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The Water Resource for Agriculture [and Discussion]

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The water resource for agriculture†

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The relation between the yield of a crop and its water loss to the atmosphere is examined and the dependence of this relation on the climatically determined potential rate of water loss is stressed. Current methods for assessing the response of crop production to relative water loss are described, with their limitations. The high overall ratio of water loss to dry matter yield harvested in crop production – estimated to average 5.6 kg g^{-1} globally – is contrasted with the much lower values calculated theoretically and measured in good field practice, demonstrating the opportunities that exist to improve the efficiency with which water is currently used in agriculture.

The technological methods available to improve this efficiency before the end of this century are reviewed together with the opportunities of extending the size of the agricultural water resource. Special attention is paid to the large potential for doing so in irrigated agriculture and the costs involved. The influence of climatic change at the level anticipated in the next few decades, on water supply, requirements and efficiency of use in irrigated and dryland food production is examined and the uncertainties involved are emphasized.

Historical introduction

Man's earliest written sources show an awareness of the importance of water supply in determining the yield of crops, no doubt because many of the early centres of civilization developed in arid or semi-arid regions in which this relation is both obvious and important. These writings also indicate an awareness of the two basic strategies available for dealing with an unfavourable water supply.

The first strategy, modification of the water supply, can be illustrated by a biblical example: the promise and warnings of Deuteronomy 11, vv. 13–18, that prescribe the conduct necessary to ensure a sufficient quantity and favourable seasonal distribution of rainfall and firmly links this to the yields of the major crops and availability of pasture. The second strategy, modification of the cropping system, can be illustrated by the following quotation from the Artha-sastra (Sanskrit manual of administration (*ca.* 300 B.C.E.)): 'According as the rainfall is more or less, the superintendent shall sow the seed which require either more or less water' (Shamastry 1915).

Quantitative studies of the relation between plant growth and water loss date from the start of experimental science. The results of Van Helmont's experiment with a potted tree (*ca.* 1577–1644) were interpreted as demonstrating that water was the sole plant nutrient. By the end of the seventeenth century this had been refuted by Woodward (1699) in a series of experiments in which the gain in plant mass and loss of water from a variety of plants growing

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in different water sources were measured. It is noteworthy that the measurements were presented in units of proportional gain of plant mass to water used.

The practical importance of the study of the relation between plant growth and water loss was emphasized in the first experimental text of plant physiology, *Vegetable Staticks* (Hales 1727). The concluding sentence of the Introduction reads 'And since in vegetables, their growth and the preservation of their vegetable life is promoted and maintained, as in animals, by the very plentiful and regular motion of their fluids, which are the vehicles ordained by nature, to carry proper nutriment to every part; it is therefore reasonable to hope, that in them also, by the same method of inquiry, considerable discoveries may in time be made...'.

Among the first of the topics investigated by the new discipline of experimental agriculture in Western Europe 150 years ago was the relation between crop yields and water loss to the atmosphere. Briggs & Shantz (1913) included a comprehensive review of these early experiments in a bulletin that contained the first results of their own extensive programme of field studies. Their extension of research on crop yield–water relation to semi-arid climates resulted in the important finding that the mass of water transpired per unit of dry matter gain, which they termed the transpiration ratio or coefficient, Et/P, was inversely related to the potential rate of water loss, Et_0 (Briggs & Shantz 1914). It is this inverse relation that explains to a large extent the major differences in values of Et/P that have been reported for the same crop grown in different climates, seasons and years (Klages 1942).

The transpiration ratio was used widely in the first half of this century for the design of irrigation projects as well as to estimate water loss from stands of natural vegetation, although usually without any correction for the rate of potential water loss (Israelson 1932). With the increased understanding of, and emphasis on, the physical basis of the water-loss process in the second half of this century, this approach fell into disrepute. However, the two physical approaches used to analyse water loss from crops, i.e. energy balance and turbulent diffusion,

