Water Productivity of Different Agricultural Systems

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Introduction

Agriculture is the major consumer of water among various sectors. Growing demands of water for urban areas and environmental management are projected to reduce the diversion of water for agriculture in the future. On an average annual basis more water will be required to feed the growing and wealthier populations with their more diversified diets (CA 2007). Climate change is also projected to have implications for water and agriculture and, as such, must be considered to determine the way water is being managed now and in the future as well. Enhancing water productivity in agriculture is an appropriate response to counter the increasing levels of water stress. Given the growing water scarcity that is resulting from increased water demand, the challenge is to increase water productivity for food and livelihoods and, thereby usher in an era of the 'evergreen revolution'. It can help alleviate poverty through improved access to water for the poor and also have multiplier effects on food security, employment and livelihood. Besides the physical availability of water, yet another cause for concern in obtaining the maximum agricultural output, or value for every drop of water used in agriculture, is the economical accessibility of water.

High water productivity may not be a suitable target, where the concurrent opportunity costs or forgone values, like the alternative potentials of the saved or lost water, are not taken into account (Zoebl 2006). Understanding the concept of agricultural water productivity and exploring opportunities for its enhancement in irrigated, rain-fed and waterlogged areas through integrated and multiple uses assume greater importance. It is very important in groundwater irrigated areas, where water is either scarce due to faster depletion of aquifers, as in the western Indo-Gangetic (IG) basin, or it is costlier to pump water, as in the eastern part of the IG basin owing to the use of diesel operated pumps. Rain-fed agriculture, occupying 60 % of the net sown area of the country, may be a more economic target for enhancing water productivity.

Most of the water productivity studies deal with crop water productivity with a single crop, or single water use with the exception of limited studies on water productivity in dairy production. Agriculture with improved water management system and/or integrated farming and multiple water use systems i.e., using the available water source(s) for more than one production system (crops, horticulture, livestock, fisheries etc.,) is one of the responses to produce 'more food with less water'. The paper presents agricultural water productivity for farming systems based on multiple water use, and crop water productivity under different water management systems.

Water Productivity

Water productivity is used exclusively to denote the amount or value of product over volume or value of water used or depleted or diverted (Kijne et al. 2003). Water productivity will depend on many factors other than the quantity of water applied or depleted. Though water is only one of the factors of agricultural production and cannot be meaningfully separated from the others, an estimate of its productivity and knowledge about the factors which influence the productivity will help understand the pathway to improving water productivity.

Agricultural water productivity takes into account multiple water users, including conventional crops, horticulture, forestry, livestock, fisheries, environment etc. It means that if all water users are taken into account and a concept of recycling and reuse of water is considered in an agricultural production system, then agricultural output per unit of total water input is referred to as agricultural water productivity. Since agricultural water productivity assessment considers the multiple uses of water, its value represents a composite or an integrated picture that is higher than the crop water productivity.

Water productivity analysis can be applied to crops, livestock, tree plantation, fisheries, and mixed systems at selected scales-crop or animal, field or farm, irrigation system, and basin or landscape, with interacting ecosystems. Since expressions for water productivity differ in each context, it is important to be clear about the agricultural output and input terms used. As regards agricultural systems, agricultural water productivity will be the sum total of factor productivity from crops, livestock, fishery, horticulture etc. However, care will have to be exercised to avoid multiple accounting of the same input.

Livestock water productivity is a measure of the ratio of outputs, such as meat, milk, eggs or traction, to water depleted, and is defined as a scale-dependent ratio of livestock production (or services) produced per unit of water depleted (Peden 2003). Methodology must be integrated with other crop, forestry and fisheries uses of water resources in the watershed/basin in order to harness the full advantage of multiple uses in an integrated farming systems approach. Livestock produced solely with irrigated forage and grain crops will have far lower water productivity when compared with livestock production relying on the consumption of crop residues, grazing and tree fodder, as the water used for plants would have been used with or without livestock feeding on it and feed is a by-product of crops (Singh and Kumar, this book). The fishery, as such, is considered nonconsumptive in terms of water use. But, when water is diverted and stored in ponds for fish, some water will be depleted through evaporation from the pond. Where fish production occurs by virtue of irrigation and/or water harvesting reservoirs, its benefit is added to water without additional depletion, and so it enhances water productivity for the same quantity of water depleted. If we increase production by keeping water in the reservoir for summer months when there are no standing crops, there would be additional evaporation which needs to be accounted for. Chapagain and Hoekstre (2003) have also cautioned against avoiding double and under accounting of water used for livestock products.

