PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

Agroecological zones and the assessment of crop production potential

M. V. K. Sivakumar and C. Valentin

Phil. Trans. R. Soc. Lond. B 1997 **352**, 907-916
doi: 10.1098/rstb.1997.0070

Agroecological zones and the assessment of crop production potential

M. V. K. SIVAKUMAR[1] AND C. VALENTIN[2]

[1] *World Meteorological Organization, Geneva, Switzerland*
[2] *ORSTOM, Niamey, Niger*

SUMMARY

The rapidly growing world population puts considerable pressure on the scarce natural resources, and there is an urgent need to develop more efficient and sustainable agricultural production systems to feed the growing population. This should be based on an initial assessment of the physical and biological potential of natural resources, which can vary greatly. The agroecological zonation (AEZ) approach presents a useful preliminary evaluation of this potential, and ensures that representation is maintained at an appropriate biogeographic scale for regional sustainable development planning. The principal AEZs of the world, as described by the Technical Advisory Committee of the Consultative Group on International Agricultural Research, are presented along with their extent and characteristics. Net primary productivity of terrestrial vegetation can be assessed from weather data, and it varies from 1 t dry matter ha^{-1} yr^{-1} in high latitude zones and dry regions to 29 t ha^{-1} yr^{-1} in tropical wet regions, depending on the climatic conditions. To assess the crop production potential, length of the growing period zones, a concept introduced by the UN Food and Agriculture Organization, is very useful as it describes an area within which rainfall and temperature conditions are suitable for crop growth for a given number of days in the year. These data, combined with the information on soils and known requirements of different food crops, can be used to assess the potential crop productivity. Some perspectives on AEZs and crop production potential are presented by describing the manner in which production potential can be integrated with present constraints. Efforts to intensify production should place emphasis on methods appropriate to the socio-economic conditions in a given AEZ, and on promotion of conservation-effective and sustainable production systems to meet the food, fodder and fuel needs for the future.

1. INTRODUCTION

The steady growth in the world's grain harvest from 1950 to 1990 has stalled during the Nineties. The 1995 world grain harvest of 1680 million tonnes (Mt), was the smallest in the previous seven years (Brown *et al.* 1996). The growing population puts considerable pressure on the scarce natural resources, and today it is well recognized that future productivity increases will have to be achieved while at the same time conserving and enhancing the natural resource base on which they depend.

The 'food first' focus of agricultural productivity research in the past focused primarily on 'vertical' relationships, i.e. investigations on plants, animals, air, water and soils within a relatively homogeneous spatial unit. However, the present task of conserving and enhancing natural resources is more complex and carries an implicit recognition of the presence of several systems within a landscape, which calls for 'horizontal analyses' requiring investigations and planning at temporal/spatial scales greater than the case with conventional studies. This requires integration of biological, physical and socio-economic factors in a holistic manner, and the availability of tools such as geographic information systems (GIS) and other spatial modelling techniques make this possible. In this paper, we describe how the agroecological zones (AEZs) approach could be used to find generalized answers as to how such an integration could be achieved.

2. WHY AN AGROECOLOGICAL ZONES (AEZs) APPROACH?

Agroecology is the application of ecological concepts and principles to the design and management of sustainable agricultural systems (Gliessman 1992). The agroecological environment of a crop, land use or a farming system has physical, chemical and biological aspects. Viewing the agroecosystem as a functional system of complementary relations between living organisms and their environment that are managed by humans with the purpose of establishing agricultural production provides a basis for integrating the overlapping ecological and environmental traits with sociological, economic, political, and other cultural components of agriculture (Francis 1986). All of these may vary across space and time. Consequently, varieties and management methods have different optima in different places.

The site–season or site–year can be considered as the basic unit of the environment (Brinkman 1987). At any given site, there are aspects that are invariant and stable, e.g. landform, soil type, etc., and aspects that vary with the seasons, e.g. temperature, rainfall and incidence of pests and diseases. Also, the severity or timing of aspects may fluctuate from year to year, depending on, for example, diseases, length of the growing season, etc. These give rise to a potentially infinite number of environments, but only part of the variation is of practical importance. Lack of recognition of such site-specific characteristics, which can have a major influence on crop productivity, frequently led to disasters in the past. A good example is the case of groundnut cultivation in East Africa under unsuitable conditions during the 1950s, which resulted in huge financial losses. It is therefore important to summarize, classify and map environmental information at different levels of generalization. The resulting classes and maps range from very broad to very detailed AEZs.

Agroecological zonation helps mainly to (i) make a quantitative assessment of the biophysical resources upon which agriculture and forestry depend; and (ii) identify location-specific changes necessary to increase food production, through a comparison of farming systems and production alternatives. With AEZs, we can at least make a good estimate of the actual potential for crop production in different areas by (i) setting priorities for use of increased inputs that are needed to increase agricultural production, and (ii) identifying the less favoured environments, in which rural populations are ecologically and environmentally disadvantaged, and the priorities for their development.

3. METHODS TO DEFINE AEZs

One of the simplest criteria for determining agroecological zonation has been mean rainfall. For example, in West Africa rainfall shows a significant north–south gradient because of the interseasonal movement of the Intertropical Convergence Zone (ITCZ) north and south of the equator. Hence, a range of vegetation patterns developed along this gradient. In almost all the climatic zonation schemes developed for West Africa, considerable emphasis has been placed on the use of two criteria: mean annual rainfall and vegetation. These schemes are inadequate for assessing crop production potential because (i) mean annual rainfall cannot be considered as a sufficiently useful index of probable season length by itself as the potential evapotranspiration, which varies from one region to another, influences the proportion of rainfall available for crop growth and hence the final yields; (ii) for annual cereals which are planted and harvested following rainfall patterns in a given year, the most important constraint is the length of the growing period (LGP); (iii) concepts and principles developed at a particular location in a given climatic zone, such as the Sahel, cannot be expected to hold good for the entire zone since soil characteristics such as texture, slope and water holding capacity and inherent soil fertility all play very important roles in cultivar performance; and (iv) the adoption of more acceptable, crop-dependent climatic criteria is necessary for crop planning applications.

