PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

Introduction and conclusions for a Discussion entitled Land resources: on the edge of the Malthusian precipice?

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INTRODUCTION AND CONCLUSIONS

This introduction is derived from the papers presented, the discussions following the presentations, and the discussion between the speakers, chairmen, organizers and a few others at a meeting hosted by the Ciba Foundation.

(*a*) *The problem*

In his famous essay, first published anonymously in 1798, the Reverend Thomas Robert Malthus, F.R.S., claimed that 'Population, when unchecked increases in a geometric ratio. Subsistence increases in an arithmetical ratio ... This implies a strong and constantly operating check on population from the difficulty of subsistence'. This essay, and the subsequent revisions published over his name, contain a wide range of data supporting these conclusions. Recent Malthusians believe that we are indeed about to arrive at a major checkpoint (Myers 1991; Ehrlich *et al*. 1993; Brown 1994). Others believe that scientific and technical advances, particularly in food production, will be able to keep pace with the increasing population, as they have done for the past 200 years, even though the annual additions to the human population are greater than ever before, and that over 800 million people remain food-insecure at the present time. The purpose of the meeting was to make a rigorous scientific assessment of the evidence regarding the ability of land resources to meet future demands, and to determine what further research is needed to strengthen the scientific base on which such assessments depend.

(*b*) *The present and the prospect*

The meeting first considered the present pressures on land and water resources arising from the population density in relation to climate, topography, and soil characteristics. The latest UN projections of global population growth (Fischer & Heilig, this volume) are that increases averaging 80 million per annum are inevitable between now and 2015. The increases will still be of the order of 50 million per annum in 2050, and will be higher unless the reproductive level falls below 2.1 children per woman. The reasons for the increases exceeding anything previously experienced are the demographic momentum created by the large number of women of child-bearing age living at present, the time-lag required for reductions in the birth rate to affect population growth, and the declining death rate. These factors are also discussed in the Royal Society publication *Population – the complex reality* (Graham-Smith 1994).

Most of the population increase will be in developing countries, with the largest absolute increase occurring in Asia (two billion of the 3.7 billion expected to be added by 2050) and the greatest relative increase in Africa (1.3 billion, a doubling of the present population). By 2050, West Africa is expected to have a population equal to that of the whole of Europe. The projections for the next three decades are robust, the projections to 2050 less so.

(*c*) *Resource assessment*

How well can the underdeveloped regions be expected to support this unprecedented growth in population? The necessary increase in food production has to come from cultivation of more land, higher yields, or an increase in the number of crops grown each year. Fischer & Heilig (this volume) report the FAO's and other data which indicate that at present there are close to 900 Mha under cultivation, and a further 1600 Mha which might be cultivated. About 30% of this land with some cultivation potential is only marginally suited to agricultural use, and much is under forest or is wetland which would be better preserved as such, which leaves some 550 Mha available. This potentially cultivable land is very unevenly distributed, and land shortages are already, or will shortly become, acute in West Asia, the Indian subcontinent, probably China, and North and much of sub-Saharan Africa.

The analysis by Fischer & Heilig demonstrates the importance and urgency of the need to have good quantitative assessments of the food production potential of the land resources of the world. Sivakumar & Valentin (this volume) drew attention to the need for better climatic data in making assessments of crop production potential, and Webster (this volume) and others to the inadequacy of much of the soil data on which current assessments are based. During a discussion at this meeting, Young reported that in his experience much of the land classified by the FAO as cultivable is in reality not so. Webster (this volume) thought that for practical purposes regional and national surveys by traditional methods, rather than by use of remote sensing and geographical information systems, are likely to be more useful to users on the ground. The World Soil Map of the FAO, with a scale of 1:5 000 000 inevitably includes areas with very different capability within each soil unit mapped. Clearly, the database on which land resource assessments are based needs to be much improved. Steps in this direction have been initiated in the Global and National Soil and Terrain Digital Databases (SOTER) Project being undertaken by the International Soil Reference and Information Centre (ISRIC) on behalf of the FAO and UNEP (Oldeman & van Engelen 1992).

