Managing water resources for crop production

J. S. WALLACE AND C. H. BATCHELOR

Institute of Hydrology, Wallingford, Oxon OX10 8BB, UK

SUMMARY

Increasing crop production to meet the food requirements of the world's growing population will put great pressure on global water resources. Given that the vast freshwater resources that are available in the world are far from fully exploited, *globally* there should be sufficient water for future agricultural requirements. However, there are large areas where low water supply and high human demand may lead to *regional* shortages of water for future food production. In these arid and semi-arid areas, where water is a major constraint on production, improving water resource management is crucial if Malthusian disasters are to be avoided. There is considerable scope for improvement, since in both dryland and irrigated agriculture only about one-third of the available water (as rainfall, surface, or groundwater) is used to grow useful plants. This paper illustrates a range of techniques that could lead to increased crop production by improving agricultural water use efficiency. This may be achieved by increasing the total amount of water available to plants or by increasing the efficiency with which that water is used to produce biomass. Although the crash from the Malthusian precipice may ultimately be inevitable if population growth is not addressed, the time taken to reach the edge of the precipice could be lengthened by more efficient use of existing water resources.

1. INTRODUCTION

(*a*) *Malthusian disaster versus sustainability*

In his *Essay on the principle of population*, first published in 1798, T. R. Malthus proposed the pessimistic view that population increase will always tend to outrun the growth of food production. He envisaged population pressures which can degrade the environment, ultimately leading to famine, war and ill-health, and concluded that these would control the population. There are also more optimistic views, for example, Boserup (1965) argues that as population densities increase so does agricultural intensification, and this not only increases production, but can also stimulate the adoption of land management techniques that conserve natural resources (see Tiffen *et al.* 1994; Reij *et al.* 1996). The debate between the pessimists and the optimists therefore becomes one of Malthusian disaster versus, in modern jargon, sustainable natural resource management. The latter concept invokes the idea of living within a set of environmental constraints such that human demand does not outstrip the means of subsistence.

For agriculture in developing countries water is a major environmental constraint. This constraint is most acute in arid and semi-arid areas, which constitute over one-third of the entire land surface of the Earth (UNEP 1992). The aridity index used in the UNEP classification is the ratio of annual rainfall to potential evaporation and, albeit crude, delineates the dry areas where water supply (as rainfall) is less than half of atmospheric demand (as potential evaporation). Although crop production can also be limited by other factors such as the availability of nutrients in the soil (Gregory *et al.* 1997), the simple UNEP classification demonstrates the vast extent of the arid and semi-arid areas where the key environmental constraint is water, and so it is in these regions that this paper will concentrate.

Making proper use of the water that is available for growing useful plants in a given environment is dependent on both technical and non-technical constraints. Non-technical constraints related to human, economic, or institutional factors may often dominate what is actually practised. There are many good examples of this, especially in irrigated agriculture, where availability of suitable soils and exploitable water supplies are necessary, but may not necessarily provide sufficient conditions for successful and sustained production (see Carter 1992). However, there are some general technical aspects that are common to many environments and to both rainfed and irrigated farming, and it is these which we will focus on. A conceptual framework for merging technical and non-technical information in the management of agricultural systems is presented towards the end of the paper.

(*b*) *Water, water everywhere, but…*

The total volume of water on the Earth is vast, *ca.* 1.4 billion (10^9) km^3 or 1.4 thousand million million million (10^{21}) litres (Maidment 1992). However, the proportion of this which is fresh and reasonably accessible is less than 1%, at *ca.* 11 million km^3. There is therefore no shortage of water on this planet, just a lack of accessibility to fresh water in some places at some times. Around 97% of the Earth's water is saline, *ca.* 2% is stored as ice and snow and vast quantities (10.5 million km^3) are stored in underground aquifers.

Phil. Trans. R. Soc. Lond. B (1997) **352**, 937–947
Printed in Great Britain

Even though all this water exists it is, at present, not always economically viable to abstract it in very large quantities, particularly in developing countries.

Of the 0.8% of the planet's water that is accessible fresh water, it has been estimated that humanity now uses about half of the accessible runoff, and one quarter of the terrestrial evaporation comes from crops and trees harvested for food, fuel and timber (Postel *et al.* 1996). Of this, agriculture is by far the largest user of fresh water, accounting for around three-quarters of the entire global consumption (Shiklomanov 1991). However, agriculture does not consume water in the conventional sense, since (globally) insignificant amounts of water are actually bound up in the products produced. The large amounts of water associated with agriculture are released through evaporation, which is eventually recycled as rainfall. Agricultural use of water is therefore usually much more environmentally clean than domestic or industrial uses, where degradation of the water quality makes its reuse difficult without expensive treatment. It should be noted that the preceding estimates of global water resources and their consumption by agriculture are at best educated guesses (Rodda 1995), and will remain so until more consistent schemes are adopted for the collection, quality control and interpretation of hydrological data.

Even with the current uncertainties in global water use, agriculture remains by far the largest user of fresh water. As population increases, the demand for food, fuel and fibre will increase, and Penning de Vries & Rabbinge (1997) estimate global demand for crops to increase by a factor of between two and six within the next two generations. Falkenmark (1997) discusses the extra water required to achieve increases in crop production of this magnitude. Her global analysis assumes that 50% of agricultural water requirements will come from runoff. Globally, this would require massive engineering works, since if we continued to build new dams at the current rate (*ca.* 500 per year) for the next 30 years, this would only provide enough water for about one-third of the food requirement in 2025 (W. B. Wilkinson, personal communication).

However, in many semi-arid areas there is limited scope for increasing the amount of water available for agriculture. This is largely because of prohibitively high social, environmental and fiscal costs of the large civil engineering works required for large dams, reservoirs and irrigation schemes. Although there is some scope for much smaller-scale innovative techniques to develop surface and groundwater resources (Lovell *et al.* 1996), these areas are likely to remain highly dependent on dryland or rainfed agriculture. Therefore, notwithstanding any beneficial climate change (should it be so), the primary input of water for agriculture in these regions is fixed, limited and highly erratic. Increased agricultural production is therefore dependent on making *better* use of existing water resources, either by increasing the total amount available to plants or by increasing the efficiency with which the water is used (or both). By water use efficiency we mean the percentage of available water (as rainfall, surface, or ground water) which is used as transpiration, since it is this which is associated with growth and yield. Later we will also consider transpiration (water use) efficiency, a misnomer since it is not strictly an efficiency, but a measure of the amount of carbon fixed by plants per unit of water transpired.

2. WATER USE BY RAINFED AGRICULTURE

The Food and Agriculture Organization (FAO) have forecast that by the year 2000 around 84% of the world's agricultural land will be rainfed and this will yield around two-thirds of global crop production (Postel 1993). This global figure includes temperate areas where rainfed yields are relatively high. In semi-arid developing countries, therefore, the proportion of food which comes from rainfed agriculture can be even higher, and over 90% in some countries. Managing water resources for crop production in these circumstances becomes a matter of making optimal use of rainfall.

