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Increasing agricultural water use efficiency to meet future food production

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Abstract

With the world's population set to increase by 65% (3.7 billion) by ∼2050, the additional food required to feed future generations will put further enormous pressure on freshwater resources. This is because agriculture is the largest single user of fresh water, accounting for ∼75% of current human water use. At present ∼7% of the world's population live in areas where water is scarce. This is predicted to rise to a staggering 67% of the world's population by 2050. Because of this water scarcity and because new arable land is also limited, future increases in production will have to come mainly by growing more food on existing land and water. This paper looks at how this might be achieved by examining the efficiency with which water is used in agriculture. Globally, in both irrigated and rain fed agriculture only about 10–30% of the available water (as rainfall, surface or groundwater) is used by plants as transpiration. In arid and semi-arid areas, where water is scarce and population growth is high, this figure is nearer 5% in rain fed crops. There is, therefore, great potential for improving water use efficiency in agriculture, particularly, in those areas where the need is greatest. The technical basis for improving agricultural water use efficiency is illustrated. This may be achieved by increasing the total amount of the water resource that is made available to plants for transpiration and/or by increasing the efficiency with which transpired water produces biomass. It is concluded that there is much scope for improvement, particularly, in the former and that future global change research should shift its emphasis to addressing this real and immediate challenge.

Keywords: Global change; Population increase; Agriculture; Water use efficiency

1. Introduction

To date the global change community has had a strong focus on the causes and impacts of increased atmospheric CO_2 level, i.e. global warming and climate change. This focus has drawn together an impressive body of international research effort and has made very significant progress in studying the physical and physiological processes which are central to understanding the effects of atmospheric CO_2 increase on vegetation. This research underpins the design of effective mitigation strategies. However, one disadvantage of this strong 'carbon' focus is that other important global issues have, by default rather than by design, received much less attention. This paper argues that the Earth is facing another important global change, which is both more important and more certain than changing atmospheric CO_2 concentration. This change is the massive increase in world population which will occur within the next 50 years. This has many far reaching implications for both science and society, but one central issue is the challenge of growing enough food for this increased population when water resources are limited and already highly exploited, particularly, in those areas of the world where the population increase is greatest. The technical research agenda which evolves from these water

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resource implications is identified as one of agricultural water use efficiency. The current levels of water use efficiency are outlined and used to demonstrate the scope for improvement. Examples of the technical basis for improved water use efficiency are given; these show how runoff, soil evaporation and drainage may be reduced in order to optimise the amount of water retained in the soil to support plant growth. The issue of water use efficiency and scale is also discussed, showing how the large scale (e.g. catchment) water use efficiency may be increased by recycling run off and/or drainage. Finally, there is a plea to the global change community to apply some of its intellectual capacity to addressing the technical agenda which evolves from the agricultural water use efficiency problem. This agenda is not only scientifically and technically challenging, but is also of major importance in contributing to the solutions to what is arguably one of the most pressing global issues currently facing mankind.

2. The most important global change

Fig. 1 is based on United Nations Population Division data and shows that the total population of the world has increased by 125% since 1950 (Fischer and Heilig, 1997). This figure also shows the best available estimates of how the world population will increase in the next 50 years. As these are estimates, three scenarios are presented based on different assumptions about fertility rates in women. The most optimistic scenario is for a low fertility rate where the world population will increase by ∼2 billion or 35%. The median projection is for an increase of 65% or an extra 3.7 billion people. If female fertility rates remain high, then the world population would double by 2050.

Two other factors need to be pointed out. Firstly, most of the world population increase will occur within the next 25–30 years. This is a very short time to prepare for the huge impacts which will be described later. Secondly, almost all of the world's population increase will be in developing countries. Fischer and Heilig (1997) have pointed out that this developing world 'population explosion' is a historically unique phenomenon. No European country has ever experienced such high population growth rates or absolute numbers, even during their fastest growth periods. In one sense, Fig. 1 is the equivalent to the time trend in atmospheric CO_2 concentration measured at the Mauna Loa observatory in Hawaii. More than any other single illustration of the atmospheric CO_2 problem, that oscillating, but constantly escalating

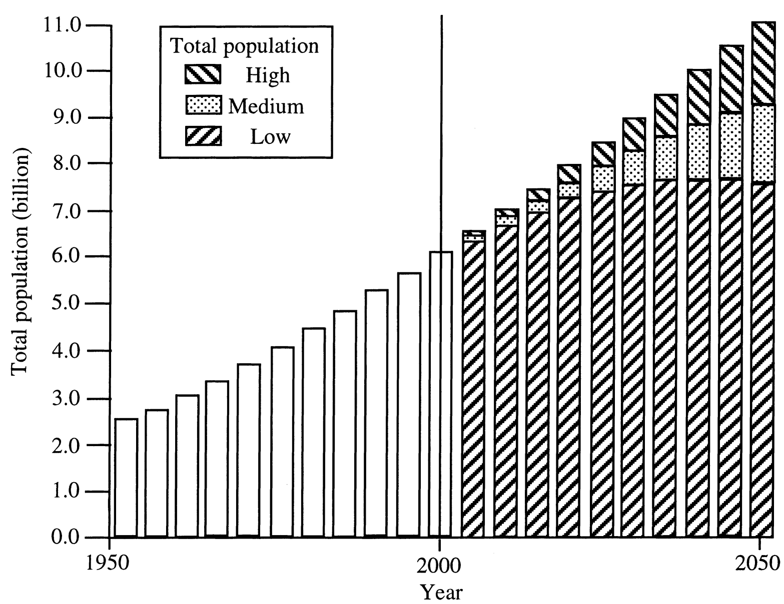

Fig. 1. Historic and future world population. Source: UN Population Division 1997 (Fischer and Heilig, 1997).

line conveyed the nature and urgency of the CO_2 issue. Although it does not oscillate, the massive and inexorable increase in the number of human beings in the world should be recognised for what it is — the most important global change facing mankind.