The work of Cocheme & Franquin (1967) on the agroclimatological survey of a semi-arid area in Africa south of the Sahara should be considered a landmark in clarifying many issues of crop–climate relationships. They gave adequate weighting to both precipitation (P) and potential evapotranspiration (PE) in the zonation scheme by using the ratio of P:PE and computing the LGP based on a realistic appraisal of crop response to available moisture. This system was used by the UN Food and Agriculture Organization (FAO) (1984) in their publication on agroclimatological data for Africa.

(*a*) *The FAO's agroecological zoning project*

The FAO's agroecological zoning project, begun almost two decades ago, was one of the first to quantify systematically the extent of potentially cultivable land in the developing countries. It was the first study to provide estimates of the yields that can be expected for different crops in different parts of the developing world under varying levels of inputs (FAO 1978). It also provided essential data for subsequent studies that assessed the population-supporting capacity of land in developing countries.

The first step in the AEZ methodology is a division of land in the developing countries into 14 major

Table 1. *Major climatic divisions for Africa* (*source*: *FAO 1978*)

no.	major climates descriptive name	suitable for consideration during the growing period for crop group	24 hour-mean temperature regime over the growing period	total extent ('000 ha)
1	warm tropics or tropical lowlands	II and III	> 20 °C	2029975
2	cool tropics or tropical highlands	I and IV	< 20 °C	96604
3	cold tropics or tropical mountains	not suitable	< 6.5/10 °C	2903
4	warm sub-tropics (summer rainfall)	II and III	> 20 °C	291894
5	cool sub-tropics (summer rainfall)	I and IV	< 20 °C	39900
6	cold sub-tropics (summer rainfall)	not suitable	< 6.5/10 °C	193
7	cool sub-tropics (winter rainfall)	I	> 6.5 °C	543198
8	cold sub-tropics (winter rainfall)	not suitable	< 6.5 °C	6663

Group I crops: wheat, potato, phaseolus bean (temperate and high altitude cultivars).
Group II crops: soybean, rice, cotton, sweet potato, cassava, phaseolus bean (tropical cultivars).
Group III crops: pearl millet, sugarcane, sorghum, maize (tropical cultivars).
Group IV crops: sorghum and maize (temperate and tropical high altitude cultivars).

Table 2: *Agroecological zones*: *developing countries*

(Source: TAC/CGIAR 1992. Note: zones that have a mean monthly temperature, corrected to sea level, above 18 °C for all months have been classified as *tropical*. Zones with one or more months below 18 °C but above 5 °C are *subtropical*, and zones with one or more months below 5 °C are *temperate*. Zones with mean temperatures greater than 20 °C during the growing period have been classified as *warm*. Zones with mean daily temperatures of 5–20 °C are *cool*, below 5 °C are *cold*, and if one part of the growing period has temperatures greater than 20 °C and the other is between 5 and 20 °C, they are classified as *warm/cool*. Zones have been classified as *arid* if the length of the growing period is less than 75 days, as *semi-arid* if the range is between 75 and 180 days, as *subhumid* if the range is between 180 and 270 days, and as *humid* if the range is greater than 270 days. For comparison, the percentage of total arable land in developed countries is 47.5%.)

agroecological zone (AEZ) for developing countries	name	length of growing period	temperature	% of LDC arable land	% of total arable land
AEZ1	warm arid and semi-arid tropics	75–180 days	> 20 °C all year round	21.4	11.3
AEZ2	warm, subhumid tropics	180–270 days	> 20 °C all year round	14.1	7.4
AEZ3	warm humid tropics	270–365 days	> 20 °C all year round	14.1	7.4
AEZ4	cool tropics	75–365 days	5–20 °C during growing period	4.9	2.6
AEZ5	warm arid and semi-arid sub-tropics (summer rainfall)	75–180 days	> 20 °C during growing period	11.8	6.2
AEZ6	warm, subhumid subtropics (summer rainfall)	180–270 days	> 20 °C during growing period	3.7	2.0
AEZ7	warm/cold humid subtropics (summer rainfall)	270–365 days	> 20 °C during one part of the growing period and 15–20 °C during the other	9.8	5.1
AEZ8	cool subtropics (summer rainfall)	75–365 days	5–20 °C during growing period	8.3	4.4
AEZ9	cool subtropics (winter rainfall)	75–365 days	5–20 °C during growing period	11.9	6.3

thermal regimes, determined by the average temperature during the period when there is sufficient moisture for crop growth. Once the temperature requirements are met, the potential yield of a crop is determined by the extent to which the crop growth cycle matches the period of moisture availability or the LGP. In the AEZ study, LGP was defined as the number of days when precipitation exceeds half the potential evapotranspiration. It includes the period required to evapotranspire up to 100 mm of available soil moisture stored in the soil profile. If the mean temperature falls below the minimum needed for crop growth, then the LGP is adjusted to allow for such periods. Information on the locations of the thermal regimes and the LGP zones was then combined to create the climatic inventory map.

The AEZ land inventory was prepared by overlaying the climatic and soil inventories to provide a base map containing data on climate, thermal regime, LGP zones, soil associations, slope, phase and soil texture. Thus, the developing countries's land area is viewed as a mosaic of about 650000 grid squares (10 × 10 km), each with a specific climate, growing period and association of soils. From these the area of each soil within each climate and LGP has been calculated for each country. These defined agroecological cells constituted the database, which is stored on a computer.