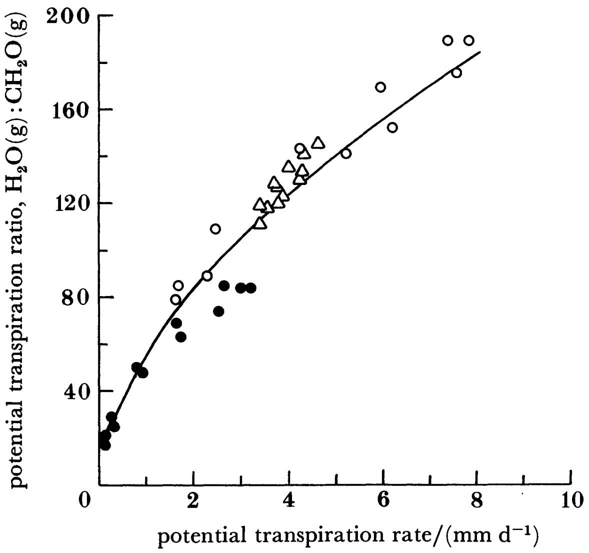

FIGURE 1. Relation between potential transpiration rate and ratio of potential transpiration to potential photosynthesis in three climates. Monthly mean values of potential transpiration (Penman 1948) and potential photosynthesis (de Wit 1965). ●, Temperate (Cambridge, England); △, tropical (Ibadan, Nigeria); ○, semi-arid (Ramat David, Israel). $Et_0/P_0 = 55.611\ Et_0^{0.574}$; $n = 36$; $r^2 = 0.97$; $s(y/x) = 0.114$.

were soon used to study the process of carbon assimilation and the relation between water vapour efflux and carbon dioxide influx (Penman & Schofield 1951; de Wit 1958). These studies provided the first non-empirical framework within which dry matter gain and the yield of crops could be related to their water loss.

Physically based estimates of potential transpiration (Penman 1948) and photosynthesis (de Wit 1965) from crop stands support the earlier experimental findings that the amount of water loss per unit dry matter gain increases with the potential rate of water loss. This conclusion, illustrated in figure 1 for three very different climates, suggests paradoxically that water is most effectively used for crop production in climates and seasons where the demand is least. Evidence from field measurements supporting this conclusion has been presented by Stanhill (1981) and Tanner & Sinclair (1983) in reviews of water use in crop production. The first reference also presents data from temperate and semi-arid climates which demonstrate transpiration ratios measured under optimum growing conditions approaching those in figure 1.

Current approaches to estimating the effect of water supply on crop yields

During the last ten years physical models of water loss from crop surfaces have been combined with empirical relations between crop yield and water loss to allow computer simulation of yield response to changes in water supply. This approach has been used to study the effect of soil, climate and salinity on the yield response to changes both in irrigation practice and rainfall régime, with considerable success in regions where water is a strongly limiting factor.

The models of water loss are based on current understanding of water movement in the soil–plant–atmosphere continuum and have been described by Hanks & Hill (1980). They use parameters that are readily measurable with recently developed techniques and are able to separate crop water loss to the atmosphere into its two major components, transpiration and evaporation.

By contrast, the relations between crop yield and water loss are based on empirical results of field experiments. Doorenbos & Kassam (1979) have summarized the results of more than 500 such experiments conducted throughout the world during the last 35 years, with the use of a linear relation between crop yield Y, and water loss Et, both of which are normalized to their climatically limited potential values, Y_0 and Et_0, respectively. The slope in the relation

$$(1-Y/Y_0) = ky(1-Et/E_0)$$

is termed the yield response factor, ky. Values for this factor for the 23 major crops whose yield responses to water were summarized by Doorenbos & Kassam (1979) are presented graphically in figure 2. For three-quarters of the crops listed, ky lies between 0.85 and 1.15.

The three crops with the highest values of ky were banana, maize and sugar cane; the three crops with lowest yield to water loss sensitivities were, in descending order, safflower, sugar beet and groundnuts.

Doorenbos & Kassam (1979) state that for a given crop, values of ky vary with the stage of crop development. When averaged for the crops for which data for the different stages was available, ky averaged 1.0 over the entire growing season, increasing from a minimum of 0.25 in the initial vegetative stage, reaching a maximum of 0.75 in the flowering phase before dropping (through 0.60 in the yield formation phase) to 0.20 at the ripening stage.