Given the existing limitations present estimates of the population support capacity of the land resources of the globe must have a very wide margin of error. Nevertheless, the conclusions and the FAO's data are presently the best available. They were used in the FAO/IIASA/UNFPA agroecological zones project to arrive at the population carrying capacity of the globe (Fischer & Heilig, this volume). Penning De Vries, Rabbinge & Groot (this volume) also use this database, but with revised estimates of the crop production potential of each of the 15 500 land units used to compile the database. In deriving the potential yields, they assume production is limited only by radiation and temperature, and by precipitation on rainfed areas; and that all surface water, except that for industrial and urban use, is available for irrigation. They calculate an aggregated maximum food supply for the world, and conclude that it is more than sufficient to feed a population greatly in excess of eight billion. However, there are severe limitations imposed on the achievement of this potential, including economic and environmental factors. It is also assumed that all land can be used for food crops, to the exclusion of all other crops. The adequacy of the food production also depends on distribution to where it is needed by trade or aid. There are great differences between regions. For instance, in China, most of the suitable land, and in India nearly all the surface water, will be needed, leaving no margin for inefficiency in water distribution, or loss of productivity through soil degradation. Even allowing for considerable errors in the calculation of production potential, it is clear that many countries are already faced with severe difficulties if they are to make food production meet their populations' needs.

The socio-economic barriers to increasing food production are also substantial (Barbier, this volume; D. L. Winkelmann in Ciba Foundation meeting 1997). They include, for example, the problems of subsistence farmers who lack land tenure, and others displaced from their traditional land by population pressure. When they find unused land, they find it is usually of poor quality, all the better land already being in use. They may have to start cultivating forestland, which many consider should be better conserved. They lack any incentives to improve the land they occupy, as they are again liable to be displaced, and hence will not normally purchase fertilizers or take other measures for the long-term improvement of the land. When the land they have occupied is exhausted – on marginal land often a matter of very few years – they move to other areas where the process is repeated, ultimately causing serious degradation of large areas of land.

(*d*) *Towards a solution*

The key factors that limit crop productivity are lack of water and essential plant nutrients, and higher yielding plant types.

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(i) *Improving water availability*

Water availability can only be substantially improved by irrigation. Can the water for irrigation be provided? Falkenmark (this volume) estimates that if the water necessary for food production by irrigation is provided, it will be quite unrealistic to expect water to be supplied at the present rate per caput in North Africa, South Asia and West Asia; and it will be difficult for society to cope in other regions in Africa and North China. In these regions, the amount circulating in the water cycle is not enough to produce the food needed in the regions themselves.

This rather dismal outlook for the semi-arid and arid regions may to some extent be alleviated if measures to improve the efficiency of water use in these regions can be improved. Such measures include reducing runoff by suitable cultivation, and ensuring that water is used by plants rather than evaporated from the soil surface by (i) sowing as soon as possible after the rainy season has started; (ii) encouraging plant cover by use of fertilizers; and (iii) mulching (Wallace *et al*., this volume). On some soils it may also be possible to reduce drainage to groundwater by a combination of management practices, including adjustment of sowing density, use of fertilizers, and proper selection of plant varieties.

(ii) *Improving nutrient availability*

Vlek *et al*. (this volume) point out that the plant nutrients needed to replenish what is yearly taken from the soil in food and fibre amounts to 230 million tonnes (Mt) of nitrogen, 205 Mt of phosphorus and 20 Mt of potassium. Current fertilizer consumption is 130 Mt per annum, supplemented by 90 Mt of biologically fixed nitrogen; so the world's soils are being depleted of nutrients by over 10 Mt per year. This global figure conceals great regional disparities. Although 80% of the population lives in the developing world, only half of the fertilizer is used there. Yet as much as 50% of the increase in agricultural production in the developing world is due to the use of fertilizer. World population growth will require a doubling in plant nutrient consumption by the developing world by 2020. In the past, given time and low population densities, slow weathering of primary soil minerals in the root zone, together with rejuvenation of the soil by natural erosion, and recycling of nutrients through vegetation on fallow land, has enabled replenishment of nutrient supplies to keep pace with losses to the ocean of nutrients in food. The current and forecast rates of nutrient removal are of quite a different order of magnitude, and amount to mining of the soil. If nutrients are not returned, the fertility of the soil and crop yields will inevitably decline. The availability of raw materials needed to maintain yields is adequate for the next 100 years. But a major increase in the capacity to manufacture fertilizers will be necessary if supply is to meet demand. Without a major change in economic conditions, it will be necessary that the capacity is built in developing countries, or that the fertilizer is provided as aid.

