GLOBAL DEVELOPMENT AND ENVIRONMENT INSTITUTE

WORKING PAPER NO. 01-04

AGRICULTURE IN A GLOBAL PERSPECTIVE

Jonathan M. Harris

February 2001

Tufts University
Medford MA 02155, USA
http://ase.tufts.edu/gdae

ABSTRACT: AGRICULTURE IN A GLOBAL PERSPECTIVE[1]

Jonathan M. Harris
jonathan.harris@tufts.edu

In the twenty-first century, it is evident that world agricultural systems will have to supply sufficient food for a population somewhere between 7.5 and 12 billion. Projections for world agriculture in the first half of the twenty-first century very widely, largely depending on assumptions about yield growth. An investigation of the patterns of yield growth for major cereal crops offers evidence that the pattern is logistic, implying that an upper limit to yields is being approached. This pattern is consistent with ecological limits on soil fertility, water availability, and nutrient uptake. It is also evident that current agricultural production is imposing serious strains on ecosystems, with widespread soil degradation, water overdraft and pollution, and ecological impacts such as loss of biodiversity and the proliferation of resistant pest species.

The issue therefore is not simply the balance of supply and demand in agriculture. It is the need to develop ecologically sustainable agricultural systems which can provide an agricultural output about twice present aggregate levels (allowing for per capita growth in consumption). This level of output would support a population of about 8 billion. In addition, a population policy which can avert any much higher growth is essential.

Evidence exists to show that ecologically sustainable cropping systems can supply overall outputs comparable to intensive high-input agriculture. (The measure of overall output is distinct from the more commonly used measure of single-crop yields.) This evidence, however, is more compelling for temperate zones with good soils. Much more research is needed on sustainable agriculture for tropical and arid zones. Agricultural policies need to be reformulated to meet the new goal of sustainability. These sustainable agriculture policies must be developed in tandem with population policies to ensure that population growth remains in the lower ranges of current projections.

[1]A version of this paper has appeared as "Carrying Capacity in Agriculture: Global and Regional Issues," Ecological Economics 29: 443-461 (1999).

1. TWO PERSPECTIVES ON AGRICULTURAL CARRYING CAPACITY

Ecologists and economists view agriculture through different lenses. From the point of view of the economist, agriculture is a sector of the economy, to be managed with the goal of increasing production to meet growing consumer demand. In economic models, technological progress in agriculture is the key to continual growth in output. From the ecologist's side, agroecosystems are seen as modifications of natural ecosystems, subject to the same biophysical principles which govern all plant and animal ecosystems. Human consumers of food are not independent of the ecosystem, but a part of it like other animal populations, and constrained by the system's carrying capacity.

The enormous achievements of human technology, in agriculture and elsewhere, have accentuated the differences between these two points of view. The Green Revolution and other technologically-driven increases in agricultural productivity have enabled human populations to achieve a continual increase in regional and global carrying capacities. Indeed, from the point of view of most economists, the concept of carrying capacity applied to humans is virtually meaningless. Economic growth models admit no upper limits to production, but envision steadily increasing output. Declining income elasticities for food consumption do limit the agricultural requirements of a given population, but so long as population continues to increase, output must grow. This growth can be achieved by increasing productivity; most economic models accordingly project a technological solution to any Malthusian threat resulting from global population growth.

An ecological perspective, on the other hand, suggests that human production, in agriculture and other areas, must ultimately be subject to biophysical limits. In addition, well before carrying capacity limits are reached, the implications of large-scale human intervention in complex ecosystems may include negative feedbacks which can undermine the resilience and sustainability of these systems. The conflict between the drive for greater production and the entropic nature of physical systems is especially evident in agriculture, where the process of production is inherently linked with natural biological and physical processes. The underlying paradigm conflict between economics and ecology accounts for the marked differences in analysis and policy recommendations regarding agricultural futures.

Not all economists are growth optimists, however. Several decades ago, Nicholas Georgescu-Roegen explored the implications of entropic limits for economic systems (Georgescu-Roegen, 1971). Since then, economists such as Herman Daly have expounded on the impossibility of unlimited growth in a closed planetary ecosystem, and argued for an ecological economics which takes account of biophysical limits (Daly 1991, 1996). An ecological economics perspective has been applied to agricultural production, for example in analyses by Juan Martinez-Alier and Vaclav Smil of the relationship of regional and global agricultural production to the nitrogen cycle and other physico-chemical limits (Martinez-Alier, 1991; Smil, 1994, 1996)[2]. These studies, like earlier work on agricultural carrying capacity by Gilland (1979), identify crucial biophysical constraints on agricultural expansion.

Do these constraints mean that the world is approaching carrying capacity in agriculture? A number of studies, including several by Worldwatch Institute (Brown, 1994, 1995, 1997) and my own recent article in Ecological Economics (Harris, 1996), have suggested that the answer is yes. On the other hand, studies published by the International Food Policy Research Institute (IFPRI) and the Council for Agricultural Science and Technology (CAST) are generally optimistic that meeting future food needs will be possible and even "increasingly easy" (Mitchell and Ingco, 1995; Waggoner, 1994). Some analysts, such as David Norse (1994) take a middle position, arguing that predictions of unprecedented food security crises are excessively simplistic, but that technological optimism understates the importance of ecological stresses. Norse does, however, imply some carrying capacity limit, which he estimates to be in the range of 12 billion people.

The wide divergence in projections of agricultural futures can be traced to the different methodological perspectives of ecological and neoclassical economics. Neoclassical models are oriented toward incremental growth without inherent limits; ecological models start from the premise that there are inherent limits to the capture and use of solar energy and planetary resources. This paper presents some initial empirical evidence on global and regional trends in agricultural productivity in the major cereal crops of maize, wheat, and rice; these trends are found to be more consistent with the existence of ecological limits than with models based on technology- and input-driven growth. The concluding section discusses some of the policy implications of the introduction of ecological limits into models of agricultural growth.