When rainfall reaches the soil surface some of it may infiltrate the soil, some may evaporate from the soil surface and the rest will run off. Ignoring, for the moment, downstream uses of runoff water, agricultural practices that maximize the amount of rainfall which infiltrates into the soil are the starting point for good water management. However, where water is limited and inadequate for producing the plants required, there are both natural and man-made systems where rainwater is redistributed from the place at which it falls to adjacent areas where it can be concentrated sufficiently to grow useful plants. Many examples of man-made water harvesting are described by Critchley & Siegert (1991) and an example of water harvesting in a natural vegetation system is described by Wallace & Holwill (1997). Once rainfall and any run-on water has reached the point where it is required, good water management techniques are those that maximize infiltration and minimize runoff, soil evaporation and drainage. The following section describes a series of measures which seek to achieve this.

(*a*) *Runoff*

If rain falls on a soil surface at a greater rate than the infiltration rate, the excess water will start to collect at the surface, and when the surface storage is exceeded, runoff will occur. There are therefore two basic ways in which runoff can be minimized, i.e. by increasing surface storage and by increasing the soil infiltration rate. A range of surface treatments can affect one or both of these factors. These treatments involve mechanical changes to the soil surface or the addition of extra materials to the surface, or both. For example, leaving crop residues or planting cover crops or contour hedgerows are examples of the latter which can reduce runoff (Lal 1989; Kiepe & Rao 1994). Vegetation cover generally increases infiltration and reduces runoff by reducing surface crusting and improving soil hydraulic conductivity (Wallace 1996). For example, in Senegal runoff decreased from 456 mm in bare soil to 264 mm in cultivated land, and further to 200 mm in fallow land containing a mixture of shrubs and herbs (Lal 1991).

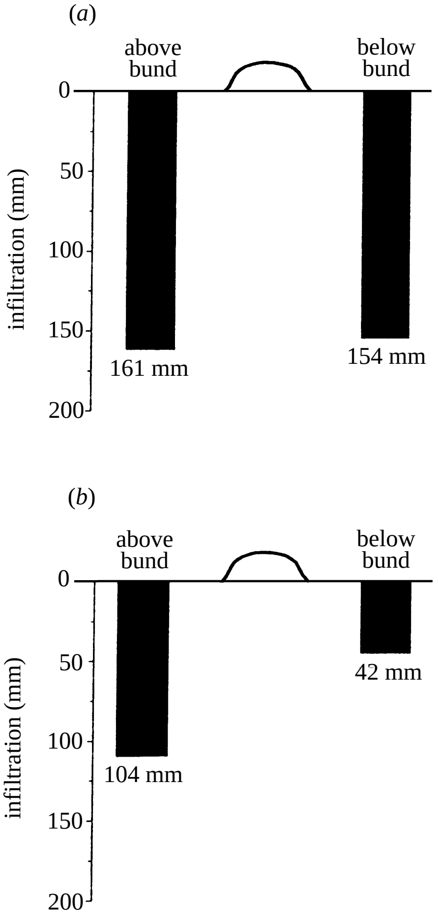

Figure 1. Infiltration above and below contour bunds in south-east Zimbabwe following a rainfall event of 141 mm. Two different soil types are shown (*a*) a red sandy clay and (*b*) a grey sandy loam over clay at 0.5 m (after Butterworth 1997).

Mulches can also be used to reduce runoff (Lal 1991) and may also reduce direct soil evaporation (Barros & Hanks 1993; Hatfield *et al.* 1996). However, whether a mulch causes a net gain or loss to the soil water balance will depend on the relative effects it has on evaporation and infiltration. These are likely to vary with different types of mulch and the frequency and amount of rainfall. A potential disadvantage of mulches (particularly crop residues) is their tendency to increase the risk of disease and pest infestation; however, detailed discussion of this is outside the scope of the current paper.

Mechanical alterations of the soil surface are widely practised to increase infiltration. These include the use of terraces, retention bunds and various tillage practices (see Critchley & Siegert 1991). Terracing has been very successfully used for hundreds of years in upland regions, e.g. in the paddy rice systems in Asia. The effect of using earth contour bunds on infiltration has been demonstrated by Butterworth (1997) on two contrasting soil types in Zimbabwe. Figure 1 shows data from his study which illustrate how bunding can be very effective at increasing the amount of rainfall which enters the soil, especially when its infiltration properties are poor. The effect of bunding is clearly soil dependent, and where soils have a high infiltration capacity, bunding becomes less effective (figure 1).

Table 1. *The effect of tillage on runoff at Nino, Mali*

(Figures are for land with a surface storage of 1 mm (after Stroosnijder & Hoogmoed 1984).)

		runoff (mm)	
year	rainfall (mm)	without tillage	with tillage
1977	368	155	76
1978	271	104	49
1979	361	141	80
average	333	133	68

Surface tillage effects on infiltration have been demonstrated by Hoogmoed *et al.* (1991) using a rainfall simulator on cultivated millet fields in Niger. Only 35 % of rainfall infiltrated undisturbed soil compared to 69 % in soil which had been recently hand-tilled using a local digging scoop. The effects of tillage can therefore be very important in very dry regions since, even in the very sandy soils, surface crusts can form and generate significant runoff on comparatively flat land (Casenave & Valentin 1991). The dramatic effects of surface crusts in Sahelian soils has also been shown by Stroosnijder & Hoogmoed (1984). Table 1 shows some results from their work in Mali in sandy soils with slopes of less than 3 %. Even on this comparatively flat land, tillage reduced mean annual runoff from *ca.* 39 % to *ca.* 19 % of rainfall. The extra 65 mm yr^{-1} of rainfall entering the soil under tillage being vital to crop survival in such an arid region.

(*b*) *Soil evaporation*

Once rainwater has entered the soil, crop production will be related to the amount of this soil-water which is used to grow useful plants. Only water that is transpired is (to a first order) agriculturally productive, and so this should be maximized, whilst direct evaporation of water from the soil surface and drainage from the bottom of the soil profile should be minimized. The scope for improvement is clear from a number of studies of dryland crops in the semi-arid regions of the Middle East and West Africa. For example, in dryland millet crops growing in Niger, Wallace (1991) reported soil evaporation losses over an entire crop season of between 35 % and 45 % of rainfall (figure 2). In dryland barley Cooper *et al.* (1983) report that up to 60 % of rainfall is lost as soil evaporation. There are clearly very substantial losses of water as soil evaporation in semi-arid agriculture, the question is how can this be reduced?