3. Water resource implications

Assuming the median population projection (Fig. 1), what are the water resource implications of having 3.7 billion more people in the world? These are largely associated with the water needed to grow their food, since large amounts of water are associated with food production. Shiklomanov (1991) has estimated that at present around three-quarters of the annual renewable freshwater resources used by man are consumed in irrigated agriculture. To estimate the inevitable increased demand for water resources to grow the food requirement of the future population, we first need to estimate how much water is required to grow our basic per capita food requirement. If we combine this information with the UN population statistics and estimates of total annual renewable freshwater resources, we can estimate the global and regional picture of future water scarcity.

Table 1 reproduces some data presented by Falkenmark (1997) which was used to derive basic per capita water requirements. This assumes a basic dietary requirement of 2700 kcal which is mostly (85%) plant based. Using figures for the water requirement per kcal of food, Falkenmark (1997) was able to estimate the annual per capita water requirement as 1570 m^3 water. In a semi-arid climate Falkenmark assumes that 50% of food would come from rain fed agriculture, so the annual per capita freshwater demand from irrigated agriculture would be 785 m^3. This is a critical assumption in this analysis, which may be a reasonable 'first estimate' for all semi-arid areas. However, it will clearly vary widely between different parts of the semi-arid zone. Another point which will be developed further in a later section is the need to take more account of rain fed agriculture when considering future food production and its water resource implications. In simple terms the more that is grown under rain fed agriculture the less the demand on freshwater resources will be.

Falkenmark (1997) also made some allowance for domestic water requirements, i.e. 36 m^3 per person per year, and a per capita industrial allowance of 180 m^3 per person per year. The total annual per capita water requirement is therefore $\sim$1000 m^3. As this is regarded as a basic requirement, some water stress is still considered to occur when the annual per capita water availability is between 1000 and 2000 m^3. Above 2000 m^3 per person there is usually little or no water stress.

Fischer and Heilig (1997) have combined a range of estimates of annual renewable fresh water with the UN population statistics to obtain per capita water availability for 21 regions of the world, for the present and in the year 2050. Fig. 2 reproduces their data in geographical form, coding areas of the world according to their current and future per capita water availability. At present, there is a total of 7% of the world's population living in areas where there is some degree of water stress, (Fig. 2a). The most acute water shortages are currently in North Africa where per capita water availability is already less than 1000 m^3. There is also some water scarcity throughout southern Africa and in the Middle East. The picture becomes much more startling if we consider the same annual renewable freshwater resources divided amongst the world population in 2050 (Fig. 2b). The prediction is that around

Table 1
Water requirements for food per capita[a]

Food	Plant-based	Animal-based	Total
Daily amount (kcal)	2300	400	2700
Daily water required per 1000 kcal (m^3)	1	5	–
Daily actual water requirement (m^3)	2.3	2.0	4.3
Annual water requirement (m^3)	840	730	1570
Assume 50% irrigated production (m^3)	–	–	785

[a] Source: FAO (see Falkenmark, 1997).

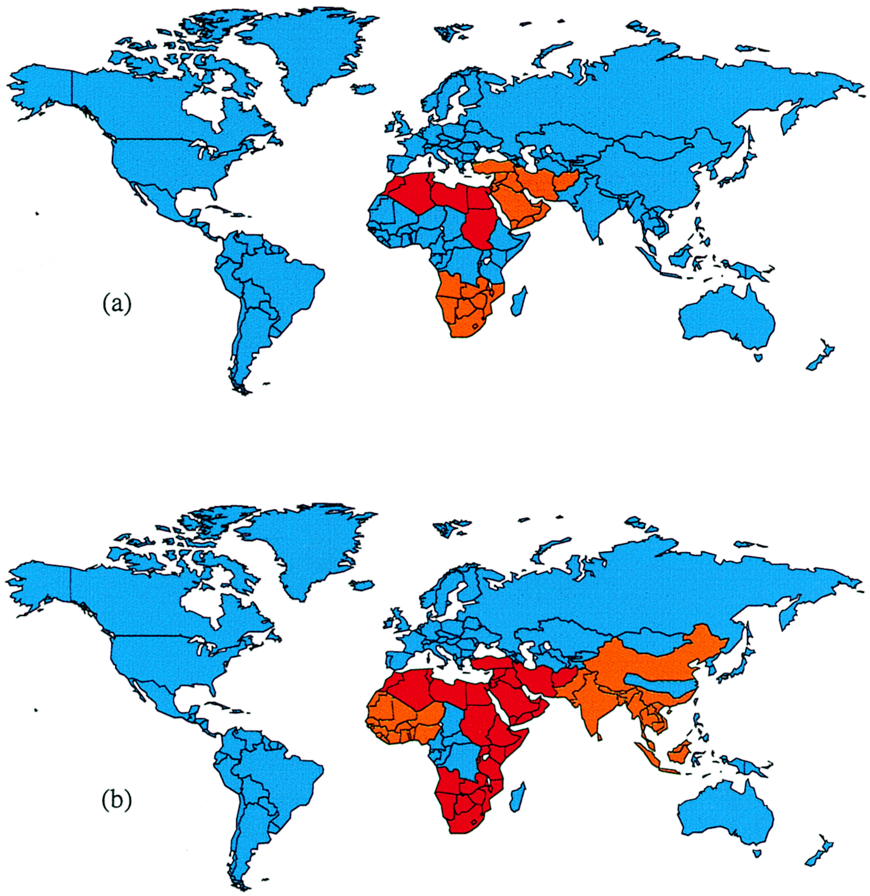

Fig. 2. Global water scarcity (a) now and (b) in 2050. Regions are coded according to their per capita annual renewable freshwater resource. Red-less than 1000 m^3 per person per year, orange-between 1000 and 2000 m^3per person per year and blue-greater than 2000 m^3 per person per year: data from Fischer and Heilig (1997).