2. LOGISTIC VS EXPONENTIAL GROWTH PATTERNS

Econometric models, such as those employed by contributors to the IFPRI study, generally base future agricultural production estimates on an assumed rate of yield growth. This yield growth is presumed to be a result of continuing technological improvement and investment in agriculture. Historical growth rates are used as a baseline for estimating future growth rates, (although the estimated future growth rates may be lower than historically observed rates, depending on the model). The result is that these models generally display exponential growth in yields over time. This is the crucial factor from which their mostly

[2] Daly and Martinez-Alier are economists; Smil is an interdisciplinary scholar dealing with relationships between economics, energy, and environment. The field of ecological economics has brought together economists, ecologists and geographers, as well as scholars in other disciplines such as history and philosophy, to explore new paradigms for analysis of the interaction between human economic activity and the environment.

optimistic conclusions about future supply/demand balance are derived. Since most population projections show population following a logistic growth path towards eventual stabilization, even a modest sustained exponential rate of growth in yields will provide a comfortable, and increasing, margin over population growth, thus accommodating increased per capita consumption. In these models, no ceiling or carrying capacity limit appears. Their conclusions, accordingly, flow directly from their methodological assumption of exponential growth in yields.

An approach more oriented to the concept of carrying capacity limits would suggest, instead, a logistic path for crop yields, with some upper limit imposed. In its early stages, a logistic growth path closely resembles an exponential path. But as the upper limit starts to exert more influence, the growth rate slows, passes through an inflection point, and ultimately approaches zero as the carrying capacity is approached. This suggests that econometric modelers may be misled by an apparently exponential pattern of yield increase, failing to discern an incipient logistic pattern -- an error which would have increasingly severe consequences as the time period under consideration was increased.

Of course, the seriousness of such an error would depend on the upper limit in question. Paul Waggoner, one of the most optimistic forecasters, does use a logistic projection for maize yields (Waggoner, 1994). For his upper limit on maize yields, he uses a yield of 21 metric tons per hectare (Mt/ha), which is close to the theoretical photosynthetic limit on yields, and is about three times the average maize yield in the United States today. His justification for this high limit is that agricultural contest winners have actually achieved this yield level, proving it to be technically possible. If we make a general assumption that ultimate limits on cereal yields are three times present U.S. levels -- given than the developing world currently has average yields less than one-half of U.S. levels -- the resulting factor of about six gives plenty of room to accommodate the demands of a population of eight to twelve billion, which is roughly the range envisioned in U.N. population projections for 2050 (United Nations, 1996).

There are good grounds for extreme skepticism regarding Waggoner's assumption that such high yield levels could ever be achieved in practice, as average yields over large regions. The theoretical genetic potentials of plant physiology are commonly constrained by unfavorable physicochemical environments (Boyer, 1982). Record yields such as those cited by Waggoner have generally taken place on soils with no significant productivity limitations; but Boyer finds that only 12% of U.S. soils are in this category. Global soils are generally subject to more stresses and productivity constraints than is characteristic of the major U.S. crop-growing areas (see e.g. Pimentel 1993, Buol 1994). This provides strong evidence for a yield limit significantly lower than theoretical potential.

However, we might apply the logistic growth principle in a more modest way by assuming that it will ultimately be possible to triple yields in regions now producing at relatively low yields: for example, to raise yields from 2 MT/ha to 6 MT/ha over a period of decades. If this were the case, an adequate supply of food would be available for a doubled population with about a 50% per capita consumption increase.

It turns out, however, that there are very significant differences in the growth paths necessary to achieve this goal, depending on whether we assume an exponential or a logistic pattern of yield growth.

Table 1 compares historical rates of yield growth for major grain-producing nations to the rates which would be required to triple yields by the year 2060. If we assume an exponential pattern of yield growth, as many economic models do, the rates required are similar to historically observed yield growth rates for the period 1961-1995. But with a logistic pattern, the required initial rates are much higher, well beyond the range of historical experience. A logistic curve fitted to the observed yield growth yields about a doubling of yields by 2060, rather than a tripling. This is a crucial difference in projecting food demand/supply balances for the twenty-first century.

Do we believe, then, in an exponential or a logistic pattern for yield growth? The answer to this question will largely determine our degree of optimism about regional and planetary carrying capacity. Most studies concur that there is limited scope for expansion of land area cultivated -- future growth in output must come mainly from improved yields (Crosson and Anderson 1994, Islam 1995)[3]. The logistic patterns which fit observed trends generally indicate a potential for doubling, rather than tripling, yields over the next fifty years. This leaves little margin for error throughout most of the developing world, where population is expected to double during this period. If we examine actual yield trends, we will find further reason for skepticism concerning the optimistic, exponential-growth projections.

3. YIELD TRENDS FOR MAJOR CROPS: MAIZE, WHEAT, AND RICE

Overall, world cereal yield growth rates have declined during the period since 1961 (See **Figure 1**). This, of course, is generally consistent with a logistic rather than exponential growth pattern. But we can also discern a difference in the patterns of yield growth between presently developed and presently developing nations -- further suggesting that the two groups of nations may be in different regions of a logistic growth curve. The pattern of total cereal yields for developed and developing nations from 1961 to 1995 is shown in **Figure 2**. Yield growth rates in developed nations have clearly slowed. This could indicate that the developed nations are approaching the upper limit of a logistic curve, while the developing nations are still on the earlier portion of the curve. The suggestion of a logistic pattern can be seen more clearly by examining the yield growth records for three major cereal crops: maize, wheat, and rice.

---

[3] See Harris (1996) for a discussion of the relative contributions of land expansion and yield growth to future agricultural production growth.

