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Water Use Efficiency in Relation to Crop Production in Arid and Semi-arid Regions

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Abstract The major focus of present day agriculture has to be on increasing the efficiency of water use to achieve sustained production from finite water resources. Water use efficiency (WUE) as assessed by various disciplines has been explained, but is discussed mainly from agronomic point of view. Various empirical models on water use developed to explain the relationship of total dry matter production or marketable yield with evapotranspiration and transpiration have been reviewed. The importance of increasing WUE by manipulation of management practices such as fertilizers, plant population and row width, weed control, rain-water harvesting and conservation, tillage, irrigation methods, and improving plant characteristics has been emphasized. The role of mulches, antitranspirants and reflectants in reducing evapotranspiration to achieve higher WUE has also been evaluated. Management factors influencing crop water use have been assessed from the point of view of constraints and practicability in the field. The upper limit of WUE that should be targeted for optimum utilization of resources has been highlighted.

Key words Water use models, water use efficiency, evapotranspiration, grain crops, management practices, arid region, semi-arid region

Man has been concerned to some degree with the efficient use of water in the production of crops for centuries. However, analyses of the relationship between crop production and water use were recorded since 1699 only, when Woodward carried out his water culture studies relating the total dry matter production to transpiration of water. At that time the world housed roughly one seventh of its present population and the question of WUE was only a matter of scientific curiosity. Today, agriculture, faced with increasing competition for water and an increasing demand for its products, must become more efficient in its use of water. Thus, the understanding of crop yield - water relationships is a critical need for proper planning and operation of irrigation programmes.

Water Use Efficiency Defined

The term water use efficiency has been defined in various ways by hydrologists, physiologists and agronomists depending upon the emphasis that one wishes to place on certain aspects of the problem. As Sinclair *et al.* (1984) pointed out, this term "has been used interchangeably to refer to observations ranging from gas exchange by individual leaves for a few minutes to grain yield response to irrigation treatments through an entire season." Water use efficiency (WUE) in general, refers to the amount of plant material produced per unit of water used, and therefore, can be written as:

$$\text{WUE} = \frac{\text{Biomass accumulation}}{\text{Water used to produce biomass}} \qquad (1)$$

Both the numerator and denominator can be expressed in several ways. The numerator may be expressed as (a) carbon dioxide assimilation, (b) grain yield, (c) or total crop biomass (usually shoot biomass is recorded ignoring biomass of the root system). The denominator may be expressed as (a) transpiration (T), (b) Evapotranspiration (ET) or (c) total water input to the system. The time scale for defining the WUE may also range from a few seconds to crop season.

As stated earlier, WUE can be looked at from many levels. At leaf or plant level the WUE can be expressed as milligrams of CO_2 per gram of water or even as moles of CO_2 per mole of water (Fischer & Turner 1978). In such studies water used as transpiration alone is considered, and hence, the term transpiration efficiency is usually used in place of WUE. Transpiration can be measured in container studies. However, it is virtually impossible to make independent measurements of evaporation and transpiration under field conditions, therefore, WUE based on field data deal with the relationships of yield to total ET. The term WUE is most often used in this sense. For agronomic purposes it is often useful in water-limited environments to compare the WUEs of crops on the basis of grain yield or economic yield per unit of growing season rainfall (Turner 1986). For example, Bolton (1981) expressed WUE in relation to the rainfall within a fallow - barley crop rotation of two years duration.

The terms "evapotranspiration" (ET) and water use (WU) are generally considered to be identical, but in fact, term ET implies a loss of water which should be reduced to the lowest possible level in order to increase WUE. The term WU implies the beneficial utilization of water for economic yield.

The economist views WUE as the increase in economic return for the investment in water. The economic view of efficient water use is most easily recognized in irrigated agriculture of arid regions where water is scarce. Costs of water are minimized by improving irrigation techniques, reducing soil evaporation, increasing water recovery by the crop, etc. The return on the investment in water is maximized by the selection of the crop.

Another way that WUE can be defined is by calculating increase from irrigation (irrigated crop yield minus dryland crop yield) per unit of irrigation water. In this context, both limited irrigation and conjunctive use of rainfall and irrigation can contribute to major improvements in WUE.

In this review emphasis is given on agronomic view of yield obtained per unit of water use.

Water Use Models

The WUE can either be based on the ET (ET efficiency) or on the crop transpiration (T efficiency). The difference is important since suppression of soil evaporation and prevention of weed transpiration can improve the ET efficiency, however, it need not improve the T efficiency, which is a measure of crop performance. The WUE may also be based on the total dry matter production or the marketable yield. Different yield-water use relationships have been obtained by many workers using these parameters.

de Wit's Model

de Wit (1958) showed that for dry, high radiation climates, yield and transpiration were related as :

$$Y/T = m/T_{max} \tag{2}$$

where, Y = total dry matter mass per area

T = total transpiration per area during growth to harvest

T_{max} = mean daily water evaporation for the same period

de Wit used either pan data or Penman (1948) combination formula to estimate T_{max}. The constant 'm' is related to the WR/pan used by Kiesselbach and by Briggs & Shantz ($1/m \sim WR/pan$), but as de Wit showed, it is preferable for yield and water use analysis. de Wit showed that 'm' was governed mainly by species and was independent of soil nutrition and water availability unless nutrition was seriously limited or soil water was too high. He proposed that this relation should hold until T approached a maximum production governed by growing conditions. For humid regions where water was not limiting, fluctuations in intercepted radiation, although reflected in transpiration and growth, would not affect appreciably the ratio T/T_{max}. For these conditions he found that :

$$Y/T = n \tag{3}$$

where 'n' is a constant, gave a better description.

The value of 'm' in Eq.(2) can be approximated with Eq.(4) from WUE and mean daily pan evaporation (E_{pan}):

$$m = Y/T \; E_{pan} \qquad (4)$$

Arkely's model

Arkely (1963) opined that de Wit required two formulae because he used pan evaporation to normalise climate differences. Arkely proposed the relation :

$$Y/T = x/(1-RH) = xe^*/(e^* - e) \qquad (5)$$

where, 'x' is a constant
RH is the mean fractional relative humidity
'e' is the vapour pressure and
e* is the saturation vapour pressure at mean temperature

Bierhuizen and Slatyer Model

Bierhuizen & Slatyer (1965) used the description for net photosynthesis (N_L) and transpiration of leaf (T_L) to obtain leaf water use efficiency:

$$N_L/T_L \approx k'/(e^* - e) \; (\Sigma_r / \Sigma_{r'})$$
(6)

where, $k' = 0.80$ mbar
Σr = sum of vapour diffusion resistances for boundary and stomata ($r'_s = 1.56\, r_s$ and $r'_b = 1.34\, r_b$)

Assuming that $\Sigma e_r/\Sigma_{r'}$ remain relatively constant except under drought, and that on a field basis Y/T is proportional to N_L/T_L, they concluded:

$$Y/T \approx k/(e^* - e) \qquad (7)$$

Stewart Model

Stewart (1972) modified Eq.(2) to include the maximum production visualized by de Wit and to provide a single yield and water use relation using ET rather than T. In his model decrements yield below a Y_{max} are in proportion to decrements of ET below a corresponding ET_{max}. Stewart developed weightings to account for marketable yield rather than total dry matter and to account for differences in sensitivity to water deficits at different stages of crop development. When ET is used rather than transpiration, reliable correlations will depend on evaporation being either small or a relatively constant fraction of ET. With annual row crops in humid regions, soil evaporation (E), which depends strongly on precipitation patterns, is highly variable until leaf area index is about 2.5 to 3. This correlation between yield and ET for annual crops in humid regions would be poorer than with transpiration and would be better in semi-arid and arid regions.