The AEZ project for Africa (FAO 1978) identified eight major climatic divisions, based on the effect of latitude and altitude, in space and time, on mean temperature (table 1). The study made an inventory of the total extent of land in Africa variously suited (or not suited) to the production of eleven crops of the assessment, and related the four suitability classes recognized to anticipated yields.

(*b*) *TAC/CGIAR classification of agroecological zones*

The Technical Advisory Committee (TAC) of the Consultative Group on International Agricultural Research (CGIAR) adapted the AEZ characterization developed by the FAO (TAC/CGIAR 1992) by subdividing the major ecological regions (tropics, subtropics with summer or winter rainfall, and temperate regions) into rainfed moisture zones using LGP, and into thermal zones using the temperature regime prevailing during the growing period. Data on LGP, temperature, and the proportion of arable land covered by each of the nine zones are presented in table 2. Information on soil and landform used in the FAO characterization was excluded from the framework used by TAC so as to keep the number of subdivisions to a manageable level. Also, TAC's geographical coverage was limited to developing countries of sub-

Table 3. *Land use and major food crops in different agroecological zones* (*source*: *TAC/CGIAR 1992*)

(AEZ) name		major regions covered	area (millions ha) (a)	(b)	(c)	major food crops
AEZ1	warm arid and semi-arid tropics	sub-Saharan Africa	469	220	65	sorghum, millet, cowpea, pigeonpea, groundnut, sweet potato
		Asia	94	31	88	
		Latin America–Caribbean	48	85	13	
AEZ2	warm, subhumid tropics	sub-Saharan Africa	143	121	49	rice, maize, sorghum, soybean, cowpea, cotton, cassava, sweet potato
		Asia	47	60	44	
		Latin America–Caribbean	110	258	34	
AEZ3	warm humid tropics	sub-Saharan Africa	113	302	44	cassava, yam, maize, bananas, plantain, rice pineapple, perennial tree crops (palm oil, rubber, cocoa, coffee)
		Asia	77	222	61	
		Latin America–Caribbean	107	386	28	
AEZ4	cool tropics	sub-Saharan Africa	89	24	19	maize, bean, sorghum tea, coffee, potato, wheat, barley
		Latin America–Caribbean	111	100	17	
		West Asia–North Africa	8	2	1	
AEZ5	warm arid and semi-arid sub-tropics (summer rainfall)	Asia	162	21	107	irrigated rice, wheat, cotton, food legumes sugarcane
		Latin America–Caribbean	42	23	9	
AEZ6	warm, subhumid subtropics (summer rainfall)	Asia	66	14	33	rice and wheat
		Latin America–Caribbean	31	4	9	
AEZ7	warm/cold humid subtropics (summer rainfall)	Asia	207	19	80	wheat, maize, food legumes
		Latin America–Caribbean	142	51	39	
AEZ8	cool subtropics (summer rainfall)	Asia	315	123	75	wheat, barley, maize, lentil, soybean, potato
		Latin America–Caribbean	152	29	40	
AEZ9	cool subtropics (winter rainfall)	Latin America–Caribbean	22	26	6	wheat, barley, pulses, oilseeds, vegetables and forage crops
		West Asia–North Africa	338	55	90	

[a] Agricultural land.
[b] Forest and woodland.
[c] Cultivated land.

Saharan Africa, West Asia–North Africa, Asia, Latin America and the Caribbean. The current extent of cultivated land throughout the world is about 1.4 billion ha (of which 270 million ha are irrigated), but there is considerable variation in the percentage amounts of land used for arable cropping in the AEZs. According to TAC/CGIAR (1992), in the nine AEZs in the developing countries of sub-Saharan Africa, Asia, West Asia–North Africa, Latin America and the Caribbean, about 950 million ha are cultivated and the total arable land is about 870 million ha. Land use patterns and the major food crops in different AEZs are shown in table 3.

4. CROP PRODUCTION POTENTIAL

One of the simplest answers to production potential is offered by the concept of net primary productivity (NPP), which is the net production of organic matter by the plants, and is therefore the fundamental basis determining the biological diversity and activity of ecosystems on the Earth (Seino & Uchijima 1992). Several methods have been developed to predict NPP values of various vegetation types. Seino & Uchijima (1992) evaluated the global distribution of NPP using weather data from 1143 stations on whole continents, and presented a map of the geographical distribution of NPP of natural vegetation. Predicted NPP values ranged from less than 1 t dry matter ha^{-1} yr^{-1} in high latitude zones and dry regions to 29 t dry matter ha^{-1} yr^{-1} in tropical wet regions, depending on climatic conditions. The latitudinal change in NPP was characterized by a curve with a clear peak in the equatorial zone and two weak troughs in the sub-tropical high pressure belts on both hemispheres.

Computation of crop productivity should go beyond the concept of primary productivity, and the FAO (1978) provides one of the best examples of the calculation of crop productivity. Information on radiation and temperature within the growing period is used together with the actual photosynthetic capacity of crops and the fraction of the net biomass which crops can convert into economically useful yield to calculate the net biomass production (B_n) and yield of crops. B_n is calculated as:

$$B_n = \frac{0.36 \times mgb}{1/N + 0.25\ c_t},$$

where B_n = net biomass production by the crop during N days of its cycle, expressed in tonnes per hectare, mgb = maximum level of gross biomass production by the crop, and c_t = coefficient of respiration of the crop. The coefficient c_t is expressed as a function of the mean temperature t by

$$c_t = c_{30}\,(0.44+0.0019t+0.001t^2),$$

where c_{30} is the coefficient of respiration of the crop for $t = 30$ °C.

