views toward their surroundings and, at least since the domestication of fire, have been modifying their environs over vast geographical areas. The environmental changes wrought by ancient peoples are so extensive as to be good suspects in the search for causes of ancient climatic perturbations, and, because most environmental changes persist, historical environmental changes may affect the contemporary climate as well as the global environment of the near future. Further, the study of past anthropogenic changes in the climate may help us to understand the implications of such current activities as massive deforestation.

Motivations for Environmental Change

Table 1 shows a crude division of human history and some motivations for environmental change during each epoch. Also listed are a number of environmental changes that have been seriously proposed as anthropogenic and suspected of inducing climate change. Of course, some of these environmental changes may have been due partly to natural causes. For example, some forests may have been converted to grassland by changing climatic conditions following the end of the last ice age, 10,000 years ago.

Although the human population of the earth has increased dramatically recently, humans have been widely distributed for hundreds of thousands to millions of years. Powerful motivations exist for small bands of pretechnological peoples to employ fire in modifying large areas, and direct evidence of such extensive modification is available. The remains of *Homo erectus*, the first hominid whose endocranial volume overlaps that of modern humans, are clearly associated with the remains of fire in sites dated at $\sim 5 \times 10^5$ years ago (*3*, *4*), and much older fossil remains of *H. erectus* are known. As humans evolved they learned to produce and employ fire, and by 10,000 to 20,000 years ago they had profoundly affected the abundance and distribution of vegetation by its use (*3*, *4*).

Preagricultural peoples not only caused numerous accidental fires but also intentionally set fires to clear brush from forests; to make hunting by humans easier and predation on humans less probable; to drive game during the hunt; to improve pasture for wild and domesticated animals; to increase the yield of seeds from wild plants; to make it easier to harvest wild nuts and berries; and to wage war (*3*).

Direct evidence that primitive peoples used fire extensively comes from ancient explorers. In 1520, when Magellan passed through the straits that bear his name, he saw so many fires set by indigenous South Americans that he named the region Tierra del Fuego, or "Land of Fire." Records of the earliest circumnavigation of Africa by Hanno refer to massive fires, which are now believed to be the annual burning over of the grazing region south of the Sahara (*5*,

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6). Native Americans burned extensive areas to improve hunting grounds and catch game, as reported by early European explorers (3, 4), and for religious and calendrical ceremonials (7).

Agriculture peoples have also laid waste to natural vegetation, primarily to expand farm and grazing land. For example, about 60 percent of central Europe was converted from forest to farmland during the last 1000 years (8). Such examples (see Table 1) demonstrate that the most significant difference between human impact on the environment in the present technological era and during the agricultural and hunting eras is an increase in diversity and rate of change rather than extent.

Land Use Changes and Microclimate

The human population density has increased to about one person per 0.04 square kilometer. Hence if each person who ever lived modified only a very small nearby area, most of the earth's surface would be altered. Changes in land use, from temperate forest to cropland, from tropical forest to savanna, or from grassland to desert, alter the microclimate. Microclimatic changes are significant because humans live within the microclimate, under the trees and among the grasses. Indeed, many environmental changes are undertaken to make the microclimate more pleasant. Simply altering ground cover affects surface albedo and runoff, changes the ratio of sensible to latent heat transport, and greatly modifies the surface winds. These variations in turn cause soil moisture, temperature, and erosion rates to change. That such changes are of great significance is evident from the extensive efforts of modern agriculture to control them (9).

Microclimatic variations are globally distributed and so represent one type of global climatic change. Human influence on climate in the past goes beyond purposeful alterations in the microclimate, however, and two major questions immediately arise for historians and climatologists: (i) Did the human species, prior to the technological era, accidentally cause regional microclimatic or macroclimatic changes? (ii) Have anthropogenic changes, intentional or inadvertent, in the environment and microclimate in one region caused changes in the climate in other parts of the globe?

We believe that the answer to both questions is yes. Below we discuss several examples of arid, tropical, and temperate regions in which there is evidence of climatic change, evidence of extensive environmental modification by humans, and good reason for believing that the two are related. Each of these regional climatic changes deserves much further research and none is completely understood at present. It is not the availability of absolutely compelling evidence that causes us to believe regional climate changes have been caused by humans, but rather the large number of cases in which the available evidence points to human intervention. Below we also estimate the geographic area altered over the millennia, and over the last 25 years, for each of five forms of land use modification. We then relate these environmental alterations to the global climate by estimating the changes in global albedo caused by the land use modifications (Table 2). The details of present-day land use are inadequately known; accordingly, it is not possible to estimate the fine-scale land use changes over the millennia and then integrate to obtain the global net change. Instead we estimate the global area in various land use categories and then employ case studies in limited regions to estimate the fraction of the category created by humans. Some scientists have proposed that all of certain land use categories, such as grasslands, were anthropogenic. We take the more conservative view that humans have not created totally any basic land use type other than urban areas and irrigation networks. It is not possible from current data to make estimates of land use area changes that are accurate to better than a factor of 2.

