Proc. Natl. Acad. Sci. USA
Vol. 96, pp. 5929–5936, May 1999
Colloquium Paper

This paper was presented at the National Academy of Sciences colloquium "Plants and Population: Is There Time?" held December 5–6, 1998, at the Arnold and Mabel Beckman Center in Irvine, CA.

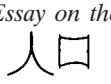
World food trends and prospects to 2025

TIM DYSON*

Department of Social Policy, London School of Economics, London WC2A 2AE, United Kingdom

ABSTRACT **This paper reviews food (especially cereal) production trends and prospects for the world and its main regions. Despite fears to the contrary, in recent years we have seen continued progress toward better methods of feeding humanity. Sub-Saharan Africa is the sole major exception. Looking to the future, this paper argues that the continuation of recent cereal yield trends should be sufficient to cope with most of the demographically driven expansion of cereal demand that will occur until the year 2025. However, because of an increasing degree of mismatch between the expansion of regional demand and the potential for supply, there will be a major expansion of world cereal (and noncereal food) trade. Other consequences for global agriculture arising from demographic growth include the need to use water much more efficiently and an even greater dependence on nitrogen fertilizers (e.g., South Asia). Farming everywhere will depend more on information-intensive agricultural management procedures. Moreover, despite continued general progress, there still will be a significant number of undernourished people in 2025. Signs of heightened harvest variability, especially in North America, are of serious concern. Thus, although future general food trends are likely to be positive, in some respects we also could be entering a more volatile world.**

The prospects for feeding humanity as we enter the 21st century often are portrayed in a daunting light. For example, we are told that the world's population has been growing faster than cereal production since the early 1980s, and therefore that global per-capita cereal output is falling now. The rate of growth of world cereal yields also is said to be declining; the strong implication is that this decline is caused by increasing environmental production constraints. Victims of famine still appear on television, and it is clear that there are many hungry people in the world. In addition to these problems, between now and the year 2025, the human population is expected to rise from about 6 billion to 8 billion. So, especially in 1998, the bicentenary of Malthus' *Essay on the Principle of Population*



(1), the issue symbolized by the Chinese characters above, which together mean population (a person and an open mouth), seems very apt.

With this as background and building on an earlier, much more detailed analysis (2), this paper gives my broad-brush assessment of world food prospects to the year 2025. Despite the statements of the previous paragraph, I am cautiously optimistic about our chances to better feed humanity in the next few decades. Nevertheless, the importance and complexity of the subject, the approximate nature of much of the data, the need to simplify, and the inevitable element of uncertainty when considering the future all should require no further emphasis.

Because of their central place in the human diet, cereals will be my chief focus in what follows. Today, roughly half of the world's cropland is devoted to growing cereals. If we combine their direct intake (e.g., as cooked rice or bread) with their indirect consumption, in the form of foods like meat and milk (about 40% of all grain is currently fed to livestock; ref. 3), then cereals account for approximately two-thirds of all human calorie intake. I consider prospects to the year 2025 mainly because world population projections have a fairly reliable record over future time horizons of about 30 years. My chief data sources are those of the United Nations Population Division (4) and the Food and Agricultural Organization (5, 6).

This paper has three main parts. The first considers cereal and food trends during recent decades, at both the world and regional levels. The second uses demographic and cereal data to sketch what I believe is a plausible broad scenario for the future evolution of world cereal demand and supply. The final part concludes with some brief comments about the context in which the world's farmers must grow more food.

Cereal Production Trends

To consider the future we first must consider the past. Fig. 1 shows per-capita cereal production for the world as a whole since 1951, when the entire human population numbered only 2.5 billion. The annual figures for per-capita output are surprisingly variable and reflect volatility in the world's harvest. Nevertheless, it is clear from the 5-year moving-average that world output generally has kept ahead of population growth, despite the addition of some 3.5 billion extra mouths. That said, there have been two periods of falling per-capita cereal production. The first happened around 1960 and mainly reflects the agricultural losses associated with Mao's disastrous "Great Leap Forward" in China. The second period has been since the early 1980s. The moving-average peaks at 371 kg in 1984 and has fallen to around 350 kg in the mid-1990s. Since 1984 the world's population has been growing faster than cereal production. Note the hint that volatility in the global harvest recently may have increased.

The fact that world population growth has been outpacing cereal production since 1984 readily attracts attention, but interpreted without any qualification, it is seriously misleading for two reasons. First, it hides the fact that much of the recent decline in world cereal production has occurred in relatively well-fed regions. Second, it does not account for the fact that the regional composition of humanity is changing. In particular, most demographic growth is happening in parts of the world with low levels of per-capita cereal consumption and, other things being equal, this fact tends to weight downward

Abbreviations: FSU, former Soviet Union; EU, European Union; ha, hectare.

*To whom reprint requests should be addressed. e-mail: T.Dyson@lse.ac.uk.

PNAS is available online at www.pnas.org.

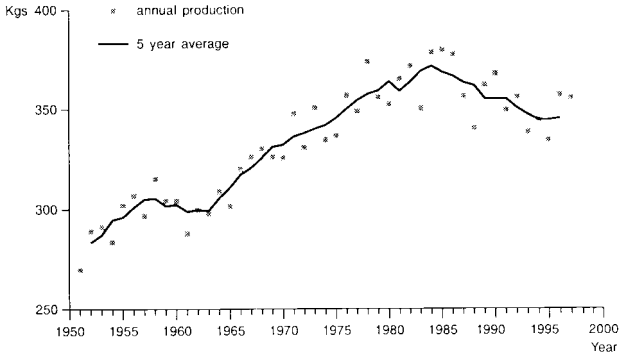


FIG. 1. World per-capita cereal production, 1951–1997. Averages for 1952 and 1996 are calculated from data for 1951–1953 and 1995–1997, respectively. Here and subsequently cereal data are expressed in production terms. Principal data sources: refs. 4 and 5. Adapted from ref. 2.

the average level of world per-capita cereal consumption (and hence production).

