Enhancing crop water productivity to ameliorate groundwater decline

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Increased use of fresh water supplies in agricultural and non-agricultural activities in the past few decades has caused an alarming rate of groundwater depletion in many regions of the world. This threatens the sustenance of crop production and the ensuing food security. There is an urgency to look for measures that sustain current levels of crop yields with reduction in soil water evaporation component of hydrological balance during cropped and non-cropped periods. This article gives an overview of management interventions at field scale to enhance water productivity in cropping systems perspective that would help to ameliorate groundwater decline.

Keywords: Cropping system, evaporation, evapo transpiration, groundwater depletion, management interventions, water productivity.

WATER is essential for agricultural production. The water needs of crop are fulfilled by water stored in the soil through precipitation received at the surface or applied as supplemental irrigation. Precipitation and snow melts are the only sources of fresh water that is stored in above-ground reservoirs or groundwater aquifers below the surface. More than 80–90% of the stored water is used for agricultural production. In humid areas, rainfall distribution is such that there is no need for additional water application. In arid and semi-arid areas, where crop failures occur due to water deficiency, farmers resort to supplemental irrigation. Earlier, crops were irrigated by water stored in tanks and reservoirs, which was conveyed to the fields by canals. With advances in withdrawal technology and growing demand, groundwater is being increasingly exploited for irrigation and other human needs. Globally, groundwater use has increased manifold during the last 50 years. For example, in the US, groundwater share in irrigation increased from 23% in 1950 to 42% in 2000. In the Indian subcontinent, groundwater use soared from 10–20 km^3 before 1950 to 240–260 km^3 by the turn of the century. In many areas of the world, the groundwater has been overexploited, i.e. annual loss of water from the aquifer exceeds its recharge. A report on groundwater use in India pointed that out of 5723 geophysical blocks in the country, 1000 were overexploited[1]. The contours of groundwater level in January 2007 (Figure 1) indicate the extent of groundwater mining. A recent study[2] revealed that in the Indo-Gangetic plain region, comprising Delhi and the contiguous three states, groundwater level fell by 4 cm per year between 2002 and 2008 equivalent to about 25 cm drop in aquifer level.

The Indo-Gangetic plains, known for its green revolution, is a glaring example of overmining of groundwater. A number of factors triggered the processes conducive to spectacular increase in production. Seeds of high yielding varieties responsive to high rates of fertilizers and irrigation became available. About the same time, farm power

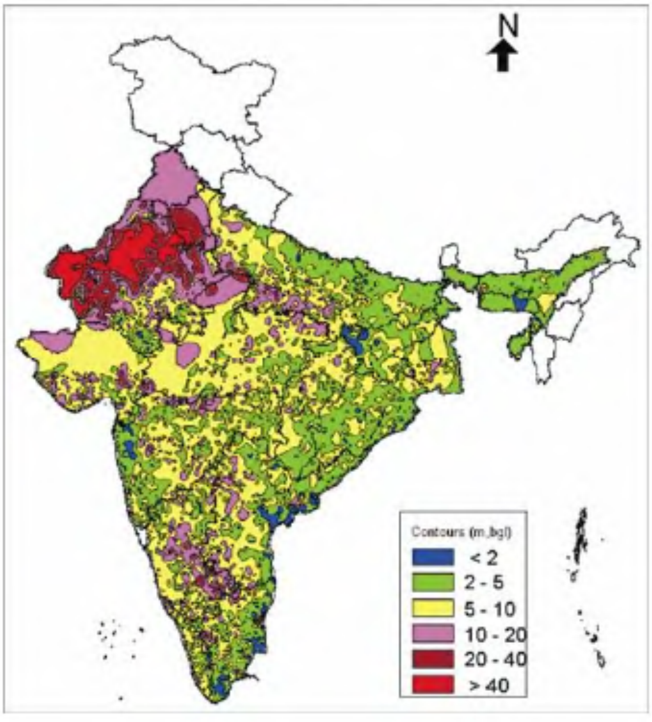

Figure 1. Contours of groundwater level in the country during January 2007. Source: Ministry of Water Resources website, www.mowr.gov.in