one in six of the Earth's population will have insufficient water to meet their basic requirements. This situation is predicted to extend over large regions of Africa and the Middle East. Other areas with currently sufficient water will experience some degree of water shortage, e.g. India, Far East and parts of China. Over the entire globe a staggering 67% of the future population of the world may experience some water stress; 10 times the number of people who are in this situation today! As the use of water for human needs increases, there are potentially severe environmental consequences due to shortages of fresh water for wetlands and other aquatic ecosystems. Human use of water also tends to degrade water quality, which again can have important impacts on ecological systems. However, here we will focus on water use in agriculture.

The sheer scale of future water shortage has led to several authors to refer to a 'Global water crisis'(e.g. see Gleick, 1993). However, the focus of this paper is to consider how this seemingly intractable situation might be resolved. On the one hand, annual renewable freshwater resources are largely fixed. Climate change may marginally increase or decrease these resources in some parts of the world, say by $\sim\pm10\%$. However, these changes are small when compared with the predicted changes in per capita water availability due to population increase which are as high as 70% in many parts of Africa.

Table 2
Estimates of the water-use efficiencies of irrigated and rainfed agriculture in semi-arid areas[a]

	Irrigated agriculture (Fraction of available water[b] (%))	Rainfed agriculture (Fraction of rainfall (%))
Storage and conveyancing	30	0
Runoff and drainage	44	40–50
Evaporation (from soil or water)	8–13	30–35
Transpiration	13–18	15–30

[a] Based on data given in Wallace and Batchelor (1997) and reproduced from Falkenmark et al. (1998).
[b] Rainfall and stored surface or groundwater.

4. Agricultural water use efficiency

A summary of the current efficiency with which water is used in both rain fed and irrigated agriculture is given in Table 2. In irrigated agriculture, a considerable amount of water is lost as evaporation and/or leakage during storage and transport of the water to the fields where the crops are grown. Bos (1985) has estimated that globally ∼30% of irrigation water is lost in storage and conveyancing. Once the remaining (70%) water reaches the field where it is required there are further losses as runoff and/or drainage. Postel (1993) has estimated the world wide irrigation efficiency, i.e. the amount of water evaporated compared to the amount of water delivered to the field, to be ∼37%. This would mean 63% of the water delivered to field is lost as runoff and/or drainage. This equates to 44% of the total water resource at source. Broadly similar figures demonstrating the poor performance of most irrigation systems have also been published by the Food and Agriculture Organisation (e.g. see Barghouti, 1999). However, some of the water “lost” from an irrigated field may return to aquifers or streams from which it can be abstracted again, provided the necessary infrastructure is available and the water quality has not deteriorated beyond acceptable limits. If this is the case the efficiency of water use over large irrigated areas may be greater than the above global mean of field level irrigation efficiencies (Bouwer, 1992). This important issue is discussed further in the section on Water Use Efficiency and Scale.

Conventional irrigation efficiencies are quoted as the ratio of water evaporated to that supplied to the field. However, of the total water evaporated during a crop season, only a fraction is transpired by the crop. For example, in flood irrigated maize (*Zea mays*) in Zimbabwe, Batchelor et al. (1993) found that evaporation from the wet soil was ∼50% of the total seasonal evaporation. The lowest direct evaporation losses might be expected to occur in fast growing irrigated rice (*Oryza sativa*). However, even here around 30% of the season’s total evaporation is from the water in which the rice is growing (Batchelor and Roberts, 1983). If these two figures for irrigated maize and paddy rice are typical, this implies that between 8 and 13% of the initial water resource is lost as direct evaporation from the soil or open water supporting the crop. This fairly crude analysis results in the conclusion that globally only 13–18% of the initial water resource in irrigated agriculture is used as transpiration by the crop. The amount of water transpired is important, since in essence it is only the water which passes through the crop as transpiration which is associated with growth and yield.

Table 2 also contains a similar analysis of water use efficiency in rain fed agriculture. The figures used are taken from studies of rain fed millet in West Africa, which were reported by Wallace and Batchelor (1997). Here, there are no storage and conveyancing losses, however, there are usually substantial runoff and/or drainage losses. Both runoff and drainage are dependent on rainfall and when runoff is high, drainage tends to be low. Data reported by Wallace and Batchelor (1997) suggest that combined runoff and drainage losses are often in the range 40–50% of rainfall, broadly similar to the equivalent losses in irrigated agriculture. The high losses in West African rain fed agriculture are due to a combination of the infrequent, but intensive rainfall and the tendency of the very sandy soils of the region to form crusts with low infiltration rates. Rain fed crops tend to be sparser than irrigated crops, so their soil evaporation losses are higher. Soil evaporation losses equivalent to 30–35% of rainfall have been reported by Wallace and Batchelor (1997) for millet grown in research plots in Niger. These figures imply that transpiration from rain fed crops in sub-Saharan conditions is likely to be between 15 and 30% of rainfall. The amount of rainfall used as transpiration may be even lower in typical farmers fields in West Africa, where Rockstrom (1997) found transpiration was as low as 5% of rainfall.