Regional Cereal Production Trends. A better picture emerges if regional trends are considered. The present work arranges the world's countries into seven regions (see ref. 2 for details). Six appear in Fig. 2. I discuss them in turn.

Sub-Saharan Africa has done very poorly in terms of food production. The explanation has many sides, but it includes ethnically heterogeneous nation states, widespread political instability, neglect of agriculture by governments, and, despite its many health problems (including the AIDS epidemic), extremely rapid population growth. The distinctiveness of crops and farming methods in this region also has meant that it has often missed out on "Green Revolution" technical developments (e.g., relating to high-yielding varieties of wheat and rice) that have boosted agricultural production elsewhere. Around 1995 this region's average per-capita cereal output was only about 146 kg, which is a low figure, even allowing for the fact that cereals are not grown in much of middle and west Africa, and average levels of per-capita cereal consumption were only slightly higher because of cereal imports and aid. Fig. 2 shows a generally declining trend in per-capita output from the 1960s onward. There are also signs of heightened harvest variability. The droughts of 1983, 1984 (when there was major famine in Ethiopia), and 1992 are very clear.

The Middle East here combines North Africa and West Asia. Fig. 2 shows that this region has experienced a significant long-run decline in its per-capita output, which is not helped by its rapid demographic growth. The annual volatility of the harvest in this water-scarce area is also striking. Average levels of per-capita cereal production during the 1990s have fluctuated between 250 and 270 kg, with no particular trend apparent since the early 1980s. However, the Middle East imports large quantities of cereals, mostly from North America. Around 1990 these imports accounted for almost a third of the region's entire cereal consumption, and they raised the average level of per-capita consumption to about 386 kg. These imports (which

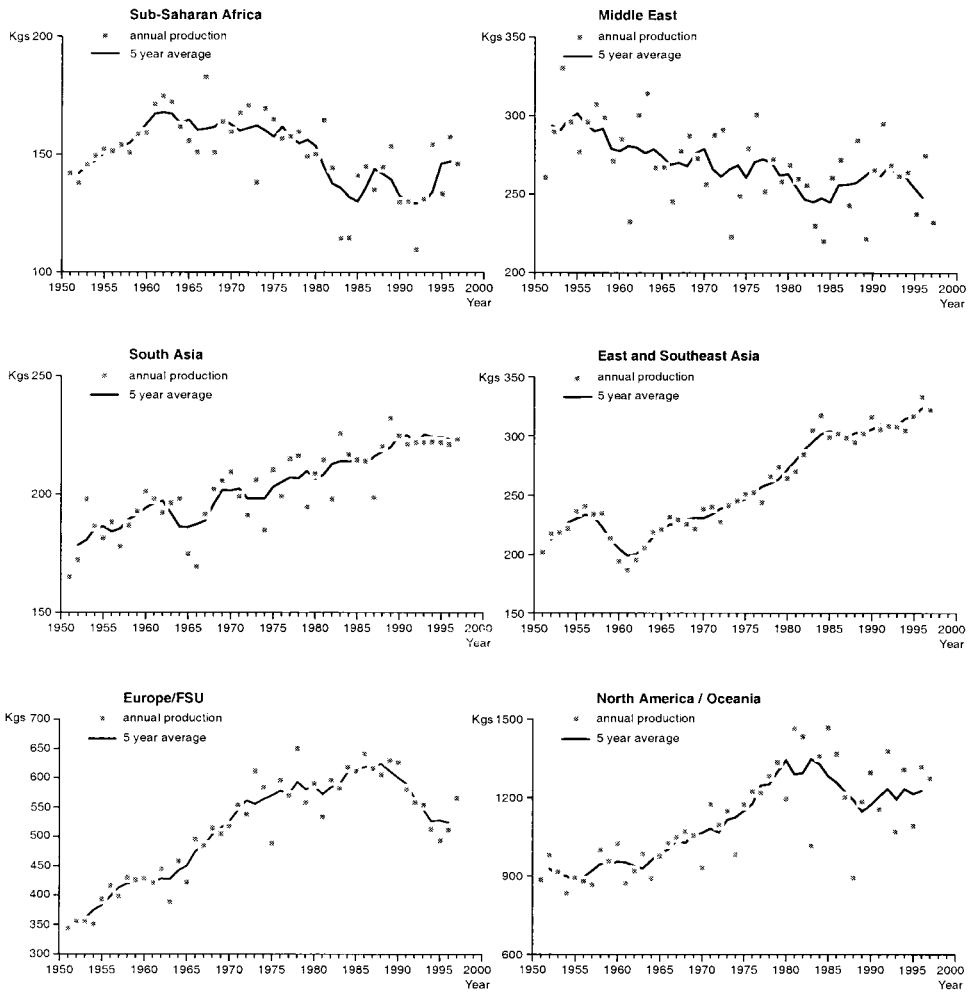


FIG. 2. Per-capita cereal production by world region, 1951–1997. Averages for 1952 and 1996 are calculated from data for 1951–1953 and 1995–1997, respectively. Principal data sources: refs. 4 and 5.

often are used to feed livestock) can be seen as an oblique way of importing water.