Desertification

Humans may have accidentally caused a number of regional climatic changes in arid lands. The Rajasthan Desert of India covers about 10^6 km^2 or ~ 0.7 percent of the earth's continental surface area. Several thousand years ago this region was the site of the Indus Valley civilization. Even though the region was arid, it was apparently then much wetter and more clement than it is today. The Rajasthan Desert is accessible to atmospheric moisture; indeed, the tropospheric humidity above it is high. Bryson and co-

Table 1. Anthropogenic changes in the environment.

Epoch	Some motives for environmental change	Some (largely) inadvertent environmental changes and examples of their timing
Hunting and gathering	Preparation of land	Deforestation of temperate regions (North America, Native American creation of grassland to about A.D. 1600; Eastern Europe, production of steppes—preclassical)
		Deforestation of tropical regions (Africa, production of savannas—since discovery of fire)
Agricultural	Expansion of farmland	Desertification (Sahara-Arabia region, beginning about 5000 B.C. to present; India, Pakistan, Sumeria, 2000 B.C. to A.D. 400; Peru, about A.D. 1200)
	Generation of energy	Deforestation of temperate regions (China, 2000 B.C. to A.D. 1950; Mediterranean Basin, 500 B.C. to A.D. 500; Western and Central Europe, A.D. 1000 to 1900; United States, A.D. 1800 to 1900)
		Deforestation of tropics (Africa, Indonesia, South America, since origin of agriculture)
Technological	Urbanization	Creation of urban heat islands
	Expansion of farmland	Concentration of surface and water pollutants
	Creation of artificial lakes	Alteration of hydrological cycle by farming and irrigation
	Production of synthetic chemicals	Destruction of soil by increased erosion
	Generation of energy	Alteration of composition of atmosphere (carbon dioxide, aerosols, smog)
	Production of raw materials	Destruction of natural plant and animal communities (desertification, deforestation, temperate and tropical regions—changes mainly after about 1800)

workers (*10*) suggest that the lack of rainfall is caused by subsidence of the atmosphere, which is caused by radiative cooling by suspended dust, which in turn is caused by lack of vegetation, which, finally, is caused by overgrazing. Rapid growth of grass in areas protected from grazing confirms that the lack of vegetation is due to overgrazing and thus ultimately to the domestication of animals. Although it is clear that the Rajasthan Desert has expanded over the millennia and that overgrazing has contributed directly to this growth by destroying vegetation, the role of dust in creating the desert is still being debated. Recently, Harshvardhan and Cess (*11*) completed calculations suggesting that the radiative cooling due to dust is less important than Bryson believed.

In the Sahara, deserts also cover ancient farming villages, demonstrating that the water balance was once more favorable. Humans have been living in the Sahara and modifying it extensively by fire and grazing activities for many thousands of years. Substantial desertification has occurred ever since the Middle Ages, and examples abound of areas, now desert, that several centuries ago were reported by explorers to be forested and populated with animals and humans (*12*). Most investigators agree that the human species is strongly incriminated in these changes, but it is difficult even today to understand the interaction of natural and human agencies in the extension of the Sahara (*12*).

Wade (*13*) suggests that the recent desertification of the Sahel, south of the Sahara, is due entirely to a rapid expansion of the numbers of people and animals in the area. He notes that despite recent drought conditions, regions in which grazing has been managed remain as pasture. A simple wire fence is enough to keep out the desert. Winstanley (*14*) argues that drought is the main agent of desertification, and that drought results from a change in the global atmospheric circulation and is thus not anthropogenic (at least not in the Sahel). While Moore (*15*) agrees that drought is an aspect of the general circulation, he suggests that desert expansion occurs because the Sahel plant ecology has been anthropogenically modified and made less hardy. He believes that the natural vegetation could have coped with the variability of weather and climate. Charney and co-workers (*16*) and Otterman (*17*) suggest that a decline in the surface density of vegetation will alter the surface albedo and change the surface water budget, thereby inducing changes in the large-scale circulation that feed back in a positive sense by causing further vegetation declines through reduced precipitation. In these models, humans may alter the vegetation, which then changes the climate; or a global climatic shift that destroys vegetation may become self-sustaining.