Tanner and Sinclair Model

Tanner & Sinclair (1983) using mechanistic arguments suggested that 'k'is a very stable term in cropping systems. The theoretical equation arrived at for ET efficiency was

$$\int Y / \int ET \approx [k_d/(e^* - e)]\,[1 - E/ET] \qquad (8)$$

If cumulative Y of a crop is plotted against cumulative ET for a season, E may be approximated empirically as the intercept on the ET axis. This does not apply to a graph of seasonal Y vs seasonal ET using different field plots that have been differentially irrigated to provide different Y and ET, since E will differ between treatments. The 'k_d' is the daily transpiration efficiency calculated as per equation given by Tanner & Sinclair (1983).

Improving Water Use Efficiency

The examination of Eq.(1) would reveal that Y/ET can be improved, but as Viets (1962) suggested, it asymptotically approaches a constant. If yield is completely independent of ET, any factor which causes an increase of yield, or a decrease of ET, would have a favourable effect on WUE. If yield is proportional to ET, water use efficiency would be constant. Actually, the numerator and denominator of Eq.(1) are not independent of each other. Both Y and ET can be influenced, either independently or differentially, by crop management and environment. From the purely mathematical point of view increasing the denominator will decrease WUE; however, from the physiological point of view, it is essential to achieve an increase in the numerator, the yield.

Lemon (1969) surveyed actual water use efficiencies in modern day agricultural systems (Table 1). For calculations, he assumed that 60 per cent of solar energy is consumed in evapotranspiration. The best intensive farming results in conversion of 1 per cent of the solar radiation and produces 0.7 to 1.2 kg dry matter t^{-1} of water used. Subsistence farming may result in a solar energy fixation of 0.1 to 0.2 per cent and dry matter production of less than 0.2 kg t^{-1} of water consumed. Even in the best experimental circumstances and under excellent growing conditions, the best 1-day photosynthetic and water use efficiencies are only in the order of 2 to 4 per cent of the solar energy conversion and 2.4 to 4.8 kg dry matter t^{-1} of water used. Lemon (1969) opined that it is theoretically possible to fix 8 to 10 per cent of the solar radiation and to decrease water use so that as much as 9.6 to 12 kg of dry matter can be produced per ton of water use.

Table 1 *Photosynthetic and water use efficiencies in different farming systems (Lemon 1969)*

Farming system	Photosynthetic efficiency* (%)	Water use efficiency** (kg per ton water)
Subsistence farming		
Average	0.04 – 0.10	0.04 – 0.12
Best	0.08 – 0.20	0.10 – 0.24
Ranch farming		
Average	0.01 – 0.20	0.12 – 0.24
Best	0.20 – 0.40	0.24 – 0.48
Intensive farming		
Average	0.25 – 0.35	0.30 – 0.42
Best	0.60 – 1.00	0.72 – 1.20
Experimental		
Season	0.80 – 1.50	0.96 – 1.80
Weeks	1.5	1.8
days	2.00 – 4.00	2.40 – 4.80
Theoretical upper limit	8.00 – 10.00	9.60 – 12.00

* Incident solar energy base

** Assumed a 60 % conversion of solar energy to latent heat

It may be concluded that every effort should be made to increase the yield which can be manipulated by management practices such as use of fertilizers, appropriate plant populations, weed control, method of irrigation, improving plant characteristics, etc. On the other hand, the evapotranspiration should be reduced by use of mulches, antitranspirants, etc.

Fertilizers in relation to Y and ET

Viets (1962) explained six possible situations which may exist for evapotranspiration and yield and similar number of relations between WUE and yield. For these models it was presumed that water is not limiting for Y or ET and that fertilizer is applied in equal increments resulting in declining increments of yield. These models were : (A) ET and Y increase linearly and no ET when Y is zero, (B) ET and Y increase linearly and ET is appreciable when Y is zero, (C) ET is independent of Y, (D) ET is independent of Y after reasonably complete cover is attained, (E) ET decreases as Y increases and (F) ET increases faster than Y increases. Only two of these models (B and D) appear to exist in field. If fertilizer increases yield, ET either increases or remains the same. If ET increases (model B), then WUE is a decreasing increment function of yield and is asymptotic to a limit that has no physical significance. If ET is independent of yield (remains the same), then WUE increases linearly with the yield (model D). The important point is that if fertilizers increase yield they increase automatically the efficiency of consumptively used water. This applies particularly to dryland conditions where all the plant available water is usually used in ET by the end of the growing season. Shan *et al.* (1988) recorded 66 per cent variation in crop yields due to variation in soil fertility, and it was observed that improvement in soil fertility increased WUE. The consumptive use may or may not increase, depending on (a) the interaction of changed plant size, cover and height with available advected energy, and (b) the effect of changes in plant cover and colour on net radiation. Viets(1962) opined that fertilizer application to correct nutrient deficiency can bring about significant increase in yield accomplished by only small increase in water use. Application of nitrogen has been shown to increase the WUE of crops including mustard (Upasani & Sharma 1986, Reddy *et al.* 1988, Sharma & Kumar 1989a); pearl millet (Singh *et al.* 1985); wheat (Singh 1987, Heitholt 1989, Rea & Cale 1991); sunflower (Fredeen *et al.* 1991); potato (Khan *et al.* 1991); finger millet (Rao *et al.* 1991); cotton (Singh & Agarwal 1988) and canola (Taylor *et al.* 1991). Similarly, application of phosphorus (Hu *et al.* 1988, Khade *et al.* 1988, Reddy *et al.* 1988) and sulphur (Upasani & Sharma 1986) has been shown to increase the WUE of crops. When soil fertility limits the growth, application of fertilizer may stimulate plant growth, thus increasing leaf surface for photosynthesis, and increases root development. This may result in increased use of water for transpiration. However, the increase in canopy cover may reduce soil evaporation, particularly from wet surface soils. Thus, fertilizer application increases WUE without any appreciable increase in ET (Table 2). Shuvanova (1984) reported that application of NPK increased the grain yields of wheat and decreased the water consumption t^{-1} of grain. Prihar (1985) concluded that only those states of India have benefited most from increase in irrigated area where fertilizer use has also increased proportionately. Where soil moisture is limited, increased root growth due to fertilizer application can utilize water from deeper soil layers (Brown 1972, Weinzierl *et al.* 1985). If the plant can utilize some extra water from lower depths, the crop can endure drought for a longer period. Potassium has been shown to influence the transpiration rate. Brag (1972) reported that low potassium concentration in the nutrient solution during a long growth period produced plants with high transpiration rate. Short term solution culture experiments revealed that adding KCl to K deficient wheat plants decreased the transpiration rate up to 50 per cent within two hours due to changes in stomatal aperture. Similar effects were recorded with pea plants.