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and machinery appeared in the market. The rise in groundwater level caused by the seepage from canal network provided irrigation water, and cheap electricity generated by hydro-electric dams provided energy for pumping out the groundwater. The newly established Punjab Agricultural University (PAU) refined the production technology and the governmental machinery disseminated it and facilitated the marketing of the produce by fixing minimum support price for crops. In the earlier years of high production, groundwater consumption by crops and other human needs on the one hand and groundwater recharge fluctuated in a close range. But as the cropped area increased, recharge lagged behind consumption and groundwater started declining; that disturbed the ecological balance of the region. In the late 1980s, a voluntary multifaculty group of PAU scientists analysed water balance of the state for the then prevailing cropping pattern[3]. Their analysis showed that based on the available information of consumptive water use in different crops, the utilizable water supply fell short of annual water demand by more than 40%. On the basis of their results, the researchers' group at PAU gave a wake-up call[3] to all concerned with planning for long-term water use. Recently, the Punjab State Farmers Commission has estimated that the aquifer level declined by about 4.7 m between 2001 and 2006 against 0.6 m from 1980 to 1986. In part of the state, aquifer has declined by well over 10 m in the past 2–3 decades. It has many economic and ecological implications. Deepening of water table has pushed up the cost to pump out water, and the shrinkage of resources is threatening the sustainability of the cropping system.

In the past, when adequate water was available in relation to cultivated area, the irrigation research was aimed at getting maximum yield per unit area with minimum wastage of water. Due to water shortage, the emphasis now needs to be shifted to maximize returns per unit of water consumption with minimum social and ecological costs. In other words, water management should aim at maximizing water productivity (WP), viz. economic yield (Y) per unit of water consumed (ET) in the cropping system perspective including non-crop period(s). In order to tackle the subject of WP, it is essential to follow the hydrological balance of a cropped field and water use-crop growth relations.

Hydrological balance of a cropped field

Water is supplied to the field at the surface as precipitation (P) and/or as irrigation (I) to ensure adequate water uptake by the crop. This water is partly lost as surface runoff (R) and partly infiltrates into the soil (IW). The IW is partly retained within soil layer comprising the root zone (ΔS), and partly moves below the root zone as deep drainage (D). Moreover, water retained in the root zone is lost as ET from cropped soil and evaporation from bare or fallow soil during non-crop period (E_b)

$$P + I = R + D + \Delta S + ET + E_b. \tag{1}$$

On a level field, well-dyked all around, the *R* is zero, and also change in soil water content (ΔS) over a long-period can be assumed to be zero. Hence eq. (1) is reduced to

$$P + I = D + ET + E_b \tag{2a}$$

or

$$P + I - D = ET + E_b. \tag{2b}$$

The P + I is the gross addition and P + I – D the net water addition to the system, while the sum of ET and E_b is the net water loss (NWL). In certain crops, frequent irrigations have to be applied to facilitate proper ET. Wetland rice is one such example, where large amount of irrigation is supplied to maintain ponded water conditions, but most of it goes back as return flow and can be recycled. However, most of the times, P + I (that is used to meet ET and D) is intuitively equated with water used by the crop. If ET + E_b exceed the net addition of water, it implies that groundwater is depleted and vice versa.