Table 2. Global albedo changes.

Process	Land type change	A, cumulative area altered		Present areal rate of change		Δr_s, surface albedo change	F, cloud cover fraction	I, insolation factor	ΔR, global albedo change	
		km²	% of earth's area	km²/year	%/year				Cumulative over past few millennia	Over ± 25 years from present
Desertification	Savanna → desert	9×10^6	1.8	6×10^4	1×10^{-2}	$0.16 \rightarrow 0.35$	0	1	4×10^{-3}	6×10^{-4}
Salinization	Open field → salt flat	6×10^5	0.1	1.5×10^4	3×10^{-3}	$0.1 \rightarrow 0.25$ to 0.5	0.25	1	1.5×10^{-4} to 4×10^{-4}	1×10^{-4} to 2.5×10^{-4}
Temperate deforestation	Forest → field, grassland	8×10^6	1.6	Small		$0.12 \rightarrow 0.15$ (summer) $0.25 \rightarrow 0.6$ (winter)	0.5	0.8 0.1	2.5×10^{-4} 4×10^{-4}	Small
Tropical deforestation	Forest → field, savanna	7×10^6	1.4	1×10^5	2×10^{-2}	$0.07 \rightarrow 0.16$	0.5	1.2	1×10^{-3}	3.5×10^{-4}
Urbanization	Field, forest → city	1×10^6	0.2	2×10^4	4×10^{-3}	$0.17 \rightarrow 0.15$	0.5	1	-2.5×10^{-5}	-1×10^{-5}
Total		26×10^6	17 (continents) 5 (total area)						6×10^{-3}	1×10^{-3}

Other arid areas of the world that have been modified by human activities include Lebanon, where excellent historical documentation exists of thousands of years of deforestation of the *Cedrus libani* and subsequent desertification. In the "Palermo Stone," dated around 2600 B.C., there is an account of the transport of "forty shiploads of cedar" from Lebanon to Egypt; the wood was highly prized and was a staple of the Phoenician economy (*5, 6*). Although most damage in arid lands is due to overgrazing or deforestation, another important problem is salinization by irrigation projects. In Iraq, 20 to 30 percent of the country's potential farmland has in this way been converted into desert (*18*).

These and numerous other examples show that people have very likely destroyed vegetation over vast areas of arid land during the last few thousand years. The vegetation loss in turn has altered the water budget unfavorably, allowing the soil to be destroyed, and desertification has been the result. Otterman (*18*) estimates that 3.4×10^7 km² of arid lands have been converted to desert. Our estimate (Table 2) of 9×10^6 km² is roughly half the area classified as deserts, excluding stony, sandy, and polar desert (*19-21*), reflecting our belief that natural forces have created some deserts; it is in accord with other qualitative discussions (*9-12*). The present rate of desertification in Table 2 was estimated at the 1977 United Nations conference on desertification (*20, 21*). Eckholm (*5*) estimates that one-third of irrigated lands today have serious salinization problems and also gives figures for the area covered by irrigation projects. These were used to determine both the cumulative amount of salted land and the present rate of conversion (Table 2).

Deforestation

In the tropics, ancient peoples altered the regional microclimate by burning humid forests as part of a constantly shifting land use practice known as slash-and-burn agriculture. Some 40 percent of the African equatorial forests have been converted to savanna over a few millennia, and half the remaining forest has been altered (*22*). Large areas of Indonesia and South America have also been modified. Brazil has lost 40 percent of its forests and all the grasslands of that country may be anthropogenic (*22*). Currently, tropical forests are being cleared at a rate of 5×10^4 to 25×10^4 km^2 per year (*20, 21*). Others have estimated that 10^7 km^2 of tropical forest has probably been destroyed in the last few thousand years (*2*). Savannas, which some consider to have been entirely converted from tropical forest, now cover 1.5×10^7 km^2. We adopt a more conservative estimate, 7×10^6 km^2, of tropical deforestation (*20, 21*), which is 5 percent of the continental surface area and about 50 percent of the present tropical forest area. Some 3×10^6 km^2 of converted tropical forest land is now under cultivation.