Yield biomass, B_y, can be calculated as

$$B_y = B_n \times H_i,$$

where H_i is the harvest index, defined as the fraction of the net biomass of a crop that is economically useful.

At a LGP of 120 days, potential net biomass production (yield) of rice, maize and soybean are computed as 13.2 (4.0), 14.3 (5.0) and 8.2 (2.6) t ha^{-1}, respectively. Information on these can be computed for any given AEZ and the data show that, in general, the potential productivity, in the absence of other constraints such as soils, drainage, fertilizers, cultural practices, etc., could be quite large. Alexandratos (1995) computed these maximum constraint-free yields (MCFY) and compared them with computed yields for 21 crops at three levels of technology: low (subsistence farming using no inputs), intermediate (some use of inputs) and high (commercial farming making full use of inputs). A region is considered *suitable* for rainfed crop production if any crop grown under any of these three technology alternatives gives a yield of 20% or more of MCFY for that technology.

Penning de Vries (this volume) described the potential and attainable levels of food production in different regions using the modelling approach. Hence, we prefer to present some perspectives on crop production potential in different AEZs.

5. PERSPECTIVES ON AEZs AND CROP PRODUCTION POTENTIAL

Although the soil and climate characteristics and the potential crop productivity in many of the AEZs around the world offer much hope for enhancing future food production, the current population increase and the expansion of cultivation into marginal lands is putting increasing pressures on land resources. Continued land degradation will present problems not so much for global supply as for development in particular subregions. In these *hot spots*, land degradation poses a significant threat to food security for large numbers of poor people, to local economic activity, and to important environmental products and services. Future policy should focus on such hot spots (Scherr & Yadav 1996). There are reasons to be hopeful, however. Many *bright spots* can also be identified–areas where land quality is improving or degradation has slowed down, usually in connection with improvements in rural investment incentives and supportive policies (Oldeman *et al.* 1990).

(*a*) *Warm arid and semi-arid tropics*

The warm arid and semi-arid tropics encompass very large areas of sub-Saharan Africa, Asia, and Latin America and the Caribbean (table 3). Population growth and poverty will continue to put strong pressures on the resource base, particularly in Asia and parts of Africa where there is little scope for further expansion. Rainfall is low, variable, and unreliable. Soils are susceptible to waterlogging or erosion, while wind erosion is a threat on the sandy soils during the long dry season. Soil constraints also include salinity and acidity.

(i) *Arid regions*

Traditionally, farming systems in the more arid areas have been based on nomadic herding. This is an appropriate response to the spatial and temporal variability of the rain. Unsustainability arises from resource degradation, due to the low carrying capacity of the land and increasing numbers of people and animals. In favourable periods, the number of animals increases, while during periods of drought, all vegetation is rapidly consumed and the soils are exposed to wind, and when rains do occur, to water erosion.

Nomadic pastorality may be complemented by traditional rainfed agricultural production. Such production is at high risk because of the uncertain rainfall. When the soil is cultivated, the soil structure deteriorates rapidly and the normally low levels of organic matter in the soil are further depleted. The net result is that the soils tend to form surface crusts that further impede entry of rain into the soil.

There are many examples of the responses of farmers to these problems by water harvesting and water spreading, in which water running into gullies is diverted onto cultivated fields. These methods enable some yields to be obtained, but they are almost always low or very low. Where water is adequate, it has been shown that responses to fertilizers are common (Pieri 1992). However, the use of fertilizers is rarely economical. It has been difficult to establish more productive animal-based systems unless water supplies can be improved, and better systems of herd management are introduced to avoid overgrazing.

Several *hot spots* for land degradation exist due to salinization in the Indus river basin, and due to wind and water erosion in West Africa. One of the *bright spots* in this AEZ is the dryland rehabilitation through holistic range management, which is quite promising for southern Africa and revegetation of Mexican rangelands.

(ii) *Semi-arid zones*

Populations in the semi-arid regions are often relatively high. Consequently, severe degradation occurs because of drought recurrence, overgrazing, overcultivation, and deforestation (for fuelwood). Production has been increased by cultivating larger areas, including much marginal land, and by more frequent cultivation of grazing land.

The degradation of land in this zone has been referred to as desertification, which is associated with soil degradation due to a loss of organic matter, erosion, crust formation, structural decline, and sometimes salinity. Together they may be more significant than postulated changes in rainfall. While farmers are aware of the need to return organic material to the soil, it is difficult to find material to use against the competing demands for fuel, animal fodder, and bedding and roofing material. Fertilizers can increase production from these areas for a decade or more, but they cannot do so indefinitely.

The erratic nature of the rainfall is intensified by the effects of overgrazing and cultivation, which damage the natural vegetation and promote the formation of impermeable crusts on the soil surface. Sustainability depends on the availability both of animal manures, or an alternative source of organic material, and of fertilizers. Under present conditions, sources of organic material are becoming increasingly difficult to find, and fertilizers are not economically available. In spite of the resilience of these areas, they are on a downward spiral of degradation. The deterioration is most pronounced on light-textured soils, which are the most common (Greenland *et al*. 1994).

The major predicted impact of expected climate change is an increase in the frequency and severity of droughts (IPCC 1995). This should lead to episodic die-off of woody vegetation, which will increase the fire-fuel load. Because human populations depend mainly on pastoralism, human responses are likely to include increasing the distribution and security of surface water for livestock. This is likely to weaken the grass layer and increase soil crusting, with acceleration of desertification.

Areas covered by Vertisols in the semi-arid tropics present their own special problems. While these soils have a high soil-water retention capacity, they are almost always too hard or too sticky to be tilled. Management of these soils is particularly difficult when only human or animal power is available. Where these soils have high contents of sodium, they are liable to become severely compacted under continuous cropping, and the soil may become barren, as has happened in northern Cameroon. However, many Vertisols can be highly productive when they are put under proper management, as has been demonstrated at the International Crops Research Institute for the Semi-arid Tropics (ICRISAT) and in the International Board for Soil Research and Management (IBSRAM's) Vertisol network (IBSRAM 1989).