Figure 1. World Cereal Yield Growth Rates 1961 - 1993

Using a 5 Year Moving Average

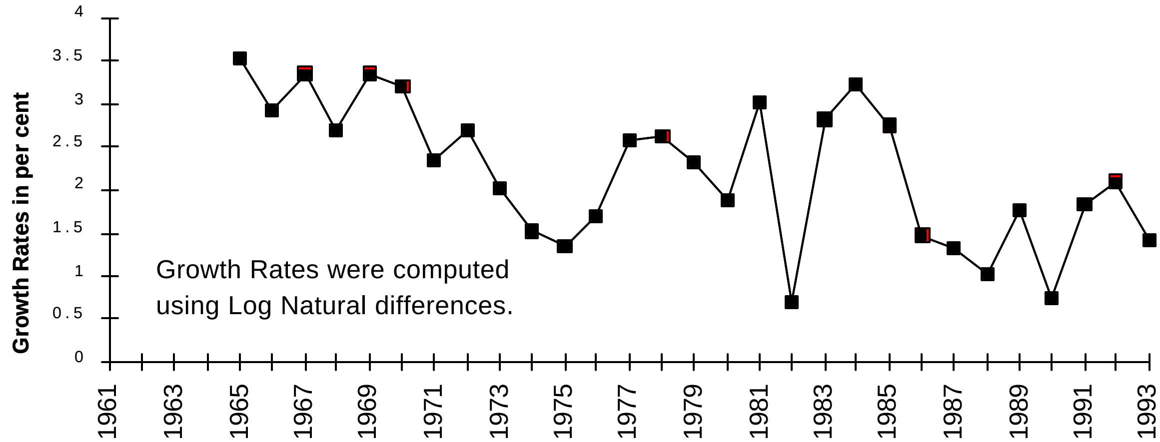


Figure 2. Total Cereal Yields Developed and Developing Countries 1961-1995

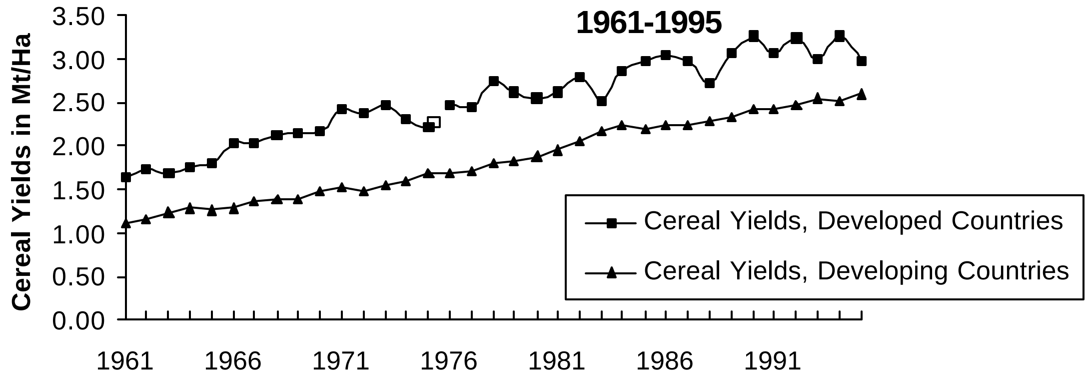


Figure 3. Developed and Developing Countries Maize Yields 1961-1995

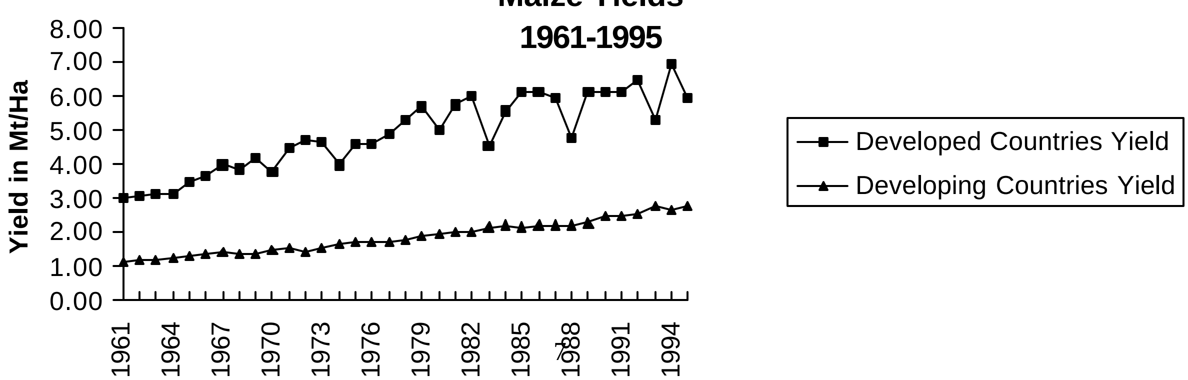
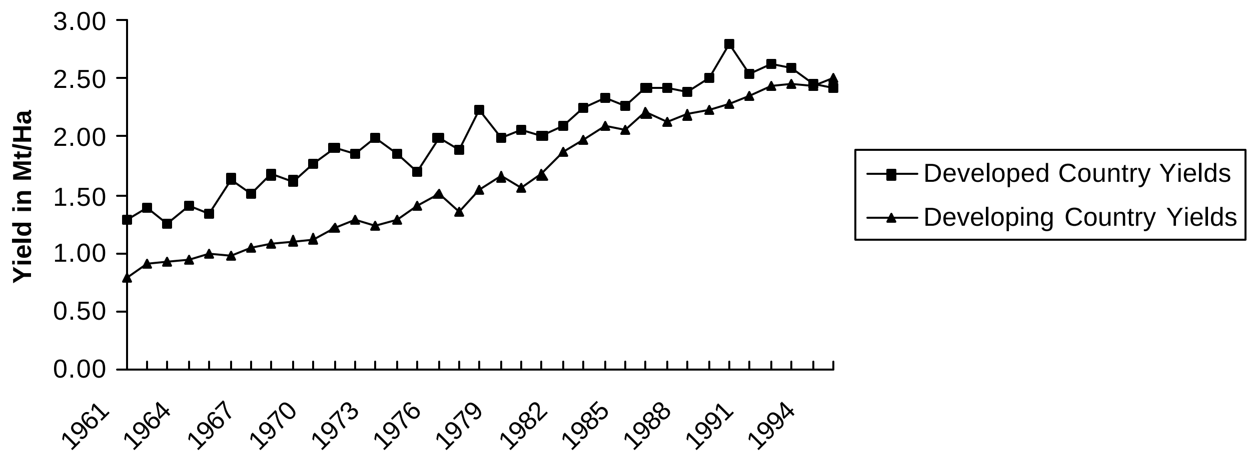


Figure 3 shows the secular yield growth pattern for maize in developed and developing nations. The rate of growth has apparently slowed almost to a standstill for developed nations since about 1980. Since 1980, we note no net increase in yields, but a pronounced yield variability. This is consistent with the hypothesis that yields in developed nations have reached upper limits, and that a particular year's yield is now determined primarily by weather or other external variables. A recent study by Naylor, Falcon, and Zavaleta (1997) provides statistical support for this empirical observation; they also suggest that high-yield cultivars are especially susceptible to weather-related yield variations[4].