Yield-ET studies have shown that the total seasonal ET is about the same for a given crop and climate even though crop yields may be limited by other factors such as plant nutrients (Jensen 1990). Hence, crop can make best use of available moisture only if soil fertility is not a limiting factor. Improved soil fertility may not increase the transpiration efficiency as such (Walker & Richards 1985, Heitholt 1989), but consequent increase in crop growth increases the proportion of productively used moisture (T) in total ET.

Atmospheric CO_2 concentration and WUE

The global atmospheric CO_2 concentration is expected to double that of the pre-industrial era (about 270 ppm) in next 50 to 75 years. Experiments conducted with enriched CO_2 concentrations highlight the implications of such change, particularly with regard to crop production. Wittwer (1967) reviewed many studies in which the effects of carbon dioxide enrichment were tested on wide range of field crop leaves over short periods of time, generally with increased photosynthetic rate. In a field study on the influence of carbon dioxide enrichment, Happer *et al.* (1973) released CO_2 into a cotton field in Georgia at the rate of 222.6 kg ha^{-1} h^{-1}. The results of their study showed that CO_2 concentration remained at least 100 ppm greater in the upper canopy under release conditions

Table 2 *Influence of fertility and supplemental irrigation on grain yield, water use and WUE of pearl millet (Lahiri 1990)*

	Grain yield (q ha^{-1})			Water use (mm)			WUE (kg ha^{-1} mm^{-1})		
	HF*	LF	Mean	HF	LF	Mean	HF	LF	Mean
Irrigated**	16.6	11.6	14.1	280.2	270.8	275.5	5.9	4.3	5.1
Rainfed	8.1	5.6	6.9	204.6	201.2	202.9	3.6	2.4	3.0
Mean	12.4	8.6	–	242.3	236.0	–	4.7	3.4	–

* HF – 80 kg ha^{-1} of N and P_2O_5, LF – without fertilizer

** Irrigation of 63.1 mm once at 10 days after sowing early drought and concluded that the open canopy crop, which intercepted only 65 per cent of the incident radiation, frequently captured 23 per cent of the released CO_2. Dense crop canopies that intercept about 95 per cent of the incident light should capture about 33 per cent of the CO_2 released. Gifford (1979) observed that addition of 250 ppm CO_2 increased dry matter production and improved harvest index and WUE of two wheat cultivars. Jones *et al*. (1985) studied the effect of CO_2 concentration levels of 330 and 800 ppm on soybean crop. Increased CO_2 concentration significantly increased the dry matter production leading to 45 per cent increase in WUE. Kimball & Idso (1983), based on the analysis of 46 cases for 18 species grown under a doubled CO_2 concentration, reported an average reduction of transpiration by 34 per cent. Plant response to increased CO_2 concentration, therefore, may be in the form of increase in total biomass and yield or decrease in transpiration due to decreased stomatal conductance. These two responses would contribute to higher WUE. With such results and with the appropriate sources of gas available, carbon dioxide fertilization in fields, may some day, be economically feasible to achieve higher WUEs.

Plant population and row spacing

The number of plants required per unit area to achieve the highest yields will depend on the nature of the crop and on its environment. Maximum exploitation of the factors needed for growth is achieved only when the plant population exercises maximum pressure on all the production factors (Donald 1963). The number of plants cannot be too small, or all the production potential will not be fully utilized; nor can it be too large, or excessive plant competition will reduce the overall efficiency of the crop.

When crop depends largely on growing season precipitation, particularly when rain occurs at frequent intervals, or when frequent irrigation is required; high plant population and narrow row spacing is more desirable. Under such conditions, the crop canopy development will be fast, reducing direct exposure of soil surface to solar radiation. It will reduce evaporation from soil surface and thus, more water will be available for T component of ET resulting in higher WUE. Lenga (1986) and Pandey *et al.* (1988) recorded high WUE at high plant densities because the crop could make full use of available water. Steiner (1986) also proposed narrow row spacing to reduce the evaporation losses from dryland sorghum.

When crops are grown mainly on stored soil moisture, rapid canopy development can deplete the soil water reserve early in the season (Table 3). The crop may face severe water stress at later growth stages resulting in poor growth and reduced yields. Passioura (1983) showed that the harvest index of wheat was a function of the seasonal ET per cent that occurred after anthesis. Peries *et al.* (1989) observed that when available soil water was higher at anthesis and during grain filling of sorghum, WUE was higher in narrow rows; while with increasing soil water deficits and high evaporative demand after anthesis, WUE was higher in wider rows. Wider rows and less plant population is, therefore, more desirable when soil water reserve is limited. Low plant population on the other hand, may not be able to fully utilize the available soil water. Fulton (1970) reported that grain yield of corn was affected severely by water stress and that closer spacing of plants increased yield only when water was not limiting. Irrigation increased the yield and water used. The WUE was also increased by irrigation but the increase was more pronounced when plant density was high. The higher plant density resulted in greater ET but lowered yield in unirrigated conditions, while irrigation

Table 3 *Effect of row spacing on water use by pearl millet grown on stored soil moisture in the post-rainy season (Azam-Ali et al. 1984)*

Row spacing (cm)	Water use (mm)			
	16-29 days	29-43 days	43 days-harvest	16 days-harvest
38	56.6	41.3	5.1	103
75	43.2	53.4	33.4	130
100	27.9	29.4	65.7	123

caused a proportionately greater increase in yield than in evapotranspiration.

High plant population, coupled with reduced row width, is a prerequisite to obtain high yields in irrigated conditions. The best approach for dryland conditions, as also suggested by Stewart & Steiner (1990), seems to keep moderate plant population with moderate row width; which is likely to produce fairly good results except in extremely dry years or extremely wet years. For tillering crops, shifting balance towards lower population may be more advantageous because if conditions are favourable for crop growth during early stage, significant tillering will occur.

Weed control

Transpiration by non-crop plants is one of the major means by which soil water that could benefit crops is lost. Weeds frequently transpire greater amounts of water per unit of dry matter produced than do the crop plants. Grupce & Grupce (1987) reported that the water loss ha^{-1} d^{-1} was 4.42 mm for wheat and 4.61 mm for weeds at the dough stage of crop growth. Weeds may deplete the soil moisture reserve early in the season and the crop may face severe water stress at reproductive stage when grown on stored soil moisture. Greater water depletion was observed early in the season in plots containing devil's-claw (*Proboscidea louisianica*), whereas in plots containing only cotton the largest reduction in water content occurred later in the season during peak bloom and early boll formation (Riffle *et al.* 1990). Jana *et al.* (1989) found high water use in summer groundnut without weed control. Controlling weeds has been known to be one of the most effective means of increasing the amount of water available to the crops, and therefore, of increasing water use efficiency. It has been estimated that the amount of water saved by eliminating weeds in a maize field was equivalent to providing an entire irrigation at the time of maximum need (Mangelsdorf 1966). Tanji *et al.* (1987) indicated that weed competition reduced wheat yield due to soil moisture depletion, and controlling weeds increased WUE significantly.