Water resources are, therefore, very inefficiently used in both rain fed and irrigated agriculture. However, although these low efficiencies may seem disappointing, the fact that they are so low provides plenty of scope for improvement and ultimately the hope that it will be possible to grow more food with existing water resources. For example, if the amount of rainfall used as transpiration could be increased from 5 to 10% in sub-Saharan Africa, a not unreasonable target, then yields in this region could be doubled. The problem of producing the food for future populations, therefore, becomes more tractable and the focus becomes one of increasing the efficiency with which water is used in agriculture.

It is important to recognise the need to increase water use efficiency in both rain fed and irrigated agriculture. The Food and Agriculture Organisation (FAO) have forecast that by the year 2000 around 84% of the world's agricultural land will be rain fed and this will yield around two thirds of global crop production (Postel, 1993). This global figure includes temperate areas where rain fed yields are relatively high. In semi-arid developing countries, therefore, the proportion of food which comes from rain fed agriculture will be even higher and in some countries is over 90%. Furthermore most of the predicted increase in world population is in these regions, so improving rain fed agriculture will increase production in the areas where the food is most required. Furthermore, the more food which is produced in rain fed agriculture the less the pressure will be on freshwater resources for irrigated agriculture. In the earlier analysis of future world water scarcity, the assumption was made of 50% food supply from irrigated agriculture. The lower this figure the lower the per capita water requirement and the fewer the areas of the world where water will be scarce. To emphasise the need to focus on rain fed agriculture, particularly, in semi-arid areas, most of the examples in the following section come from this agricultural sector.

5. The technical basis for improvement

In principle, there are only two ways of increasing water use efficiency in agriculture. First, it may be possible to use more of the water resource as transpiration. Second, it may be possible to fix more carbon per unit of water transpired. For clarity, it is worth considering these two possibilities separately.

5.1. Increasing transpiration

More of the initial water resource can be routed into transpiration by reducing any of the water losses which occur before or when the water reaches the field where the crop is grown. Following the approach used by Gregory et al. (1997), the water use efficiency (WUE) of a crop can be written as

$$\mathrm{WUE} = \frac{\mathrm{e_w}}{\{1 + (L + E_\mathrm{s} + R + D)/E_\mathrm{t}\}} \tag{1}$$

where WUE is defined as the amount of biomass (W) produced per unit of water resource (as rainfall, surface or groundwater); L the losses in storage and conveyancing; E_s evaporation from the soil (or open water in paddy rice etc.); R runoff; D drainage from the crop root zone and E_t the crop transpiration; $\mathrm{e_w}$ 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 (W/E_t). A range of physical engineering, hydrological and agronomic techniques can be applied to maximise E_t and minimise L, E_s, R and D. Plant physiological techniques and micro-climate manipulation can be used to increase $\mathrm{e_w}$ (see later). Let us first consider the physical means of increasing WUE.

The four ways of potentially increasing transpiration are therefore by reducing L (in irrigated agriculture), and by reducing R, E_s and D (in both irrigated and rain fed agriculture). Storage and conveyancing losses in irrigated agriculture may be reduced using a range of engineering or management techniques which decrease evaporation and leakage from reservoirs and irrigation channels. Details of these techniques are outside the scope of this paper, but are well documented in the irrigation engineering and water resources management literature.

Surface runoff has been shown to be a major loss of water in both irrigated and rain fed agriculture. Where rainfall is high, land is steep and/or soils have

Table 3
The effect of soil tillage on runoff from sandy soils in West Africa[a]

Year	Rainfall (mm)	Runoff (no tillage (mm))	Runoff (with tillage (mm))
1977	368	155	76
1978	271	104	49
1979	361	141	80
Average	333	133	68

[a] Source: Stroosnijder and Hoogmoed (1984).

poor infiltration rates, high amounts of surface runoff are to be expected. However, even in the low rainfall climate of West Africa, runoff from flat fields with very sandy soils can be very significant. For example, Rockstrom (1997) found runoff totalled 25–30% of annual rainfalls between 490 and 600 mm in relatively flat (2–3% slope) sandy millet fields in Niger. Even higher runoff amounts, up to 40% of annual rainfalls of 270–370 mm, were reported by Stroosnijder and Hoogmoed (1984) for similar sandy land in Mali (Table 3).

Runoff can be reduced by increasing surface storage and/or the soil infiltration rate. These can be achieved by mechanical changes to the soil surface or the addition of extra materials to the surface, or both. The most striking mechanical change is terracing. This has been used very successfully for hundreds of years in upland paddy rice systems in Asia. Less radical mechanical changes include the use of contour bunds or different forms of tillage. For example, the effect of using earth contour bunds on infiltration has been demonstrated by Butterworth (1997) on two contrasting soil types in Zimbabwe. Fig. 3 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. Surface tillage can also have a major effect on runoff. This is demonstrated in the study by Stroosnijder and Hoogmoed (1984) where simple surface tillage using local hand tools halved the amount of runoff (Table 3). In this study, the extra 65 mm per year of rainfall entering the soil under tillage is vital to crop survival in such an arid region.