Assessment of Agricultural Water Productivity

Agricultural water productivity may be computed for the crop period or for the whole year considering the production value—first from crops only (crop water productivity) and then considering other water users including trees, livestock and fish in case of multiple uses per unit of water inflow (including rainfall, groundwater and canal water) as well as water used (total inflow excluding runoff) in the field, farm, irrigation system, basin and landscape. The values of denominator i.e., water input may be different for different situations. In the estimation of water productivity, we are interested in water inflows (rain plus irrigation, or just rainwater in rain-fed agriculture) and water depletion (evaporation and transpiration). The amount of water depleted through evapotranspiration by crops will not be considered again while accounting for depletion in case of crop residues/ straw for livestock, to avoid double accounting. Similarly, in case of fisheries, water depletion through storage losses is to be considered as input only when water storage in the pond/ tank is exclusively maintained for breeding fish.

Case Studies of Agricultural Water Productivity Assessment

Canal and Tubewell Commands

Assessment of water productivity in mixed use systems including crops, livestock, fisheries, and trees in the irrigation command of RP Channel-V of Patna Main Canal in the Sone Command at Patna and in the tubewell command area in Vaishali, Bihar is discussed. Crop water productivity was computed considering crop output per unit of irrigation water applied, inflow diverted (including rainfall, groundwater and canal water) as well as water used (total inflow excluding runoff), whereas agricultural water productivity was computed considering the output of various water uses like cereal crops, horticulture, trees, fisheries and livestock. Water productivity was computed during kharif (monsoon) and rabi (winter) seasons considering the production value— first from crops alone and then considering other water uses including trees, livestock and fish (Sikka et al. 2008).

1. Survey and Data Collection/Measurement

A comprehensive survey was undertaken in the RP Channel V command and tubewell command area at Vaishali, and data/information from 90 farmers of the former and 85 farmers of the latter, were collected during kharif (monsoon) and rabi (winter) season. The comprehensive survey included: number of family members, number of farm workers, total area, total area in the command, details of trees, livestock, inputs (seed, fertilizer, manures, pesticides, weedicide, irrigation water and human labor), total input cost and total output (main product and by product).

2. Estimation of Value Production

Value of Crop Production: Data regarding the various aspects of cultivation of different crops such as area under each crop, quantity and value of various inputs used, quantity and value of the main product as well as by-products produced were collected from farmers in the selected commands. From this data average value production per hectare was worked out for various crops grown in the commands in kharif as well as in rabi seasons. This average value product includes both the main product as well as the by-product. Actual area under different crops was derived from the plot-wise data obtained from GIS mapping technique. Value production of each crop was derived by multiplying the area under each crop with the respective average value of the product per unit area. The value product from various crops was added to get the total value of production from crops.

Value from Trees: Data regarding the number and type of trees grown, quantity and value of the main product as well as by-products obtained from the trees was collected from the farmers. As trees are perennial, it was difficult to collect such data for a particular season and data was instead, collected for one year. From this data the average value production per tree per year was worked out separately for various species. The actual number of trees belonging to different species were counted and recorded. The average value of production was multiplied with the number of trees of different species and added together to get the value of production from trees per year in the command. While estimating the value of the product, biomass addition in the trees was not included. Similarly, the wood value of trees was also not considered. Only the value of fruits, firewood and fodder was considered.

Value from Fish: Fish production was very limited in the selected commands. Only three farmers were engaged in fish production in outlet 4 of the RP Channel V. Data regarding the production aspects of fish were collected and value from fish production was estimated accordingly.