The differences between the microclimates of tropical forests and of denuded areas are immense. When forests are removed the daily ground temperature variation is greater and the soil is less protected from torrential downpours, both resulting in destruction of the land for agriculture purposes and presenting major problems for human beings (*5*). To our knowledge, only Potter *et al.* (*23*) have studied the interaction of tropical regional microclimatic changes and the global climate. They estimated both the albedo and water budget changes due to conversion of all remaining tropical rain forest to grassland and found that the changes might induce globally significant climate changes. Their estimate of the albedo of cleared tropical forest, however, seems too large (*24*). Since the tropical forests converted to grassland over the millennia are comparable in area to the tropical forest remaining, it is quite possible that the global climate has already been affected by tropical deforestation.

In the Mediterranean Basin and in China, early civilizations long ago destroyed their temperate forests, but in North America and most of Europe the destruction of temperate forests has been concentrated during the past 10^3 years and especially during the last 500 years; reforestation is now occurring. Some have estimated that over the millennia 1.5×10^7 to 2×10^7 km^2 of temperate forests have been converted to arable land and grassland (*2*). This is about 10 to 15 percent of the earth's continental surface area and is comparable to the total area now in temperate grassland and nontropical cultivated land. In Table 2 we adopt a more conservative area estimate of 8×10^6 km^2, which we derive by assuming that the present 1.2×10^7 km^2 of temperate evergreen and deciduous forest is 60 percent of the original forest area. The fraction of forest destroyed is in agreement with the results of most investigators (*5, 6, 8, 20, 21*).

In 1824 Thomas Jefferson recognized the need for a study of the significance of temperate deforestation for regional or global climate (*25*). It does not appear that such a study has been conducted before now. The microclimates of temperate forests and grass or croplands are clearly very different [for example, see (*26*)].

The most intriguing relation between temperate deforestation and macroclimatic change is the apparent near coincidence of extensive North American and European deforestation with the Little Ice Age (*27*). The Little Ice Age is the period from roughly A.D. 1200 to 1900 during which mountain glaciers were more advanced and vegetation in marginal areas was under greater stress than they are at present or were before A.D. 1200. The period from roughly 1400 to 1600 was somewhat milder than the periods from 1200 to 1400 and from 1600 to 1900, although the details of the climate from 1200 to 1600 are rather poorly known (*1, 27*). The global mean temperature during the Little Ice Age is thought to have been $\sim 0.5°$ lower than the present value, with high-latitude sites most affected (*27*). In the United States the greatest period of deforestation was the 19th century. By World War I American forests had declined by 60 percent (1.5×10^6 km^2); reforestation of about 5×10^5 km^2 has since occurred (*20, 21*). Within Europe extensive deforestation began in about 1100; advanced until 1300; then, because of plague, declined markedly between 1350 and 1450; and began again in earnest by 1500. As in the United States, the forest minimum was reached during World War I and some reforestation has since occurred. About 80 percent of central Europe was forested in A.D. 900, but only 25 percent by 1900 (*8*). The deforestation was so extensive that Britain experienced a wood crisis in 1550 and therefore turned to coal (*28*). Curiously, a serious coal pollution problem was noted in Britain between 1300 and 1400 and after 1550, but not between 1400 and 1550, in good agreement with the periods of deforestation and with the warmer interlude of the Little Ice Age.

In addition to the fact that the timing of deforestation and of the Little Ice Age seem to have coincided in some detail, there is a physical mechanism for a relationship. The microclimates of forested and cleared regions differ in many ways, but one of the most dramatic is in the winter albedo. The albedo both of snow-covered deciduous and of snow-covered coniferous forests is generally lower than that of snow-covered farmland by 0.2 to 0.5 (*24*). Since the winter albedo of forest land is generally 0.2 to 0.3, deforestation nearly doubles the winter albedo. Such a large change in albedo over an area as extensive as Europe would doubtless affect the regional climate and might well have disturbed the climate over a significant fraction of the globe.

There are, of course, other possible causes of the Little Ice Age such as volcanic activity (*29*) or solar activity (*30*), both of which had observable variations during the period. Also, the present reforestation in Europe and the United States has returned only a small fraction of the land to forest, so it is not clear, considering only deforestation, why the earth's climate should have warmed so extensively from 1900 to 1940. In addition, the history both of climate changes and deforestation rates is not so precisely known that we can be confident of their phasing, or that the deforestation was rapid enough to account for the speed of the climate variation. More investigation is clearly warranted.