Hot spots for land degradation include areas prone to wind erosion in the Sahel and where rangelands are being converted to grain production in West Asia. Nutrient depletion in the semi-arid croplands of Burkina Faso and Senegal (leading to outmigration) and large areas of Africa under transition to short fallow or permanent cropping are also at risk. Vegetation degradation, particularly near water sources in Africa, and loss of vegetation due to intensive collection of fuelwood in Africa also pose particular problems.

Bright spots for land improvement include multi-cropping areas through water harvesting and improved water management in India. There is some potential to expand the irrigated land in the semi-arid tropics of sub-Saharan Africa and in Latin America and the Caribbean. Low-resource, low-risk production systems appropriate to the harsh environments in the semi-arid tropics can provide the scope for increasing production.

(*b*) *Warm subhumid tropics*

The total area covered here is 845 million ha, about half of which is found in Latin America (mainly Brazil). Approximately 20.1% of the total forest and woodland of the nine AEZs is in the warm subhumid tropics, and in some Asian countries more than half of the forests have been destroyed. Since rainfall in this zone is higher and more consistent, the problem of water management is less serious than the problem of soil acidity, which is more common in upland areas of all regions. The soils have low organic matter and nutrient levels, which are further reduced by cultivation. Tillage of these soils, especially when mechanized methods are used (Lal 1991) can also lead to surface crusting, creating water availability problems. Alluvial soils in the lowlands are more fertile and support intensive crop production. Coastal ecosystems, particularly in Asia, present special problems. Saline water incursion is a serious problem that is likely to increase if sea levels rise.

In Latin America these areas are often used for pastures, but they need lime and fertilizers if they are to be productive (Sanchez & Salinas 1981). The productivity could be enhanced greatly if suitable pasture legumes could be identified. Under cultivation, organic matter maintenance is the most critical factor, since by complexifying toxic aluminium it ameliorates the problem of acidity as well as modifying soil structure and contributing to the nutritional status of the soil. It should be possible to identify sustainable pasture–crop or tree–crop systems for these areas, but to date there has been limited success; most tree and pasture legumes are not adapted to the high acidity and low phosphate status of the subhumid tropics.

Hot spots for land degradation are the sandy soils of north-eastern Thailand and south-eastern Nigeria, where there is considerable nutrient mining, and the Cerrados of Brazil due to mechanization with inappropriate ploughing techniques, leading to loss of vegetation and loss of topsoil.

Bright spots for land improvement are areas which have demonstrated sustainable yield increases in India and Sri Lanka, cotton growing areas in West Africa, and the maize growing regions in Africa.

(*c*) *Warm humid tropics*

The warm humid tropics occupy the largest proportion (41.8%) of all the forest and woodlands covered by the nine AEZs. The drier parts of this region are characterized by a bimodal rainfall pattern, and the wetter parts by a single prolonged wet season. The soils are mostly of low inherent fertility with low-active clays.

The major causes of unsustainability in this zone are low inherent soil fertility and the high erosivity of rainfall. Under forest cover, nutrients are efficiently recycled, and the soil is fully protected. However, tropical areas are losing forests rapidly, e.g. 9.65 million ha of forest area was lost annually between 1980 and 1990 (Brown *et al*. 1996). The failure to return organic matter to the soil as forest litter leads to a sharp decline in biological activity in the soil, and as a result the aggregation of the soil is lost and it becomes compacted. Experimental data show that after forest clearing, the yields rapidly fall to near zero. Under cultivation, nutrients are removed in harvested products; moreover, they are leached because they are no longer intercepted by trees' roots. This leads not only to nutrient deficiency, but also to acidification. Hence cultivation of these soils is inherently unsustainable. Long-term experiments confirm the rapid loss of fertility and the need to replenish nutrients and correct acidity. They have also shown that systems without protection of the soil with a mulch or cover crop are unsustainable, even if fertilizers and lime are used. Systems based on no-tillage and residue mulches allow a satisfactory soil conservation level, but have not been widely adopted because of the difficulties of weed control without the use of herbicides.

If the vegetative cover of the soil in this zone is removed, heavy rainfall induces the collapse of the structure of the soil. This process can be dramatically enhanced if inappropriate mechanized methods of land clearing are used. As a result, runoff and consequent erosion increase. The high erosivity of the rainfall subjects unprotected soils to severe erosion. The most adapted land use systems are those which mimic the initial rainforest, conservative agroforestry and tree-based farming systems with perennial crops, such as rubber, oil palm, and cocoa. A leguminous cover crop can complement the protection afforded by the canopy of the perennial, and with good management it may be possible to grow annual food crops under the canopy. Such systems are sustainable only when they are economically viable, a condition strongly controlled by external markets. This severely limits the area that can be used in this way.

Alley cropping and other agroforestry systems mimic the protection of the forest, but their management is very demanding and the advantages offered over traditional shifting cultivation systems, even where these are deteriorating, have not been particularly attractive to small farmers.

The traditional system of shifting cultivation in the humid zone was successful as long as there was sufficient land for farmers to leave the soil to rest under naturally regenerating forest for periods in excess of a decade (Robinson & McKean 1992). As demographic pressure has increased and more and more people have been forced to seek land in the forested areas, traditional systems have been replaced by crude slash-and-burn, in which the cultivation period is prolonged and the forest regeneration is endangered and is inadequate to maintain fertility. The net result is deforestation with its various undesirable consequences.