Adding materials to the land surface is another way of reducing runoff. For example, leaving crop residues or planting ‘cover’ crops or contour hedgerows have been shown to reduce runoff (e.g. see Lal, 1989; Kiepe and Rao, 1994). Mulches can also be used to reduce runoff (e.g. Lal, 1991) and may also reduce direct soil evaporation (Barros and 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

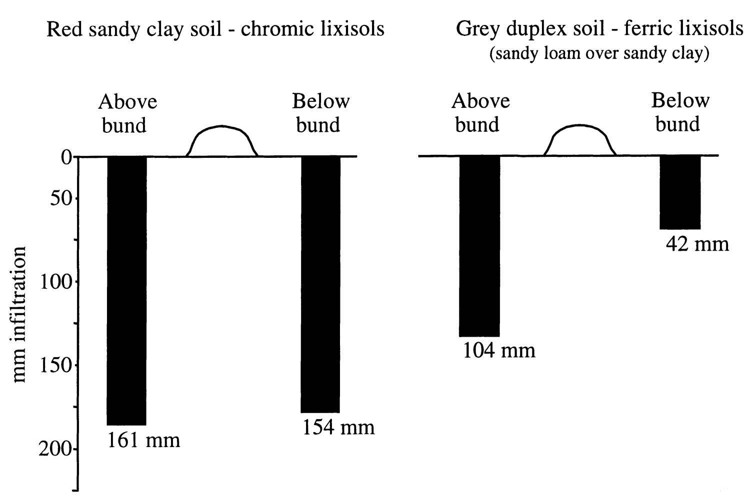

Fig. 3. The effect of soil bunding on infiltration in south-east Zimbabwe following a rainfall event of 141 mm. Note the infiltration on the clay soil is greater than the rainfall due to runoff to the area above the bund (data from Butterworth, 1997, reproduced from Wallace and Batchelor, 1997).

frequency and amount of rainfall. In conclusion therefore, although the principles of the techniques used to reduce runoff are well known, the above examples illustrate the need for research into the effects of surface treatments on runoff processes so that appropriate and effective measures can be applied in the correct circumstances.

Reductions in direct evaporation of water from the soil (or open water) surface could also improve the efficiency with which water is used in agriculture. One simple way of achieving this is to reduce the number of irrigation applications. Alternatively, in irrigated agriculture where there is adequate finance, another solution is to use modern 'high tech' systems such as drip irrigation. One of the reasons these systems work is because there is less wet soil surface exposed to the atmosphere and hence less soil evaporation. Highly expensive systems may not be applicable in some areas, but the same principles of reducing the exposure of wet soil can be applied. For example, the high soil evaporation losses, cited earlier (Batchelor et al., 1993) from flood irrigated maize were reduced by applying water to the crop using simple unglazed clay pipes buried beneath the soil surface, Fig. 4(a). These pipes were made locally at very low cost and significantly improved water use efficiency and crop yield. This is shown in Fig. 4(b), where most of the 30 crop treatments studied showed improved water use efficiency and yield under subsurface irrigation compared with flood irrigation.

Tillage can also alter 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 (*Triticum aestivium*) crop in the 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 farmer's fields in Iowa, USA and found that ridge and chisel plough tillage increased evaporation by between 20 and 130% in the first 20 days after planting of their soybean (*Glycine max*) and maize crops. The largest evaporation rates were recorded

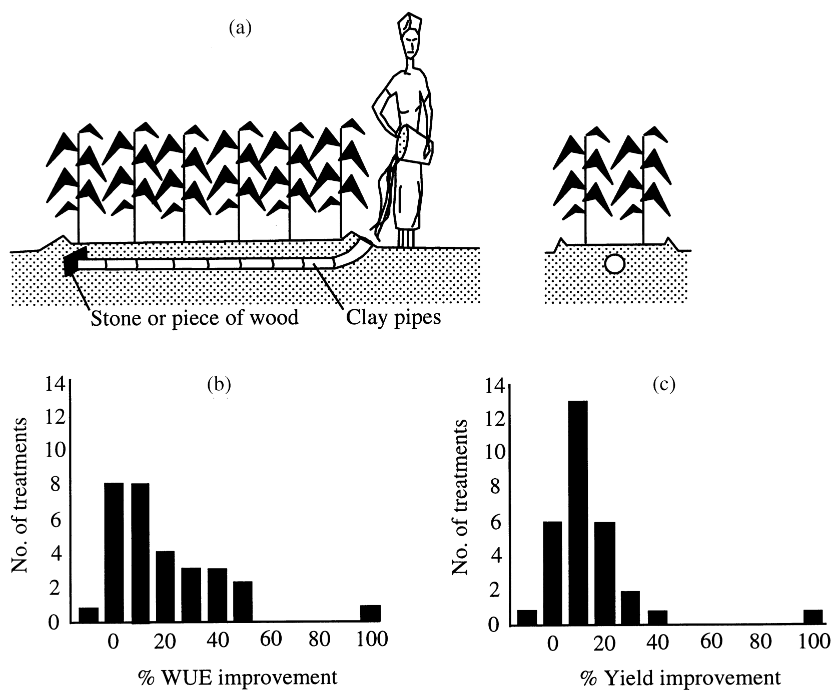

Fig. 4. The improvement in (b) water use effectiveness (WUE) and (c) yield in a total of thirty subsurface and flood irrigated treatments carried out in the Lowveld region of Zimbabwe between 1989–1994: from Batchelor et al. (1996).