Implications for Global Albedo and Surface Temperature

In order to place the regional environmental changes just discussed in a global perspective, we present in Table 2 an estimate of the spectrally averaged, atmosphere plus surface, global albedo changes that may have occurred cumulatively over the millennia, and during the past 25 years, due to several land use modifications. We find the global albedo change from each cause, i, to be $\Delta R_i = A_i I_i\ [F_i \Delta r_t + (1 - F_i)\ \Delta r_s]$; the terms are defined in Table 2, except for the albedo change in the presence of clouds, Δr_t, which we obtain, neglecting aerosols and gases, by considering multiple reflections between cloud and ground from $r_t = r_c + (1 - r_c)^2 r_s / (1 - r_s r_c)$. We have adopted a cloud albedo $r_c = 0.48$ to obtain the observed global albedo of 0.3 with a mean surface reflectivity of 0.1. The surface albedo changes Δr_s were obtained by differencing measurements of the surface albedo of various land use types (*24*). The albedo measurements vary somewhat within a given land use type, due partly to temporal changes caused by solar zenith angle or seasonal vegetation alteration and partly to real variations in albedo within a land use type. In general, the albedos of most land use types are known well enough that albedo differences between land use types larger than about 0.05 can be considered reliable.

In Table 2 the area modified for each land use change has been described above, except for urbanization, for which we employ Wong's (*20*) estimate of the land required per urban dweller and assume 10^9 urban dwellers in the world. We also use Wong's estimate of the rate of increase of urban area. The industrialized area of the world (*2*) is 5×10^5 km^2. The albedo change attributed to salinization is partly due to destruction of vegetation, which exposes bare ground, and partly due to creation of salt flats. The albedo changes in Table 2 (*18, 24*) are particularly uncertain for salt flats, whose measured albedo (*24*) seems lower than qualitative observations (*5, 6*) and older studies (*19*) suggest. The albedo differences in summer between temperate forests and arable land are very small and thus difficult to derive adequately; however, a large albedo difference occurs during winter in areas with snowfall. About half the temperate forests lie in a region of winter snow (*24*). Hence we consider only half the temperate deforested area in Table 2 when computing the winter albedo difference. The albedo change caused by urbanization is also small and difficult to specify accurately, but the change seems to be slight.

Table 2 also incorporates the facts that the cloud cover differs from the globally averaged value of 0.5 over certain regions of the globe through F, and that the insolation is a function of latitude and season through I. For temperate forests we consider the summer aibedo difference to persist over half the altered land for all the year. For the remaining half of the altered land we assume the winter albedo difference to persist for one-third of a year. The values of I reflect these assumptions.

The global albedo changes in Table 2 are uncertain by factors of 2 or 3. Some investigators have assumed larger values than we have for the areas of land altered. The albedo changes are not precisely known, and corrections for cloudiness and latitude are difficult to make with precision. Nevertheless, Table 2 illustrates several important points. The leading cause of global albedo change is desertification, although tropical and temperate deforestation and salinization are also significant. All changes except for urbanization produce an increase in the earth's albedo and a cooling of the planet. The cumulative anthropogenic albedo change is much larger than the change during the past 25 years.

Simple climate models (*31*) suggest that if the global albedo changes from its value of 0.30 by 0.01, a surface temperature change of ~ 2 K will result. Of course, even the most sophisticated current climate models are in an early stage of development and cannot correctly incorporate many processes, such as the feedback between ground albedo changes and cloud cover changes. Hence this relation between albedo change and global temperature change is only an indication of the magnitude of the true relationship. Keeping this caveat in mind, Table 2 implies that during the past several thousand years the earth's temperature could have been depressed by about 1 K, due primarily to desertification, which might have significantly augmented natural processes in causing the present climate to be about 1 to 2 K cooler than the climatic optimum (*1, 2*) of several thousand years ago. Global temperature changes of this magnitude have profound consequences for human populations. Table 2 also suggests that land use changes during the past 25 years were capable of depressing global temperatures by ~ 0.2 K. Observations show that since 1940 the global mean temperature has declined by ~ 0.2 K, despite an accelerated increase in the carbon dioxide content of the atmosphere (*1, 2*). Extrapolation of present rates of change of land use suggests a further decline of ~ 1 K in the global temperature by the end of the next century, at least partially compensating for the increase in global temperature through the carbon dioxide greenhouse effect, anticipated from the continued burning of fossil fuels. However, further such changes are unlikely, because virtually all the surface area of the earth will, at present rates, have been converted to high-albedo land use by then. The surface albedo of the earth will reach an asymptotic limit long before the carbon dioxide abundance will.