Surface tillage can alter the rate of soil evaporation. For example, Hammel *et al.* (1981) estimated that tillage by sweep cultivator or disk reduced evaporation during the establishment phase of their wheat crop in north-west USA. Their model predicted that the tilled soil layer would conserve subsoil water by slowing or preventing capillary flow of water to the surface, where it would be lost by evaporation. In contrast, Hatfield *et al.* (1996) measured evaporation rates over farmers' fields in Iowa, USA, and found that ridge and chisel plough tillage increased evaporation by between 20 %

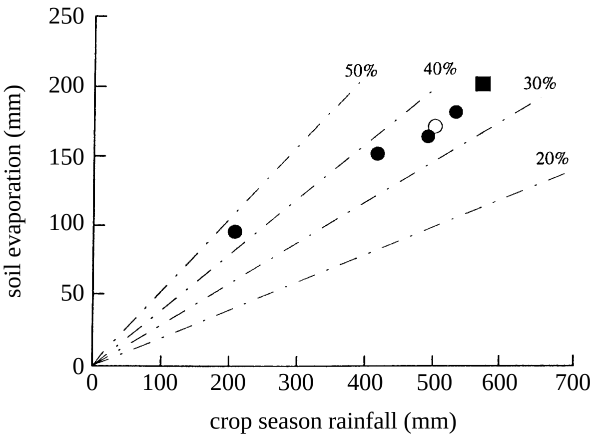

Figure 2. Cumulative seasonal evaporation from the soil (E_s) in millet crops as a function of rainfall: ●, data from Bley *et al.* (1991); ■, data from Wallace *et al.* (1988); and ○, data from Fecther *et al.* (1991). The dashed lines show E_s as a percentage of rainfall.

and 130 % in the first 20 days after planting of their soybean and maize crops. The largest evaporation rates were recorded over fields where the tillage produced a high degree of soil disturbance which exposed large amounts of moist soil to drying. Clearly, tillage can have an important effect on soil evaporation, but its net result will depend on soil type and water content, tillage practice, and the weather over the period considered.

There is also some potential for reducing soil evaporation via the use of mixed cropping systems such as agroforestry and intercrops. For example, measurement and modelling of soil evaporation in a *Grevillea robusta* agroforestry system in Kenya has demonstrated the potential for reducing soil evaporation using canopy shade (Wallace *et al.* 1997). Figure 3 shows a time series of cumulative evaporation from bare soil and tree canopy-shaded soil for an 18-month period. Without any canopy shade *ca.* 55 % of the rainfall is lost as soil evaporation. Directly beneath the tree shade soil evaporation is reduced to 39 % of rainfall. The agroforestry system studies had *ca.* 50 % ground cover, therefore the net effect of tree canopy shade was to reduced soil evaporation by *ca.* 100 mm yr^{-1}, equivalent to 13 % of rainfall. This substantial saving in water decreases as tree canopy cover decreases, but clearly demonstrates the potential for improved water use which can be achieved by increasing ground cover in rainfed agricultural and agroforestry systems. The effect of canopy size on soil evaporation is discussed in more detail by Gregory *et al.* (1997).

(*c*) *Drainage*

As with runoff and soil evaporation, drainage is usually considered as a loss at a field scale. In deep sandy soils, typical of many parts of the semi-arid regions, drainage from rainfed crops can be substantial. For example, Bley *et al.* (1991) report drainage calculations for millet crops made using the SWATRER model for a 28-year period at four different locations in Niger. For Niamey, 26 % of the mean annual rainfall of 595 mm was lost as deep drainage. In wet years drainage increased to over 400 mm. Only when mean annual rainfall decreased to less than *ca.* 200 mm did drainage become insignificant. Similar figures are reported by Ong *et al.* (1991) for crops growing on the Deccan plateau in India, where the best cropping systems still lose *ca.* 33 % of rainfall to drainage.

Reduction of drainage losses in rainfed crops is difficult as it is dependent on the rapid development of

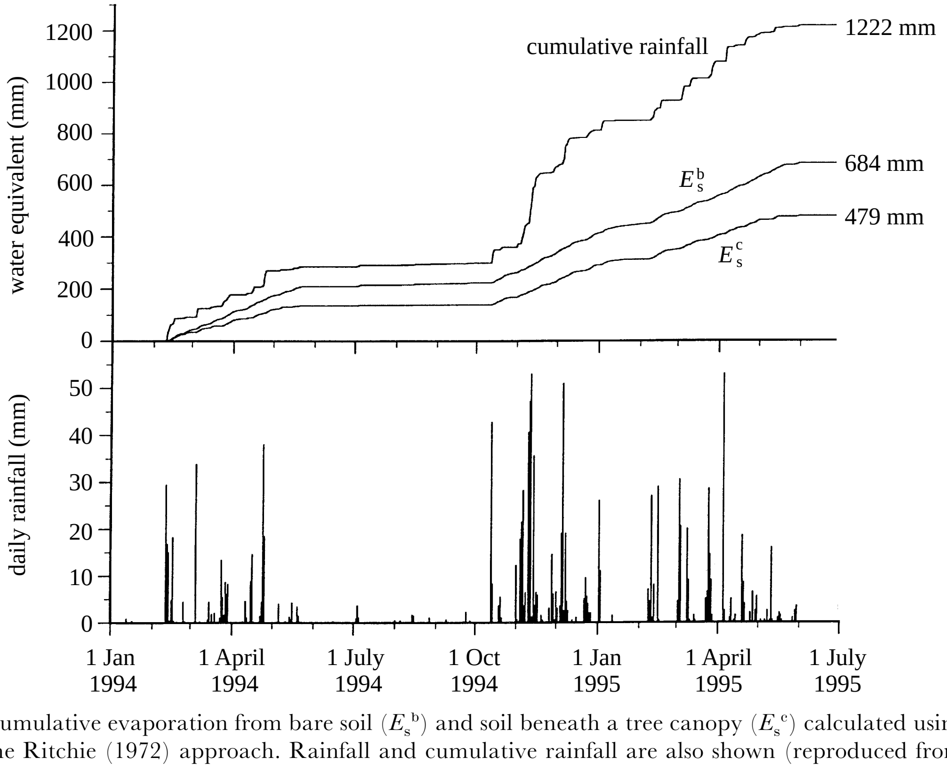

Figure 3. Cumulative evaporation from bare soil (E_s^b) and soil beneath a tree canopy (E_s^c) calculated using a model based on the Ritchie (1972) approach. Rainfall and cumulative rainfall are also shown (reproduced from Wallace *et al.* 1997).

annual root systems. However, perennial species such as trees generally have deeper root systems, which can be much more effective in abstracting soil water and reducing drainage. For example, Calder *et al.* (1992) have reported results from *Eucalyptus* plantations in southern India where drainage losses are not only reduced to zero, but the trees develop roots at such great depth that they can abstract water in excess of the annual rainfall. In this rather extreme, and ultimately unsustainable case, water was being mined from progressively lower depths in the unsaturated zone. Drainage is therefore one of the hydrological terms which can be most easily modified by the presence of trees or other perennial vegetation. Since trees can, in principle, utilize water outside the rooting zone of annual crops, and also outside the crop growing season, they have been proposed as potential companion species for crops in agroforestry systems (Huda & Ong 1989).