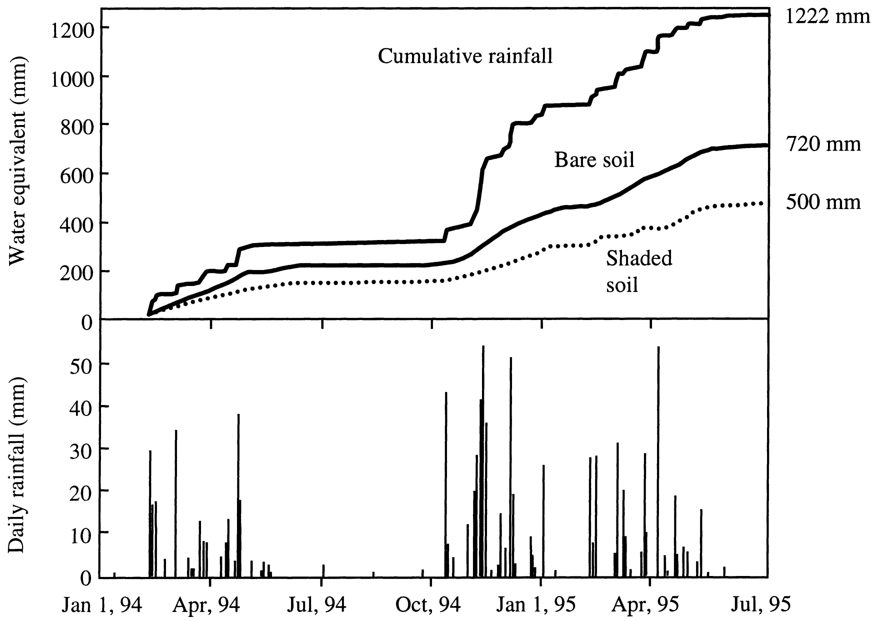

Fig. 5. Cumulative evaporation from bare soil and soil beneath a tree canopy calculated using a model based on the Richie (1972) approach. Rainfall and cumulative rainfall are also shown (reproduced from Wallace and Batchelor, 1997).

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.

Soil evaporation can also be reduced by decreasing the amount of energy reaching the soil surface. This can be achieved using shade from the crop canopy itself or by growing crops under trees in agroforestry systems. 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., 1999). Fig. 5 shows a time series of cumulative evaporation from bare soil and tree canopy shaded soil for an 18 month period. Without any canopy shade ∼59% of the rainfall is lost as soil evaporation. Directly beneath the tree shade soil evaporation is reduced to 41% of rainfall. The agroforestry system studies had ∼50% ground cover, therefore, the net effect of the trees was to reduce the area average soil evaporation by ∼117 mm per year, equivalent to 15% of rainfall. This substantial saving in water decreases as canopy cover decreases, but clearly demonstrates the potential for improved water use which can be achieved by increasing ground cover in rain fed agricultural and agroforestry systems. Again as with the techniques for reducing runoff, the basic techniques for reducing soil evaporation are known, but the suitability and net effect of a particular approach in a given environment require further study.

The final component of the water balance that can be reduced to improve transpiration is drainage. In high rainfall zones and often under irrigation, drainage can amount to a substantial fraction of the total water resource. In irrigated systems drainage depends on the frequency and timing of irrigation. Again contrary to expectation drainage can also be very significant in semi-arid rain fed agriculture. Table 4 shows some model calculations of drainage from rain fed millet (*Pennisetum americanum*) in Niger (Bley et al., 1991). The simulations performed assumed that the millet grew on similar deep sandy soils common throughout Southwest Niger and Mali. At 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

Table 4
Model calculations of annual drainage from rainfed millet in West Africa[a]

	Gao	Tillaberi	Niamey	Gaya
Rainfall *P* (mm)	217	445	595	746
Drainage *D* (mm)	3	83	157	272
D/*P* (%)	1	19	26	36

[a] From Bley et al. (1991).

to less than ∼200 mm did drainage become insignificant. Drainage from farmer's fields may be even higher (40–50% of rainfall) than the figures deduced from Bley's research station experiments due to poorer crop development and local redistribution of runoff in farmer's fields (Rockstrom, 1997; Gregory et al., 1997). For crops growing on the Deccan plateau in India Ong et al. (1991) reported that the best cropping systems still lost ∼33% of rainfall as drainage.

Reduction of drainage losses in rain fed and irrigated crops is difficult as it is dependent on the rapid development of annual root systems. However, perennial species such as shrubs and trees generally have deeper root systems which can be much more effective in abstracting soil water and reducing drainage. Gash et al. (1997) found indirect evidence for this in natural savannah, a mixture of perennial shrubs and annual grasses, growing south of Niamey, Niger. They found that seasonal evaporation from millet was 30% less than that from a nearby savannah area. This difference is similar to the drainage loss from millet calculated above by Bley et al. (1991). It is, therefore, reasonable to conclude that the savannah vegetation had minimal drainage due to the ability of the perennial shrubs to abstract water from depth in the soil. Drainage is, therefore, one of the hydrological terms which can be highly modified by the presence of trees or other perennial vegetation. Since trees can, in principle, utilise water outside the rooting zone of annual crops and also outside the crop growing season, they have the potential of increasing water use efficiency when mixed with crops in agroforestry systems. Research is needed to identify crops which have rapid root development, especially in terms of exploiting soil depth. There is also a need to study and find tree/crop mixtures which are viable and at the same time make better use of the available water resources.

5.2. Increasing the transpiration water use ratio

The alternative way of increasing agricultural water use efficiency is by increasing the transpiration water use ratio, e_w (see Eq. (1)). This is inversely proportional to the mean saturation deficit of the atmosphere, d (Monteith, 1986),

$$e_w = \frac{k}{d} \tag{2}$$

where k is a physiological characteristic specific to a given crop. Total dry matter production (per unit area in a given time) is simply the product of E_t and e_w, where E_t is the transpiration. Theoretical considerations and experimental studies have shown that (at least under fairly idealised conditions) the product $e_w\ d$ is quite conservative among species groups (Ong et al., 1996). For example, in C3 species $e_w\ d$ is $\sim 4\,\mathrm{kg\,mm^{-1}\,kPa}$ and about twice this ($8\,\mathrm{kg\,mm^{-1}\,kPa}$) 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, since dry matter production per unit of water transpired decreases by a factor of two as saturation deficit increases from ∼2 in moist temperate climates to ∼4 kPa in semi-arid areas (Squire, 1990).