South Asia mainly comprises the populous countries of the Indian subcontinent (India, Pakistan, and Bangladesh). The trend in Fig. 2 is dominated by India, which contains around 70% of the region's people. The 5-year curve shows the effects of significant famines in the mid-1960s and early 1970s, which cost lives. But during the last two decades there has been no major food crisis, and average levels of per-capita cereal output have risen to around 225 kg in the mid-1990s. Notice that despite the plateau of the 1990s, levels of per-capita production are still significantly higher than those of the early 1980s. Note, too, the hint of a remarkable recent reduction in harvest variability.

East and Southeast Asia is dominated by China, although it includes other major populations, especially Indonesia and Japan. This region's trend in Fig. 2 clearly reflects the agricultural output losses of China's calamitous "leap" around 1959–1964, when perhaps 20 million-30 million died in famine. However, the subsequent trend in per-capita cereal production generally has been upward. Notice the sharp acceleration after the agricultural policy reforms that were introduced in China around 1978. This acceleration also reflected the introduction of hybrid rice and, still more, large increases in the use of chemical fertilizers by Chinese farmers. This region has continued to experience a rise in average per-capita cereal output since the early 1980s, albeit at a slower rate. By the mid-1990s regional production averaged about 316 kg per head.

It is obvious that the last two regions in Fig. 2 hold the key to the decline in world per-capita output since 1984. The first is Europe, here including the countries of the former Soviet Union (FSU). The second is North America/Oceania, a hybrid region, essentially comprising the traditional major cereal exporters of Canada, Australia, and, above all, the United States. Both of these regions produce cereals in comparative abundance. In the mid-1990s the average per-capita output in Europe/FSU was about 530 kg, and the figure for North America/Oceania exceeded 1.2 tons per person. Although the U.S., Canada, and Australia together contain less than 6% of the world's population, they currently produce about 20% of the global cereal harvest.

To understand why Europe/FSU and North America/Oceania both have experienced recent declines in per-capita cereal production requires a little history. In brief, the story is as follows. In the decades after the Second World War, until the 1970s, the countries of Western Europe, particularly those that now form the European Union (EU), were major net cereal importers from the three traditional exporters of North America/Oceania. In the 1980s this situation changed, because the EU, with its heavily protectionist Common Agricultural Policy, rapidly emerged on the world stage as a significant rival cereal-exporting bloc, which offloaded cereal surpluses on the international market at heavily subsidized prices. In turn, this provoked retaliatory responses from the traditional cereal exporters, especially the U.S., and by 1990 world grain prices were exceptionally low, at roughly 60% of their 1980 level.

Neither of the key players in this drama (the U.S. and EU) could avoid the fundamental logic of the situation. Accordingly, both have had to introduce policies designed to reduce cereal support costs, decrease stocks (which are expensive to maintain), and reduce their cereal cropland through the idling of significant areas of land. That said, the policy response has been much swifter in the United States (and Canada and Australia) than in Europe. Because many European countries benefit from the Common Agricultural Policy the policy has been hard and slow to change. Indeed, the chief cause of the really precipitate recent decline in per-capita cereal output shown in Fig. 2 for Europe/FSU lies elsewhere. The main explanation for the cereal output collapse of the 1990s has been the massive economic and political disruption resulting from the fall of communism in eastern Europe and the FSU. Consider, for example, that in 1990 the Soviet Union had a near-record cereal harvest of 227 million tons, but by 1995 the component countries of the FSU produced only 122 million tons of cereals. A decline of 105 million tons is roughly equivalent to losing production equal to about 4 years of growth in world cereal demand.

Finally, a word is in order regarding Latin America, the region not shown in Fig. 2. Levels of per-capita cereal output in Latin America are relatively low, around 260 kg in the mid-1990s (although cereals are probably a poorer proxy for food in general here than is the case for any other developing region). The trend for Latin America is actually very similar to that shown for North America/Oceania in Fig. 2. In particular, per-capita cereal output declined from a peak in the early 1980s to a trough around 1990, and then there was a period of limited recovery in the 1990s. The explanation for this similarity of trend is the common influence of international market conditions, notably as they affected Argentina, which is the region's second biggest cereal producer (after Brazil) and the largest exporter by far. Confronted by a steadily deteriorating world price, Argentina's farmers had little choice but to shift large areas of land out of wheat in the 1980s.

Concluding Remarks on Recent Trends. I conclude this review of past trends with six comments.

First, it should be clear that world cereal production has grown more slowly than population growth chiefly because of deliberate policies and political developments in North America/Oceania and Europe/FSU. With the exception of Latin America (a special case) average per-capita cereal output in the mid-1990s exceeded that in 1984 in all other world regions. It is especially noteworthy that the two large Asian regions, which together contain 57% of humanity, both have experienced significant rises in per-capita cereal production.

Second, those who point to a "dramatic slowdown" in world cereal yields (see ref. 7, p. 142) are mistaken. Fig. 3 shows that the trend is more or less linear, or "arithmetical" to use Malthus' term. Of course, on a rising base this linear trend translates into a declining percentage increase, but that is inevitable. There was a brief yield pause in the early 1990s, largely because of major yield declines in the former communist states of Europe/FSU. But in the last few years the global yield has resumed its upward march. My earlier research (2) took the world yield around 1990 of 2.711 metric tons per hectare (ha) and projected it forward by using the average slope of +42.6 kg/ha per year experienced during 1981–1993. This procedure implies a 1997 yield of 3.009 tons/ha, only very slightly higher than the actual yield of 2.979 tons (see ref. 6). Inasmuch as anything can be gleaned about regional yield trends in the brief period since 1993, then sub-Saharan Africa and the Middle East have done poorly. But both South Asia and East and Southeast Asia have performed much as projected on the basis of their yield trends during 1981–1993, and

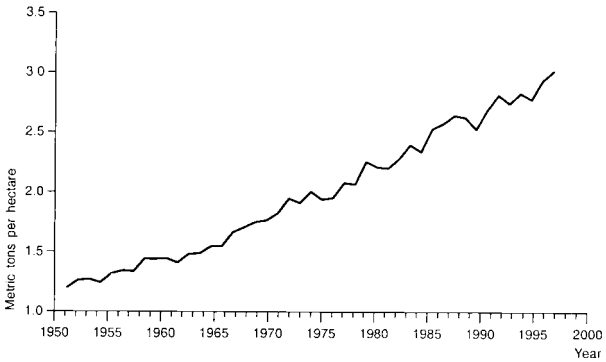


FIG. 3. World cereal yield, 1951–1997. Principal data source: ref. 5.