When deep drainage (or groundwater recharge) is considered at the catchment scale, annual estimates tend to be lower than the field scale figures given above. This is because drainage from parts of the catchment further up the topo-sequence may be an important source of water for areas nearer the valley bottom. For example, with mean annual rainfall in excess of 800 mm, groundwater recharge in Zimbabwe and Malawi was estimated by Wright (1992) to be typically in the range 10–20 % of the annual rainfall. In lower rainfall areas of Zimbabwe, Houston (1988) used three independent methods to show that estimated recharge was even lower, in the range 2–5 % of annual rainfall. Some drainage at the field and catchment scale may also be vital, for example, to avoid water logging and to replenish aquifers and maintain and prolong base flows in rivers and ephemeral streams.

(*d*) *Transpiration efficiency*

There are essentially two basic ways of altering the efficiency of water use in agriculture. The first is to route more of the rainfall (or other water resource) into transpiration, i.e. by adopting the water use efficiency measures that have already been discussed in the previous sections. The second is by increasing the transpiration efficiency or the water use ratio, i.e. the ratio of the amount of carbon fixed by a plant per unit of water transpired, e_w (g dry matter per mm water). Monteith (1981) proposed the concept that resources (e.g. light or water) were captured by a crop and these were converted into biomass using conversion coefficients; e_w in the case of water. The total amount of water captured by a crop is the transpiration, E_t; and so total dry matter production is simply the product, $E_t e_w$. Theoretical considerations and experimental studies have shown that (at least under fairly idealized conditions) e_w increases as the saturation deficit of the air (D) decreases, and that the product $e_w D$ is quite conservative among species groups (Ong *et al.* 1996). For example, in C3 species $e_w D$ is *ca.* 4 kg mm^{-1} kPa, and about twice this (8 kg mm^{-1} kPa) in C4 species (Squire 1990). The net effect of atmospheric humidity on any given species is therefore one of the most important factors affecting productivity in dryland areas, since dry matter production per unit of water transpired decreases by a factor of two as saturation deficit increases from *ca.* 2 kPa in moist temperate climates to *ca.* 4 kPa in semi-arid areas (Squire 1990).

There are therefore two ways in which, in principle, agricultural production could be increased by increasing e_w. First, by choosing (or genetically engineering) crops with a higher value of e_w, e.g. C4 species or secondly, to manipulate the crop microclimate so as to reduce D. In practice, however, C4 species do not always have higher values of e_w, since once conditions become non-ideal, i.e. under drought, there are more tolerant C3 species such as cowpea and cotton than, for example, the comparatively sensitive C4 maize and sorghum cultivars (Ong *et al.* 1996).

Microclimate manipulation is one of the possible advantages of agroforestry systems. In these the presence of an elevated tree canopy may alter the radiation, temperature and humidity around the understorey crop. Where crops have been grown using trees as shelter belts, decreases in D have been reported for several crops (Brenner 1996). Data from an agroforestry trial in Kenya also show that the air around a maize crop growing beneath a *Grevillea robusta* stand is more humid than the free atmosphere above the trees (Wallace *et al.* 1995). The decrease in D beneath the tree canopy in agroforestry systems is a consequence of the changes in the surface energy balance due to tree shade and slower transfer of water vapour away from the understorey due to the physical presence of the trees. If the microclimate around the understorey crop has a lower saturation deficit, the transpiration efficiency of a crop under the trees may therefore be higher than in a sole crop grown without trees.

Another approach to improving agricultural water use efficiency is to grow crops and/or use irrigation water in areas where the saturation deficit is low. For example, Tanner & Sinclair (1983) argue that there is substantial scope for improving agricultural water use efficiency in the USA by matching crop production with areas of low saturation deficit. They also propose that the greatest gains in improving crop water use efficiency are to be had by putting greater emphasis on water management and irrigation technology in humid areas.

3. WATER USE IN IRRIGATED AGRICULTURE

It is generally accepted that the total area irrigated worldwide is in excess of 235 million ha, or *ca.* 16 % of the world's agricultural land (Postel 1993). This produces approximately one-third of the global harvest. By far the largest area under irrigation is in developing countries (*ca.* 80 %), particularly Asia (*ca.* 62 %). Despite the huge global demand to increase crop production there has been a marked decline in the rate of expansion of irrigated land since the late 1970s.

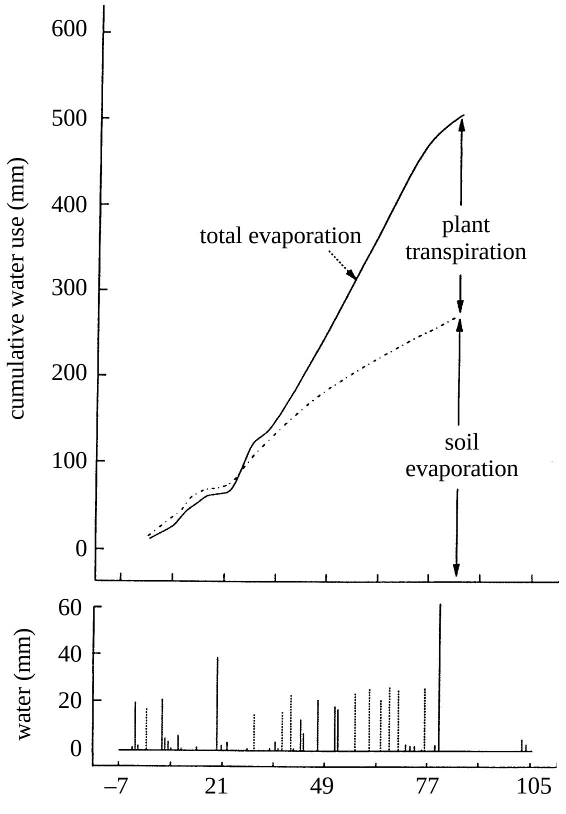

Figure 4. Partitioning of total crop water use to plant transpiration and soil evaporation for a flood irrigated maize crop in south-east Zimbabwe. In the lower graph solid lines denote rainfall and dotted lines denote irrigation (after Batchelor *et al.* 1993).

Whereas the net irrigated area grew by 2–4 % yr^{-1} between 1960 and 1980, the annual rate of increase has only averaged about 1 % since then. The reasons for this decrease in the rate of expansion include limitations on the availability of land and water resources, and the high economic, social and environmental costs of large irrigation schemes. There is also an increasing tendency to favour small-scale irrigation developments, for which operation and maintenance costs are less of a burden on government authorities (Jensen *et al.* 1990). Apart from being farmer owned and managed, small scale irrigation has the major advantage that it integrates well into rainfed farming systems and can make use of water from a range of sources (e.g. wells, rivers, small dams).