Developing nations' maize yields are steadily increasing, and currently less than half developed nation levels. This clearly leaves considerable margin for further growth in developing nations, but in the range of doubling rather than tripling yields. To do much better, we would have to share Waggoner's optimistic view that not only can yields continue to rise significantly in developed nations, but that these gains can be transmitted to developing nations.

Figure 4 shows the story for wheat yields. Here also developed country yields seem to show a slowdown in growth, with an actual decline over the last five years. But in the case of wheat, developing

Figure 4. Developed and Developing Countries Wheat Yields 1961-1995



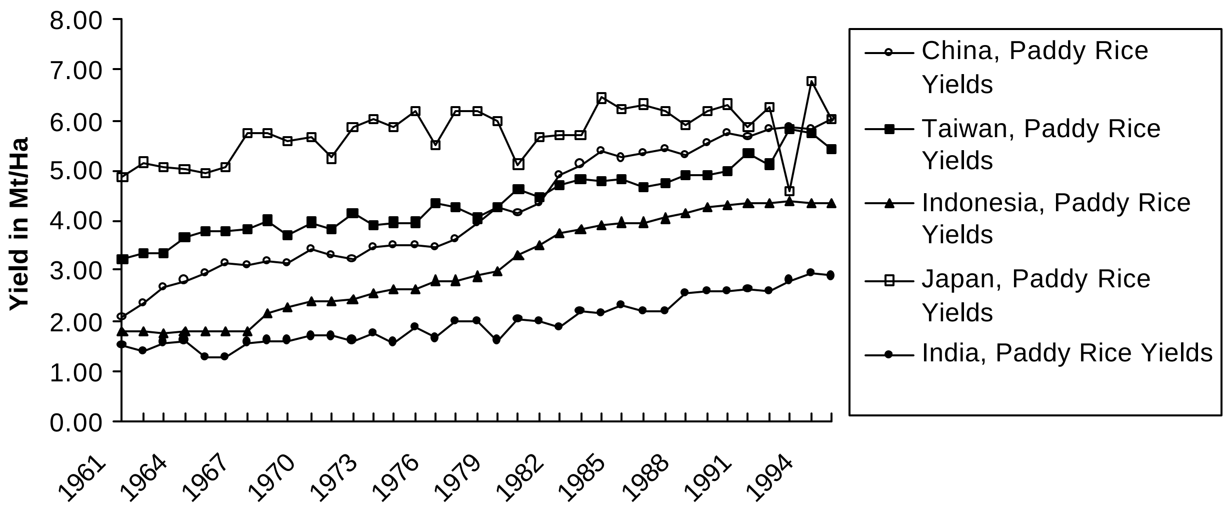
countries also appear to show some slowdown, and their achieved levels are much closer to those of developed nations. This leaves less margin for growth in either developing or developed nations. These trends, of course, could be reversed -- but the dose of optimism necessary to project this is larger for wheat than for maize.

[4] The oscillating pattern at the top of the yield growth curve is even clearer in U.S. cereal crops, especially maize (see Figures 5 and 8).

In Asia, where rice is of particular importance, the pattern of yield growth for major nations is shown in **Figure 5**. Japanese yields have been stagnant for the last quarter-century, at about 6 Mt/ha[5]. Taiwan and China have increased yield steadily, and are now approaching the Japanese level. Indonesian rice yields have grown more slowly, and are now about two-thirds of Japanese levels, while Indian rice yields have reached about half the Japanese benchmark. These data are suggestive of a ceiling on yields, represented by intensive Japanese cultivation, with other major producers approaching this ceiling. This is consistent with agronomic research indicating that the climate-adjusted yield potential for rice in Asia is 8.6 MT/ha, but that production of rice on a commercial scale rarely exceeds 80% of theoretical potential (Cassman and Harwood, 1995).

Thus for all three of these major cereal crops, the observed pattern of yield growth is more consistent with a logistic than an exponential trend. If indeed the developed nations are in the top portion of a logistic curve, we cannot expect dramatic further gains in yields for these countries (with the possible

Figure 5. Selected Country Paddy Rice Yields 1961-1995



exception of the former Soviet Union, where gross inefficiencies have reduced agricultural productivity). We can also expect that the developing nations which have done well recently in raising yields may have trouble sustaining their recent growth rates (China in particular bears watching in this regard). Two "yield gaps" still remain to be exploited: the difference between theoretically achievable and achieved levels in high-yield countries, and the difference between presently high-yield and presently lower-yield countries. But the size of these gaps may be limited, and for some regions these limits may be quite stringent.

[5] Japanese rice yields also appear to display a greater variability, which is consistent with the hypothesis that weather and other external factors dominate the determination of yields in specific years once technological possibilities for boosting yields have been fully exploited.