Latin America and North America/Oceania have done better still. It is important to appreciate that it is inevitable that there is annual fluctuation in the world yield. And periods of plateau, particularly in certain locations and for specific crops, are an integral feature of overall yield advance. Thus, with generally low international prices, the 1990s have seen indifferent yield performance for wheat. We cannot be complacent, but there is no particular cause for concern about recent world cereal yield trends.

Third, the basic relationships linking volumes of world cereal stocks, world cereal aid donations, and international cereal prices during recent decades are fairly clear. Fig. 4 shows that stock and donation levels have tended to vary directly with each other and inversely with prices. After my preceding discussion of the recent rivalry between the U.S. and EU, notice how the level of world cereal stocks has fallen sharply since the peak of the 1980s, largely because of their shared policy need to run down the size of their publicly held stocks. This common policy objective may partly explain why in the early 1990s cereal aid donations were somewhat higher than might have been anticipated given previous experience. However, a more important part of the explanation was the sudden appearance of new recipients for aid, i.e., the collapsed former communist states.

Fourth, of course, we do not live by cereals alone. There is considerable evidence that in most world regions human diets have become more diverse since the early 1980s (e.g., see refs. 8 and 11). As living standards generally have risen and populations have urbanized, so consumption and production levels of fruit, vegetables, livestock products, and processed foods all have tended to rise, too. In this context the Food and Agricultural Organization calculates indices of per-capita food output, which use price data to weigh estimates of the production quantities of all the main types of food. For the developing world as a whole this index was 114 in 1990–1992 (1979–1981 = 100; see ref. 12); only for sub-Saharan Africa do these indices suggest that food output has not been able to keep up with population growth. Increases in noncereal food output have been especially marked in South Asia (a corresponding index of 117) and, still more, East and Southeast Asia (index of 128), reflecting significant gains in India and China, respectively. So the evidence is strong that in most parts of the world human diets have been becoming more varied. And in many locations cropland that has been shifted out of cereals, because of their low relative prices, has been switched to grow other food and nonfood crops.

Fifth, both the frequency and demographic impact of famines have been considerably reduced, which is part of the message from Fig. 2. However terrible they may be, recent

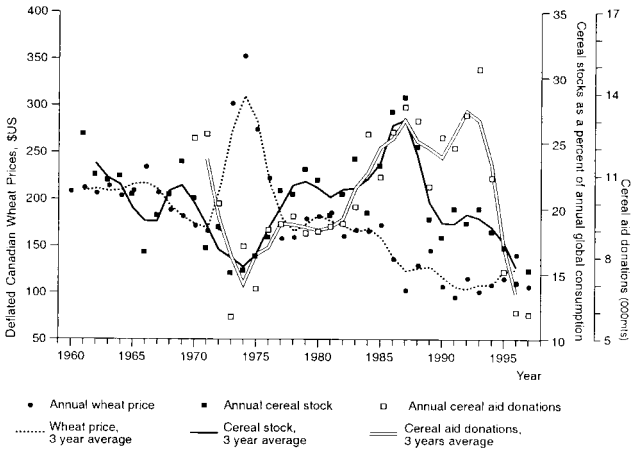


FIG. 4. World cereals: prices, stocks, and donations, 1960–1997. Principal data sources: refs. 3 and 8–10. Adapted from ref. 2.

events in places like North Korea and southern Sudan are probably less than those that engulfed countries like Mozambique and, certainly, Ethiopia in the 1980s. And they are certainly small compared with the major famines of the early 1940s, or the Chinese calamity around 1960. From all of these cases it is obvious that warfare and dislocation arising from political upheaval are the chief causes of famine in the modern world. The role of agricultural production failure, by itself, is comparatively small. Moreover, nowadays ways to combat what is usually the principal proximate cause of famine deaths (epidemic disease) generally are improved, although they cannot always be implemented. Today famine has become largely a sub-Saharan tragedy, and even there one authority has described the chances of an African dying in a famine as "vanishingly small" (see ref. 13, p. 31).

Finally, for two reasons, we now may be entering an era of rather greater international cereal price volatility than has prevailed for some time. One reason is the lower level of world cereal stocks, itself conditioned by the recent policies of the U.S. and EU. Undoubtedly, this lower stock level influenced the sudden cereal price rise of 1996, although it is worth noting that even in 1996 the international price was probably no higher than in 1985 or 1989 (see Fig. 4). It may be that any "trigger point" of world cereal stocks, below which some writers (14) suggest grain prices will become more variable, has shifted downward. The second reason is the worrying rise of cereal harvest volatility in North America. It should be stressed that for five of the seven regions in this study there are no signs of any increase in cereal harvest variability (see ref. 2). Indeed, for South Asia I already have remarked on a seeming recent diminution of harvest fluctuations, which are related to a series of good monsoons, which may be a beneficial result of climate change. Sub-Saharan Africa has experienced a long-run rise in harvest volatility, but this rise has a negligible impact on world output because the region produces less than 5% of the global harvest. However, just a glance at Fig. 2 reveals the major rise in North America's harvest volatility. This rise is important because the region is still the main supplier of cereals to world markets. This increased volatility in North America is largely weather-induced (witness the output declines of 1983, 1988, 1993, and 1995), and it is possibly a negative result of climate change.