Combinations of tree crops with arable cropping systems, and rotations of forest plantations with arable production can be sustainable if the efficiency of the tree crops in recycling nutrients and controlling acidity is maintained. Productivity may be retained by careful management of nutrient levels, including those of trace elements, and acidity can be controlled with fertilizers and lime; but it has yet to be demonstrated that such systems are economically sustainable. After reviewing the extensive literature on shifting cultivation published since 1960, Robinson & McKean (1992) concluded that the problem is worse today in degree and scale, and much of the problem lies with social aspects. Farmers' perceptions and decisions, economic trends, and government policy all affect the problem, and will have to be reconciled in order for the problem to significantly reverse overall trends of degradation.

Hot spots for land degradation are the forest frontiers of Indonesia, Malaysia, Vietnam, Cambodia and Laos. There are likely to be conflicts between farming and protected areas in Madagascar, the humid Amazon and lower Amazon basins, the Pacific rainforest of Colombia and Ecuador, and the Atlantic lowland of Central America. Vegetation degradation due to expansion of *Imperata* occurs in Indonesia, Vietnam, and the Philippines, infestation of *Imperata* and *Chromolaena* on degraded soils in Africa, and overgrazing in Haiti and Caribbean basin lowlands are major problems.

Bright spots for land improvement do exist in areas where there is a diversification to perennial crops, e.g. perennial plantations in areas of low population density with fragile soils in Malaysia, India, southern Thailand, and the Philippines.

(*d*) **Cool tropics**

Cool tropical areas are particularly important in Latin America, the Caribbean and East Africa. Since the high population densities in these areas have been practising intensive cultivation for centuries, the land has been overexploited, resulting in the long-term decline of soil fertility and in widespread soil erosion.

Shallow soils, acidity, and steep slopes are the major constraints in the cool tropics. Traditional methods for sustaining farming in these areas include the construction of terraces and the maintenance of a cover on the soil of a perennial pasture or an organic mulch of materials taken from the forest growing on adjacent, and usually more steeply sloping, parts of the mountain or hillside. These traditional methods have broken down as population has increased, and as forests and pastures have been destroyed by overexploitation. Widespread deforestation has resulted in the long-term decline of soil fertility and in extensive soil erosion. The major cause of unsustainability in the steeplands is water runoff and the consequent erosion which occurs whenever steep slopes are cultivated.

Erosion is these areas is not necessarily man-induced. It often involves mass movement of soils and landslides as well as loss of topsoil, and the results are often easily observable. Steeplands are typically zones where the effects of sustainability must be viewed on a variety of space scales, from field plots to subcontinental watersheds. While the effects of unsustainability are most pronounced and easily observed in mountain areas such as the Andes and the highlands of East and Central Africa, the problems are common to most areas where slopes exceed 15%.

Hot spots for land degradation are the Central American hillsides that are prone to erosion. There are constraints to yield increases in the densely populated highlands in Rwanda, Burundi, and Kenya, and there are no obvious sources of productivity increase. Nutrient depletion is the major problem in the Central American hillsides.

Bright spots for land improvement do exist and can be seen in the implementation of effective and widespread adoption of conservation tillage, mulches, etc., in Central America. Afforestation through community-based forest plantations in the Andes and Guatemala is a good example. Crop diversification (e.g. conversion to coffee and other perennials on hillsides in Mexico and Central America, and crop diversification with erosion control in Colombia) is also a good strategy.

(*e*) ***Warm arid and semi-arid subtropics with summer rainfall***

This region covers large areas of Asia and Latin America and the Caribbean. The important difference is that over 457 million people in Asia are supported on an arable land area of 107 million ha, while in Latin America and the Caribbean 14 million people depend on an arable land of only 9 million ha. Rainfall is low, variable, and unreliable, and the LGP is less than 180 days. Hence, a large proportion of the arable land in this AEZ is irrigated (41% in Asia and 32% in Latin America and the Caribbean) which makes this zone one of the most productive in the developing world.

The unreliable rainfall in this AEZ , together with its warm climate and high solar radiation levels, creates problems of moisture availability for crops. The irrigated areas in India, China and Pakistan are among the most productive in the developing world. A major problem in these irrigated areas is salinity and alkalinity on soils with high base status. Hence, more efficient water management systems are needed to sustain productivity. Most of the projected increases in this AEZ will have to come through intensification of existing production systems and there is a growing interest in enhancing the efficiency of the rice–wheat production system.

(*f*) ***Warm subhumid subtropics with summer rainfall***

Most of this zone covers Asia (China, India, and North and South Korea) and Latin America (Argentina). Soils are mainly fertile alluvial or loess-derived, and are used for irrigated crop production. As is the case with the previous AEZ, the rice–wheat production system is the dominant cropping system with good rainfall and fertile alluvial soils. The theoretical production potential on existing cultivated lands in China, India, North and South Korea is 141 Mt of grain equivalent, compared with the current 54 Mt.

The rice-based farming systems of the wetlands of Asia are probably the longest sustained production systems in existence. In parts of China, rice appears to have been grown continuously for 7000 years, and the main pillars on which such sustainability rests are the replenishment of nutrients in deposited sediments and from high nitrogen fixation, no erosion from bounded fields, no acidification, relatively low weed problems, high phosphate availability, and no nitrate pollution of ground waters. These wetland areas have also been the centre of major success of the Green Revolution.

National average yields in China and Indonesia now exceed 5 t ha^{-1}, and the concern about sustainability is not, as it is elsewhere, about raising very low yield levels, but of maintaining and increasing high levels. Long-term experiments at the International Rice Research Institute (IRRI) have shown a disconcerting downward trend for more than 20 years, and long-term rice–wheat systems in India also reveal a downward trend.