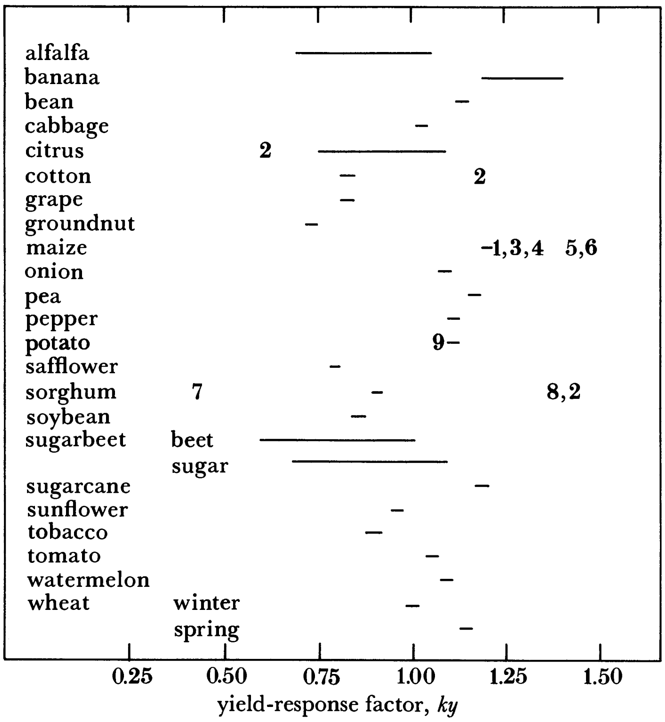

FIGURE 2. Yield-response factor ky in the equation $(1-Y/Y_0) = ky(1-Et/Et_0)$. Horizontal lines represent range of values derived by Doorenbos & Kassam (1979) from review of experimental field data. Numbers refer to independent experimental data given in table 1, whose parameters refer to equations in the original form $y/y_0 = ky(Et/Et_0)$.

TABLE 1

no.	crop	ky(slope)	offset	r^2	reference
1	alfalfa	1.05	−0.06	0.88	Retta & Hanks, (1978)
2	citrus (grapefruit)	0.61	+0.38	0.55	Stanhill (1981)
2	cotton	1.20	−0.06	0.88	Retta & Hanks (1978)
1	maize	1.22	−0.22	0.90	Stanhill (1981)
3	maize	1.26	−0.30	—	Hanks *et al.* (1978)
4	maize	1.30	0	—	Stewart *et al.* (1977)
5	maize	1.46	−0.51	0.87	Wenda & Hanks (1981)
6	maize	1.54	−0.57	—	Stutler *et al.* (1981)
2	sorghum	1.36	−0.29	0.88	Stanhill (1981)
7	sorghum	.45	+0.55	—	Stewart *et al.* (1975)
8	sorghum	1.33	−0.07	—	Faci & Fereres (1980)
9	potato	1.09	−0.07	0.98	Shalhevet *et al.* (1983)

The approach outlined above allows yield response to water supply to be readily calculated from estimates of Y_0 and Et_0, which can be either calculated from meteorological data or directly measured at the site of interest, and computed or measured values of Et. The methods available are given by Doorenbos & Kassam (1979).

The accuracy of this approach, however, depends on (i) the correctness of the assumption that ky is in fact a crop constant of wide application and (ii) the suitability of the simple linear relation. Doorenbos & Kassam did not discuss these points or present data that would allow their evaluation. An attempt to do so has been made by comparing values of ky which they present, with those derived from recent crop water-requirement experiments conducted under quasi-commercial field conditions, which were not included in the data they reviewed and for which the measured values of the four parameters needed to derive *ky* are available.

The results of this comparison, shown in figure 2, indicate that, for maize and sorghum (the two crops for which most data are available) the within-crop range in *ky* is greater than that between crops. One reason is that in most cases the relation between Y/Y_0 and Et/Et_0 has a significant negative offset value, implying that a threshold value of relative water loss occurs before any yield is obtained. This offset value of Et/Et_0 has been interpreted by Hanks (1974) as representing the fraction of Et_0 contributed by non-productive evaporation from the soil surface, *E*. However, as the variation in Et/Et_0 derives from different levels of water supply, the fraction E/Et is probably not constant, as the water supply will affect both the size of the crop canopy and the wetness of the soil surface, the sink and source functions of evaporation from soil.