The Future: Cereal Demand and Supply

So, although not without problems, recent trends have not been as dismal as they sometimes are portrayed. And, in turn, this conclusion allows me to make some speculations about the future that are more upbeat than downbeat, though with elements of both beats. Inevitably, what follows is very broad-brush, and it involves a mixture of projection, extrapolation, and judgment (for more detail and qualification see ref. 2). I first will examine the evolution of world cereal demand, and then consider supply.

Although there are different approaches to estimation (see ref. 15) there is little doubt (*i*) that since the 1950s population growth has been responsible for a rising share of world cereal demand growth, and (*ii*) that population growth will be the chief cause of cereal demand growth in the period to 2025. Table 1 gives some illustrative calculations based on the United Nations' 1996 "medium variant" (essentially best-guess) population projections to the year 2025. And following my earlier work, I use 1990 as the base year.

Table 1 shows that in the period to 2025 the world's population is expected to rise by just under 800 million per decade, to slightly over 8 billion. The largest absolute additions, by far, will occur in South Asia and sub-Saharan Africa. These are regions of low per-capita cereal production and consumption, but together they account for more than 55% of the total anticipated demographic growth. An initial calcula-

Table 1. Regional projections of population and cereal demand (millions of tons) 1990–2025

Region	Population, millions		Cereal consumption in 1990		Projected cereal demand in 2025 based on	
	1990	2025	Per capita, kg	Volume, mill. tons	Population increase only	Population plus income
Sub-Saharan Africa	490	1,197	150	73.6	179.8	179.8
The Middle East	276	534	386	106.6	206.4	231.9
South Asia	1,193	2,021	237	282.2	478.1	549.7
East and Southeast Asia	1,794	2,387	338	605.8	806.2	1,040.9
Latin America	440	690	265	116.6	182.7	217.9
Europe/FSU	788	799	634	499.3	506.5	506.5
North America/Oceania	304	410	780	237.1	319.5	319.5
World	5,285	8,039	363	1,921.3	2,679.0	3,046.5

Following previous work (2), I retain 1990 as the base year for projection. The estimated demand on population plus income assumes no change in per-capita cereal consumption in sub-Saharan Africa, Europe/FSU, and North America/Oceania. However, in the remaining regions rises are assumed, taking average per-capita cereal consumption in 2025 to 434 kg (in the Middle East), 272 kg (South Asia), 436 kg (East and Southeast Asia), and 316 kg (Latin America). For details of the basis of these assumptions see ref. 2. Principal sources: refs. 2, 4, and 5.

tion of the volume of world cereal demand in 2025 holds per-capita cereal consumption constant in each region (at the levels prevailing around 1990) and then projects demand forward solely on the basis of the anticipated population growth. Table 1 shows that on this population-increase-only assumption, world cereal production must rise from around 1.921 billion tons in 1990 to about 2.679 billion in 2025 to match the rise in demand. Note, too that, on this basis, world per-capita cereal production would fall to 333 kg (2,679/8,039) simply because of the changing regional composition of humankind (i.e., even though per-capita consumption levels would stay constant in each region). This fall illustrates my previous point that very different regional rates of demographic growth have implications for global cereal demand that, to the extent that demand stimulates supply, are weighing downward average levels of world output.

Of course, levels of per-capita cereal consumption will not remain constant. Rising incomes will increase levels of consumption in some regions; although, in others, health concerns about eating meat could reduce levels of per-capita intake. Also, factors like population aging and urbanization could exert a modest influence on the evolution of future world demand. Although no one can predict how these factors will evolve, a second set of calculations can capture some of the broad implications. Accordingly, I believe it plausible to assume some continued rise in overall per-capita cereal consumption in the Middle East, South Asia, Latin America, and, most importantly, East and Southeast Asia. Essentially, this computation has been done by means of a considered extrapolation from the corresponding regional per-capita cereal consumption trends of the period 1970–1990 (see ref. 2). The resulting average levels of per-capita cereal consumption in 2025 assumed here for the four regions are given in the notes to Table 1. However, the poor record of sub-Saharan Africa means that I have retained the assumption of constant per-capita consumption for this region. And the same applies for both Europe/FSU and North America/Oceania, although here my rationale is that levels of per-capita consumption are unlikely to rise from those prevailing around 1990, and they could even decline (for example with a reduction in demand for livestock products). The conjectural nature of these calculations should require no emphasis. However, the population plus income column of Table 1 suggests that roughly 3 billion tons of cereals will have to be produced in 2025 to match the volume of world cereal demand.

Can the world's farmers produce 3 billion tons for 8 billion people in 2025? Preliminarily, the evidence already reviewed suggests that they probably can, or, at least, something very close to it. Although the trend in world per-capita cereal output is rather misleading (partly because the regional composition of humanity is changing) the trend in the world cereal yield (see Fig. 3) is more telling, because the regional composition of the world's harvested cereal area has changed less. And, clearly, it is yields that hold the answer to future world food production. If from 1990 we extrapolate the world cereal yield in Fig. 3 on the previously mentioned average increment for 1981–1993 (of 42.6 kg/ha per year) then the average yield in 2025 will be around 4.20 tons. And coupled with the world harvested cereal area around 1996 (of about 702 million ha) this yield alone would produce 2.95 billion tons of grain. Even by using the average increment experienced since 1990 (of about 38.3 kg/ha) gives a yield of 4.05 tons in 2025 with corresponding output of 2.85 billion tons. Moreover, these calculations do not allow for any increase in harvested cereal area. Furthermore, here I have projected demand and supply independently, but, of course, in the real world they continually interact. The scope for adjustment between the evolution of global cereal demand and supply, e.g., in terms of changes in consumption patterns, or areas of cropland sown with cereals, is considerable. However, again, matters are better considered at the regional level.