Economic factors are one cause, as the responses to input are falling as yields increase, so that against a falling world rice price the system becomes economically unsustainable. Problems in the maintenance of the water supply systems are another. Where rainfall is supplemented by irrigation, as it is in most of the more productive rice areas, there are serious problems of waterlogging and salinization. In areas which are naturally flooded, deteriorating conditions in the catchment areas, leading to greater depth of floods and more frequent and persistent submergence of the crop, are another cause.

(*g*) ***Warm/cool humid subtropics with summer rainfall***

The warm/cool humid subtropics with summer rainfall cover mainly Asia (China) and Latin America (Argentina, Brazil and Paraguay). Although this zone has the lowest proportion of arable land of all the nine AEZs, it supports a population of 550 million people. Major advantages of the warm/cool humid subtropics with summer rainfall is the abundant moisture availability and high potential productivity. Large areas in China, Brazil and Paraguay and some areas in Argentina present opportunities for intensive vegetable cultivation and aquaculture.

(*h*) ***Cool subtropics with summer rainfall***

This zone covers a large area in Asia (Bhutan, Mongolia, Nepal, China, India, North and South Korea) and in Latin America (Uruguay and Argentina). Globally, this AEZ supports a population of 443 million people. Over 60% of the soils in this zone outside China have slopes of over 30% and are shallow, with low clay and organic matter contents. Some of the soils present problems of salinity and alkalinity.

Characterized by cool and harsh climate and a large diversity in topography and land use potential, this AEZ has a smaller proportion of arable land (table 2). Steep slopes in the mountainous areas present problems similar to those described already for the steep soils of AEZ (§5*d*) (cool tropics). The risk of soil erosion continues to be high, and maintenance of soil fertility through an effective integration of traditional crop and livestock production systems is necessary. Areas with adequate soil moisture offer good potential for growth in the low-lying plains of northern China and Latin America.

(*i*) *Cool subtropics with winter rainfall*

Over 82% of the cool subtropics with winter rainfall occur in the West Asia–North Africa region and the rest in Latin America (Chile and Argentina). The climate is characterized by cool-to-cold winters and hot summers and high rainfall variability. The crop growing season in winter is characterized by a semi-arid moisture regime. Soils are shallow and are low in clay and organic matter. On irrigated lands, widespread salinization and waterlogging are the major problems.

The West Asia–North Africa region, which has by far the largest area under this AEZ, offers limited potential for bringing new rainfed land into cultivation or expanding the irrigated area. Uncontrolled mechanization and extension of cultivation into marginal lands is leading to stagnation in yield levels and declining availability of feed for ruminant livestock. Although wheat yields increased to some extent, yields of barley, pulses, oilseeds, vegetables and forage crops have been stagnant.

There are opportunities for diversification and intensification through more effective water management as can be seen in the installation of water-saving irrigation technologies in Jordan and water harvesting and gully prevention in Tunisia and Libya. Diversification to perennial crops such as olive, pistachio, and fruit plantations in Tunisia, Morocco, and Egypt is showing much promise. Similarly, shrub plantations in Syria and Jordan for livestock feed are helping to improve livestock productivity.

6. AN IMPROVED TOOL FOR AEZ APPROACH TO FOOD SECURITY PROBLEMS

The basic principle of the AEZ approach is to understand the multiplicity of agronomic, economic and environmental criteria that determine the performance of an agroecosystem, and then determine the nature and extent of changes that need to be introduced to achieve greater productivity. For more efficient of use of land resources in the future, three points of view should be confronted and integrated in order to diagnose the situation in a given AEZ, and to establish some trends: (i) the dynamics of land use and land cover. This refers mainly to the state of the natural resources; (ii) the dynamics of the production systems, including the farming systems as well as the storage and market issues. These refer mainly to the management of the natural resources; and (iii) the changing policies, including the problems of equity. This refers mainly to the access to the natural resources. Remote sensing developments in the recent years now make it feasible to routinely monitor the dynamics of land use and land cover. On-farm surveys and rapid rural appraisal techniques could be used to establish the dynamics of production systems. Agricultural policy cells of national governments could provide the information on changing policy. Integration of this information, at least for selected *hot spots* and *bright spots* in each of the AEZs in a GIS framework, could help us to understand the interrelationships between agronomic, economic and policy factors, in order to develop conservation-effective and sustainable production systems to meet the food, fodder and fuel needs of the future.

7. CONCLUSIONS

The global AEZs are stable over time. Their definition enables comparisons to be made among similar biophysical situations subjected to a wide range of socio-economic and land use conditions. In particular, they show that the downward spiral of degradation observed in the *hot spots* has been hampered or even reversed in some *bright spots*. Some of the lessons from these success stories can help us find answers to problems in other places in the world. However, it should be understood that solutions are not always technical in nature, but are also founded on social, cultural and economical considerations. Finding suitable solutions to the resource management problems in future may well depend on our ability to take a more holistic view of the gamut of biophysical, socio-economic and policy issues that integrate concerns of productivity, stability, sustainability and equitability.

8. REFERENCES

Alexandratos, N. (ed.) 1995 *World agriculture: towards 2010. An FAO study*. Chichester, UK: John Wiley & Sons.

Brinkman, R. 1987. Agroecological characterization, classification and mapping: different approaches by the International Agricultural Research Centers. In *Agricultural environments: characterization, classification and mapping* (ed. A. Bunting), pp. 31–42. Wallingford, UK: CAB International.

Brown, L. R., Flavin, C. & Hane, H. 1996 *Vital signs 1996–97. The trends that are shaping our future*. London: Earthscan Publications Ltd.

Cocheme, J. & Franquin, P. 1967 *An agroclimatological survey of a semi-arid area in Africa south of the Sahara*. Technical note No. 86. Geneva: World Meteorological Organization.