If the experimental data listed in figure 2 are constrained to fit the zero-origin model of Doorenbos & Kassam, the average value of *ky* derived is 1.07 with a standard deviation of ± 0.12 for the eleven data sets, many of which represent averages of a number of years experimentation. In extreme cases, values of *ky* derived from individual years varied by as much as 20% for the same crop, site and water supply treatments (Hanks *et al.* 1978).

The above results suggest that while, in the absence of local information, the current approach with generalized crop response factors and a simple linear model may be useful as a first approximation for estimating the effect of water supply on crop yields, it should not serve as a substitute for the results of local field experimentation. These should be used with the most appropriate model of yield–water supply relations, which may well be considerably more complex than the simple linear model described, especially in temperate climates.

Size and efficiency of water resource currently used in agriculture

The restraints to crop production attributable to water supply and the limitations to the efficiency of its use imposed by physiological processes interacting with the environment emphasized in the preceding section in practice only apply to the more arid agricultural areas and the most productive intensive systems of agriculture. This is because, in most agricultural systems, water supply *per se* is not now the major yield-limiting factor and many technological opportunities are available for increasing the efficiency with which the existing water supply is used. Before considering these, together with the possibilities of increasing the size of the water resource that can be made available for agriculture before the end of this century, the current size and efficiency of agricultural water use will be examined.

For this purpose the annual flux of evapotranspiration from the agricultural land area of the world has been estimated by multiplying the areas of both arable and permanent crops and permanent pasture during the period 1960–1979 (F.A.O.) by values of annual evapotranspiration (Baumgartner & Reichel 1975). The products, listed in table 2, are sums of national values each arrived at by using maps of both land use and evapotranspiration to allow for the (often large) regional variations.

Over the 20-year period averaged, the agricultural water use has almost certainly increased with the increasing area and intensity of agricultural land use. Over this period, the total agricultural area increased by less than 3%, all in countries classified by F.A.O. as 'developing', which now constitute 62% of the total agricultural area. Two-thirds of this increase was in the area cropped and the remainder in permanent pasture. Although there was no net increase in the agricultural land in 'developed' countries, the cropped area increased by 9% at the expense of permanent pasture. Over the two decades the increase in production (62% for both cereal and pulse crops, 49% for sugar, 24% for roots and tubers, 132% for meat and 39% for milk) was much greater than can be attributed to the increase in area. These increases in yield per unit area imply, on the basis of the yield–evapotranspiration relations previously discussed, that water loss to the atmosphere per unit agricultural land area has also increased.

Table 2. Evapotranspiration, food production and transpiration ratio of agricultural land surfaces, 1960–1980

evapotranspiration ($km^3\ a^{-1}$)	arable and permanent crops	permanent pasture	total
Africa	1617	4734	6351
Asia	3611	2016	5627
Europe	728	430	1158
North and Central America	2030	2049	4079
South America	804	2781	3585
Oceana	871	2177	2548
U.S.S.R.	556	1043	1599
global total	9717	15230	24947
production $10^{-6}/(t\ a^{-1})$	1960	1970	1980
fresh mass: crop	1931	2450	2880
fresh mass: animal	416	525	643
estimated dry mass: crop	1128	1424	1742
estimated dry mass: total	1189	1505	1843
transpiration ratio (dry mass basis)/($kg\ g^{-1}$)			
crop production	8.6	6.8	5.6
total	21.0	16.6	13.5

A large proportion of the total evapotranspiration flux from agricultural land, $24.9 \times 10^3\ km^3\ a^{-1}$, is from irrigated areas. Lvovich (1970) estimated the latter at $1.7 \times 10^3\ km^3\ a^{-1}$ for 1965, yielding an annual rate of water loss to the atmosphere from irrigated land that is equivalent to a water depth of 1.13 m. This compares with the global average of $0.67\ m\ a^{-1}$ for all crop lands and of $0.50\ m\ a^{-1}$ for permanent pasture. The latter rate of water loss is approximately the same as the average for all the land surface of the earth, that is, $0.54\ m\ a^{-1}$ ($= 71 \times 10^3\ km^{-3}\ a/130.8 \times 10^6\ km^2$; Baumgartner & Reichel 1975).