Several speakers stressed the importance of soil organic matter. The few long-term trials on soil management in the tropics are showing that for a short time, sometimes up to ten years, yields can be maintained with inorganic fertilizers alone, but thereafter they gradually decline. When supplemented with continual additions of organic manures or mulches, yields may be maintained or improved (Greenland 1995; Greenland *et al*. 1997; Syers, this volume). The reasons are still not entirely clear. Part of the freshly added organic matter is rapidly (half-life is about one year) decomposed by soil microbes to lower molecular weight compounds; the rest is converted into more stable forms. Both pools contribute to the structural stability of the soil Aggregates disperse less easily, so that finer particles do not block the coarse transmission pores that enable water and oxygen to enter the soil freely. In addition, the available water holding capacity of the soil is increased, and erosivity decreased. Organic matter also increases the soil's capacity for retaining exchangeable nutrient cations such as potassium, calcium and magnesium, and micronutrients such as zinc. This reservoir serves to buffer the concentration of these cations in the soil solution, and maintains their concentrations in appropriate proportions for plants' needs. Organic matter is also a reservoir of organic nitrogen, phosphorus and sulphur compounds that are released by mineralization to the inorganic nitrate, phosphate and sulphate that roots can absorb. The seemingly special virtue of a high rate of organic turnover may lie in the steady rate of release of these nutrients close to root surfaces, which in the case of nitrate and sulphate aids their absorption by the roots before they are leached beyond the root zone. In acid soils, the ability of organic matter to complex aluminium reduces the toxicity associated with aluminium ions in the soil solution. Further, the microbial population that is stimulated may compete with pathogenic organisms that would otherwise infect roots. The relative importance of these actions differs between soils, and further intensive research is needed to clarify which constituents of soil organic matter are important in different situations.

Returning larger quantities of organic matter to the soil is important not only to maintain and improve soil fertility, but also as a sink for carbon, which could otherwise contribute to atmospheric carbon dioxide and methane, and hence to the greenhouse effect. A relatively small gain in soil carbon is sufficient to offset a large part of the carbon added to the atmosphere as a result of burning of fossil fuel (Sanchez *et al.*, this volume).

It is therefore important to seek methods that can increase economically the level of soil organic matter. Land and animals must be managed with these needs in mind. Agroforestry systems are effective in returning greater amounts of organic matter to the soil, but need careful management if the tree crop is not to compete too vigorously with the arable crop. They have the advantage that the tree crop can continue to feed in the deeper subsoil that remains moist after the topsoil that supports the arable land has dried. Tree species that yield useful products —in addition to their contributions to soil organic matter, limitation of erosion and recycling of nutrients—offer the most acceptable systems of agroforestry. Many more studies on 'Cinderella' species with high potential are needed to adapt them to combination with effective crop production systems (Sanchez *et al.*, this volume).

In the tropics, some soils are too acid for successful crop production, or may become too acid with continued use of inorganic fertilizers. Economically available sources of lime are often scarce. Increased levels of soil organic matter can help to reduce the problems of aluminium toxicity which arise in acid soils. Selection and breeding of crop varieties better adapted to these adverse conditions can also help.

Except on very nutrient rich soils, the dogma advanced by some proponents of the organic farming movement, that cropping can be sustained without increasing nutrient supplies and replacing those nutrients removed in crops with fertilizers or from other external sources, is a dangerous illusion that will restrict the necessary production of much needed food in many under-developed countries. An integrated nutrient management approach is needed, in which appropriate organic matter additions are combined with use of organic fertilizers. Intensive research is needed to determine the most effective and economic methods by which this can be done on different soils (E. Craswell in Ciba Foundation meeting 1997).