Value from Livestock: Average quantity of milk and dung produced per animal per day was worked out from the data collected from the farmers. This was multiplied with the actual number of animals in the command area to get the total production per day. Average prices were used to value this physical production. Total value from livestock per day was obtained by multiplying physical production. Then this value was multiplied by the number of days in the accounting period to get the total value of production per command. But this entire value of production cannot be attributed to the command area, as the livestock are not dependent on the production from the command area alone. Feed and fodder come from the outside also. Command is meeting only 23–40 % of the fodder requirement. As the total fodder cost in milk production was about 60 %, only 60 % of the value product was attributed to fodder. Since 23–40 % is met from the command area, that percentage of the value of production was attributed to the command area. No additional water input is considered for feed and fodder, which is met from the command area, as the total water applied from the outlet to the command is already accounted for, and feed and fodder are by products of the main crops.

The following assumptions were made while valuing the production from livestock in the study:

- The fodder cost in the total cost of milk production was assumed to be 60 %. Hence 60 % of the production was considered from fodder
- Services from bullocks were not considered
- Animals not in lactation period were not considered while calculating milk production
- Increase in body weight of the animal and calves produced were not included
- Value of grass grown on bunds and grass grazed by animals could not be considered

3. *Estimation of Total Water Inflow*

- All the different sources of water to the command of RP Channel-V of Patna Main Canal in the Sone Command at Patna and tubewell command in Vaishali were identified. The command area of RP Channel-V is irrigated by canal and tubewell, while the command area of the Vaishali District is mostly irrigated by tubewell.
- To carry out the measurements of the volume of water reached to the fields, three outlets—at head, middle and tail reaches were selected in RP Channel-V to install V-notch. Flow data from three outlets, at the head, middle and tail reaches were collected with the help of V-notch for both kharif and rabi seasons. Whereas for the tubewell command area at Vaishali, data were collected for pumping hours also with the help of V-notch.
- Water head at the outlet of RPC-V was measured on a daily basis and the total water delivered was also calculated on a daily basis. For calculating discharge in the channel, the volume of water flowing at the head, middle and tail is calculated with help of V-notch.
- Daily precipitation was recorded using rain gauge.

The total water entering the domain (rainfall, canal and tubewell) was calculated for the respective command area and the same was incorporated in the SWAP model. Water diverted to the command areas of RP Channel–V and tubewell commands in Vaishali was found to be utilized by different crops. SWAP model was used to calculate interception, runoff, evaporation and transpiration separately. The water balance components for both kharif and rabi crops were calculated for all three outlet commands and two tubewell commands. The details are available in Sikka et al. (2008).

Finally, water productivity was computed considering value from crop production, trees, fish and livestock and water diverted by various users, as given in Table 1.

Table 1. Crop and agricultural water productivity.

Water Productivity (Rs/m^3)	Outlet 4 Head Reach	Outlet 17 Middle Reach	Outlet 27 Tail Reach	Tubewell 2 Land consolidation	Tubewell 11- Fragmented landholding
Area (ha)	30.61	43.68	4.65	18.74	13.21
Crop WP per unit of irrigation water applied	4.79	4.95	8.39	29.61	14.03
Crop WP per unit of water inflow including rainfall	2.42	2.73	3.11	2.81	2.39
Agricultural WP per unit of irrigation water applied	5.28	5.90	10.66	38.73	18.09
Agricultural WP per unit of water inflow including rainfall	2.67	3.25	3.96	3.68	3.09

Source: Sikka et al. (2008)

Crop water productivity (Rs/m^3) in relation to applied water ranged from 4.79 to 8.39. When rainfall was also included in the inflow, it ranged from 2.42 to 3.11 in the outlet commands. In tubewell commands, the applied water productivity ranged from 14.03 to 29.61, whereas it was in the range of 2.39 to 2.81 when rainfall was also included. Agricultural water productivity (Rs/m3) considering applied water varied from 5.28 to 10.66. When rainfall was also considered, it was between 2.67 and 3.96 in the outlet commands. In tubewell commands, the agricultural water productivity ranged from 18.09 to 38.73 for applied water and 3.09 to 3.68 for total water inflow including rainfall. Lower water productivity under total inflow in tubewell command may be attributed to very high proportion of rainfall in the total water used. The analysis indicates that both in the canal commands and tubewell commands, agricultural water productivity of applied as well as total water inflow (including rainfall) taking into account other water users like trees, fodder, livestock, fish etc., provides a better picture of the actual productivity of water.