The low current level of water-use efficiency in world agriculture can be demonstrated by comparing the transpiration ratio derived for all crop land of $5.6\ kg\ g^{-1}$ crop yield harvested in dry matter form (table 2) with values for net dry water production and evapotranspiration measured with crops growing under optimum field conditions. These range from $0.16\ kg\ g^{-1}$ in temperature climates to $0.31\ kg\ g^{-1}$ in arid climates (Stanhill 1981), values which approach the theoretical maxima indicated in figure 1. Even if it is assumed, conservatively, that only 20% of net dry matter produced is harvested as crop yield, the large margin for improvement is clear.

A similarly large gap exists between the global crop transpiration ratio and that derived from crop water-requirement experiments. For example, the marginal yield response derived from ten wheat irrigation experiments in Israel (Shalhevet *et al.* 1976) gives an average transpiration ratio of 0.7 kg water per gram harvested.

Technological opportunities for increasing agricultural water-use efficiency by the year 2000

The major opportunity for achieving such an increase lies in irrigated agriculture. Although this now constitutes only one-seventh of all the crop area, and is not expected to exceed one-sixth by the end of the century (F.A.O. 1981), the previous estimates show that 17% of the total agricultural water loss from crop land is from irrigated areas. An increase in the water-use efficiency of these lands is also important because of the disproportionately high contribution of irrigated land to agricultural production. Two thirds of the world's population lives in countries largely dependent on irrigated land for their food and F.A.O. estimates indicate that food production per unit irrigated area is 2.5 times that from non-irrigated crop land. This ratio is in approximate agreement with that for the evapotranspiration rates presented above.

The efficiency of water use in irrigated cropping, here defined as the proportion of water released for irrigation that is finally evapotranspired by crops, is currently very low. Even in the U.S.A. the overall value usually quoted is only 30%. Although this efficiency is greater in the area under the control of individual farmers, it is still generally much below that obtainable by using readily available, simple and cheap irrigation technology, and even further from the efficiency possible with advanced, but more expensive, pressurized irrigation systems.

The extent of the improvement in irrigation efficiency that is easily obtainable and the costs of such an improvement are well demonstrated by the results of an extensive study in central Chile (Gurovich 1979). Fields receiving traditional irrigation practice, i.e. surface applications at times and amounts dictated by the availability of water and labour, were compared with matched fields using improved design for gravity irrigation with a simple scheduling system based on crop water requirements. Water application rates were reduced by an average of 4540 $m^3\ ha^{-1}$ (from 14535 in the traditional to 9995 $m^3\ ha^{-1}$ in the improved fields); evapotranspiration was increased by 343 $m^3\ ha^{-1}$ (from 5301 to 5644 $m^3\ ha^{-1}$), and hence efficiency increased from an average of 35% to 56%. The yields were higher for all the eleven crops studied, the average increase for fields receiving improved irrigation being 18%.

The environmental benefits of increased irrigation efficiency are probably as important as the reduction in water application and increase in yields. Environmental hazards associated with low efficiency include increased height of water table, impeded drainage and reduced depth of rooting and soil salination.

Improvement in irrigation efficiency is often profitable even without allowing for environmental benefits, although the costs are not insignificant. This is especially so in developing countries where most irrigated land is found and where the cost is almost certainly the major factor limiting the speedy adoption of improved irrigation technology.

In the study quoted above the annual cost of irrigation rose from U.S.$ 80 ha^{-1} in traditional practice to U.S.$ 240 ha^{-1} for improved practice, the major increase being in the operational costs, which rose from U.S.$ 71 to 185 ha^{-1}. In this example, as for the major irrigated areas of the world, no direct charge was made for water, so that no cost reduction has been allowed for water saved.

On a global scale the sums required to improve old and to construct new irrigation schemes in the 90 developing countries of the world are vast. Based on 1975 costs the F.A.O. estimates them at between U.S.$ 10.5 and 12.7 billion in 1990, rising to U.S.$ 12.1–14.6 billion by the year 2000 (F.A.O. 1981).