Eq. (2) shows that there are two ways that agricultural production could be increased by increasing e_w. The first is by increasing k, the physiological characteristic which depends on the biochemistry controlling the photosynthetic processes in plant cells. This may be achieved by plant selection (e.g. C3 or C4 species), or by breeding or genetically engineering crops with a higher value of k. The second way to increase e_w is to reduce d, either by manipulating the crop micro-climate, or its macro-climate, i.e. growing crops at times or in places where the air is more humid.

Macro-climate manipulation involves matching crop production to areas of low saturation deficit. For example, Tanner and Sinclair (1983) have argued that there is substantial scope for improving agricultural water use efficiency in the USA using this approach. Another macro-climatic approach is to grow crops and/or use irrigation water in areas where d is low. This implies some counter intuitive conclusions, such as using irrigation water in more humid areas and irrigating during the wet season. Tanner and Sinclair (1983) 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. The use of water for supplementary irrigation is one example of this type of approach.

There are also possibilities for reducing *d* by manipulating the micro-climate around crop. For example, in agroforestry systems the presence of an elevated tree canopy may alter not only the humidity, but also the radiation and temperature around an understorey crop. Some evidence for this has been found where crops have been grown using trees as shelter belts, and 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). Wallace and Verhoef (2000) have used an agroforestry model to predict the effect of tree cover on the water use ratio of an understorey crop. Fig. 6 shows the results of their simulation which predicts that both the crop and tree water use ratios will increase by ∼25% as the tree cover increases from 0 to 1. The total system water use ratio includes the evaporation from the soil, so it is lower than the water use ratios of the component species. However, this also increases by ∼25% in this simulation. Clearly, this improved micro-climate is only of benefit to the crop as long as there is adequate water in the soil to meet both the tree and crop requirements. This highlights the need to identify the tree/crop mixtures and soil and climate combinations within which this may be the case.

To summarise, there are two main ways of increasing the efficiency with which water is used in agriculture. We can try to convert more of the water resource into transpiration and/or we can try to increase the transpiration water use ratio. The former may be achieved using a range of physical engineering, hydrological and agronomic techniques. The latter is largely the province of plant physiologists, plant breeders and, more recently, geneticists. It is worth considering the potential gain in water use efficiency, which could be achieved from these two areas. Since large amounts of water are lost in storage, and conveyancing or as runoff, drainage and soil evaporation (∼85%, Table 2) then if 10% of this water could be re-routed into transpiration, the total amount of transpiration would increase from 15 to 23.5%. This 57% increase in transpiration could lead to a similar increase in

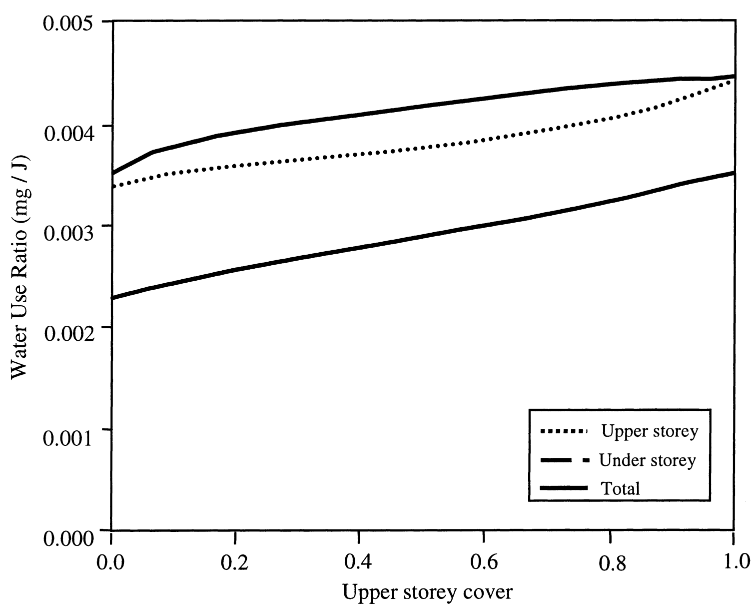

Fig. 6. Variation of water use ratio with upper storey fractional ground cover in a two species mixture with a dominant upper storey (from Wallace and Verhoef, 2000).

crop yield, assuming for simplicity, that the harvest index remained constant and factors other than water are not limiting yield. In contrast a 10% improvement in transpiration water use ratio, would not increase the fraction of the total water resource water used in transpiration, and would only produce a potential 10% increase in yield. When the amount of the total water resources used as transpiration is low (i.e. ∼15%), then improvements in the quantity of water transpired are likely to produce greater efficiency gains than improvements in the transpiration water use ratio.

6. Water use efficiency and scale

The above techniques for improving water use efficiency can be considered in terms of different spatial scales. At the smallest scale of an individual plant the transpirational water use efficiency is most applicable. Here breeding and genetic manipulation may be used to improve growth per unit of water transpired. Moving up in scale to groups of plants, water use efficiencies can be a mixture of improvement in transpirational water use efficiency, e.g. as might be achieved by the micro-climatic modification resulting from mutual shading in a plant community or by reductions in soil evaporation, runoff or drainage which may be achieved using complementary plant mixtures, as in intercropping or agroforestry. These 'field' scale efficiencies may optimise water use within the area concerned, however, Seckler (1996) has pointed out that in some irrigation systems, reuse of water shed from one field can increase the overall efficiency of the entire irrigation scheme. For example, in large scale irrigation schemes such as those in Egypt, despite low field level efficiencies, the overall water use efficiency of the entire system is close to 80% (Seckler, 1999). This 'multiplier effect' is demonstrated in Fig. 7, where the runoff and drainage water identified in Table 2 is recycled for use in subsequent irrigation's. Realistically not all the water which runs off or drains from a field will be recoverable, some will evaporate and some will end up in inaccessible parts of the aquifer or river network. The calculation performed here assumes 50% of runoff and drainage water can be reused. In using this water in subsequent irrigation's, further losses via storage and conveyancing, runoff and drainage and evaporation and transpiration are assumed to occur in the same proportions as in the first irrigation. Fig. 7 shows that overall irrigation efficiency does rise with reuse, but it requires water to be recovered and reused quite a few times to raise overall efficiency towards 80% or more. Note that every reuse will require energy and may increase the degree to which the water is polluted if agri-chemicals are used in the irrigation scheme. There is a second important point made in Fig. 7. Although overall water use efficiency could approach 80%, transpiration water use efficiency