Evapotranspiration and crop growth

Of the two components of ET, transpiration (T) occurring from the crop surface is a productive loss and is directly related to biomass production, while E occurring from soil surface is an unproductive loss. Plant physiologists express the ratio of biomass to T as transpiration efficiency (TE) for comparisons among cultivars, etc. while agronomists prefer the use of the term water use efficiency (WUE), the ratio between biomass (or economic yield) and ET, that is synonymous with WP. A linear relationship has been reported between yield and ET with a small negative intercept

$$Y = -a + b\mathrm{ET}, \tag{3}$$

This equation implies E component of ET as a constant value (= a/b) in Hanks[4] analysis. Increase in ET might, thus, lead to greater T component and T/ET ratio that represent higher WP. The ET loss from the field is determined by atmospheric evaporativity (E_0, maximum amount of water that the atmosphere can take up from free water), extent of crop cover (leaf area index), soil wetness and root proliferation in the potential root zone. Immediately after the soil is wetted, ET occurs at potential rate (ET_p). But as the soil dries with time, the actual ET from the field, ET_a, starts to lag behind ET_p. Particularly, the E rates decline rapidly as a dry layer develops at the surface. It is a physiological fact that the crop yields begin to decrease when the ET_a/ET_p ratio falls below a certain threshold. Hence, for securing potential yields, the crop must be irrigated before this ratio reaches the threshold value. Seasonal ET for various crops can be obtained by integrating the daily ET from seeding to harvest. Water lost during seedbed preparation should also be debited to crop ET for working out WP as this water is spent for establishing the crop.

Groundwater control

Groundwater level changes in response to accretion and depletion of the aquifer. Ecologically, the average annual depletion from groundwater reservoir should equal the average annual addition. Therefore, to replenish ET loss and maintain groundwater balance, it is imperative to conserve rainwater and the water in the surface water reservoirs as much as possible. This article focuses on the measures to manipulate ET and ET-crop yield relations to ameliorate groundwater decline. This is necessary for sustenance of agricultural production because water available for depletion is fixed, and the agricultural-based human needs are growing.

Thus, our objective to ameliorate declining groundwater boils down to reducing NWL, i.e. $ET + E_b$ losses and increasing WP. Increase in WP implies that given quantity of crop yield is produced with less water. Undoubtedly, changes in WP in response to management interventions are advantageous in many other ways, yet for ameliorating the groundwater decline, we must invent technologies that would decrease ET without negative effects on economic yield and environment.

Strategies for reducing water loss

Strategies for reducing water loss differ in relation to available water supply in the target region(s).

Assured water supply regions

In regions of plentiful water availability, the growers are interested in increasing yield per unit land as irrigation provides the insurance for using costly inputs like fertilizers and pesticides. Research efforts were largely confined to irrigation scheduling and refining systems of irrigation with emphasis on reducing energy and labour costs with little interest in ET savings. Strategies to secure high WP fall into four categories, viz. (i) genetic manipulation, (ii) crop adaptation to weather conditions in growing season, (iii) irrigation water management and (iv) agronomic practices.

Genetic manipulation: Traditional geneticists and biotechnologists are engaged in crop improvements with respect to chosen targets. In order to increase WP and to reduce ET losses, it will be helpful to raise the harvest index (HI) of the prospective crops. Though the HI is strongly influenced by environmental conditions, it is a genetic character and is approximated by slope of the upper bound of the grain yield versus dry matter plot passing through the origin[5]. The quantum jump in the yield of rice and wheat (associated with green revolution) and maize (in USA) is attributable to rise in HI from 0.35 before the 1960s to 0.5 plus in the succeeding years[6]. But further increase in HI of these crops and other crops appears to have low probability. Similarly, decreasing transpiration ratio (water transpired to produce unit biomass) of crops is rather a difficult task. Previous studies on transpiration and drought resistance have met with little success. But the biotechnology experts pin a lot of hopes on genetic manipulations that favour high WP. Rapid canopy development that covers the soil will help reduce the E component of ET and hence raise WP. Another useful area of study is breeding for high yielding but shorter duration varieties and hybrids.