Irrigated farming may be sustainable if the basic principles of water management and salinity control are recognized and implemented. Unfortunately, the productivity of many existing irrigated areas is in decline as a result of a combination of technical, economic, and institutional factors. Probably the greatest technical cause of declining agricultural production on irrigated land is water logging and salination of soil in arid and semi-arid areas (Jensen *et al.* 1990). It is estimated that 20–30 million ha of irrigated land are severely affected by salinity, and another 60–80 million ha suffer to varying extents (Hennessy 1993).

(*a*) *Irrigated water use efficiency*

The efficiency with which water is used in irrigated agriculture can be considered in three components. There is the efficiency with which water is stored in reservoirs and transferred along channel networks to the field during conveyancing. Once at the field not all water is evaporated, so the irrigation efficiency is the ratio of crop evaporation to total water supplied to the field. Third, not all of the crop evaporation occurs through transpiration.

It is estimated that the global efficiency of storage and conveyancing of irrigation water is in the order of 70 % (Bos 1985). Worldwide irrigation efficiencies (i.e. crop evaporation: total water supplied to a field) are estimated to average only 37 % (Postel 1993). However, some of this lost water returns to streams or aquifers from which it can be abstracted again, provided the necessary infrastructure is available and the water quality has not deteriorated beyond acceptable limits. The efficiency of water use over large irrigated areas may therefore be larger than the above mean of field level irrigation efficiencies (Bouwer 1992).

Of the water that is evaporated only a fraction is transpired. For example, figure 4 shows the cumulative evaporation from a flood-irrigated maize crop that was grown during the hot rainy season in south-east Zimbabwe (Batchelor *et al.* 1993). In this experiment over half the water used by the crop was lost as effectively non-productive soil evaporation. Batchelor & Roberts (1983) have also shown that large amounts of water are also lost as direct evaporation from the water in which paddy rice is grown. Over the entire dry season in north-east Sri Lanka, open water evaporation constituted 29 % of the total crop evaporation. Most of the open water losses (and soil evaporation losses in the case of the irrigated maize crop) occur at the beginning of the season when the crop leaf area index is low. To reduce these losses crops that develop rapid ground cover are needed.

There are a wide range of options available for improving irrigation efficiency at the field level (see table 2). Poor management is cited as the most frequent cause of inefficient water use on irrigation schemes (Jensen *et al.* 1990), and it is clear that few of the options listed in table 2 will result in a significant increase in efficiency if the overall management is of a low standard. Attempts to improve the efficiency of irrigation that are centred solely on a technological, agronomic or institutional quick fix are rarely successful.

Although it is not possible to discuss all the options listed in table 2 in detail, three of the options are of particular interest. First, demand-based irrigation scheduling, such as the tensiometer irrigation scheduling described by Hodnett *et al.* (1990), is used frequently on irrigation trials but rarely used on large irrigation schemes. One reason for this has been the lack of cheap and reliable soil moisture sensors. However, it is possible that further development of dielectric soil moisture sensors (e.g. the capacitance probe described by Dean *et al.* (1987)) will lead to the

Table 2. *Examples of options available for improving irrigation efficiency at a field level*

improvement category	options
agronomic	improved crop husbandry; introduction of higher-yielding varieties; adoption of cropping strategies that maximize cropped area during periods of low potential evaporation and periods of high rainfall
technical	laser levelling of flood irrigation schemes to improve irrigation uniformity; adoption of practices that increase effectiveness of rainfall; introduction of more efficient irrigation methods, such as drip irrigation and subsurface irrigation, that reduce soil evaporation, improve uniformity and reduce drainage
managerial	adoption of demand-based irrigation scheduling systems; use of deficit scheduling; better use and management of saline and waste water; improved maintenance of equipment
institutional	user involvement in scheme operation and maintenance; introduction of water pricing and legal frameworks to provide incentives for efficient water use and disincentives for inefficient use; introduction of integrated catchment management; improved training and extension

production of cheap, reliable and robust soil moisture sensors. It is only with such sensors that irrigation applications can be matched closely to crop demand or even to be set at less than crop demand as in the case of *deficit irrigation*. Second, irrigation methods such as drip irrigation can be used extremely effectively to increase the yields, crop quality, and water use efficiency of many crops, largely because they reduce soil evaporation and drainage losses. However, it should be recognized that these methods are particularly sensitive to management. Third, there is potential for better use and management of saline and poor quality water in areas prone to soil salination. Research and experience in recent years have demonstrated that waters of much higher salinities than those customarily classified as unsuitable for irrigation can be used given appropriate management and cropping strategies (Rhoades *et al.* 1992; Oster 1994).

4. INTEGRATED CATCHMENT MANAGEMENT

This paper has reviewed the scope for improving water use efficiency in rainfed and irrigated farming systems and discussed technologies and management techniques that can lead to significant improvements in water use efficiency at the field scale. However, several examples were given where drainage and runoff losses at a field scale were not necessarily as large at a catchment scale. Drainage or runoff at the field, farm, or village scales may be an important source of water for users further down the catchment and may also contribute to stream flow, reservoir storage and groundwater recharge. Consequently, improvements in water use efficiency at the village level may provide benefits to users in that location only, and possibly at the expense of water users in other parts of the catchment. The *physical* challenge is to understand how efficiently water is used in different parts of a catchment so that the overall catchment efficiency can be improved.

There is also a parallel *socio-economic* challenge to develop the appropriate economic, social, and institutional instruments for the implementation of improved water use efficiency techniques at a catchment or regional scale. It is becoming increasingly recognized that active participation of stakeholders in resource management at the local level is essential. However, decisions taken at the village level should be consistent with natural resource management strategies developed for an entire catchment where a larger group of stakeholders may include urban and industrial water users. This can be achieved through the use of integrated catchment management (Blackmore 1994). Although the development and implementation of integrated catchment management programmes are slow processes, results from a number of dryland areas give some cause for optimism that this approach can be successful in reducing environmental degradation, encouraging collective responsibility for resources, and promoting sustainable resource management (Bottrall 1992; Blackmore 1994). Several major international soil, water, and nutrient management research programmes are also adopting the holistic integrated catchment management approach (Syers 1997). Integrated catchment management also provides a way of dealing with the off-site environmental effects of land use, which Tinker (1997) cites as potentially the most important, as these do not impact the local farmer directly.

As many of the problems affecting land and water resources are interrelated and cannot be solved individually, strategies of integrated resource management are necessarily complex. Strategies must include consideration of the resources available and the many stakeholders with (often conflicting) interests in these resources at a number of different levels, as well as economics, politics and environmental health issues. There is also a need to reconcile short-term national and household food security requirements with the longer-term goals of conservation of natural resources. It may be possible to achieve this ambitious type of programme by user-driven activities that are based on findings from cross-sectoral research initiatives, such as the Romwe Catchment Study in south-east Zimbabwe (see Butterworth *et al.* 1995).