Accordingly, Table 2 summarizes some simple calculations regarding regional yields. I stress that they are not meant as detailed projections, but rather as a backcloth for discussion. Again 1990 is taken as the base year. The first two columns provide the regional cereal areas harvested and corresponding yields around 1990. The third column gives the average annual increments in yield experienced over the period 1981–1997, broadly the period for which some authors (7) claim to detect major problems in world cereal yield growth. The fourth column shows what the regional cereal yields will be in 2025 on the assumption that the average increments experienced for 1981–1997 continue into the future. The fifth column gives the corresponding levels of cereal production in 2025 on the assumption that the areas harvested remain constant as around 1990. And the final column shows the regional shortfalls or surpluses implied when these production figures are compared with the previous projections of demand.

The broad picture that emerges from Table 2, to which I fully subscribe, is that there is going to be an increasing degree of regional mismatch between the expansion of demand and the capacity to meet that demand. In general, the world's developing regions are going to increasingly depend on cereal imports, both in absolute terms and as a proportion of their total consumption. So the volume of world trade in cereals must rise, probably more than doubling between 1990 and 2025. The U.S., Canada, and Australia will continue as the main source of cereals for world markets, but increasingly they will be joined in a subsidiary role by Europe/FSU. Notice that even on these rough illustrative assumptions the total global

Table 2. Projected cereal yields and production in 2025 by region

Region	Average area harvested 1989–1991, million ha	Average yield, 1989–1991	Average annual cereal yield increase, kg/ha per year 1981–1997	Linearly projected yield 2025	Projected production on the basis of constant area, million tons	Shortfall/surplus compared to projected demand
Sub-Saharan Africa	59.3	1.165	10.6	1.536	91.1	−88.7
The Middle East	40.2	1.642	23.6	2.468	99.2	−132.7
South Asia	140.3	1.919	52.0	3.739	524.6	−25.1
East and Southeast Asia	145.1	3.817	70.9	6.299	914.0	−126.9
Latin America	48.4	2.119	40.5	3.537	171.2	−46.7
Europe/FSU	171.4	2.816	22.8	3.614	619.4	+112.9
North America/Oceania	98.4	3.734	55.4	5.673	558.2	+238.7
World	703.1	2.711	39.0	4.076	2,977.7	−68.5

The total 2025 cereal production figure given above is the sum of the regional figures, as is the total shortfall. I stress that the above figures are simply a backcloth for discussion. They are based on the unlikely assumption of no change in harvested cereal area. A quantitative integration of broadly plausible area changes is available elsewhere (see ref. 2). Principal sources: refs. 2, 4, and 5.

shortfall is only 68 million tons; although, to reiterate, there is considerable scope for adjustment. I now look briefly at the prospects for each region.

Sub-Saharan Africa is unlikely to see much improvement in its overall food situation. The population is expected to more than double between 1997 and 2025, but there is nothing in the region's agricultural history to suggest that it will increase its food output to meet the demographically driven expansion of demand. Average yields may not rise much, and despite the assumption of Table 2 increases in food output often will come from an expansion of the cropland area. It seems highly unlikely that the annual volume of cereal imports (including cereal aid) will increase to anywhere near 88 million tons by 2025. Only a minority of countries will be able to afford to buy sizable amounts of food, and this fact alone may reduce much of any 68 million ton global shortfall such as is implied by Table 2. It is conceivable that per-capita food consumption in the region could decline. Surely, and above all, sub-Saharan Africa deserves attention and assistance, both apropos agriculture (on the supply side) and reproductive health/family planning (on the demand side). Moreover, despite all of its problems, it is important to acknowledge the region's tremendous potential. Furthermore, there are some encouraging recent developments, like falling birth rates now in most countries, and signs (admittedly very weak) of a democratic wave, notably, but not only, in South Africa (16). In the long run progressive political change may be vital for helping to solve this region's many problems.

The Middle East certainly will depend even more on cereal imports in the next few decades. Indeed, it is perfectly possible that this region could be meeting half (or more) of its total cereal consumption through imports by 2025. Water constraints and population growth are parts of the explanation for this situation. Most countries in the region are likely to be able to finance most of their imports. For example, some have oil reserves or benefit from tourism. Other countries, such as Egypt, will finance their imports partly through the export of specialist foods to Europe, where they already provide rising competition for growers in locations like Spain and Greece. However, Sudan is one major country that will almost certainly have difficulty in purchasing sufficient cereal supplies. And Sudan is a vivid reminder of the region's general political instability, which could profoundly affect national levels of food security in the coming decades (for a quantitative attempt to integrate socio-political stability into estimates of national food security see ref. 2).

South Asia emerges from Table 2 with the smallest projected regional cereal shortfall, whether measured in absolute or proportional terms. There are several reasons for thinking that this region will not develop a huge cereal import requirement despite its considerable future population growth. First, there is South Asia's current low level of per-capita cereal consumption, which remains comparatively low even if a significant increase during the period to 2025 is incorporated. Of course, this outlook is not a happy consideration, because it reflects widespread undernourishment, but it is a fact. Second, there is the commonly prevailing vegetarian diet. This diet may diminish, especially in urban areas, thereby raising the indirect consumption of grain. However, vegetarianism certainly will stay as a strong influence in the next few decades, and it will restrain the growth of total cereal demand. A final reason cereal imports may rise only modestly in the coming decades is that the current average regional yield is low, suggesting scope for improvement. Note in Table 2 that even the linearly projected cereal yield for 2025 is below that which prevailed in East and Southeast Asia around 1990. Much of the recent, and future, rise in South Asia's yields will come from greater use of chemical fertilizers. For example, in India the level of annual applications has risen from 49 to 80 kg/ha of cropland between 1984 and 1994, and a similar story applies for both Pakistan and Bangladesh (see ref. 3).