Water Productivity in Multiple Use Systems

Integrated farming systems and the multiple uses of water provide great opportunities for enhancing the water productivity of agriculture and livelihood at various scales by integrating fisheries, livestock, aquatic crops, horticulture etc., with crops into the existing irrigation and water use systems/water infrastructures. Evidences of such multiple use systems (MUS) could be found in canal and groundwater irrigated, rain-fed, waterlogged, coastal and hilly areas/watersheds. Besides increasing water productivity, MUS system also reduces the investment costs and risks associated with single use. Analysis of factor and total water productivity of the sub-system and system as a whole also provides an insight into the tradeoffs for alternative options. Some examples of agriculture water productivity of multiple use systems are discussed below.

Secondary Reservoir-cum-Fish Pond in Tubewell Irrigation

Routing of tubewell water for irrigation through a secondary reservoir-cum-fish pond to enhance water productivity is another example. In a study at ICARRCER, Patna routing of tubewell water from secondary reservoir gave additional benefits in terms of a fish harvest of 11.0 t/ha with weekly water exchange during summer (Bhatnagar et al. 2004). The factor of water productivity in breeding fish in the secondary reservoir was computed after accounting for depletion through evaporation from the reservoir during the off-crop period and the amount of water exchanges required after maturity of the rabi (winter) crop. The factor of water productivity for the fishery was estimated to be Rs 16.11/m^3, with an evaporation of 137.44 m3 and an additional water exchange of 406.25 m3 (Bhatnagar et al. [Draft Bulletin]). Water productivity of the system could easily be further increased by making beneficial use of the exchanged water for raising vegetables.

Multiple Use Systems (MUS) in Waterlogged Areas

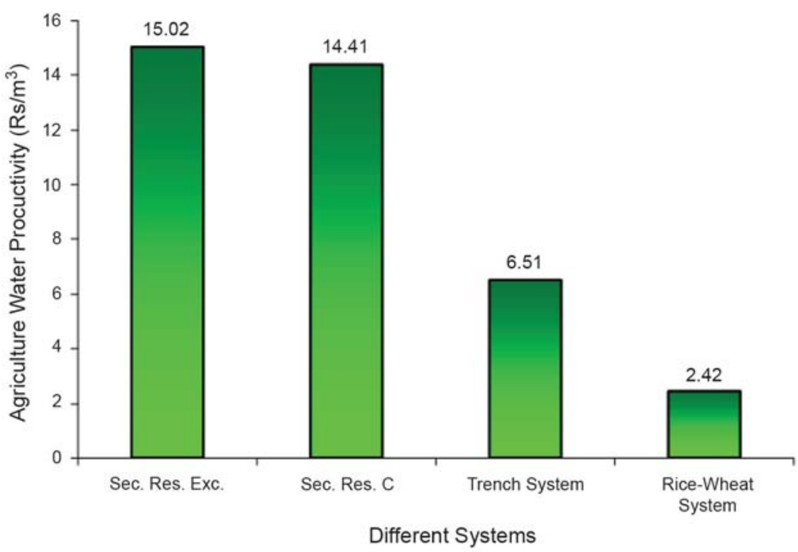
(i) To enhance productivity of seasonally waterlogged lands in canal commands, secondary reservoir (fed by canal seepage and supplemented by tubewell), fish trenches-cum-raised bed for fish-horticulture production and rice-fish culture using nylon-pen under waterlogged area, were undertaken at ICARRCER, Patna. In the secondary reservoir concept, two reservoirs were constructed in the seasonal waterlogged area. Multiple uses of water by fish culture in reservoir, horticulture (two tiers: banana/ guava/ lemon and vegetables) on bunds, routing water to cereal crops, and duck-rearing were evaluated. Water was supplemented from tubewell to maintain a minimum water level in the reservoir for fish production (Sikka et al. 2008).

Agricultural water productivity for the three types of farming systems based on multiple water use was analyzed taking into account the water diverted into the pond to replenish water in the seepage fed pond during the lean season and valuation of outputs from crops, vegetables fruits, eggs, and fishes for the year. Water productivity values for different MUS systems are shown in Figure 1. The results indicate about 2.7 to 6 fold increase in water productivity by integrating different components over the traditional rice-wheat system. Water productivity was maximum (Rs.15.02/ m3) in the secondary reservoir (with exchange of water) where fish, fruits, vegetables and duck-rearing were integrated with rice and wheat, as against Rs.2.42/ m3 in the rice-wheat system alone.