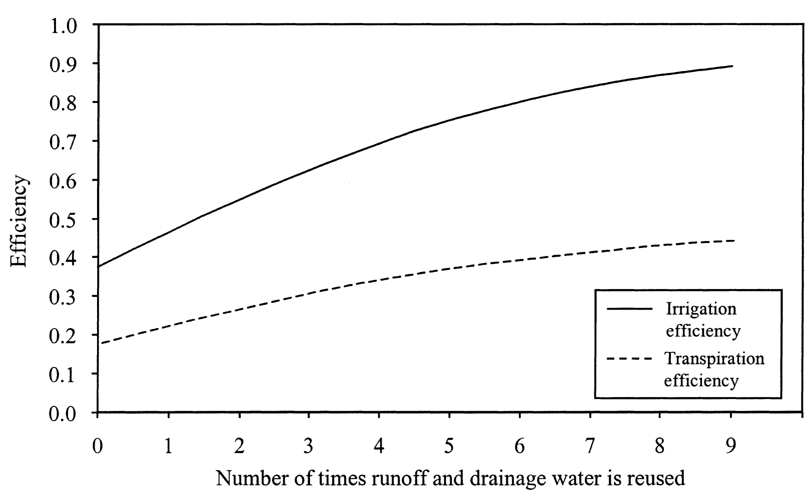

Fig. 7. Change in irrigation efficiency with reuse of runoff and drainage water. Assumed 50% of runoff and drainage is recycled.

remains much lower than this and can never reach such high values unless the proportion of water which is evaporated directly from the soil (or open water surface) is reduced. The research requirements from this area centre on the need to identify appropriate ways of reducing soil (and open water) evaporation as well as how much run off and/or drainage from a given area is reusable.

Moving up further in scale to a complete landscape also allows techniques other than recycling to be considered as a means of increasing the overall water use efficiency of a large area. For example, deliberately allowing water to move from one part of a landscape to another may result in an improvement in the overall efficiency with which water is used. For example, where rainfall is too low to grow a viable crop over an entire area, it may be possible to channel water from bare areas to another point in the catchment where there is sufficient water to grow a crop. These 'water harvesting' techniques have been used in ancient agricultural systems and can still be seen in parts of sub-Saharan Africa today. A modern dimension to this reallocation of water arises from the concept of using limited water resources for crops with the highest value. The particular crops will vary with location and will depend on local markets. When the highest value commodities are not stable food crops, the money generated can be used to buy food, and if this comes from outside the region it effectively reduces the indigenous per capita water requirement. This is the case in Israel, where despite a per capita water supply of only 300–400 m^3 per year, there is a sufficient supply of staple foods as these are imported. This has been referred to as trade in 'virtual water' and can offer a solution to local water scarcity provided the countries economy is suitable. The generic research question in this area focuses on achieving overall efficiency gains by assessing the way in which water can be used in different places and at different times across an entire catchment.

The above 'field', catchment and regional scale efficiencies may optimise water use within the areas concerned, but may have a detrimental impact on areas outside these areas. For example, Falkenmark et al. (1999) have pointed out that there may be serious downstream impacts of irrigation schemes; the extensive environmental degradation in the Aral Sea is probably the most well known example. Ultimately complete hydrological systems, including surface and groundwater, need to be considered if the full range of human and environmental demands on the water environment are to properly assessed. Where there is insufficient water to meet all demands, the effect of sub-optimal supply on each sector will need to be quantified before informed and balanced judgements can be made on how to allocate the water resources.

7. Conclusions

In conclusion therefore, the greatest and most serious global changes we face today are driven by population increase. It is clear that the water requirements associated with producing food for the future world population are huge, and almost certain to happen. For the foreseeable future, annual renewable freshwater resources are largely fixed. There may be some areas where freshwater resources increase or decrease according to rainfall changes due to climate change, however, these are likely to occur at the level which is small compared with the increased human demands for fresh water. The problem of providing the food for a much greater world population, therefore, becomes focused on the area of growing more on existing water (and land) resources. Despite there being plenty of scope for increasing the efficiency with which water is used in agriculture, the global scientific community is not currently giving this area sufficient attention. However, these efficiency measures need to be studied in both rain fed and irrigated agriculture and at both field and catchment scales. Many hydrological and agronomic principles are available for improving the amount of water which is productively used by plants as transpiration. However, there is a need to find appropriate, affordable solutions for the particular circumstances which exist in different parts of the water scarce world. The more recently emerging field of improving the efficiency with which carbon is fixed per unit of water transpired will require the application of the combined skills of plant physiologists, breeders and geneticists. This presents a real and exciting challenge to the global scientific community, not only to apply their skills to the above problems, but also to broaden their horizons and be proactive in involving the social, economic and political experts who are in a better position to successfully transfer technical solutions to practical implementation in the field. There can be no greater global challenge today on which physical and social scientists can work together than the goal of producing the food required for future generations. A concerted focus on improving water use efficiency in agriculture will increase the productivity of both rain fed and irrigated agriculture. The prize is that more areas of the world, and especially those arid and semi-arid areas where population growth is greatest, will be able to sustain their future populations.

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