Selection of crops and cropping systems: Crops and crop varieties differ in their seasonal demand for ET_p. Where water is available to meet ET_p, the seasonal demand can be worked out reliably by simulation modelling using crop coefficients and weather parameters[7]. Because the precipitation follows an annual cycle, ET needs to be worked out for the entire year by integrating ET loss for the cropped and bare periods. Since the biomass or yield is linearly related to normalized ET, it is obvious that WP would be higher under lower E_0. As far as possible, this fact must be considered in decisions on seeding dates of crops. A case in point is the banning of transplanting of wetland rice in May, the hottest month of the year in Punjab region of Indo-Gangetic plains. A shift in transplanting to 10 June or later is expected to shed a few centimetres of ET over the growing season without affecting grain yield[8,9]. This saving in ET by shifting transplanting time occurs as the E_0 close to harvest-time is 3–5 mm per day compared to 10–12 mm per day during transplanting time.

Water management practices: Water management experts have studied the effects of irrigation scheduling and methods and systems of irrigation application on the performance of crops. The major objective of these researchers has been to increase irrigation efficiency by more uniform distribution in the crop root zone for economizing irrigation water and application costs. The concept of WP was not largely invoked in issues pertaining to water management as it was not realized that the entire water applied to soil was not used in ET. Irrigation scientists did develop quite innovative and easy to follow irrigation schedules for important crops that economized irrigation water without reducing yield[10]. Methods of application as surface, overhead and subsurface application and system of irrigation were also studied. Very few studies involved ET losses *per se*. A leading US irrigation engineer[11] remarked, 'Basically irrigation system has little effect on water consumption by most crops that are fully irrigated'. Nonetheless, some reports[12] show that cotton sown in spaced furrows required less irrigation when alternate furrows were watered than flooding. It is likely that partial wetting of the surface might have reduced E component of ET and thus increased WP. Likewise, drip irrigation during establishment of orchards, citrus groves and vineyards, when trees are small, reduces direct evaporation by avoiding wetting part of the surface. Practices like laser levelling, bed planting and furrow irrigation have little effect on ET loss, but may favour yields and WP by alleviating production constraints.

Agronomic practices: Seasonal ET of a fully irrigated crop in given weather conditions is unlikely to vary. But crop yields differ due to agronomic interventions that reduce the intensity of constraints to production. Commonly followed agronomic practices for increasing crop yields include seeding at right time, securing optimum plant population, proper tillage and fertilizer application, and pest control. For example, soils suffer from deficiency of one or more essential nutrients. Deficiency of nitrogen is almost universal in our soils. Removal of plant nutrients through bumper yields depletes the soil of other nutrients too. More recently, deficiencies of micronutrients are encountered in intensively cultivated soils. Addition of deficient elements through fertilizers enhances economic yield. Integrated nutrient management combining fertilizers with manures and crop residue have similar positive effects on crop yields leading to improved WP. Similarly, soil physical constraints may restrict root proliferation in the profile which may cause stress and reduce HI and yield of the crop. Deeper tillage stimulates greater root proliferation which ensures sufficient water uptake by the crop to avoid water stress even under intense climates. Weed control and plant protection measures help maintain the yield by eliminating weed competition and avoiding disease stress.

Suitably chosen and properly timed mulching has shown considerable promise in reducing direct evaporation losses from soil. In fact, apart from selection of crops and varieties, mulching is the only practice that reduces ET loss from the system. Mathematical modelling and elaborate experiments under controlled conditions reveal that straw mulch and tillage-induced soil mulch help in reducing direct evaporation from soil. The magnitude and longevity of benefit depends on the weather conditions, soil texture, rate and time of application, and type of mulching material[13]. Jalota and Arora[7] estimated the components of water balance for three annual cropping systems, viz. maize–wheat, cotton–wheat and sugarcane with and without mulching @ 6 t ha^{-1} of rice straw. The mulching reduced E component in summer maize of 105 days duration by 18.5 cm in medium and 13.1 cm in coarse-textured soil. Corresponding reduction on the two soils were 23.8 and 16.3 cm in 175 day-duration cotton, and 23.6 and 17.6 cm in 320 day-duration sugarcane. Mulching has been reported to increase economic yield and save irrigation water in many field, vegetable and horticultural crops[14]. The yield increase with mulching was attributed to favourable effects on hydrothermal regime of soil.