The economic analysis indicates that integrating fish in the rice-wheat system gave a net income of Rs. 29,694/ha, which is 6 % higher than the traditional rice-wheat system yielding of Rs. 27,965/ha per year. Under seasonally waterlogged areas up to 1m depth, a system based on fish trenches-cum-raised beds horticulture and fish system generated a net income of Rs.80,951/ha/year, which is 189 % higher over traditional rice-wheat system. Under seepage-fed secondary reservoir supplemented with groundwater, a system of horticulture on bunds + fish + duckery yielded net returns of Rs.1,32,590/ha/year, which is 374 % higher over traditional rice-wheat system (Sikka et al. 2008).

(ii) Multiple water use based farming system with on–dyke horticulture and fish-prawn-poultry system in farmers' field in Orissa provided an excellent opportunity to productively use water- logged area. The farmers converted 2.47 ha of waterlogged area into 1.64 ha of pond and 0.83 ha of raised embankment. While the pond area was utilized for fish and prawn culture,

Figure 1. Agriculture water productivity of multiple water use systems at ICAR-RCER, Patna.



21 m wide embankment was used for planting mango, teak, areca nut, coconut, banana, papaya, pineapple, mushroom etc. Net water productivity of multiple use system was estimated to be Rs.7.5/m^3 against Rs.0.95/m^3 for lowland rain-fed paddy alone and Rs.6.0/ m^3 with vegetable production (Samra et al. 2003).

(iii) Aquaculture was integrated with the subsurface water harvesting structures (SSWHS) meant for providing irrigation during post monsoon season in the coastal areas of Orissa. Water productivity varied from Rs.15.84/m^3 to Rs.50.84/m^3 with an average of Rs.36.20/m^3 while taking the total income into account. Net water productivity (considering only benefits) ranged from Rs.9.00/m^3 to Rs.53.70/m^3 with an average of Rs.23.26/m^3 (Sahoo et al. 2003; Srivastava and Satpathy 2004).

Multiple Use Systems in Rain-fed Areas

The harvested water in the rain-fed areas can be judiciously used for multiple uses such as drinking, supplemental irrigation, livestock, fisheries etc., to optimize water productivity. Integrated farming system based on multiple uses of water in low to high rainfall rain-fed regions while improving productivity of water has provided additional monetary benefits to small and marginal farmers.

(i) Rainwater harvesting and multiple use-experience of Horticulture and Agro-forestry Research Program (HARP) of ICAR-RCER: In the experimental farm of HARP in Ranchi, a rainwater harvesting pond was constructed with a capacity of 1,200 m^3. The command area of 0.7 ha consists of litchi based multi-tier horticultural system. Fish production in the pond, vegetable/ fruits/ pulse production on the bunds (measuring 3.0 m width around the ponds), supplemental irrigation to cereal production on a limited area of 0.125 ha with surplus runoff storage during monsoon season, and irrigation through gravity fed drip irrigation to multi-tier horticulture are the multiple uses of the harvested rainwater in the system. The farming system accounts for the production of cereals, pulses, oilseed, fruits, vegetables and fish and thus offers income diversification for the marginal tribal farmers and a regular flow of income. Agricultural water productivity (with total water depletion of 826 m^3) was estimated to be Rs.31/m^3 for the farming system as a whole during the year 2007 (Personal Communication 2009).

(ii) Multiple uses of harvested rainwater in undulating terrains of the eastern plateau has been demonstrated by constructing an unlined tank of 1,468 m^3 with a catchment and command area of 3 ha and 0.95 ha, respectively (Srivastava et al. 2004). Fish and prawn was grown in a pond with two rows of papaya planted on the embankment and one row of banana planted on the free board area of the inward slope. Water productivity (on the basis of utilized water) increased from Rs.3.84/ m^3 for crop alone to Rs.5.35/m^3 with multiple water use (Srivastava and Satpathy 2004).