(iii) *Improving crop potential*

A major factor that has undermined Malthusian forecasts recently has been the increase in food production that occurred between 1960 and 1990 (Greenland *et al.* 1997). The higher yields have come from the happy coincidence of several technological advances, notably the increased responsiveness to nitrogen fertilizer of the short-strawed varieties of cereals (mainly rice and wheat) that resist lodging, a rapid expansion of irigation facilities, and the resistance of the newer high-yielding crop varieties to insect pests and diseases. The route to a comparable advance in the next 30 years, based on advances in plant physiology and breeding of new high-yielding plant types is not clear (Evans, this volume). Possibly, genetic engineering will provide an answer, for instance by simplifying gene transfer from wild species. Photosynthetic efficiency has not been measurably improved by empirical selection, nor by studies of the biochemical processes involved. The whole photosynthetic process is controlled by many genes and the path to improvement is likely to be complex. Advances are more likely to come from improvements such as the selection of varieties that stay green longer during grain filling, whose stomata stay open for longer periods each day, or that have more productive tillers.

There is no doubt that atmospheric carbon dioxide concentrations are rising, and without concerted action, will continue to rise. In controlled experiments, yield increases averaging about 30% have been observed in a range of species, but seasonal variations in weather, water and nutrient availability tend to reduce the apparent advantage substantially in field conditions. Overall, the effect of the global increase in atmospheric carbon dioxide concentration on agricultural production is uncertain (probably about 7–8% with doubled CO_2), but its impact on yields over the next 25 years is likely to be small (Gregory *et al.* this volume, and 1998).

Most farmers know what existing varieties are suitable for each patch of soil they cultivate. To use their knowledge in selection of varieties and improvement of crop management practice, it is important that a 'bottom-up' approach is employed by researchers, so that full advantage is taken of this age-old knowledge base. Such a policy has already contributed to improvements in the rate at which innovations coming from the CGIAR and other research centres have been adopted. In practice, soil and climate conditions are amazingly diverse, and many well-trained assistants are needed to work with the scientists and farmers to obtain the best results from such a policy. In many countries it is essential that dramatic increases in yields are obtained in the next two or three decades.

(*e*) *Land degradation*

Efforts to increase crop yields are being negated in many countries by the concomitant degradation of soil resources. The evidence for this comes from declining national average yields. Production in those countries where yields are declining has increased only by cultivating large areas of soil that are only marginally suited to crop production (Greenland *et al.* 1997). The net result is declining per caput food supplies. The Global Assessment of Soil Degradation project (Oldeman 1994) estimated that worldwide there were 1094 Mha affected by water erosion, 548 Mha affected by wind erosion, 240 Mha chemically degraded and 83 Mha physically degraded. Although as with estimates of crop production potential these figures are based on inadequate data, they do provide an indication of the extent of the soil degradation problem. What is even less clear is the extent of the economic losses associated with soil degradation (Lal, this volume). Much more needs to be known of the rate at which soil productivity declines under stress due to cultivation, and the reversibility of this degradation, which differs between soils because of the differences in their resilience to different kinds and intensities of stress.

(*f*) *Environmental effects*

Soil degradation causes not only undesirable changes in the soil itself, but also a number of off-site effects, leading to environmental degradation. Indiscriminate use of fertilizers, manures, and pesticides can pollute groundwater and streams (B. Yaron in Ciba Foundation Meeting 1997). These issues have been well rehearsed in developed countries. Unfortunately, as Tinker (this volume) points out, there is little hard data about water quality in most less developed countries. Nevertheless, the same principles apply in both, and as land management intensifies, similar care will need to be exercised to avoid pollution problems.

Erosion is a more serious problem in the tropics than in temperate regions, because of the higher erosivity of the rainfall. Hence the off-site problems of erosion are more important. These include the siltation of dams and canals, which threatens the productive potential of many irrigation schemes. Wallace *et al.* (this volume) describe how some larger dams have lost over half their storage capacity in a few years. Inadequate drainage to remove salt is also an increasingly important problem in many arid countries that depend on irrigation for crop production.