Weeds not only increase the ET component of WUE but reduce the crop yields also. Weeds cause crop yield losses by competing for soil nutrients, moisture and sunlight; by necessitating the use of control measures which may themselves injure the crop; by interfering with harvesting and other operational techniques; and by hosting crop pests and diseases (Kock 1984). The extent of yield loss in rainy season crops can vary from 37 to 80 per cent (Friesen & Korwar 1982). Shelke & Bhosle (1990) from a five year study found 74 per cent average yield reduction in cotton due to weeds. Devil's-claw (*Proboscidea louisianica*) alone reduced cotton lint yield by as high as 96 per cent (Riffle *et al.* 1990).

The magnitude of crop losses due to weeds depends on type of crop and its variety, crop density, type and density of weed flora, productivity of the site, and time and duration of weed infestation. Crops and their varieties differ in susceptibility to weed competition. Fast growing crops and varieties may smother weeds early in the season. This competitiveness, however, depends on type of weed flora also. Rapeseed was found to be a stronger competitor for water than lamb's quarters (*Chenopodium album*) but wild mustard (*Sinapis arvensis*) was the strongest competitor; when rapeseed, wild mustard and lamb's quarters were grown in replacement series experiments (Blackshaw & Dekker 1988). Crop and weed densities play important role in determining crop competitiveness and yield losses. Wilson *et al.* (1990) observed the greatest competitive effects of wild oat (*Avena fatua*) at low barley and wheat densities. At average crop densities, low wild oat infestations resulted in cereal yield losses of approximately 1 per cent for each wild oat plant m^{-2}. Similarly, Liebl & Worsham (1987) found that wheat grain yields were reduced by an average of 4.2 per cent for every 10 Italian ryegrass (*Lolium multiflorum*) plants m^{-2} within the range of 0 to 100 weeds m^{-2}.

The time span during which weeds cause maximum yield losses (critical period) is very important. For most annual crops this period is 2 to 6 weeks after germination or transplanting, but it may vary depending on crops and their growing conditions. For example, Shelke & Bhosle

(1990) found that critical period for crop-weed competition in cotton was between 20 to 60 days after sowing. It is, therefore, important that the critical competitive period for crops and weeds must be known for each crop-weed association, and every effort should be made to control weeds at this time. Thus, control of weeds would help in increasing crop yields on one hand and reducing transpiration losses on the other and consequently increasing the WUE of crops. Verma & Srivastava (1989) recorded significant improvement in WUE of wheat by cultural and chemical control of weeds. Weeds can be controlled by adopting several methods, however, detailed discussion on this topic is out of scope of this article. Regnier & Janke (1989) discussed both traditional (crop rotation, use of competitive and/or allelopathic crop varieties and cover crops, and tillage) and more recent weed management practices (relay cropping, dead and living mulches, flame weeding and ridge tillage), as well as the use of classical biological control agents, mycoherbicides, and herbicides derived from natural compounds. The weed management programme should also consider methods of planting the crop, time of planting to minimize weed growth, water management in irrigated fields, spacing and seed rate of crops. The factors affecting decision on efficient weed control strategies were reviewed by Martin & Pannell (1990). They include weed density, weed competitiveness, weed seed carry over, crop yield potential, herbicide damage to crops and development of herbicide resistance. Wiese (1983) concluded that the most effective weed control is obtained by exploiting differences in the biological characteristics of crops and competing weeds.

In summary, weeds wastefully use soil moisture and reduce crop yields by competing with the crop for various growth factors; the strongest competition generally being for the most limiting factor. The magnitude of yield loss depends mainly on the competitiveness of crop and weed species, their densities and, time and duration of crop-weed competition. In general, weeds grow fast and are most damaging during the early stages of crop growth when crop is less competitive. Weed control by cultural, chemical and/or biological means is inevitable during this critical period of crop-weed competition for higher crop yields and WUE.

Water conservation and management

In rainfed agriculture water is usually the most limiting factor. Yield decreases linearly with a decrease in ET when soil water limits plant growth (Howell 1990). It is clear from Fig.1 that ET is considerable before any economic yield

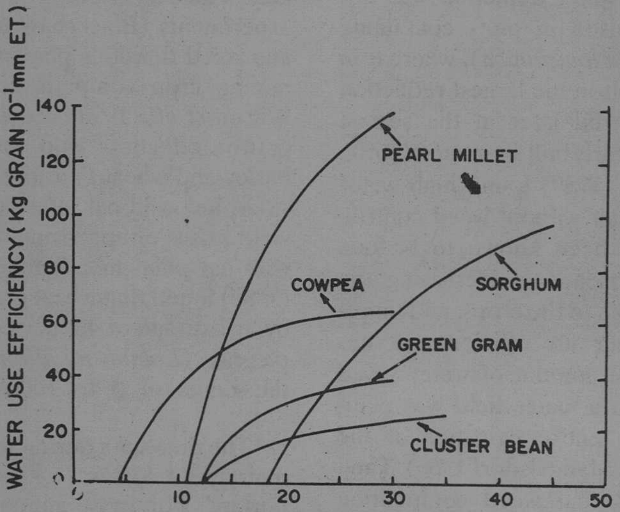

Fig 1 Relationship between WUE and seasonal ET as predicted by the yield-ET regression (Singh 1988c)

is produced (intercept on x-axis), and then yield increases with further increase in ET resulting in over all increase in WUE. Lahiri (1980) reported linear relationship between WUE of pearl millet and seasonal rainfall above a threshold value of about 70 mm. Pandey *et al.* (1987) observed that biological productivity of seven C_3 crops was linearly related to ET. The WUE of mustard was found to increase with increase in soil moisture content in upper 1 m profile (Singh 1984), and each extra 1 mm water increased seed yield by 14.7 to 38.1 kg ha^{-1}.

Rainfed crops meet their ET requirement from the precipitation retained in the root zone. Loss of water from the system other than by crop ET or reduced component of T to total crop ET will lower rainfall-use efficiency. El-Swaify *et al.* (1985) recorded water balance data for traditional cropping systems for vertisols and alfisols. In both cases, more than 25 per cent of rainfall was lost as runoff and only about 40 per cent was used for ET during the growing season. An improved management system developed by them allowed both rainy and post rainy season cropping, thereby dramatically increasing the seasonal WUE. All the practices that will result in increased retention of precipitation in root zone, reduce evaporation losses from soil, reduce moisture use by non-crop plants, and increase ratio of T to total ET will invariably result in increased utilization of precipitation for crop production and, therefore, increase in WUE.

When rainfall rates and amounts exceed the infiltration rate and water holding capacity of the root zone, runoff occurs. Soil and water conservation practices such as land levelling and grading, furrow diking, contour tillage and terracing can be used to increase surface storage, reduce slope gradient and/or length, and conduct water from fields at non-erosive velocities (Unger *et al.* 1988). Practices such as deep ploughing, para-ploughing, vertical mulching and maintenance of stubbles on soil surface can increase the infiltration rate. Deep tillage and profile modification have beneficial effect for several years (Eck 1986). Deep tillage increases plant rooting by reducing soil mechanical resistance even in soils with no high density layers (Chaudhary *et al.* 1985). Practices like broad bed furrow, vertical mulching, and contour sowing improved the WUE of sorghum (Kalane *et al.* 1990).