Water Productivity (WP) of Different Water Management Systems

There are many well known crop water productivity improvement measures including supplemental and deficit irrigation, water saving devices, soil conservation, soil fertility improvement and resource conservation technologies (RCTs) like zero-tillage and bed planting. However, assessment of WP improvements under such situations is lacking. An attempt is made to present some values in this regard.

WP under RCTs

A study was carried out in Pabnawa Minor of Bhakra Canal System in Kurukshetra, Haryana to assess water productivity under zero-tillage and bed planting in rice-wheat system in the western IG plains (Chandra et al. 2007). In each of the four selected watercourses (Table 2), 15 farmers' fields were selected for detailed monitoring of water use and crop yields. In the selected fields in PH, PM1 and PT section of the water course, wheat was planted using zero-tillage and bed planting techniques. However, wheat crop was planted using conventional tillage practices in the selected fields of PM2 command. Information related with different agricultural and water management practices adopted by farmers in the selected fields, was collected on a specially designed data collection form. Systematic observations were recorded for water use on a daily basis from the selected farmers' fields.

Table 2. Details of selected watercourses.

Irrigation Minor	Watercourse	Technology	Design discharge (m^3/sec)	Gross command area (ha)	Cultivated command area (ha)
Pabnawa	Pabnawa Head-end (PH) 2820R*	Zero-tillage Bed Planting	0.028	231.6	208.9
Pabnawa	Pabnawa Middle (PM1) 53705L	Zero-tillage Bed Planting	0.041	320.2	300.0
Pabnawa	Pabnawa Middle (PM2) 53705 R	Conventional Tillage	0.025	341.3	169.6
Pabnawa	Pabnawa Tail-end (PT) 80000L	Zero-tillage Bed Planting	0.052	283.0	253.4

Source: Chandra et al 2007

Note: Letters L and R refer to left and right banks of the watercourse

Wheat water productivity in the bed planting method of crop establishment is generally higher than that under zero-tillage and conventional tillage (CT) at the plot level in the different reaches. Water productivity of wheat in bed planting (BP) is greater than that under zero-tillage and wheat water productivity in zero-tillage is greater than that under conventional tillage across plot to watercourse scales. The irrigation water productivity for rice under BP is higher (22 to 28 %) than that of CT, but land productivity is lesser than conventional tillage (Table 3). There is a trade-off between water productivity and land productivity in bed planted rice.

Results of this analysis indicate the superiority of zero-tillage over conventional tillage both in terms of the water productivity in irrigation and land productivity in wheat, besides profitability of wheat production. Water productivity under both zero-tillage and conventional tillage decreases as one moves from plot level to watercourse level (i.e., for the three levels of analysis). Higher level of water productivity under zero-tillage over conventional tillage at the

Table 3. Water and land productivity of bed planted rice and conventional tillage rice.

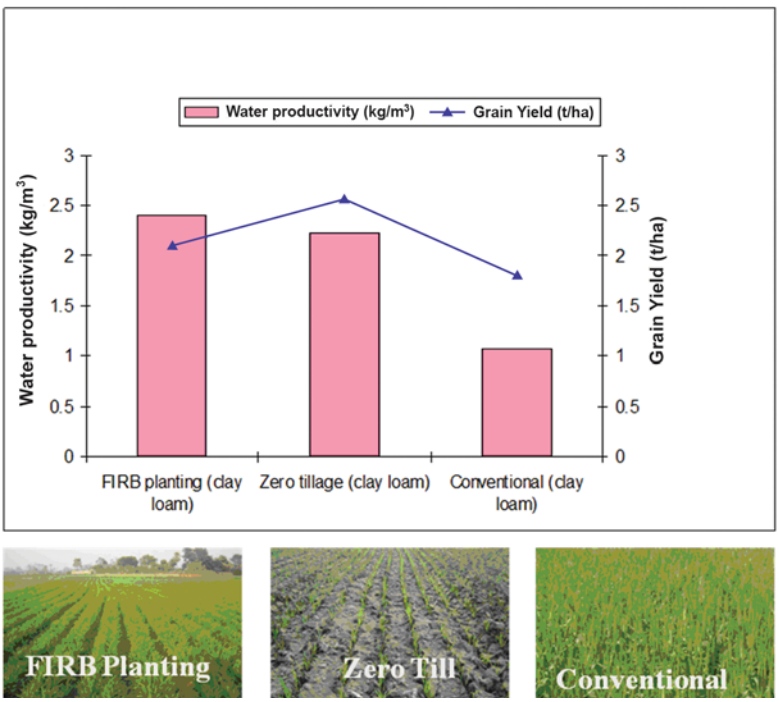
Location	Method of Sowing	Irrigation Water Productivity (kg/m^3)	Gross Water Productivity (kg/m^3)	Average Yield (t/ha)
PH	BP	0.38	0.37	4.76
PM1	BP	0.39	0.38	5.43
PT	BP	0.49	0.46	4.93
PM2	CT	0.31	0.30	5.53