4. SOME REGIONAL ISSUES

Assuming modest demand growth, a rough doubling of cereal yields throughout the developing world would be necessary for self-sufficiency in the year 2025, with an estimated 2025 world population of just over 8 billion, including 7 billion in the presently developing world[6] These projections are consistent with estimates of slightly more than doubled cereal demand in developing nations by 2025 (Alexandratos and de Haen, 1995). A logistic yield growth trend probably allows for about a doubling of developing nation yields, but leaves little further room for growth -- a major concern if we extend our projection period to 2050, when current U.N. medium projections indicate a world population between nine and ten billion, with over eight billion in the currently developing nations (United Nations, 1996). Imports from developed nations could serve as a safety valve; almost all projections show net imports by the developing world at least doubling by 2025 (See e.g. Islam ed., 1995). But of course in order to supply these imports, the developed world must increase production, boosting either yields or area cultivated. There are also significant economic implications to permanent import dependence, especially for the least developed nations. The logistic analysis suggests that the world food supply/demand balance could tighten significantly during this period. While there is no necessary indication of massive shortfalls, even a modest tightening can drive prices up sharply (we have seen a recent example of this in the 1996 cereal price spike when wheat and corn prices doubled).

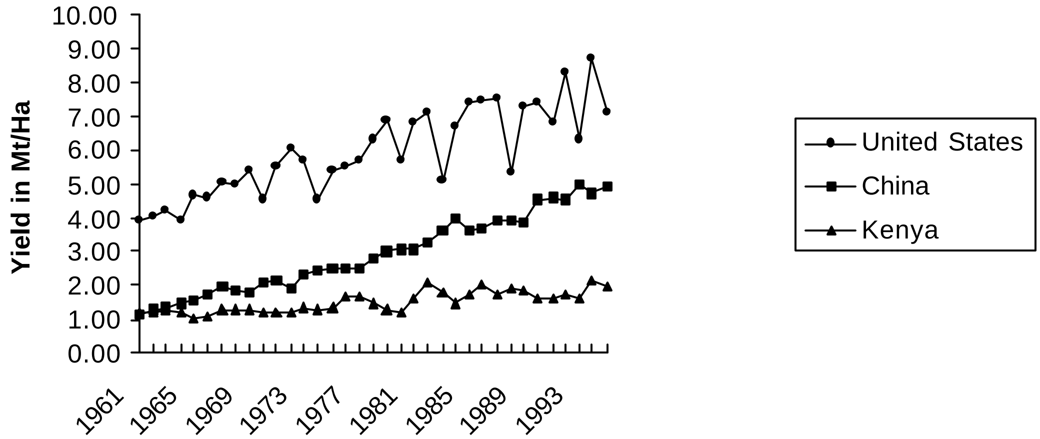
Moving from a global to a regional perspective, we find wide differences both in population growth rates and in agricultural yield trends for major crops. It is important, therefore, to consider the picture for large regions. In each region the nature of the problem, and the probable constraints on carrying capacity, are different.

In AFRICA, yields are generally low, and rates of yield growth are also low. F.A.O. data show cereal yields in Africa barely increasing over the last fifteen years (F.A.O., 1994). The pattern of Kenyan maize yields shown in **Figure 6** is typical of the virtually flat yield growth record for much of Africa. This leaves a large theoretical yield gap to be exploited. However, rates of population growth in Africa are the highest in the world, with a population doubling projected by 2025, and close to a tripling likely by 2050 (Population Reference Bureau, 1996; United Nations, 1996). Concerns here are centered on the institutional difficulties of reversing a long-term low yield growth trend, as well as on water limits throughout much of the region. For self-sufficiency, Africa would need to nearly triple yields by 2025, and quadruple them by 2050, assuming a 0.5% rate of per capita consumption growth to overcome current nutritional insufficiency and a 1% per annum rate of cultivated land expansion (Harris, 1996). If this yield growth is not feasible, the gap will have to be filled by a massive increase in imports, which many poorer African

[6] See projections in Harris, 1996, based on Population Reference Bureau (1996) and U.N. (1996) medium variant population projections.

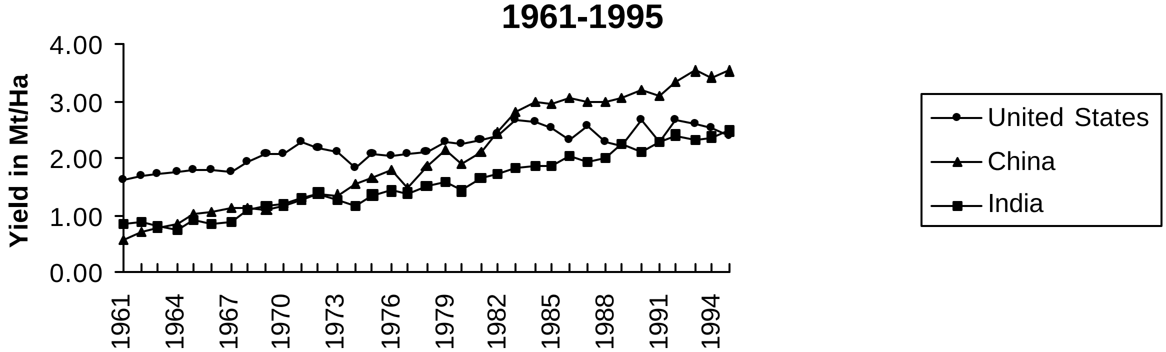
nations can ill afford.

Figure 6. Selected Country Maize Yields 1961-1995



In EAST AND SOUTHEAST ASIA the importance of rice and the relatively narrow exploitable gap in rice yields suggest limits to population carrying capacity; rates of population growth are slower here, but at least 300 million people will be added by 2025 (Population Reference Bureau, 1996). Chinese rice yields, as we have noted, are approaching the Japanese level, which may represent an achievable maximum. Maize yields in China have risen steadily, approaching U.S. levels (**Figure 6**); wheat yields have now surpassed U.S. levels (**Figure 7**). Wheat yields can rise significantly higher under favorable rainfall conditions, as shown by French and British yields of around 6-7 MT/Ha, but water supply is a major constraint on rainfed wheat.