Contrary to the conventional tillage practices adopted to increase the soil water recharge, zero tillage has been reported to be more effective (Greverse *et al.* 1986). Under zero tillage, Greverse *et al.* (1986) recorded WUE of wheat ranging from 53.7 to 186 kg wheat grain ha^{-1} cm^{-1} depending on soil texture, whereas WUE under conventional tillage was 49.7 kg grain ha^{-1} cm^{-1}. Zeljkovich *et al.* (1988) recorded no beneficial effect of higher soil water content under zero tillage on wheat yields but it increased the yield and WUE of soybean grown immediately after wheat. They, however, found zero tillage practice beneficial only in low rainfall years, while conventional tillage resulted in overall higher yields of wheat and soybeans. When substantial amount of stubbles is maintained on the soil surface under zero tillage practice, it seems to increase infiltration, reduce evaporation losses and thus increase soil water content (Greverse *et al.* 1986). Where adequate stubble mulch is not maintained, conventional tillage practices give better results. Rao & Agarwal (1985), Rao *et al.* (1986) and Verma & Srivastava (1989) found the conventional tillage to be more beneficial than zero tillage.

Low water holding capacity of soils, particularly in sandy soils, may result in loss of water below the root zone by deep percolation. Water holding capacity of soils can be improved by addition of organic matter thereby increasing the yield and WUE of crops (Cisse & Vachaud 1988, Hu *et al.* 1988). Use of Jalshakti (a polymer) has also been reported to improve WUE (Prakash *et al.* 1991). Deep percolation from light soils can also be reduced by installing a bituminous or other impermeable layer below the root zone (Robertson *et al.* 1973). However, this practice can be adopted on a small scale and for production of high value crops only.

Water harvesting can be a useful practice where rainfall is low. Runoff can be allowed from higher slopes onto the terraced lower sides in hilly areas (Evenari *et al.* 1968). In plains, water harvesting system that uses a portion of the land as catchment to harvest runoff and divert it to adjacent crop area can prove beneficial. Numerous catchment construction materials have been used for increasing the runoff. Compacted earth catchment is the cheapest one but its runoff yields are poor. On the other hand, catchments treated with paraffin wax, silicon, butyl rubber, plastic and sheet metal can produce nearly 100 per cent runoff (Cooley *et al.* 1975), but are very expensive. In arid situation, Singh (1988a) treated the catchment with pond sediment and recorded that from 0.5 catchment to crop area ratio, each ha of crop area received 140 to 636 mm of rainwater, while the rainfall received was 117 to 528 mm in different years. In this case average runoff efficiency was 66 per cent. As a result, 3717 kg of pearl millet grain ha^{-1} was obtained with only 69 per cent of normal rainfall (Singh 1988b). In areas where runoff is inevitable due to high intensity rainfall, or is desirable to avoid water logging, the runoff water if collected in ponds, can be used to give supplemental irrigation.

The WUE is very sensitive to changes in soil water potential during the growing season (Craciun & Sommer 1986). Application of irrigation water when soil water potential is low increases crop yield, but simultaneously increases crop ET as well. The WUE, therefore, may increase with irrigation, if the increase in yield is substantial compared to increase in ET (Singh *et al.* 1986, Chavan & Pawar 1987, Sharma *et al.* 1987, Al-Janabi 1988, Sharma & Kumar 1989b); or WUE may first increase and then decline with increased levels of irrigation (Singh *et al.* 1987b, Alexander *et al.* 1988) or it may decrease with increased levels of irrigation (Khan & Agarwal 1985, Malik *et al.* 1985, Kumar *et al.* 1986, Chaudhary *et al.* 1988, Reddy *et al.* 1988, Roth *et al.* 1988b, Chavan *et al.* 1989). Hunsaker & Bucks (1987) observed that the optimum level of seasonal gross water applied for maximum wheat yields was 7 per cent higher than that required for maximum WUE. They recommended that with a heterogeneous soil and on efficient basin irrigation system, scheduling irrigation near full ET requirements was desirable for obtaining high wheat yields and maximum WUE.

Frequent irrigations, though sometimes necessary for yield maximization, usually lower WUE (Khade *et al.* 1986, Malavia *et al.* 1987, Singh *et al.* 1988a) because moist surface soil results in increased loss of soil moisture through evaporation. Irrigation depths can be increased to reduce irrigation frequency. Less frequent irrigations (with more water per irrigation) increase WUE without any conspicuous reduction in crop yields (Singh 1987, Singh *et al.* 1987a). Sandhu *et al.* (1984) observed that grain yield and WUE were higher with the two 9 cm irrigations applied at ID:CPE ratio of 0.75 than with three 6 cm irrigations applied at 0.6 ratio, when wheat was grown with 30 cm irrigation water, 12 cm of which was applied as pre-sowing irrigation. However, too heavy irrigations, particularly in light textured soils, may result in loss of water through deep percolation. Secondly, if available water in root zone depletes too low between two irrigations such that crop faces water stress, it may adversely affect the yield and WUE. Mild water stress did not significantly affect WUE of wheat but a more severe water stress, especially under sub-optimal water supply considerably decreased the WUE (Heitholt 1989).

The time of water stress is also an important factor. Substantial reductions in yield due to plant water stress at critical growth stages may occur even though the total amount of water delivered during the cropping season may be adequate (Jensen *et al.* 1990). Howell & Hiler (1975) observed that linear regression with ET explained only 41 per cent variability in sorghum yield. When yield was regressed with ET during three growth periods, viz., late vegetative to early boot, boot to bloom, and milk to soft dough; the coefficient of determination increased to 93 per cent. Booting to bloom stage was the most sensitive to water stress. Similarly, the greatest adverse effect of water stress on yield and WUE of wheat was observed during jointing and flowering stage (Singh *et al.* 1986), whereas, Tripathi *et al.* (1989) found the crown root initiation stage to be the most critical stage in wheat. If only limited irrigations are available, irrigations at critical growth stages can give maximum yield per unit of water applied. Malik *et al.* (1985) recorded the highest grain yield of wheat with irrigations at crowning and flowering. Irrigation scheduling on the basis of soil moisture tension may give the poorest result under such conditions (Prasad *et al.* 1989).

Several methods of irrigation, from flood irrigation to drip irrigation are used depending upon the other governing factors. Most studies to date confirm that the irrigation method does not significantly change the seasonal ET of the crop where the objective is to maximize yield per unit land area. The change in water requirement with different methods under sufficiency conditions is due to change in irrigation application efficiency. The irrigation application efficiency of drip irrigation system is high because runoff and deep percolation losses are reduced. Irrigation application efficiencies for drip system may be around 90 per cent, for sprinkler system about 60 to 90 per cent, whereas, for surface irrigation systems, it may be around 60 per cent only. Since irrigation methods differ in their application efficiencies, these also differ in the magnitude of irrigation water use efficiencies. Singh *et al.* (1978) reported that drip irrigation was capable of providing the same yield of potatoes with half the water needed for furrow irrigation. Hiler & Howell (1973) reported higher water use efficiencies for trickle irrigation than for other irrigation methods. Sammis (1980) also obtained higher WUEs for potatoes with trickle than with sprinkler and furrow irrigation. Subsurface irrigation may also give high WUE. Shih (1988) found the subsurface irrigation system to give higher WUE compared with micro irrigation in sugarcane. Sepaskhah *et al.* (1976) reported more than two fold increase in WUE of beans with subsurface irrigation compared with furrow irrigation method.