Table 1 suggests that East and Southeast Asia is the only region where, especially given the presence of China, future economic growth could have a broadly comparable impact on the growth of total cereal demand as will future population growth (of course, this region's demographic growth is rapidly slowing). So, irrespective of the numbers in Table 2, it seems very probable that East and Southeast Asia will have the largest absolute cereal import requirement of any region in 2025. That said, there seems to be no particular reason for alarm regarding the growth of China's cereal demand. The country has important agricultural potentials (e.g., the upgrading of grasslands); until recently its cropland area probably has been seriously underestimated and, relatedly, its yields overestimated (see e.g., refs. 17 and 18). China's recent performance in raising cereal yields has been, and continues to be, strong. Finally, the country's political leadership is very aware of the importance of increasing national food output as demand rises (recall the characters at the beginning of this paper). So when some people (19) ask "who will feed China?" The answer is plain: mainly, the Chinese. China and East and Southeast Asia as a whole will significantly increase their volumes of cereal imports but almost certainly not to the massive levels that some (7, 19) have suggested. Again, as everywhere, socio-political stability will be a crucial ingredient for continuing food security. And if this component is factored in, then by some reckoning China may be no more food secure than India, despite its better agricultural performance (2).

Latin America has relatively favorable prospects. Of course, some countries (e.g., Peru and Bolivia) have major food

problems. And in most countries there are significant food difficulties arising from inadequate purchasing power among poorer sections of the population (although overnutrition is an increasing problem in much of the region, too). However, the region as a whole is comparatively advanced, demographically, economically, and politically. As previously intimated, focusing on cereals can be misleading because Latin America is a major producer and exporter of products like sugar, soybean, meat, coffee, cocoa, and vegetables. Should cereals become more profitable in the decades ahead then Argentina and perhaps Brazil could become significant cereal exporters, for example, to China.

Finally, this brings me to the two main exporting regions, Europe/FSU and North America/Oceania.

Table 2 implies annual net cereal exports from Europe/FSU exceeding 110 million tons by around 2025, which seems plausible. Note that this surplus results from extrapolating the very modest annual yield increment of only 22 kg/ha per year experienced during 1981–1997. The small size of this increment was almost entirely the outcome of the yield collapse experienced in Eastern Europe and the FSU. In fact, an average increment closer to 47 kg for this region is perfectly credible over the longer run (see ref. 2). There will be continued major yield rises in the EU. Here are two recent illustrations: between 1989–1991 and 1995–1997 France's average cereal yield rose from 6.24 to 6.81 tons, and the United Kingdom's, from 6.17 to 6.98 tons. Consequently, the amount of idled cereal land in the EU may well be raised, although it also could be reduced (i.e., more land could be brought into cultivation if the need arose). In addition, there is great potential to raise cereal production in Eastern Europe (notably Poland) and large areas of western Russia, Ukraine, and Kazakhstan in the FSU. Undoubtedly, reforming the farming sector in most of these former communist countries is proving to be a lengthy and extremely difficult process. It is complicated by issues of access to European markets and applications for EU membership. In turn, these issues raise the important problem of Common Agricultural Policy reform.

Finally, the capacity for continued cereal yield and output growth in North America/Oceania is also strong. Again, comparing averages for 1989–1991 and 1995–1997, and in increasing order of export importance, cereal yields rose from 1.66 to 1.91 tons/ha in Australia, 2.47 to 2.69 tons in Canada, and 4.58 to 5.04 tons in the U.S.. With an average yield for the region of 4.08 tons in 1995–1997, an average of around 5.5 tons in 2025 seems to be a realistic target. Indeed, the average regional yield in 1994 was nearly 4.5 tons [assisted by good U.S. out-turn for maize (corn)]. To reiterate, a greater problem apropos production in this region may be increasing harvest volatility, with obvious implications for world prices. The other regional prospect of which we can be sure is that there will be continued agricultural rivalry with the EU, which will extend far beyond cereals.

Conclusion

Inevitably this paper has omitted a lot, and one's view as to whether the prospects to 2025 are good or bad depends partly on the particular criteria that are used. Surely the prospects are mixed. However, in my view, over this specific time horizon, they are more good than bad.

In 2025 the world's farmers will be producing roughly 3 billion tons of cereals to feed the human population of around 8 billion, which will require an average world cereal yield of about 4 metric tons/ha (see also ref. 20). It also is likely that some regions will, for different proximate reasons, experience an increase in their harvested cereal area. For example, in sub-Saharan Africa with meager yields this increase may happen because of population growth, whereas in Latin America it could happen to meet export demand.

We know that there are significant problems of soil structure when land is cultivated year after year (e.g., see ref. 24). But problems of water for agriculture probably will be much more important. World agriculture will have to use its water supply very much more efficiently in the coming decades. And water is a resource that must be better priced.

Of course, there will be new crops and improved seeds. But most of the required increase in the world's harvest will come from the application of procedures and knowledge that we already have to the current world harvested area. It is inescapable that humanity will depend even more on synthetic nitrogen fertilizers for its food supply (e.g., see ref. 21). My calculations using Gilland's equations (22) suggest that there may have to be an approximate doubling of global use of synthetic nitrogen to produce 3 billion tons of grain (2). Another vital resource for the future will be a continuing rise in the level of population, and hence farmer, education in most regions. And farming everywhere is likely to involve much greater dependence on information-intensive farm management procedures, as well as heightened attention to variation of conditions within individual fields, whether done through the reading of subtle color change in crop leaves or by satellite imagery.