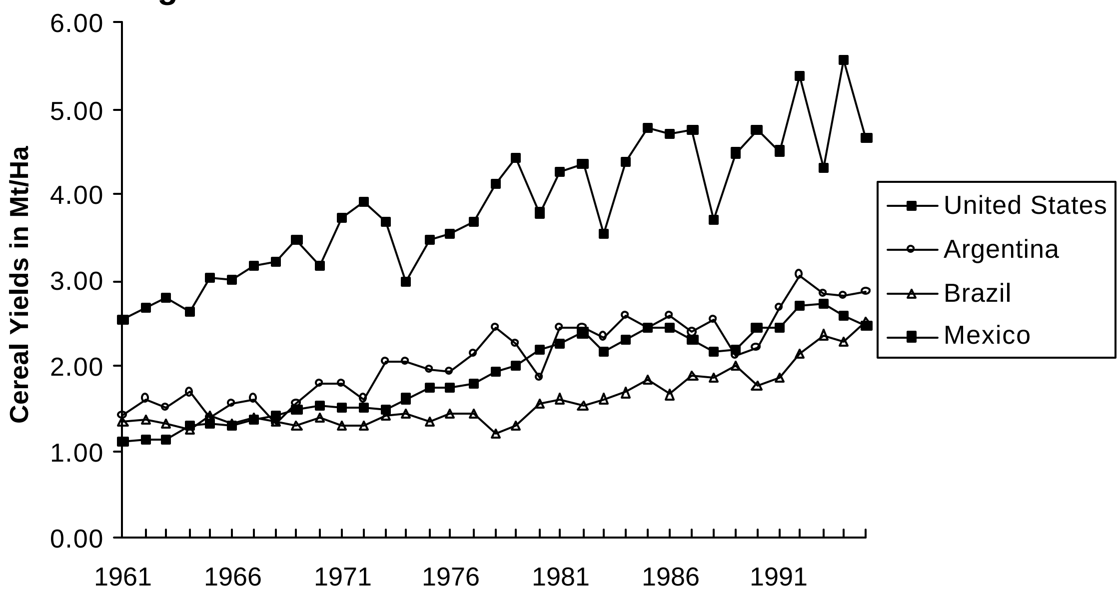
Figure 7. Selected Country Wheat Yields 1961-1995



In SOUTH ASIA, a steady rate of growth in Indian wheat yields (**Figure 7**) has also equalled the U.S. yield level; water constraints here will certainly be a major issue for future yield growth. Rice yields could in theory double to Japanese levels (**Figure 5**); again the water constraint is important. South Asia will certainly need to double overall cereal yields to accommodate population and demand growth; sustaining the steady yield growth to date will require extensive investment in irrigation, and will pose problems of absolute water limits, and competition between agriculture, industry, and urban areas for available supplies.

In LATIN AMERICA, average cereal yields are now around 2.5 metric tons (**Figure 8**). Population and demand growth through 2025 could be accommodated by raising these averages to the

Figure 8. Total Cereal Yields for Selected Countries 1961-1995



current U.S. average level of 4-5 MT/Ha. To achieve this would require the appropriate inputs of water and nutrients as well as institutional infrastructure. A considerable degree of agronomic and institutional optimism is required to project that this will in fact be achieved and sustained throughout the region.

Thus several strong caveats apply to a projection of doubling yields in the developing world:

** The rice yield gap for major countries does not appear to be great, putting projections of a doubling of rice yields in doubt.

** The yield gap for rainfed wheat is also small, and the potential for duplicating the performance of current high-yield nations is limited by weather conditions.

** There is a possibility, but no guarantee, of further growth in yields in the already high-yield nations. The yield patterns for intensive rice agriculture in Japan and intensive maize cultivation in the U.S. suggest that some practical yield ceilings exist not far above present levels.

** Water supplies represent a significant constraint on yield growth throughout much of Africa and Asia.

** In a context of limited rather than unlimited yield growth, productivity losses to erosion and soil degradation bulk larger. The pattern of the past thirty-five years, where such losses are overwhelmed by steady and rapid yield growth, no longer applies.

** The environmental damages associated with intensive agriculture -- including soil degradation, fertilizer and pesticide runoff, water pollution and overdraft -- all become more difficult to manage when demand pressures militate against such measures as crop rotation, fallowing, and low-input techniques.

** The ecosystem damage and biodiversity loss associated with the spread of cultivation onto marginal lands will also be more prevalent in a high-demand scenario.

These conclusions are very different from the supply-side optimism characteristic of most econometric projection models. A picture emerges of a world approaching absolute carrying capacity limits over the next few decades, with binding regional constraints -- even if everything goes right in terms of agricultural investment and institutional infrastructure. It is also important to recall that the goal of feeding 8 billion people must not merely be achieved, but must be sustained, taking into account such cumulative problems as soil erosion, agriculture's direct and indirect contribution to greenhouse gas accumulation, and depletion of groundwater supplies.

5. IMPLICATIONS FOR MANAGEMENT OF AGROECOSYSTEMS

Given the reality of ecological limits, the central question is the feasibility of an ecologically sustainable agriculture which can support a population of about 8 billion, and of a population policy which can avert any much higher growth. Rather than viewing the global agricultural system like an industrial production process with a goal of ever higher productivity, we must see it as a modified system of natural productivity subject to specific limits. While the photosynthetic limit of area productivity is far above current yields, much more stringent limits apply to most areas in practice. The "harvest index" for grains -- the proportion of plant biomass which can be devoted to edible seed -- has already approached the physiological limit in Green Revolution grains (Brown, 1997; Evans, 1980, 1993, referenced in Brown 1997). Across wide areas, soil quality and water availability further limit yield potential. The management focus must accordingly shift from increasing productivity to maintaining the conditions under which present yields can be sustained in current high-yield areas, and improving yields in current low-yield regions through methods which do not undermine natural productivity.

There is now a burgeoning literature on agroecological techniques which can sustain high yields without degrading soils and depleting or polluting water supplies (see e.g. Lockeretz et al. 1981; Patrinquin 1986; National Research Council 1989; Edwards et al. 1990; Altieri 1995; Thrupp 1996; Hanson et al 1997). The evidence that organic agriculture can sustain yields comparable to those of intensive high-input techniques is, however, more developed for temperate areas with good soils such as the United States and Europe. Good principles and techniques for sustainable agriculture in tropical areas have been documented (see e.g. Section IV, "Sustainable Agricultural Systems in the Tropics" in Edwards et al, 1990 and "Case Studies" section in Thrupp 1996), but the question of whether these areas can attain yields similar to current high-yield regions is still open.