In summary, a significant amount of soil moisture is lost in ET before any economic yield is produced. After this threshold value of ET yield increases almost linearly with increase in ET, giving increased WUEs. To conserve rainwater in dryland conditions to meet this ET demand, surface runoff can be minimised by land levelling and grading, terracing, contour tillage, etc., and infiltration can be increased by deep ploughing, para ploughing, mulching, etc. Tillage practices designed to maximise infiltration tend to produce soil conditions conducive to evaporation, so a balanced approach is necessary. Sweep tillage, a minimum tillage practice, however reduces evaporation because plant residues are left on the surface acting as mulch. Low water holding capacity of light textured soils can be improved by incorporating organic matter or hydrophilic polymers. Impermeable layers like that of bitumin can be installed to reduce deep percolation. Alternatively, extra water from heavy showers may be collected in ponds for future needs. Water harvesting practices, particularly in arid regions, increase the chances of crop survival and of obtaining fairly good results. Excessive water application may be avoided by conjunctive use of rainfall and irrigation. Irrigations may be scheduled in such a way that the most sensitive crop growth periods coincide with minimum water deficit whereas moderate water deficit during relatively insensitive periods can be tolerated. Although highly efficient irrigation methods like subsurface and drip irrigation systems are available, their choice is governed by several other factors as well.

Improving Plant Characteristics

The ultimate yield of a crop is determined by the interaction of its genetic characteristics with the environment in which it is grown and to management practices to which it is subjected. The first choice should be for high yield potential with low water requirement. Crop species differ widely in their efficiency of dry matter production and water use (Rao & Agarwal 1985, Rao *et al.* 1986, Dhole *et al.* 1987, Pandey *et al.* 1987, Joshi 1988, Patil 1988, Roth *et al.* 1988a, Singh *et al.* 1988c). The WUE of crops like maize, sorghum, pearl millet and sugarcane is high while in crops like greengram, soybean, peas, lentil, etc., it is low. The carbon metabolism pathway of plants has a marked influence on their transpiration efficiency. Plants exhibiting crassulacean acid metabolism (CAM) open their stomates at night and fix CO_2 in malic acid, which is then assimilated during the day by C_3 pathway while stomates remain closed. The closed stomates during the day time reduce transpiration to almost negligible level. The transpiration efficiency of C_4 crops is also almost two fold higher than that of C_3 crops (Downes 1969, Tanner & Sinclair 1983, Pandey *et al.* 1987). Stanhill (1986) opined that higher transpiration efficiency found in C_4 plants could be attributed to their ability to continue photosynthesis at CO_2 concentrations which are one third to one fifteenth of those recorded to sustain the process in C_3 plants. This results in increased CO_2 uptake by C_4 plants due to higher gradient of CO_2 without corresponding increase in water vapour losses.

The transfer of CAM or C_4 pathways to C_3 species, if possible, holds promise for considerable improvement in their WUE. However, the problem with conventional breeding methods is that the first generation hybrids between different species are not fertile. Though some success has been achieved in development of fertile hybrids between C_3 and intermediate C_3-C_4 species (Brown *et al.* 1985) yet none of them is crop species. Another approach to transfer the carbon metabolism pathway can be through genetic engineering. Traits controlled by a few genes (preferably one) like herbicide resistance, insect resistance, etc. have been successfully transferred from plant or animal species to the crop plants (Gasser & Fraley 1989, Oxtoby & Hughes 1989). However, the transfer of CAM or C_4 pathway to C_3 species involving the identification, cloning and transfer of large number of genes, seems to be a formidable task with the existing level of technology.

Variations in WUE occur not only among different species but also among varieties of crops like clusterbean (Stafford 1987), mustard (Singh *et al.* 1988b), pearl millet (Nimbalkar *et al.* 1985), pigeonpea (Bhute *et al.* 1990), cowpea (Hall *et al.* 1992) and soybean (Nigam *et al.* 1989). Plants do not use water with the same efficiency throughout their life cycle, and differences in WUE exist between different growth stages of the same crop (Joshi 1988, Roth *et al.* 1988a) and even among different leaves of the same plant (Wullschleger & Oosterkuis 1989). Efficiency of water use by a cultivar depends on the growing conditions. Rao *et al.* (1986) observed variations in WUE from 81 to 156 kg ha^{-1} cm^{-1} for barley and mustard, and from 46 to 95 kg ha^{-1} cm^{-1} for chickpeas under different management conditions. The variety that gives higher WUE under rainfed conditions may be surpassed by another variety under irrigated conditions (Chaudhary *et al.* 1988, Chitanwis *et al.* 1989, Sharma & Kumar 1989b). Therefore, the crop selection in terms of both species and cultivar, should be based on their suitability to growing conditions.

The varietal differences in WUE may be due to their genetic build up that affects both morphological traits controlling the rate of transpiration and water absorption by roots from the soil profile, and the physiological functions responsible for photosynthesis, respiration, translocation and storage of photosynthates to economically harvested plant parts. Plant breeders since long, have been attempting to evolve better adapted and high yielding varieties. As a result of their efforts a large number of improved high yielding varieties and hybrids of different crops having better WUE are now available for cultivation (Jensen 1987). Siddique *et al.* (1990) attributed the improved WUE in modern wheat cultivars to their faster development, earlier flowering, improved canopy structure and higher harvest index. Donald & Hamblin (1976) and Gifford & Evans (1981) attributed yield improvement of modern cultivars mainly to the better partitioning of dry matter production towards economic yield, rather than to increase in dry matter production as such. Heichel (1983) also opined that the most significant gains from plant breeding in the relatively short time will likely continue to be in increasing harvest index.