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Irrigation efficiencies much greater than 56% are readily attainable with pressurized irrigation systems, but at a greater cost. Sprinkler systems commonly have an efficiency of 80% but their cost has been estimated to average U.S.$ 7000 ha^{-1} compared with an average of U.S.$ 300 ha^{-1} for controlled flooding systems (F.A.O. 1981). Even higher efficiencies, up to 90%, have been achieved with automated drip irrigation, but the cost of such systems can be double that of sprinklers.

High-efficiency irrigation systems are also typically energy intensive, both in their operation and in the energy invested in the system components. For example, a central pivot system using water from an aquifer 100 m below the surface sequesters 107 GJ of fossil fuel per hectare maize crop (Batty & Keller 1980).

Recent developments in irrigation technology, such as laser land-levelling, pulsed-water application, microcatchments and runoff recovery systems, have demonstrated that gravity application systems can be operated at efficiencies comparable with those of pressurized methods, but with substantial savings in energy and capital.

Water-use efficiency can also be significantly improved in non-irrigated crop production by the adoption of a number of readily available techniques. In global order of importance these are practices that reduce unproductive water loss by above- or below-surface water runoff, or by transpiration through weeds or evaporation from bare soil. The adoption of conservation methods can increase rainfall infiltration and reduce surface losses of both water and top-soil. Improved cultivation and varieties can increase the depth of rooting and so reduce the water draining below the root zone. By ensuring a complete ground cover of transpiring crop canopy during that part of the growing season when water is available, moisture losses from the soil or by weeds can be reduced.

A major increase in the efficiency of water use in agriculture would undoubtedly result if the processes of water loss and dry matter gain could be uncoupled by genetic selection or engineering or both. Such an achievement presents a formidable task and appears unlikely in the near future, considering the lack of exceptions to the strong correlation found so far in both naturally or consciously selected plants. Nevertheless, as a long-term goal, it is important that research in this field be continued.

Technological opportunities to increase water supply in agriculture by the year 2000

The possibilities for increasing irrigation efficiency discussed above offer the greatest immediate opportunity for increasing water supply in agriculture. The extent of this resource is seen from Lvovich's (1970) estimate that in 1965, 2300 km^3 of water was withdrawn globally for use in irrigation, constituting 81% of all water withdrawals. It was estimated that by the year 2000, water withdrawal for irrigation would increase to 4250 $km^3\ a^{-1}$, but by then the proportion taken for irrigation would be reduced to 33%.

Even a modest increase in the present low irrigation efficiency would allow an expansion in the size and duration of irrigated crop production without the development of new water resources, leaving these for energy-generation, industrial, and urban users better able to pay for their development.

Other techniques could be adopted immediately and are available for the exploitation of water resources that are at present largely unused, both in irrigated and dryland agriculture.

The most economical of such sources is the sky. Unfortunately, the number of agricultural areas in which precipitation enhancement through cloud seeding is both likely to succeed and would also directly benefit rain-fed crops is very few. Nevertheless, there is at least one well documented case where an operational cloud-seeding programme significantly contributes to irrigated agriculture through its enhancement of aquifer recharge (Gagin & Neumann 1981).

Brackish water provides a large and generally neglected water source. It is, however, of growing importance in some semi-arid regions as a result of the development of new techniques of irrigation application, soil-profile leaching and soil amendments. These permit a variety of tolerant crops to be grown, giving yields at levels similar to those obtained with non-saline water without salinization of either soil or aquifers (Shainberg & Oster 1978). Precise control of both the timing and volume of irrigation applications is necessary, but otherwise the techniques do not involve any great expense.

This is not so for the variety of water-treatment techniques now available. Employing these, a wide range of currently unusable water resources can be rendered applicable for irrigation. Such resources range from very brackish water, through industrial, urban and agricultural waste waters, to the sea itself. One reason for the expense of such treatments is their high-energy requirements. For sea water these range, with the desalination method and size of the plant, from 29–73 MJ m^{-3} (Stanhill 1981). Another important component of the cost is the expensive corrosion-resistant materials needed.