Extensive evidence exists as to the impacts of current agricultural techniques in degrading soils, depleting and polltuing water supplies, overloading the ecosystem with nitrate runoff, and promoting the development of resistant pest species (Pimentel ed. 1993; Postel 1992; Smil 1997; Bull 1982). The correction of these systemic problems through agroecological techniques must rank as a goal of at least as great importance as increases in agricultural productivity. In the light of the evidence on yield growth patterns presented in this paper, the achievement of these two goals during a period when world population grows towards 8 billion would be a massive accomplishment, and clearly presses against the outer limits of planetary possibilities.

If we accept this rough indication of carrying capacity limits, patterns of population growth become critical. Projections, of course, are only projections; most median estimates of world population for the year 2025 are around 8 billion, but with a range of about 1 billion between the lowest and highest projections for that year. The disparity becomes dramatically larger for 2050; the most recent U.N. series shows a low estimate for 2050 of 7.7 billion (implying that world population growth will have peaked and begun to decline by 2050), and a high estimate of 11.2 billion (United Nations, 1996; Population Reference Bureau, 1997). Our analysis of yield trends implies that while the lower figure is within carrying capacity subject to reasonable assumptions, the higher figure is not. Even the U.N. medium estimate of 9.4 billion for 2050 seriously strains carrying capacity on the assumption of logistical trends in grain yields. Chen and Kates, who favor a higher-range population estimate, suggest a "normative" requirement of a three- to four-fold increase in food supplies for nutritional security in 2060 (Chen and Kates, 1994). This is clearly outside the range of reasonable expectations given logistical yield trends.

Some analysts, such as Seckler and Cox (1994) view the "low" series as the most likely long-term estimate of global population trends, given observed patterns of fertility decline. If this is borne out, the prospects for maintaining adequate food supplies would clearly be much brighter. But as we move towards the median or high population growth variants, the likelihood of greater environmental damage and biodiversity loss, as well as the possibility of serious food shortages, becomes much greater. Any supply shortfall, of course, would lead to food price increases affecting the world's poorest peoples most severely.

The other important demand-side variable is per capita consumption. Economic growth has generally been associated with increased demand for feedgrains, which greatly increases the overall income elasticity of demand for grains[7]. The demand projections discussed above assume a modest (approximately 0.5% per annum) increase in demand for cereals throughout the developing world. A pattern of steady increase in meat and dairy product consumption could easily double this estimated growth rate (the recent trends in Chinese direct and indirect cereal consumption bear this out[8]). Thus a lower population projection could easily be offset by more rapid per capita demand growth.

The lack of upper limits in most economic models of agricultural growth leads to an excessive emphasis on expansion of production, and an insufficient consideration of environmental constraints and the need for population limits. A logistical growth model, for which there is strong supportive evidence, should lead us to focus instead on environmentally sustainable production techniques, efficiency in consumption, and measures to limit population growth.

---

[7] See e.g. Brown 1997, in which F.A.O. and U.S.D.A. data on increasing animal protein consumption and feedgrain use are reviewed (F.A.O. 1987, U.S.D.A. 1996, 1997).

[8] Brown (1997) reviews U.S.D.A. data showing that China's feedgrain use increased from less than 20 million tons in 1978 to more than 100 million tons in 1997. Feedgrains now represent about one quarter of China's total grain consumption.

REFERENCES

Alexandratos and de Haen, 1995. "World Consumption of Cereals: will it Double by 2025?" Food Policy 20 (4): 359-366.

Altieri, Miguel A., 1995. Agroecology: The Science of Sustainable Agriculture (2nd ed.). Westview Press, Boulder, Colorado.

Boyer, J.S., 1982. "Plant Productivity and Environment," Science 218 (29): 443-448.

Brown, Lester R., 1994. Full House: Reassessing the Earth's Population Carrying Capacity. Worldwatch Environmental Alert Series. W.W. Norton, New York.

Brown, Lester R., 1995. Who Will Feed China?: Wake-Up Call for a Small Planet. Worldwatch Environmental Alert Series, W.W. Norton, New York.

Brown, Lester R., 1997. The Agricultural Link: How Environmental Deterioration Could Disrupt Economic Progress. Worldwatch Paper #136. Worldwatch Institute, Washington, D.C.

Buol, S.W., 1994. "Soils". In: W.B. Meyer and B.L. Turner eds., Changes in Land Useand Land Cover: A Global Perspective. Cambridge University Press, Cambridge, UK.

Bull, David, 1982. A Growing Problem: Pesticides and the Third World Poor. Oxfam, Oxford, U.K.

Cassman, K.G. and R.R. Harwood, 1995. "The Nature of Agricultural Systems: Food Security and Environmental Balance," Food Policy 20 (5): 439-454.

Chen, Robert S. and Robert W. Kates, 1994. "World Food Security: Prospects and Trends," Food Policy 19 (2): 192-208.

Crosson, Pierre and Jock R. Anderson, 1994. "Demand and Supply: Trends in Global Agriculture," Food Policy 19 (2): 105-119.

Daly, Herman E., 1991. Steady-State Economics (2nd ed.). Island Press, Washington D.C., 1991.

Daly, Herman E., 1996. Beyond Growth: The Economics of Sustainable Development. Beacon Press, Boston, Massachusetts.

Edwards, Clive A., Rattan Lal, Patrick Madden, Robert H. Miller, and Gar House eds., 1990. Sustainable Agricultural Systems. Saint Lucie Press, Florida.

Evans, L.T., 1980. "The Natural History of Crop Yields," American Scientist, July/August.

Evans, L.T., 1993. Crop Evolution, Adaptation, and Yield. Cambridge University Press, Cambridge, U.K.

F.A.O., 1987. World Crop and Livestock Statistics. F.A.O., Rome, Italy.

F.A.O., 1995. Production Yearbook. F.A.O., Rome, Italy.