5. CONCLUDING REMARKS

Globally there is a vast amount of fresh water, most of which has not yet been exploited. At this scale it would therefore appear that there is sufficient water to grow the food needed for future populations. However, Falkenmark (1997) has demonstrated that there are large areas of the world, e.g. Africa and Asia, where there may be *regional* shortages of water for food production. Falkenmark's calculations are based on regional and continental water supply and demand figures in which there is considerable uncertainty (Rodda 1995). The uncertainty in the supply figures can only be reduced by improved large-scale measurement and modelling of rainfall, runoff and groundwater, especially in currently ungauged areas. Calculations of water demands for agricultural production, especially in semi-arid regions, could be improved by taking more account of the dominance of rainfed farming.

The fraction of the globally accessible fresh water that is currently used in agriculture is not very efficiently used. At a field scale much water is not agriculturally productive, i.e. there are large components such as runoff, soil evaporation and drainage. As a crude estimate, in both dryland and irrigated agriculture, only about one-third of water resources are used to grow useful plants. Many innovative techniques have been demonstrated whereby higher water use efficiencies might be achieved. Large amounts of runoff can be reduced by a range of surface treatments. These can be very 'low tech' and achieve substantial increases in soil water infiltration. Direct soil evaporation can be reduced using surface treatments and sole crops and/or plant mixtures with increased shading of the soil surface. It may also be possible to increase transpiration efficiency using plant mixtures and by microclimate manipulations and/or by matching crop growth with areas and times of high atmospheric humidity. More effort needs to be put into developing social, political and institutional structures that encourage farmers to adopt these simple technological improvements.

When considering water resource management at a catchment (or larger) scale we need to take into account the interactions between different units in the landscape. The more holistic vision should be to consider the efficiency with which water is used at different places in a catchment and the degree to which different uses degrade the water quality. Ultimately, water efficiencies should be calculated (and optimized) not only in physical terms, but also in economic, social, and environmental terms. Changes in the management of water resources should in future seek to optimize this holistic water use efficiency.

Finally, we conclude that although the crash from the Malthusian precipice may ultimately be inevitable if population growth in developing countries is not addressed, the time taken to reach the edge of the precipice could be lengthened by more efficient use of existing water resources. This extra time may help avoid the misery and vice envisaged by Malthus, but only if it is used to develop water management policies and strategies that minimize environmental degradation and promote sustainable development.

We are grateful to John Butterworth for the use of his data from Zimbabwe and to Jeremy Cain, Chris Huntingford and Dominic Waughray for their constructive comments on the draft manuscript. We would also like to acknowledge the financial support provided for the authors' research by the UK Natural Environment Research Council's Centre for Ecology and Hydrology and the UK Overseas Development Administration.

REFERENCES

Barros, L. C. G. & Hanks, R. J. 1993 Evapotranspiration and yield of beans as affected by mulch and irrigation. *Agron. J.* **85**, 692–697.

Batchelor, C. H. & Roberts, J. M. 1983 Evaporation from the irrigation water, foliage and panicles of paddy rice in north-east Sri Lanka. *Agric. Met.* **29**, 11–26.

Batchelor, C. H., Lovell, C. J. & Murata, M. 1993 Micro-irrigation techniques for improving irrigation efficiency on vegetable gardens in developing countries. ICID Workshop on Micro-irrigation, The Hague, pp. 31–39.

Blackmore, D. J. 1994 Integrated catchment management. The Murray–Darling Basin experience. Water Down Under Conference, Adelaide, vol. I, pp. 1–7.

Bley, J., van der Ploeg, R. R., Sivakumar, M. V. K. & Allison, B. E. 1991 A risk–probability map for millet production in south-west Niger. In *Soil water balance in the Sudano–Sahelian zone* (ed. M. V. K. Sivakumar, J. S. Wallace, C. Renard, & C. Giroux), pp. 571–581. Proceedings of the Niamey Workshop. Wallingford, UK: IAHS.

Bos, M. G. 1985 Summary of ICID definitions on irrigation efficiency. *ICID Bull.* **34**, 28–31.

Boserup, E. 1965 *The conditions of agricultural growth: the economics of agrarian change under population pressure*. London: George Allen & Unwin.

Bottrall, A. 1992 Institutional aspects of watershed management. In *Proceedings of Overseas Development Association conference on priorities for water resources allocation and management*, pp. 81–90. London: Overseas Development Administration.

Bouwer, A. 1992 Agricultural and municipal use of waste water. *Wat. Sci. Tech.* **26**, 1583–1591.

Brenner, A. J. 1996 Micro-climatic modifications in agroforestry. In *Tree–crop interactions — a physiological approach* (ed. C. K. Ong & P. A. Huxley), pp. 159–187. Wallingford, UK: CAB International.

Butterworth, J. A. 1997 Groundwater recharge in a rural dryland catchment in south-east Zimbabwe. Ph.D. thesis, Department of Soil Science, University of Reading, UK.

Butterworth, J. A., Lovell, C. J., Bromley, J. *et al.* 1995 Romwe catchment study: first interim report. Institute of Hydrology Report, Overseas Development Association 95/9, p. 87. Wallingford, UK: Institute of Hydrology.

Calder, I. R., Swaminath, M. H., Kariyappa, G. S. *et al.* 1992 Deuterium tracing for the estimation of transpiration from trees. Part 3. Measurements of transpiration from *Eucalyptus* plantation, India. *J. Hydrol.* **130,** 37–48.

Carter, R. 1992 Small-scale irrigation in sub-Saharan Africa: a balanced view. Priorities for water resource allocation and management conference, pp. 103–116. London: Overseas Development Association.

Casenave, A. & Valentin, C. 1991 Influence des etats de surface sur linfiltration en zone Sahlienne. In *Soil water balance in the Sudano–Sahelian zone* (ed. M. V. K. Sivakumar,

J. S. Wallace, C. Renard & C. Giroux), pp. 99–108. Proceedings of the Niamey Workshop, February 1991. Wallingford, UK: IAHS.

Cooper, P. J. M., Keatinge, J. D. H. & Hughes, G. 1983 Crop evapotranspiration—a technique for calculation of its components by field measurements. *Field Crop Res.* **7**, 299–312.

Critchley, W. & Siegert, K. 1991 *Water harvesting: a manual for the design and construction of water harvesting schemes for plant production.* AGL/MISC/17/91, p. 133. Rome: Food and Agriculture Organization.

Dean, T. J., Bell, J. P. & Baty, A. J. B. 1987 Soil moisture measurement by an improved capacitance technique. I. Sensor design and performance. *J. Hydrol.* **93**, 67–78.

Fechter, J., Allison, B., Sivakumar, M. V. K., van der Ploeg, R. R. & Bley, J. 1991 An evaluation of the SWATRER and CERES-Millet models for south-west Niger. In *Soil water balance in the Sudano–Sahelian zone* (ed. M. V. K. Sivakumar, J. S. Wallace, C. Renard & C. Giroux), pp. 505–513. Proceedings of the Niamey Workshop, February 1991. Wallingford, UK: IAHS.