The high costs render treated water uneconomic for most irrigated crop production if the cost of treatment is met by the farmer. This, however, is often not the case with urban waste-water treatment and some successful and profitable systems of agriculture based on this source of water have been in operation for 100 years.

Climate change, desertification, and the agricultural water resource

As both water supply and demand in agriculture are determined by climate and are generally inversely correlated, the balance between them, which governs the size of the water resource and its effect on production, is sensitive to even small changes in climate.

The size of the random variation to be expected varies considerably. For total annual rainfall the coefficient of variation ranges between 10% in stable temperate climates and 30% in semi-arid regions. It is probably more than a coincidence that similar values of interannual variation were found in an analysis of the national average yields of wheat from two such regions after allowing for the effect of technological advances (Stanhill 1977). One important point that emerged from this analysis was that the effect of climatic variation on yield increased with technological improvements, refuting the view that such progress also serves to 'weatherproof' agriculture.

Although crop water demand, as represented by potential evapotranspiration, is a more conservative parameter than rainfall, its interannual variability is significant and should be included when assessing the variance to be expected in water balance. This is especially so because in a number of important agricultural regions, the season displaying high climatic variability often coincides with crop stages that are very sensitive to water balance. As an example of the relative variability of water demand and supply, the annual variance in evaporation at six sites in Britain, when taken with its covariance with rainfall, was found to average 23% of that in rainfall (Stanhill 1960).

Calculations of the variation in water supply and demand that can be expected in the coming decade assume that climate variation is both invariant in size and random in nature. Recently, both these assumptions have been disputed. The evidence, possible mechanisms and implications for food production of the possibility that the variability of the climate is increasing, and that non-random changes are occurring, have recently been reviewed (Lamb 1981).

The evidence for increasing variability is, however, by no means clear. For example, a study of the frequency of unusual conditions of rainfall, air temperature and pressure in England and Wales over the last century failed to show any evidence for such a trend for annual, seasonal, monthly or pentad periods (Ratcliffe *et al.* 1978). A similar conclusion was reached from an analysis of rainfall in the Sahel region (Bunting *et al.* 1976).

Whether constant or increasing, the size of random climate variation is sufficiently large to obscure the emergence of non-random changes of the magnitude expected before the end of this century. Nevertheless, the prospect of such a change is of immediate interest especially for irrigated agriculture. This is because of the rate of increase in the area under irrigation (which has averaged 3% per year over the last two decades), the cost of this development and the time-scales required both for their construction and over which they are designed to operate.

The prime cause of non-random changes in climate is currently thought to be the increasing CO_2 concentration of the atmosphere, now $1–2/10^6\ a^{-1}$ and expected to double its pre-industrial level of $270/10^6$ during the coming century (Clark *et al.* 1982). Half of the increase that has taken place to date can be attributed to agricultural expansion that releases the carbon stored in forests and grassland on their conversion to crop and pasture land.

The effects of this increase in CO_2 concentration on the water resource are multiple and their calculation requires information on the global carbon balance, atmospheric circulation and the long-term response of vegetation, which is in many cases not available. The direct, positive effects envisaged include a decrease in stomatal conductance and hence transpiration; when coupled with the increased rates of photosynthesis, dry-matter production and yield to be expected, this should increase water-use efficiency.

The indirect and largely negative effects that have been simulated to result from a doubling of CO_2 concentration include substantial changes in the pattern of rainfall distribution together with a global rise in air temperature that will increase water demand. It has been estimated (Kellogg 1984) that most cropland devoted to cereal production will be subject to a significant change in soil moisture conditions as a result of these climate changes. Approximately half of the areas of wheat, maize and barley are expected to be under a wetter régime and half will be subject to drier conditions. However, in the case of rice, the major irrigated crop, the largest areas of production, including all the areas in China and India, are expected to be wetter. Clearly, the possibility of these changes is of immediate relevance to irrigation planners; unfortunately, the reliability of these estimates is unknown.