FAO (Food and Agriculture Organization) 1978 *Report on the agroecological zones project*. World Soil Resource Report No. 48. Rome: FAO.

FAO (Food and Agriculture Organization) 1984 *Agroclimatological data. Africa. Vol. 1*. Rome: FAO.

Francis, C. A. 1986 *Multiple cropping systems*. New York: Macmillan.

Gliessman, S. R. 1992 Agroecology in the tropics: achieving a balance between land use and preservation. *Environ. Mngt* **16,** 681–689.
Greenland, D. J., Bowen, G., Eswaran, H., Rhoades, R. & Valentin, C. 1994 *Soil, water, and nutrient management: a new agenda*. Bangkok: International Board for Soil Research and Management.
IBSRAM (International Board for Soil Research and Management) 1989 *Management of Vertisols for improved agricultural production*. Patancheru, India and Bangkok, Thailand: ICRISAT/IBSRAM.
IPCC (Inter-governmental Panel on Climate Change) 1995 *IPCC second assessment: climate change 1995*. A report of the Intergovernmental Panel on Climate Change. Geneva and Nairobi: World Meteorological Organization and United Nations Environment Programme.
Lal, R. 1991 Tillage and agricultural sustainability. *Soil Till. Res.* **20**, 133–146.
Oldeman, L. R., Kakkeling, R. T. A. & Sombroek, W. G. 1990 *World map of the status of human-induced soil degradation: an explanatory note*. Wageningen, Netherlands and Nairobi, Kenya: International Soil Reference Information Center and United Nations Environment Programme.
Pieri, C. J. M. G. 1992 *Fertility of soils. A future for farming in the West African savanna*. Berlin: Springer-Verlag.
Robinson, D. M. & McKean, S. J. 1992. *Shifting cultivation and alternatives: an annotated bibliography*. Wallingford, UK: CAB International.
Sanchez, P. A. & Salinas, J. G. 1981 *Low input soil management techniques for Oxisols and Ultisols of tropical America*. Madison, USA: American Society of Agronomy.
Scherr, S. J. & Yadav, S. 1996 *Land degradation in the developing world: implications for food, agriculture, and the environment to 2020*. Food, agriculture, and the environment discussion paper 14. Washington DC: International Food Policy Research Institute.
Seino, H. & Uchijima, Z. 1992 Global distribution of net primary productivity of terrestrial vegetation. *J. Agric. Met.* **48**, 39–48.
TAC/CGIAR (Technical Advisory Committee/Consultative Group on International Agricultural Research) 1992 *Review of CGIAR priorities and strategies—part I*. Washington DC: CGIAR.

Discussion

P. Wood (*Oxford Forestry Institute, UK*). Per capita consumption of wood in the world is about 0.5 t ha^{-1}. This would at least double with a doubling of the population, more if wealth rises. Could you please comment on plantation for wood production (timber) as a component in the land use-planning AEZ processes?

In rainfed farming, especially in India, many farmers depend heavily on nutrient transfers from forests nearby. This is largely unquantified and is a major factor in natural resource degradation. Could you please comment on this neglected aspect of natural resource sustainability?

M. V. K. Sivakumar. Yes, indeed plantations for wood are becoming quite popular and lucrative in some parts of the developing world. For example, in India, in the past 5–10 years the private sector has become a major developer of plantations for timber, and the returns offered to the investor are quite attractive. Social forestry for wood is also catching up and farmer cooperatives are forming. This is a reflection of the growing demand for wood, and organized, environmentally sustainable efforts to meet these demands should be encouraged as a component of effective land use planning.

Use of green manure and forest litter for enhancing the soil nutrient status is a common practice in India. When the population pressure was low, the forest regeneration kept pace with the rate of vegetation removal and it did not pose a major problem. With the current population growth however, this practice is leading to forest degradation. One of the solutions being tested is the planting of green manure trees on farm bunds. Given the small size of individual farms in India, the area available for such planting is indeed significant and could meet some of the green manure needs. Social forestry offers another solution in this area and is becoming increasingly popular.

P. Bullock. (*Soil Survey and Land Research Centre, Cranfield University, UK*). The concept of agroecological zones has been in vogue for at least 20 years. I can understand its usefulness in providing broad general views on food production potential, population carrying capacity, etc., for use by institutes such as FAO. To what extent is it having much impact at the within-country level with policy makers and planners—and if it's not, why not?

M. V. K. Sivakumar. It is indeed correct to say that the agroecological zoning approach helps provide general answers to questions over matters such as food production potential, and it has been used quite successfully by FAO for such purposes. However, it is increasingly being recognized at national levels as well that agroecological zones (AEZs) could be used as planning units and could help integrate efforts directed towards effective exploitation of the production potential. The situation today is dynamically different from that which existed, say ten years ago. GIS tools are increasingly being used at the national and sub-national levels to manipulate different databases and produce simple, easily understandable maps for use by planners and policy makers. I am optimistic that we will be finding more and more AEZ applications in the next few years.

T. Henzell (*TAC-CGIAR*). Figures have been quoted today for populations, land areas, and even production potentials. But land degradation has been dealt with in terms of hot spots and bright spots. This is essentially an anecdotal approach. Based on your experience in West Africa, how can we get ecological zones, say the desert margins versus humid zones?

M. V. K. Sivakumar. Assessment of land degradation is a research topic that has been receiving a lot of attention in recent years. UNEP and ISRIC, in cooperation with SC-DLO, ISSS, FAO and ITC, have presented a world map of the status of human-induced land degradation at a scale of 1:15 million, with complementary statistics on extent, degree, and causative factors of different forms of soil degradation. It should be possible to overlay the AEZs on this map to get a first approximation estimates of the relative importance of land degradation in different AEZs.