In the past, breeding for increased WUE (transpiration efficiency) has been limited by lack of screening criteria and methods that can identify desirable genotypes. Moss *et al.* (1974) suggested association of plant physiologist for identifying various traits for more efficient water use. They listed several factors controlling water use which may be amenable to genetic regulations. However, it will be more desirable if in place of multiple physiological selection criteria, a single character can be identified and incorporated into the breeding programme. Passioura (1972) observed that when the crops have to exist on stored moisture, increasing the hydraulic resistance of roots increases yield by conserving more of soil water for use after anthesis. Ismail & Hall (1992) indicated that variation in WUE among several

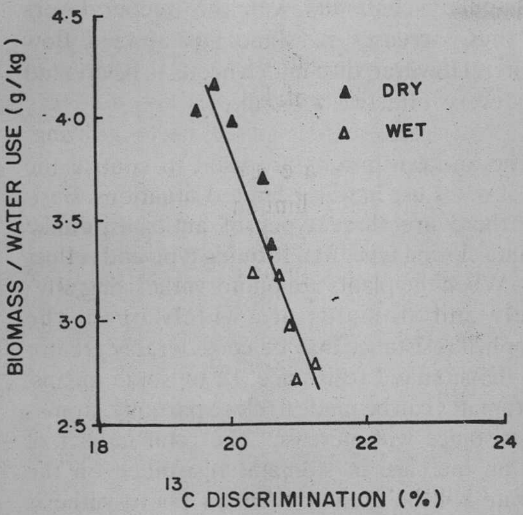

Fig 2 Correlation between C-isotope discrimination (δ) and water use efficiency (Ismail & Hall 1992)

C_3 species can be detected by measuring ^{13}C discrimination (δ) by leaves. They recorded a very highly significant negative correlation ($r = -0.93$, $P = < 0.001$) between WUE and δ (Fig. 2). The physiological basis for the genotypic differences in WUE and δ were not elucidated but it was shown that they were not necessarily due to differences in earliness or vegetative vigour. Similar genotypic association between WUE and δ have been reported for several C_3 species including wheat (Farquhar & Richards 1984, Turner *et al.* 1989), barley (Hubick & Farquhar 1989), sunflower (Virgona *et al.* 1990), peanut (Hubick *et al.* 1986), and cotton (Turner *et al.* 1989). Recently, Walker & Lance (1991) observed that Si accumulation in barley DM correlated well with ^{13}C discrimination in field conditions. They concluded that Si content could be used as a corroborative indicator of WUE in normal field condition.

To sum up, improvement of photosynthetic rates for high biomass production can improve transpiration efficiency. If C_4 CO_2-fixation pathway could be transferred to less efficient C_3 species, the transpiration efficiency of these plants would be improved. This may become possible in future with major development in techniques like genetic engineering. Plant breeding programmes can make use of some morphological traits like glaucousness, erect leaf posture, small leaf size, etc. Selection for high harvest index can be another approach for high transpiration efficiency. The relationship between WUE and ^{13}C isotope discrimination or silicon content may also be used as a criterion in breeding programme.

Reducing Evapotranspiration

Water retained in soil is lost through the combined process of evaporation from soil and transpiration from plants. Reducing this loss would be important for both decreasing crop water requirement and, under certain environmental conditions, for alleviation of water stress. One of the common practices to reduce evaporation from soil is the use of mulches. Maintaining a crop residue mulch on soil surface may also increase soil water content by reducing runoff and increasing infiltration rate due to reduced soil dispersion and surface sealing. Mulches reduce evaporation by reflecting part of the incoming solar radiation that otherwise would be absorbed as heat; by acting as a thermal insulator and thus restricting the flow of heat from atmosphere to soil; and by increasing the thickness of still air layer above the soil surface that increases the resistance to vapour transfer from soil surface to atmosphere.

From long term field experiments in Great Plains, U.S.A., Greb (1983) found that the increase in soil water content was significant with the use of mulches in the range of 2.2 to 6.6 t ha^{-1}. The water storage per ton of mulch however, decreased from 10.0 mm t^{-1} ha^{-1} to 7.7 mm t^{-1} ha^{-1} when mulch rate was increased from 2.2 to 6.6 t ha^{-1}. On an average each t ha^{-1} of crop residue saved about 9 mm of water from evaporation, and increased wheat yields by 54 to 144 kg ha^{-1} at different locations. Similarly, Unger (1978) placed 0, 1, 2, 4, 8, and 12 t ha^{-1} of wheat straw and recorded the fallow-season precipitation storage efficiency of 23, 31, 31, 37, 44 and 46 per cent, respectively. The grain yields of sorghum planted after the fallow period were more than doubled with 8 and 12 t ha^{-1} mulch as compared with no mulching. Maesschalck *et al.* (1985) recorded upto 90 per cent increase in the yields of maize, greengram, cowpea, chillies and *Paspalum motatum* with the use of mulches. Pandey *et al.* (1988) also recorded an increase in grain yield of pearl millet from 1.83 to 2.34 t ha^{-1} and in WUE from 5.45 to 7.45 kg grain ha^{-1} mm^{-1} over control with 5 t ha^{-1} of straw mulch.

Since residue mulches reduce evaporation from the wet soil surfaces, these are most effective during the rainy season when evaporation rate is high from bare soil surface. Slowing the evaporation rate in these conditions favours deeper soil moisture penetration. At the end of rainy season (or after irrigation) when drying starts the rate of water loss from a residue covered soil is higher (Fig. 3) because the surface soil remains wet for much longer period; thus over a longer period, cumulative water loss may be almost equal in mulched and bare soils.

The non availability of straw is a major problem particularly in developing countries where it is used to feed cattle, and usually the use of mulches is uneconomical. Gregory (1989) opined that the cost of labour and of nitrogen fertilizer needed to overcome immobilization might make this technique unprofitable for anything other than kitchen-garden plots.

Evaporation can also be reduced by creating dust mulch on soil surface. Shallow tillage disrupts the capillary continuity with the deeper layers and thus increases resistance to upward flow of water. However, dust mulch needs to be created after every effective rainfall.

The antitranspirants are used to control the rate of water use in water-limited situations. Basically there are three types of antitranspirants; stomata closing type, film forming type and reflectants. When the plants are photosynthesizing effectively and stomates are widely open, the mesophyll resistance may be considerably greater than the stomatal resistance. If, by some means, the stomates can be made to close partially, stomatal resistance will increase. The total impact of such an increase in stomatal resistance on the ET rate will be greater than on photosynthesis rate because the total diffusion pathway to water is less than that of CO_2 which has an additional liquid phase resistance upto the chloroplast. Therefore, any increase in stomatal, cuticular and boundary layer resistances is likely to reduce transpiration more than carbon exchange (Stanhill 1986). Thus WUE can be increased. This concept has been elaborated by Zelitch & Waggoner (1962) and Waggoner *et al.* (1964). Atrazine, Abscisic acid (ABA), Phenyl mercuric acetate (PMA), Dodecnyl succinic acid (DSA), Methyl-ester of Noenyl succinic acid (NSA), Glyceryl half ester of Decenyl succinic acid (GLOSA), etc. have been used as antitranspirants in green

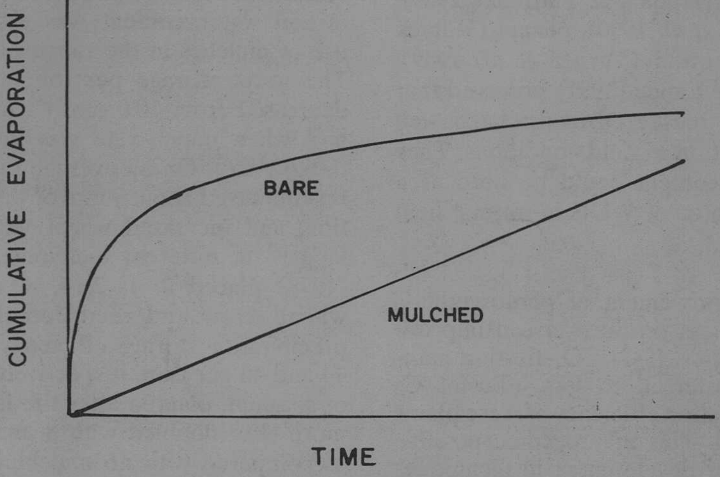

Fig 3 Schematic diagram showing cumulative evaporation over time from bare and a mulched soil

houses and fields as well. Many of them have shown toxic effects to plants, and results of field studies have not been particularly encouraging. Fulvic acid applied to wheat plants as a 0.05 or 0.1 per cent spray, although reduced stomatal conductance by as much as 55 per cent in particular studies, the results were neither consistent nor predictable (Dunstone *et al.* 1988). Stark & Dwelle (1989), however, recorded consistently higher WUE of potato with the use of an experimental antitranspirant EXP-4464A. The reasons for lack of effectiveness of this technique in field remain speculative at this time.