One aspect of climate change, even at its present level, that is of particular agricultural significance, is the positive feedback of unfavourable anomalies in the water balance that may be generated when a hot dry spell occurs over a sufficiently large area and is coupled with a weak atmospheric circulation pattern. A simulation study of such a situation during midsummer in central Europe (Rowntree & Bolton 1983) indicated that dry soil conditions could persist for as long as 50 days and expand to include Scandinavia, Spain and north Africa in the drought area. Even under conditions of a strong, moist airflow, initial hot dry conditions maintained themselves for up to 20 days.

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Self-perpetuation of unfavourable water conditions could also be caused by land-use changes if these are on a sufficient scale and occur in seasons and areas where climate-forming processes are not robust. Changes such as deforestation and overgrazing and cropping lead to a decrease in transpiration and an increase in surface reflection of solar radiation, changing the surface energy balance.

It has been suggested that this bioclimatic reinforcement could be an important element in desertification, the process in which over-exploitation of the fragile ecosystems of semi-arid lands compounds the effects of climate change. The mechanism, first suggested by Charney (1975), is that over-exploitation during periods of less than average rainfall, reduces the surface cover of vegetation, bares the brighter underlying soil and reduces the radiation balance at the surface by increased short-wave reflection. The resulting increased subsidence of the overlying air column inhibits precipitation and the regrowth of vegetation cover.

On the basis of a review of the observational and theoretical studies Anthes (1984) has concluded that there is now considerable support for the hypothesis that convective rainfall in semi-arid regions is enhanced by increases in vegetation cover, especially when this is not homogeneous.

Even without such a bioclimatic reinforcement it is clear that the reduction of surface vegetation cover has an important negative effect on the water balance in areas susceptible to desertification. By reducing infiltration rates and increasing those of surface runoff, the proportion of the limited water resources that are available for productive transpiration is reduced.

One positive aspect of desertification is that, being largely a manmade process, it is also a reversible one. Many examples exist of agricultures successful for long periods in semi-arid regions that are now unproductive deserts. Systems such as the Nabatean runoff farming, developed in the Negev desert more than 1000 years ago, then supported cities with considerable populations. The fact that several such farms have been successfully restored to production under a highly variable rainfall régime which only averages 100 mm a^{-1} (Evenari *et al.* 1971), demonstrates the extent to which enterprise coupled with appropriate technology can extend the water resource in agriculture.

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Discussion

J. V. Lake (*Agricultural and Food Research Council, Letcombe Laboratory, Wantage, Oxon OX12 9JT*). Professor Stanhill mentioned that the coefficient of variation of annual wheat yield in Israel was the same as the coefficient of variation of rainfall in the growing season. However, when crops are abundantly supplied with water, solar radiation may become a dominant cause of yield variation. For example, Dr Bewley, Director of the (then) Cheshunt Experimental Station, showed that the annual yield of glasshouse tomatoes correlated closely with the number of sunshine hours during the growing season (more exact methods of measuring solar radiation were not then in ordinary use). The yields of glasshouse tomatoes have increased several fold since Dr Bewley's day; can Professor Stanhill or Dr Rudd-Jones, the present Director of the Glasshouse Crops Institute, say whether solar radiation is still a dominant factor in determining annual glasshouse crop production?

D. Rudd-Jones (*Glasshouse Crops Research Institute, Worthing Road, Littlehampton, West Sussex BN17 6LP*). I can confirm Dr Lake's comment that there is a direct and simple relation between intercepted solar radiation and yield in tomato crops, as was first recognized by Dr Bewley. However, the methods of environmental control used by most progressive glasshouse growers are now so sophisticated that the variability in yield for full season tomato crops is small and total yields are in excess of 150 t ha^{-1}. However the average yield taken over all holdings, including those with less sophisticated environmental control, is probably no more than half this figure.

May I also mention the energy requirements which relate to the exploitation of solar radiation in crops grown at different latitudes? Some years ago Professor Stanhill estimated that tomato production under glass in southern England required 40 times the gross energy input of a comparable crop in an unheated glasshouse in Israel, where hours of sunshine are more than double those in England from November to February and a third higher for the rest of the year. On mentioning this to Professor Stanhill, he reminded me that this difference in the energy requirements of production equates with the cost of transporting the tomatoes from Israel to the U.K., so that the British glasshouse grower can still maintain a competitive position in the market.

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