Possibly the most serious cause of off-site problems associated with soil degradation is the decrease in water entry and storage in the soil. This leads to greater run-off, and often to widespread flooding. Again there is inadequate information about the extent and severity of these various off-site effects and their economic consequences. Only long-term trials conducted on a catchment basis can provide the necessary information (Greenland *et al*. 1997). There are few of these in developing countries. Techniques for managing them efficiently are urgently needed as they are costly and need to be maintained for many years: but without such information the value of land protection and improvement cannot be assessed.

(*g*) *Conclusions*

From the discussions at the Royal Society and the meeting of speakers, chairmen and others at the Ciba Foundation, the organizers have drawn the following conclusions.

1. If all resources are harnessed, and adequate measures taken to minimize soil degradation, sufficient food to feed the population in 2020 can be produced, and probably sufficient for a few billion more.
2. Most of the extra food will be produced by those countries with a greater extent and better quality of land resources; there are many countries where serious food problems will be experienced in the next two decades.
3. Transfers of food from countries with greater resources to food deficit countries and regions will continue to be necessary unless substantial and rapid improvements can be made in food production and in economic development in those countries with inadequate natural resources.
4. Production increases on a sustainable basis will only be achieved in resource-poor countries as a result of increased understanding of the basic principles of crop production and sustainable land management. The necessary knowledge will only be gained through improved education at all levels of society, and by close and continued collaboration between scientists, extension workers, and farmers (male and female) in research and development activities.
5. To feed the world for the foreseeable future the research efforts of the developed countries must be not only restored but increased, and collaboration with developing countries enhanced, so that the fall in the rate of increase in cereal yields from a high of almost 3% per annum in 1965 to close to 1.3% per annum at the present time can be reversed, with the changes in the rate of improvement being concentrated on those areas where it is most needed and economically possible.
6. In the underdeveloped world, research into soil, water and nutrient management must be intensified. Long-term trials conducted on a catchment basis are essential if the sustainability and environmental acceptability of various management practices are to be properly assessed.

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REFERENCES

Brown, L. R. 1994 Facing food insecurity. In *State of the world* (ed. L. R. Brown, C. Flavin & S. Postel). London: Earthscan Publications Ltd.

Ehrlich, P. R., Ehrlich, A. H. & Daily, G. C. 1993 Food security, population and the environment. *Pop. Dev. Rev.* **19**(1), 1–32.

FAO 1995 World agriculture: towards 2010. An FAO study (ed. N. Alexandratos). Rome: Food and Agriculture Organization.

FAO, IIASA & UNFPA 1982 *Potential population supporting capacities of lands in the developing world*. New York: UN Population Division.

Graham-Smith, F. (ed.) 1994 *Population—the complex reality*. London: Royal Society.

Greenland, D. J. 1995 Long-term cropping experiments in developing countries: the need, the history and future. In *Long-term experiments in agricultural and ecological sciences* (ed. R. A. Leigh & A. E. Johnson), pp. 187–209. Wallingford, UK: CAB International.

Greenland, D. J., Gregory, P. J. & Nye, P. H. 1997 Land resources and constraints to crop production. In *Feeding a world population of more than eight billion people: a challenge to science* (ed. R. Riley & J. C. Waterlow). New York: OUP.

Gregory, P. J., Ingram, J. J. *et al.* 1998 Effect of global change on managed production systems. In *GCTE: a synthesis of current knowledge* (ed. B. Walker & W. Steffan). Cambridge University Press.

Malthus, T. R. 1798 *An essay on the principle of population as it affects the future improvement of society*. St Paul's Churchyard, London: J. Johnson.

Myers, N. 1991 *Population, resources, and the environment: the critical challenge*. New York: UN Population Fund.

Oldeman, L. R. 1994 The global extent of soil degradation. In *Soil resilience and sustainable land use* (ed. D. J. Greenland & I. Szabolcz), pp. 99–118.

Oldeman, L. R. & van Engelen, V. W. P. 1992 *A World Soils and Terrain Digital Data Base (SOTER): an improved assessment of land resources for sustainable utilisation of the land*. Wageningen, Netherlands: International Soil Reference and Information Centre.

UN 1996 *World population prospects. The 1996 revision*. New York: United Nations Population Division.