Tropical deforestation is the second most effective climatic level listed in Table 2. The massive extinction of equatorial forests can therefore have important implications for the global as well as the regional climate. We suggest that major deforestation in equatorial latitudes may be a matter of international concern, and note the systematic destruction of the Amazon jungle now under way, the activity of several corporations in a single country. This activity may even be desirable, as a counterbalance to greenhouse heating of the earth; but it would seem prudent, on an issue of possible global importance, to study its implications in some detail before proceeding unilaterally.

Human Impact on the Global Climate

Considering only global albedo changes, we find it possible that human alteration of the environment has made a significant contribution to the observed global climatic shifts of both the last several decades and the last several millennia. Many large regions of the world, including the Rajasthan Desert of India, major areas of the Middle East, Saharan Africa, tropical Africa, South America, and perhaps Europe and the United States, may have experienced significant regional climatic changes due to human alteration of the environment. It is certainly true that the microclimates of vast areas of the earth are the direct result of human activities, since about 15 percent of the earth's continental surface area has been dramatically modified by humans. It is possible that significant climatic changes may have been anthropogenically induced as early as 10^6 years ago. In contrast to the prevailing view that only modern humans are able to alter the climate, we believe it is more likely that the human species has made a substantial and continuing impact on climate since the invention of fire.

Many factors act to alter the regional and global climate. We believe that the effects of humans on both ancient and modern climates are not insignificant in comparison with other causes of climate change. Much work needs to be done to estimate better the magnitude of human impact on the climate. Of particular value would be satellite studies of present global land usage, coupled with studies of land use changes in selected regions so that the history of environmental change can be determined on a fine spatial scale. Additional studies of the albedo change, and of other meteorologically significant variations, due to land use modification are required. Finally, the meteorological interactions between microclimate modification and regional climate change require further study. Such work holds the promise not only of elucidating past climate changes and their possible human origin, but also of providing insight into the climate of the future.

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Fish Culture in the United States

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Summary. The culture of channel catfish, trout, and crayfish is a well-established, profitable enterprise, but aquaculture provides only a fraction of the protein consumed by Americans, who prefer red meat. This situation could change, since pond-raised fish require less energy for protein synthesis than land animals, the supply of ocean food fish no longer appears inexhaustible, and fish culture can utilize resources unsuitable for other agriculture.

Americans are traditionally not fish eaters, as evidenced by an annual per capita consumption of 6.1 kilograms of fish compared to 60.1 kilograms of red meat (*1*). Supply, price, and quality of marine fish fluctuate considerably because the ocean is an unmanaged source whose yield is unpredictable. Supply can be controlled more effectively when fish are cultured under managed conditions, like corn in a field. High quality can be maintained because farmed fish usually reach the processing plant alive. If fish were farmed on a major scale in the United States, red meat would face healthy competition for the protein dollar.

Fish culture is an ancient practice. A classic account of the culture of common carp was written by Fan Lei in 475 B.C. (*2*). Fish culture was common in Eastern Europe and Southeast Asia in the 13th and 14th centuries (*2*). Although fish culture has made significant contributions of protein in many countries for many years, the methods used were relatively crude. Fish culture as a science emerged only during the past 25 years in the developed countries. Japan has been one of the leaders, increasing its production of pond-cultured fish from 0.1 million ton in 1971 to 0.5 million ton in 1976 (*3*). In Israel in 1977, 58 percent of the total fish catch (marine and freshwater) came from culture ponds (*4*). In the United States, aquaculture provides only a fraction of the protein consumed, but could provide much more.

Benefits of Aquaculture

The percentage of edible lean tissue in fish is appreciably greater than that in beef, pork, or poultry (Table 1). For example, more than 80 percent of the dressed carcass of channel catfish (*Ictalurus punctatus*) is lean tissue; only 13.7 percent is bone, tendon, and waste fat. The caloric value of dressed fish is about one third that of the edible portion of beef or pork. The net protein utilization value of fish flesh, 83 (as compared to 100 for egg), is slightly higher than that of red meat, 80 (*5*), although the essential amino acid profiles of fish and red meat both reflect high protein quality.

Fish can convert food into body tissue more efficiently than farm animals. Table 2 gives sample comparisons. The reason for the superior food conversion efficiency of fish is that they are able to assimilate diets with higher percentages of protein, apparently because of their lower dietary energy requirement. However, the superiority of fish in this respect is not absolute, since poultry convert the protein in their food to protein in their bodies at nearly the same rate.

The dietary energy requirement for

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