Georgescu-Roegen, Nicholas, 1971. The Entropy Law and the Economic Process. Harvard University Press, Cambridge, Massachusetts.

Gilland, Bertrand, 1979. The Next Seventy Years: Population, Food, and Resources. Abacus Press, Southborough, U.K.

Hanson, James C., Erik Lichtenberg, and Steven E. Peters, 1997. "Organic versus conventional grain production in the mid-Atlantic: An economic and farming system overview," American Journal of Alternative Agriculture.

Harris, Jonathan M., 1996. "World Agricultural Futures: Regional Sustainability and Ecological Limits," Ecological Economics 17 (2): 95-115 [Data analysis by Scott Kennedy].

Islam, Nurul ed., 1995. Population and Food in the Early Twenty-First Century: Meeting Future Food Demand of an Increasing Population. International Food Policy Research Institute.

Lockeretz, W., G. Shearer and D.H. Kohl, 1981. "Organic Farming in the Corn Belt," Science 211: 540-547.

Martinez-Alier, Juan, 1987. Ecological Economics: Energy, Environment, and Society. Blackwell, Oxford, U.K.

Mitchell, Donald O. and Merlinda D. Ingco, 1995. "Global and Regional Food Demand and Supply Prospects," in Islam ed, 1995.

National Research Council, 1989. Alternative Agriculture. National Academy Press, Washington, D.C.

Naylor, Rosamond, Walter Falcon, and Erika Zavaleta, 1997. "Variability and Growth in Grain Yields, 1950-94". Population and Development Review, 23 (1): 41-58.

Norse, David, 1994. "Multiple Threats to Regional Food Production: Environment, Economy, Population?" Food Policy 19 (2): 133-148.

Patrinquin, David G., 1986. "Biological Husbandry and the Nitrogen Problem," Biological Agriculture and Horticulture (U.K) 3: 167-189.

Pimentel, David ed., 1993. World Soil Erosion and Conservation. Cambridge Studies in Applied Ecology and Resource Management, Cambridge University Press, Cambridge, UK.

Population Reference Bureau, 1996. 1996 World Population Data Sheet. Population Reference Bureau, Washington, D.C.

Population Reference Bureau, 1997. Population Today, 25 (4). Population Reference Bureau, Washington, D.C.

Postel, Sandra, 1992. Last Oasis: Facing Water Scarcity. Worldwatch Environmental Alert Series. W.W. Norton, New York.

Seckler, David, and Gerald Cox, 1994. Population Projections by The United Nations and the World Bank: Zero Growth in 40 Years. Winrock International Institute for Agricultural Development, Center for Economic Policy Studies Discussion Paper No. 21.

Smil, Vaclav, 1994. "How Many People Can the Earth Feed?" Population and Development Review 20 (2): 255-293.

Smil, Vaclav, 1996. Cycles of Life: Civilization and the Biosphere. W.H. Freeman, New York.

Smil, Vaclav, 1997. "Global Population and the Nitrogen Cycle," Scientific American (July) 277 (1): 76-81.

Thrupp, Lori Ann ed., 1996. New Partnerships for Sustainable Agriculture. World Resources Institute, Washington, D.C.

United Nations, 1996. World Population Prospects: The 1996 Revision.

United States Department of Agriculture, 1996. Livestock and Poultry: World Markets and

Trade. U.S.D.A. Foreign Agricultural Service, Washington, D.C.

United States Department of Agriculture, 1997. Grain: World Markets and Trade. U.S.D.A. Foreign Agricultural Service, Washington, D.C.

Waggoner, Paul E., How Much Land Can Ten Billion People Spare for Nature? (Council for Agricultural Science and Technology, Task Force Report No. 121, 1994).

The Global Development And Environment Institute (G-DAE) is a research institute at Tufts University dedicated to promoting a better understanding of how societies can pursue their economic goals in an environmentally and socially sustainable manner. G-DAE pursues its mission through original research, policy work, publication projects, curriculum development, conferences, and other activities. The "G-DAE Working Papers" series presents substantive work-in-progress by G-DAE-affiliated researchers. We welcome your comments, either by e-mail directly to the author or to G-DAE, Cabot Center, Fletcher School, Tufts University, Medford, MA 02155 USA; tel: 617-627-3530; fax: 617-627-2409; e-mail: gdae@tufts.edu; web: http://ase.tufts.edu/gdae.

Papers in this Series:

00-01 Still Dead After All These Years: Interpreting the Failure of General Equilibrium Theory (Frank Ackerman, November 1999)

00-02 Economics in Context: The Need for a New Textbook (Neva R. Goodwin, Oleg I. Ananyin, Frank Ackerman and Thomas E. Weisskopf, February 1997)

00-03 Trade Liberalization and Pollution Intensive Industries in Developing Countries: A Partial Equilibrium Approach (Kevin Gallagher and Frank Ackerman, January 2000)

00-04 Basic Principles of Sustainable Development (Jonathan M. Harris, June 2000)

00-05 Getting the Prices Wrong: The Limits of Market-Based Environmental Policy (Frank Ackerman and Kevin Gallagher, September 2000)

00-06 Telling Other Stories: Heterodox Critiques of Neoclassical Micro Principles Texts (Steve Cohn, August 2000)

00-07 Trade Liberalization and Industrial Pollution in Mexico: Lessons for the FTAA (Kevin Gallagher, October 2000)

00-08 Waste in the Inner City: Asset or Assault? (Frank Ackerman and Sumreen Mirza, June 2000)

01-01 Civil Economy and Civilized Economics: Essentials for Sustainable Development (Neva Goodwin, January 2001)

01-02 Mixed Signals: Market Incentives, Recycling and the Price Spike of 1995. (Frank Ackerman and Kevin Gallagher, January 2001)

01-03 Community Control in a Global Economy: Lessons from Mexico's Economic Integration Process, Tim Wise and Eliza Waters, February 2001)

01-04 Agriculture in a Global Perspective (Jonathan M. Harris, June 2001)

01-05 Better Principles: New Approaches to Teaching Introductory Economics (Neva R. Goodwin and Jonathan M. Harris, June 2001)