Benefit from mulching with crop residues is a time-variant phenomenon[13]. Initial evaporation rate is higher on bare than mulched soil. After a certain period depending on the soil, weather and mulch characteristics, the reverse occurs. Therefore, cumulative evaporation reduction with mulch peaks off after a certain time, and then starts declining because evaporation rate from the bare soil falls below that from the mulched soil. It was also established that combinations of straw mulching and tillage for different E_0 were more effective in reducing the decline of evaporation reduction peak. This means more moist soil conditions if a crop is growing or there is carry-over of higher water content in surface layers for a longer period. These observations under controlled conditions need to be verified, validated and transformed into a field practice.

Limited water supply regions

Under limited water supply, precipitation and supplemental irrigation is not adequate to meet potential ET needs which results in yield loss. Thus, there is a need to maximize WP per unit of ET. Interactions of crop production factors and water availability are stronger and assume greater importance under these conditions. Passioura[15] remarked that when WP of cereal crops in water-limited environments is less than 2 kg m^{-3} of transpired water, stresses other than water, like weeds and diseases, poor nutrition and inhospitable soil need to be managed.

It is essential to select crops and cropping systems based on timing and magnitude of water availability. Crops with stable yields, that complete their life cycle within period of uninterrupted water availability, are preferred under water-limited conditions. Cultivars with shorter duration of growth fit better under double cropping. Freedom from weeds, diseases and pests ensures a healthy crop that would respond to other field practices to achieve high WP. Common practices to enhance crop yield are to improve soil fertility status, and soil physical manipulations to help the crop to extract and evapotranspire more water. Crop yield increases with added fertility under limited water are well documented. Most agronomic practices increase WP by accelerating early canopy development that reduces E component and increases T/ET ratio. But if early biomass production is

Table 1. Measured ET, grain yield and water productivity (WP) of wheat as affected by fertilizer N and irrigation regimes

	ET (mm)		Grain yield (t ha^{-1})		WP (kg m^{-3})	
Irrigation regime	N_0	N_{80}	N_0	N_{80}	N_0	N_{80}
No irrigation	129	140	0.69	1.13	0.53	0.83
125 mm irrigation	286	309	1.63	3.67	0.57	1.19

Source: Gajri *et al.*[17].

disproportionately high, it may exhaust the available water and the crop may suffer from water stress and its HI decreases. This may reduce economic yield. Therefore, factors aiding rapid early growth may end up in low WP. It calls for rationalizing the use of factors in a way to avoid negative effects due to their over-use.

Two important inputs are fertilizers and small supplementary irrigation. The probable water supply should permit an estimate of achievable yield and the soil fertility status be adjusted to obtain that yield. If the growing season rain exceeds the expected amount, more fertilizer may be added to take advantage of the additional water. Timing of small supplemental irrigation is crucial for best returns. There are certain critical stages for soil wetting, like wetting of seed zone to ensure proper crop stand. Early post-seeding irrigation promotes root growth[16]. If application of plant nutrients is made before the preseeding irrigation, they move some distance below the surface and remain available for a longer period. Wetting frequency should be kept minimum to avoid unproductive E losses. Fertilizer rates interact with irrigation for crop yields and WP[17]. The effect of combination of N and irrigation on wheat yield and WP was much higher than their additive effects (Table 1). Nitrogen application alone increased ET slightly and the effect of irrigation was larger. Mean ET with 125 mm irrigation was 297 mm against 135 mm for no-irrigation. The difference in ET is greater than the amount of irrigation applied to the crop. This is the priming effect due to more prolific root development with irrigation.