The second approach to transpiration reduction is use of film forming substances. Films such as emulsions of latex, polyvinyl waxes, polyethylene, and higher alcohols such as hexadecanol have been applied with varying results. The film materials, however, have greater permeability to water molecules than to carbon dioxide and, therefore, seriously reduce WUE. Secondly, they are of limited usefulness on growing plants because repeated applications are required to cover new leaf surface.

The reflectant materials that reduce energy load on leaf may be considered to be more promising antitranspirants. In case where leaves are treated, the effect of increased reflectivity, should be a decrease in net radiation. Evapotranspiration and sensible heat flux generation should be reduced, but photosynthesis should not be directly affected unless the availability of photosynthetically active radiation becomes critical as it well might be with certain types of crops. Barring this effect, the net result of reflectant application should be an improvement in water use efficiency. The crops that are light unsaturated under their normal growing conditions (corn, sorghum, sugarcane, etc.), the application of materials that reflect away visible radiation may reduce both photosynthesis and evapotranspiration. Since most common reflectants such as kaolinite, diatomaceous earths, aluminium silicates, etc. reflect most effectively in the visible wave band, the practice seems most applicable to crops that are light saturated in their regions of adoption. Khade *et al.* (1989) observed that kaolin application increased the WUE of sunflower at different irrigation levels. Giri & Singh (1984) observed that 36.0 mm water was saved in wheat crop due to application of kaolin and net returns increased by about 30 per cent. Even in light saturated crops use of reflectants may be useful when applied at critical growth stages. Moreshet *et al.* (1977) found that though net photosynthesis in sorghum was reduced by 23 per cent (solar radiation by 26 per cent) immediately after application of a kaolinite coating, yet grain yield increased consistently due to the treatment. They attributed this result to specific beneficial physiological effects at the time of panicle initiation and to early senescence in the treated plants that hastened translocation to the developing grain. Similarly, Pandey *et al.* (1988) recorded that 6 per cent spray of kaolin increased the WUE of pearl millet from 5.45 to 6.55 kg grain ha^{-1} mm^{-1} of water used.

Aboukhaled *et al.* (1970) analysed changes in spectral reflectivity of bean plants treated with various reflectant materials. They demonstrated that short-wave albedo could be effectively increased and transpiration reduced. The application of kaolinite to the leaves of rubber and bean plants increased short-wave albedo (400-700 nm) from about 10 per cent to 65 per cent. A smaller but significant increase in reflectivity in the near infrared was also noted. Doraiswamy & Rosenberg (1974) reported increased reflection in visible wave band (380-750 nm) in soybeans applied at a rate of 196 kg ha^{-1}. They, however, did not find major difference in the near infrared reflection. Seginer (1969), while studying theoretical aspects of the effect of non selective reflective materials on canopy transpiration, found that about 30 per cent of saving in irrigation water could be attained when natural albedo was increased from 0.25 to 0.4 of the incident short-wave radiation.

Mulching, particularly stubble mulch, increases precipitation storage efficiency and reduces soil evaporation. Contribution of mulches in soil evaporation reduction is most significant when rains are frequent or when frequent irrigations are given. Although the successful use of antitranspirants has been reported in literature, the results are inconsistent. Reflectants can be used effectively if crop canopy is light saturated. However, reflectants and film forming substances present difficult problems in canopy coverage, particularly when crop growth is fast. Stomata closing agents may be more useful because smaller amounts of material are needed and often do not need complete coverage. Antitranspirants may judiciously be used to reduce water stress effects at critical crop growth stages or in high value crops because their frequent use in field crops is generally economically unviable.

Limitations in Increasing WUE

The crop yield is an important determinant of how efficiently water is used. We had an objective to develop efficient and high yielding varieties of crops. An enormous effort has been expended on this objective. Impressive results have been achieved in a few crops only. For major crops high yielding varieties are yet to come which should have high response to applied fertilizers and should efficiently use the other inputs including water. The quantum jump with respect to all these is yet to come. The varieties should also be pest and disease resistant which indirectly influence the WUE. The use of trickle or drip irrigation though saves considerable quantities of irrigation water and gives higher WUE under limited water supply conditions also has some limitations of use. Some important possible disadvantages of trickle irrigation compared to other irrigation methods include (1) emitter clogging, (2) rodent and other animal damage, (3) salt accumulation near the plants, (4) inadequate soil water movement and plant root development, and (5) economical and technical limitations (Bucks *et al.* 1982). The weed control is also required to reduce loss of water through transpiration. The methods of completely controlling weeds are tedious and may be uneconomical. It is estimated that if only 1 per cent of a typical stand of weeds survives control methods, it is capable of producing over 100 million new weed seeds ha^{-1} (Day 1966). A whole array of new techniques and chemicals has supplied the farmer with means for selective control of weeds in most crops yet with their own limitations. The problem of persistence of herbicides in the soil giving detrimental residual effects and soil environmental pollution needs consideration.

Numerous antitranspirants and reflectants have been suggested for reducing transpiration losses. For antitranspirants of film forming type the problem is to have a material having selective permeability, i.e., higher permeability for CO_2 than for water. There appears to be little chance of finding a normal polymer substance through which gases pass by diffusion that will meet this requirement. This is because the solubilities and coefficients of diffusion of gases and vapour in polymer films are inversely proportional to their molecular weights and dimensions. The H_20 molecule is therefore basically more mobile than that of CO_2 (Poljakoff-Mayber & Gale 1972). The problem with antitranspirants of stomata closing type is to obtain nontoxic materials which only affect the stomata, and are long lasting. Similarly the reflectants should also be nontoxic, must stick and spread evenly on leaf surfaces. They should be sufficiently permeable to gases so as not to interfere with photosynthesis and respiration. The most desired reflectants for light saturated plants are of the kind which reflect above 0.7 μ and transmit below this wave length and such types, which could be suitable for field conditions, do not appear to exist at present.

Above all, we have to decide whether maximum WUE or minimum water requirement should be our goal ? Viets (1962) opined that the maximum WUE is contingent on maximum yield under a given situation with respect to water supply. This is true whether ET is increased or not. However, the cost of practices necessary to achieve these higher yields must be related to their marginal returns in monetary terms. Thus, the most profitable agriculture must stop short of maximum production to have an optimum level. As yield stops short of this maximum production, so must water use efficiency.

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