Hammel, J. E., Papendick, R. I. & Campbell, G. S. 1981 Fallow tillage effects on evaporation and seed zone water content in a dry summer climate. *Soil Sci. Am. J.* **45**, 1016–1022.

Hatfield, J. L., Prueger, J. H. & Sauer, T. J. 1996 Comparison of evapotranspiration equations over different surfaces. In *Proceedings of the evapotranspiration and irrigation scheduling conference* (ed. C. R. Camp & E. J. Sadler), pp. 1065–1070. St Joseph, Michigan: American Society of Agricultural Engineers.

Hennessy, J. 1993 Water management in the 21st century. XVth ICID Congress, The Hague, keynote address, pp. 1–31.

Hodnett, M. G., Bell, J. P., Ahkoon, P. D., Soopramanien, G. C. & Batchelor, C. H. 1990 Control of drip irrigation of sugarcane using 'index' tensiometers: some comparisons with control by the water budgeting method. *Agric. Wat. Mngt* **17**, 189–207.

Hoogmoed, W. B., Klaij, M. C. & Brouwer, J. 1991 Infiltration, runoff and drainage in the Sudano–Sahelian zone. In: *Soil water balance in the Sudano–Sahelian zone* (ed. M. V. K. Sivakumar, J. S. Wallace, C. Renard & C. Giroux), pp. 85–98. Proceedings of the Niamey Workshop, February 1991. Wallingford, UK: IAHS.

Houston, J. 1988 Rainfall, runoff and recharge relationships in basement rocks of Zimbabwe. In *Estimation of natural groundwater recharge* (ed. I. Simmers), pp. 349–365. Dordrecht, The Netherlands: Reidel.

Huda, A. K. S. & Ong, C. K. 1989 Crop simulation models and some implications for agroforestry systems. In: *Meteorology and agroforestry. Proceedings of the ICRAF/WMO/UNEP workshop on application of meteorology to agroforestry systems planning and management* (ed. W. E. Reifsnyder & T. Darnhofer), pp. 115–124. Nairobi: ICRAF.

Jensen, M. E., Rangeley, W. R. & Dieleman, P. J. 1990 Irrigation trends in world agriculture. In *Irrigation of agricultural crops. Agronomy monograph 30* (ed. B. A. Stewart & D. R. Nielsen), pp. 31–67. Wisconsin, USA: ASA.

Kiepe, P. & Rao, M. R. 1994 Management of agroforestry for the conservation and utilisation of land and water resources. *Outlook on Agriculture* **23**, 17–25.

Lal, R. 1989 Agroforestry systems and soil surface management of a tropical alfisol. II. Water runoff, soil erosion and nutrient loss. *Agrofor. Sys.* **8**, 97–111.

Lal, R. 1991 Current research on crop water balance and implications for the future. In: *Soil water balance in the Sudano–Sahelian zone* (ed. M. V. K. Sivakumar, J. S. Wallace, C. Renard & C. Giroux), pp. 31–44. Proceedings of the Niamey Workshop, February 1991. Wallingford, UK: IAHS.

Lovell, C. J, Batchelor, C. H., Waughray, D. K. *et al.* 1996 Small-scale irrigation using collector wells pilot project: final report. Institute of Hydrology report ODA 95/14, 106 pp. Wallingford, UK: Institute of Hydrology.

Maidment, D. R. 1992 *Handbook of hydrology*. New York: McGraw Hill.

Monteith, J. L. 1981 Does light limit crop production? In *Physiological processes limiting plant productivity* (ed. C. B. Johnson), pp. 23–39. London: Butterworths.

Ong, C. K., Odongo, J. C. W., Marshall, F. & Black, C. R. 1991 Water use by trees and crops. V. Hypothesis. *Agrofor. Today* **3**, 7–10.

Ong, C. K., Black, C. R., Marshall, F. M. & Corlett, J. E. 1996 Principles of resources capture and utilisation of light and water. In *Tree–crop interactions—a physiological approach* (ed. C. K. Ong & P. A. Huxley), pp. 73–158. Wallingford, UK: CAB International.

Oster, J. D. 1994 Irrigation with poor quality water. *Agric. Wat. Mngt* **25**, 271–297.

Postel, S. L. 1993 Water and agriculture. In *Water in crisis: a guide to the world's fresh water resources* (ed. P. H. Gleick), pp. 56–66. Oxford University Press.

Postel, S. L., Daily, G. C. & Ehrlich, P. R. 1996 Human appropriation of renewable fresh water. *Science* **271**, 785–788.

Reij, C., Scoones, I. & Toulmin, C. 1996 *Sustaining the soil: indigenous soil and water conservation in Africa*. 260 pp. London: Earthscan.

Rhoades, J. D., Kandiah, A. & Mashali, A. M. 1992 The use of saline waters for crop production. Irrigation and drainage, 133 pp. Paper 28. Rome: Food and Agriculture Organization.

Ritchie, J. T. 1972 Model for predicting evaporation from a row crop with incomplete cover. *Wat. Resour. Res.* **8**, 1204–1213.

Rodda, J. C. 1995 Guessing or assessing the world's water resources. *J. IWEM* **9**, 360–368.

Shiklomanov, I. A. 1991 The world's water resources. In *Proceedings of the International Symposium to commemorate 25 years of the IHP*, pp. 93–126. UNESCO/IHP.

Squire, G. R. 1990 *The physiology of tropical crop production*, 236 pp. Wallingford, UK: CAB International.

Stroosnijder, L. & Hoogmoed, W. B. 1984 Crust formation on sandy soils in the Sahel. II. Tillage and its effect on the water balance. *Soil Tillage Res.* **4**, 321–337.

Tanner, C. B. & Sinclair, T. R. 1983 Efficient water use in crop production: research or re-search? In *Limitations to efficient water use in crop production* (ed. H. M. Taylor, W. R. Jordan & T. R. Sinclair), pp. 1–27. American Society of Agronomy, Crop Science Society of America and Soil Science Society of America.

Tiffen, M., Mortimore, M. & Gichuki, F. 1994 *More people, less erosion: environmental recovery in Kenya*. 311 pp. Chichester, UK: John Wiley & Sons.

UNEP 1992 *World atlas of desertification*. 69 pp. London: Edward Arnold.

Wallace, J. S. 1991 The measurement and modelling of evaporation from semi-arid land. In *Soil water balance in the Sudano–Sahelian zone* (ed. M. V. K. Sivakumar, J. S. Wallace, C. Renard & C. Giroux), pp. 131–148. Proceedings of the Niamey Workshop, February 1991. Wallingford, UK: IAHS.

Wallace, J. S. 1996 The water balance of mixed tree–crop systems. In *Tree–crop interactions—a physiological approach* (ed. C. K. Ong & P. A. Huxley), pp. 189–123. Wallingford, UK: CAB International.