Source: Chandra et al 2007

farm and watercourse level suggests benefits of water saving under zero-tillage at the watercourse level. These results are based on limited but rarely available field data. However, they do illustrate suggestive indicators of enhanced WP under RCTs.

Water productivity of wheat in the clay loam soils of Bihar in bed planting, zero-tillage and conventional tillage on the farmers' fields are shown in Figure 2. It is evident that water productivity is highest under bed planting followed by zero-tillage, with the lowest under conventional tillage. Though, the water productivity of wheat is slightly less in zero-tillage than in bed planting, land productivity is higher in zero-tillage over bed planting and conventional tillage. This suggests that there is a tradeoff between water and land productivity in bed planted wheat, and under a water-scarce situation bed planting may be preferred.

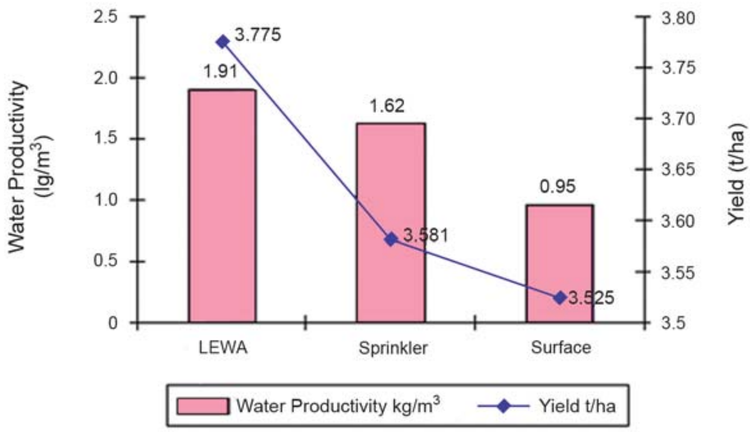
Figure 2. Water productivity and grain yield of wheat under different sowing methods.



WP under Micro-irrigation

Water productivity in Banana was raised by 72 % in a dry-land watershed at Saliyur in Coimbatore District when the conventional surface method of irrigation was replaced by drip irrigation. Water saving irrigation methods help in improving water productivity. Molden et al. (2007) have reported gains in water productivity varying from about 40 % to over 200 % for various crops (banana, sugarcane, cabbage, cotton, grapes, potato and tomato) in shifting from conventional surface methods to drip irrigation in India. Water productivity of LEWA (Low Energy Water Application) device for wheat at Patna was estimated to be 1.91kg/m^3 against 1.62 kg/m^3 and 0.95 kg/m^3 for sprinkler and surface methods of irrigation, respectively (Figure 3).

Figure 3. Water productivity and yield of LEWA in wheat.



Conclusions

The concept of agricultural water productivity and the methodologies for its assessment have been demonstrated through a number of field studies focused on multiple use based farming systems in the irrigated, rain-fed and waterlogged areas. Since agricultural water productivity takes account of different water uses and production systems, it presents a better and composite picture of water productivity obtained in farming systems. The advantages of harnessing synergies of multiple water use based farming systems are reflected in significantly higher values of agricultural water productivity as compared to crop water productivity alone. These results are based on simple but conceptualized methodology based on certain assumptions, which may have limitations in accounting procedures, and leave room for more elaborate field studies for evolving a comprehensive methodology of computing total and factor productivity of water in multiple water use based farming systems. The values of water productivity are based on the prevailing market prices of outputs for the respective years in different studies and, therefore, this limits their comparison on a relative basis for the given set of systems.

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