It is highly unlikely that there will be any wonder breakthrough that will solve the problem of raising world food production. On the contrary, it will continue to be hard work. Moreover, the process of raising yields and agricultural advance is extremely complex. Many of the multitude of developments that together will influence the world food outlook (e.g., relating to education, health conditions, technology, transport and communications, and institutional structures) primarily are fashioned by the wider world, i.e., beyond agriculture itself.

Crucial among these will be developments in the realm of political economy. Almost everywhere socio-political stability will be the most important element for maintaining food security in the future. I have noted the importance that political reform could have in sub-Saharan Africa over the longer run. Then there is the issue of how the situation in Eastern Europe and the FSU (and reform of the Common Agricultural Policy) will unfold. There is also the related matter of international trade arrangements, where it seems probable that the momentum toward increasing liberalization will be maintained. Partly for this reason, it is hard to envisage that average world food prices will be higher in 2025 than applied, say, in the early 1990s (see ref. 23), although prices could well be more volatile.

There will still be many hungry people alive in the year 2025. But if the scenario envisaged by this paper applies, then there must be a reasonable chance that the absolute number will be fewer than is the case today. Also, we should not lose sight of the rapidly growing problem of overnutrition in some urban areas of the developing world. However, the very substantial demographic growth that will happen in the world's worst-fed regions almost guarantees the continuation of a considerable volume of undernourishment. Significant areas, especially in sub-Saharan Africa, may effectively remain "lost" to development, including agricultural development. In such locations population growth will contribute to environmental damage as people try to eke out a bare living from the land.

In conclusion, the main thrust of this paper has been to show that, in general, the world food situation has been improving. And I have argued that this trend probably will continue during the next few decades. World food output will continue to rise, although there will be a growing degree of mismatch between the expansion of food demand and the capacity to supply that demand. Accordingly the balance will be met by a considerable expansion of the world food trade. As a result, most people probably will be better fed in 2025 than is the case today.

This work was funded partly by the United Kingdom Economic and Social Research Council (Economic and Social Research Council Award L320-27-3024).

1. Malthus, T. R. (1798) *An Essay on the Principle of Population* (Johnson, London).
2. Dyson, T. (1996) *Population and Food: Global Trends and Future Prospects* (Routledge, London).
3. The World Resources Institute, United Nations Environment Program, United Nations Development Program & World Bank (1998) *World Resources 1998–99* (Oxford Univ. Press, New York).
4. United Nations (1996) *World Population Prospects: The 1996 Revision* (United Nations, New York).
5. Food and Agricultural Organization (1951–1997) *Production Yearbook* (Food and Agricultural Organization, Rome).
6. Food and Agricultural Organization (1998) *FAO Quarterly Bulletin of Statistics* (Food and Agricultural Organization, Rome).
7. Brown, L. R. & Kane, H. (1995) *Full House* (Earthscan, London).
8. Mitchell, D. O. & Ingco, M. D. (1993) *The World Food Outlook* (The World Bank, Washington, DC).
9. Brown, L. R. (1998) in *Vital Signs, 1998, 1999,* eds. Brown, L. R., Renner, M., Flavin, C. & Starke, L. (Earthscan, London), pp. 38–39.
10. Food and Agricultural Organization (1983–1997) *Food Aid in Figures* (Food and Agricultural Organization, Rome).
11. Mitchell, D. O., Ingco, M. D. & Duncan, R. C. (1997) *The World Food Outlook* (Cambridge Univ. Press, Cambridge).
12. Dyson, T. (1994) *Popul. Dev. Rev.* **20,** 397–411.
13. Seaman, J. (1993) *Inst. Dev. Studies Bull.* **24,** 27–31.
14. Brown, L. R. (1998) in *State of the World 1998*, eds. Brown, L. R., Flavin, C. & French, H. F. (Earthscan, London), pp. 79–95.
15. Alexandratos, N. (1997) *Popul. Dev. Rev.* **23,** 877–888.
16. Lansner, T. R. (1995) in *Freedom in the World,* eds. Adrian Karatnycky, I. R., Cavanaugh, K., Finn, J., Graybow, C., Payne, D. W., Ryan, J. E., Sussman, L. R. & Zarycky, G. (Freedom House, New York), pp. 25–30.
17. Alexandratos, N. (1996) *Agric. Econ.* **15,** 1–16.
18. Crosson, P., ed. (1996) *Perspectives on the Long-term Global Food Situation 2* (Federation of American Scientists Fund, Washington, DC), pp. 1–8.
19. Brown, L. (1995) *Who Will Feed China: Wake-up Call for a Small Planet* (Norton, New York).
20. Evans, L. T. (1998) in *Feeding a World Population of More than Eight Billion People*, eds. Waterlow, J. C., Armstrong, D. G., Fowden, L. & Riley, R. (Oxford Univ. Press, New York), pp. 89–97.
21. Smil, V. (1997) *Sci. Am.* **277,** 58–63.
22. Gilland, B. (1993) *Endeavour New Ser.* **17,** 84–88.
23. Winkelmann, D. L. (1998) in *Feeding a World Population of More than Eight Billion People,* eds. Waterlow, J. C., Armstrong, D. G., Fowden, L. & Riley, R. (Oxford Univ. Press, New York), pp. 264–272.
24. Cassman, K. (1999) *Proc. Natl. Acad. Sci. USA* **96,** 5952–5959.