Wallace, J. S., Gash, J. H. C., McNiel, D. D. & Sivakumar,

M. V. K. 1988 Evaporation from a sparse dryland crop in Niger, West Africa. In *Proceedings of the international conference on dryland farming* (ed. P. W. Unger, T. V. Sneed, W. R. Jordan & R. Jensen), pp. 325–327. Texas Agricultural Experiment Station, Amarillo, Bushland, Texas.

Wallace, J. S. & Holwill, C. J. 1997 Soil evaporation from tiger-bush in Niger. *J. Hydrol.* 188–189, 426–442.

Wallace, J. S., Jackson, N. A. & Ong, C. K. 1995 Water balance of agroforestry systems on hillslopes. Final report to the ODA forestry research programme, September 1995. Report no. ODA95/10, 39 pp. Wallingford, UK: Institute of Hydrology.

Wallace, J. S., Jackson. N. A. & Ong, C. K. 1997 Soil evaporation in a *Grevillea robusta* agroforestry system. II. Modelling the effects of tree canopy shade. *Agric. For. Meteorol.* (In the press.)

Wright, E. P. 1992 The hydrogeology of crystalline basement aquifers in Africa. In *The hydrogeology of crystalline basement aquifers in Africa* (ed. E. P. Wright & W. G. Burgess), pp. 1–28. London: Geological Society.

Discussion

P. Gregory (*The University of Reading*, *UK*). In your comparison of evaporation beneath trees and bare soil you demonstrated that shading reduced evaporation from the soil surface and conserved water in the soil. However, in an agroforestry system, the tree roots may rapidly use this water so that it is still not available to the crop.

Response. It is true that some tree species may compete vigorously with a companion crop for water. However, other species may not, and it is a major goal of agroforestry research to find tree/crop mixtures which are complementary rather than competitive in their use of water. This point is elaborated upon by Dr Sinclair in the following comment. The demonstrated effect of shade will also apply to monocultures—so there is a general point being made that in certain soils and in certain rainfall climates, shading of the surface can conserve soil water.

F. L. Sinclair (*The University of Wales*, *UK*). The answer to Peter Gregory's question about the extent of competition for water that occurs between trees and crops is that it depends on the tree species and the way that the tree is managed. Different tree species use water from different parts of the soil profile, depending on their rooting habit and physiology, with seasonal patterns that vary according to the phenology of their leaf area development and duration. Furthermore, the response of tree root systems to shoot pruning varies. Shoot pruning is the main way in which farmers can manipulate tree–crop competition for water while obtaining fuel wood that provides an immediate economic return to the labour input involved. Our recent agroforestry experimentation in collaboration with the University of Maiduguri in Nigeria on soils with vertic properties in the Sudano–Sahelian zone of West Africa found that *Prosopis juliflora*, despite being twice as productive in terms of above-ground dry matter and having a much higher fine root length, has a much higher ecological-combining ability with sorghum than *Acacia nilotica*, when the trees are pruned. In *P. juliflora*, pruned trees had lower fine root length than unpruned trees, but root length was unaffected by pruning in *A. nilotica*. Therefore, despite using more water overall, the pruned *P. juliflora* was less competitive with crops because it obtained a lot of its water requirement from soil not accessible to the crops. The well-known reverse phenology of *Faidherbia albida*, provides perhaps the clearest example of niche differentiation in time—with the tree in leaf in the dry season when the crops are not growing.

C. Valentin (*ORSTOM*, *Niger*). In your excellent presentation you mentioned runoff as a negative factor in the water balance, given that under some circumstances runoff is more difficult to combat than to harvest (for instance in the ancient techniques in Israel, and present techniques in southern Tunisia or in Burkina Faso). I wonder whether runoff should not be regarded in a more ambivalent way. Could you please comment on that?

Response. Yes, I did not have time to elaborate in my oral presentation, however, in my written paper I acknowledge the important role of 'water harvesting' in both man-made and natural vegetation systems.

R. Lal (*Ohio State University*, *USA*). Two papers presented on water resources arrived at conclusions opposite to one another. Dr Wallace said freshwater supply is not a problem. Dr Falkenmark said 4.6 billion people will face water scarcity by 2025. Can we resolve this discrepancy?

Response. I think the answer lies in the scales we are referring to. My conclusion that fresh water supply is not a problem refers to the entire globe. However, I also believe Dr Falkenmark is correct to identify subareas of the globe where there may be *regional* water scarcity.

J. Kijne (*IIMI*, *Sri Lanka*). Would you please comment on the two options to deal with the real or presumed future scarcity of water for agriculture: improved water management at field level and the development of new water resources through the construction of additional storage reservoirs? Consider that at present about half the crops in India and China are produced under irrigation, and in Pakistan the percentage is even higher, at 80%. Most of the additional crops in these countries to feed their growing populations has to come from irrigated lands.

Response. My own opinion is that the increased food production must come from both irrigated *and* rainfed agriculture. Noting that currently *two-thirds* of global crop production comes from rainfed agriculture means that we must also consider how to increase production in these systems. The main point of my paper is that water is not very efficiently used in dry land (or irrigated) agriculture and that there are a range of techniques for improving water use efficiency and hence yield.

M. V. K. Sivakumar (*WMO*, *Geneva*). You referred to several technical reasons why water use efficiency should be increased. There is also a non-technical, but more aggressive argument for enhancing water use efficiency. This comes from the 'urbanites'. Many cities in the developing world are already facing water shortages and water rationing is becoming more and more a rule than an exception. Urbanites are complaining that agriculture, which is currently consuming over 75% of the water resources, should be asked to reduce their needs and divert that water to cities. This provides a compelling argument to enhance water use efficiency in the future, as agriculture may not be able to continue the current rate of water consumption to serve the competing needs for the same water resource.

Response. A good point and one which I will add to my future arguments for improved agricultural water use efficiency.

R. Riley (*FRS*). After J. S. Wallace's paper, Max Perutz asked a question about desalination. Subsequently I said: 'I understand that a new centre, supported by several major donors is to be built in Muscat to research on desalination'. I understand that the present cost of desalination is about \$1.50 m^{-3}. For the process to be widely used the price must come down to about \$0.1 m^{-3}.

Response. If water can be cost effectively desalinated in the future this would be of enormous benefit to mankind and greatly relieve the pressures on fresh water resources.

D. W. Billing. Under water resource management, could you mention the aspect of managing water for fishery resource production, for aquaculture (e.g. tilapia fish farming in rice areas) and fish farming in the marine environment. The potential for food production increases from lakes, rivers, ponds and the oceans is significant and should not be ignored.

Response. Of course food production from fisheries is an important source of human nutrition. However, with limited space and time for my written and oral presentations, I have interpreted the meeting title of 'Land resources ...' to exclude lakes and oceans.