Field investigations demonstrated that maize seeded in deep-tilled fields required less applied nutrients and less frequent irrigation than with conventional tillage[18] for comparable crop yields. This was attributed to deeper and more prolific root system with deep tillage. Greater proliferation of crop roots with irrigation and/or with loosening by tillage[19] provides an interim relief against the development of water stresses and helps to increase crop yield. Conservation tillage – a concept that involves surface retention of crop residues and minimum soil disturbance to maintain crop yields – has a scope in improving WP, more so in dryland areas. Molden *et al.*[20] concluded that there is considerable scope for improving crop WP in many dryland and irrigated regions of the world by following improved agronomic and water management practices.

Cropping system perspective to WP

It has been established that the agricultural production is limited by the amount of water available for depletion. The water availability follows an annual cycle and is assessed as a yearly average over a long time-period. Each crop depletes water through ET during a certain period of the year and is followed by a non-crop period during which bare soil continues to lose water, albeit at a lower rate – largely through E termed as E_b. Depending upon the crop rotation, the cropping cycle may take one or more year(s). Thus, the non-crop periods would occur more than once a year in double cropping to many times in longer-duration crop rotations. Currently, WP is reported for each crop based on its yield and ET loss during its growth. The WP values, thus obtained, permit comparison among crops, cultivars and production factors. They indicate how efficiently a given crop uses water. But, our interest is in improving WP of water depleted annually from the reservoir. This calls for the assessment of NWL during the year by a cropping system including the duration of the non-crop period(s). The WP based on this water loss provides a more realistic comparison of cropping systems performances.

This concept is illustrated by using data from Arora *et al.*[21] and Jalota and Arora[7] to compare WP of three cropping systems of Punjab, viz. rice–wheat, cotton–wheat and maize–wheat (Table 2). ET from the crops and E_b for the non-crop periods were estimated by a water balance model using information on soil–crop–weather–management factors. Economic yield of the component crops of the system was converted to wheat equivalent yield by multiplying crop yield(s) with the ratio of sale price of crop to sale price of wheat. WP was computed in two ways, viz. (i) wheat equivalent yield of the cropping system was divided with sum of growing season ET loss from the two crops and (ii) wheat equivalent yield in the system was divided by NWL during the whole year ($ET + E_b$). The analysis revealed that WP of different cropping systems in the two sets differed widely. WP based on crop ET was highest in rice–wheat followed by cotton–wheat. But, when NWL by the cropping system during the whole year was used as a denominator, highest WP was found in cotton–wheat system. Further, values of WP based on crop ET alone were quite close for cotton–wheat and maize–wheat systems. But, when NWL was

Table 2. Water productivity based on crop ET and net water loss in different cropping systems

Cropping system	ET* (mm)	E_b** (mm)	Component crop yield (t ha^{-1})		Wheat equivalent yield (t ha^{-1})	WP ($kg\ m^{-3}$) based on	
			C_1	C_2		ET	NWL
Rice–wheat	1030	210	6.0	4.5	9.7	0.94	0.78
Cotton–wheat	980	90	2.0	3.5	8.6	0.88	0.80
Maize–wheat	860	220	3.5	4.5	7.2	0.84	0.67

*Source: Arora *et al.*[21]; **Source: Jalota and Arora[7].

used to compute WP, values were much higher in cotton–wheat than maize–wheat. Apparently, the higher WP in cotton–wheat system is the result of lower E_b loss compared to the other systems. It is therefore, recommended that field scale management interventions for enhancing WP must follow the cropping system perspective and aim at minimizing E_b losses by shortening the non-crop period and/or reducing E loss. Such analyses of physical WP can also be interpreted in terms of economic WP by translating crop yield to monetary returns.

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ACKNOWLEDGEMENT. S.S.P. thanks Prof. Raghbir Singh, Chandigarh for discussions and encouragement.

Received 30 November 2009; revised accepted 13 July 2010