ASSESSMENT OF CROP WATER PRODUCTIVITY IN IGNP AREA

(ICAR – ICARDA COLLABORATIVE PROJECT # 8)

International Centre for Dry Area
ICAR – Central Arid Zone Research Institute

1. Introduction

A key question facing agricultural scientists in the 21st century is how to produce sufficient amounts of food, feed and farm income while protecting and improving environmental quality (Robertson and Swinton, 2005). Approximately 854 million people are food insecure globally (Borlaug, 2007). There are warnings of even bigger challenges to food security by 2050 when the present population of 6.7 billion reaches 9.5 billion, before stabilizing at about 10 billion by the end of the 21st century (Lal, 2009). Food insecurity is also related to a worldwide decrease in per capita arable land (Horrigan et al., 2002), a decrease in renewable freshwater supply (Barnett et al., 2005), the decline in production capacity of soils (Lal, 2009), and projected changes in the climate (Parry et al., 2004).

Water is a key driver of agricultural production. Globally, agriculture accounts for more than 80% of all freshwater used by humans, most of that is for crop production (Morison *et al.,* 2008). Irrigation has helped boost agricultural yields and outputs in semi-arid and arid environments and stabilized food production and prices (Hanjra et al., 2009a, 2009b; Rosegrant and Cline, 2003), and the revenue from the agriculture sector (Sampath, 1992). Only 19% of agricultural land cultivated through irrigation supplies 40% of the world's food (Molden et al., 2010) and has thus brought substantial socioeconomic gains (Evenson and Gollin, 2003). However, continued increase in demand for water by non-agricultural uses, such as urban and industrial uses and greater concerns for environmental quality have put irrigation water demand under greater scrutiny and threatened food security. As the world's population grows and incomes rise, farmers will – if they use today's methods – need a great deal more water to keep everyone fed: another 1600 km^3/yr just to achieve the UN Millennium Development Goals of halving hunger by 2015 (SEI, 2005), and another 4500 km^3/yr with current water productivity levels in agriculture to feed the world in 2050 (Falkenmark *et al*., 2009; Rockström *et al*., 2009). This is more than twice the current consumptive water use in irrigation, which already contributes to depleting several large rivers before they reach the ocean. It is becoming increasingly difficult, on social, economic and environmental grounds, to supply more water for irrigation. In future, less water will be available for agricultural production, while at the same time food production must be increased to feed the growing population. Increasing crop water productivity (WP) is a key response option to meet this challenge (Kijne *et al*., 2003a; Molden *et al*., 2007). Reasons to improve agricultural WP include: (i) to meet rising demands for food from a growing, wealthier, and increasingly urbanized population in light of water scarcity, (ii) to respond to pressures to re-allocate water from agriculture to cities and ensure that water is available for environmental uses, and (iii) to contribute to poverty reduction and economic growth (Molden *et al.*, 2010). Recent forecasts warn of impending global problems unless appropriate action is taken to improve water management and increase crop water productivity (Seckler et al., 1998; Alcamo et al., 1997; Rosegrant et al., 2002, 2005; Shiklomanov, 2000; Vorosmarty et al., 2004; Bruinsma, 2003; SEI, 2005; Falkenmark and Rockstrom, 2004).

Reviews dealing with the analysis of CWP, calculated by the ratio between the final harvest yield and the seasonal values of actual evapotranspiration (Zwart and Bastiaanssen, 2004; Molden and Oweis, 2007; Hsiao *et al.*, 2007; Katerji *et al.*, 2008) have highlight different strategies for improving CWP. Integrating biological water-saving measures with engineering solutions (water saving irrigation method, deficit irrigation, proper deficit sequencing, modernization of irrigation system, etc.), and agronomic and soil manipulation (seed priming, seedling age manipulation, direct- or wet-seeded rice, proper crop choice, increasing soil fertility, addition of organic matter, tillage and soil mulching, etc.) has been suggested to improve CWP.

The CWP value is a complex indicator because it can be ascribed (Katerji *et al.*, 2008) mainly to agro-techniques (water regime, mineral supply and water quality), plant factors (species, varieties and sensitivity of the growth stage to the stress), and environment (climate, atmospheric pollution, soil texture and climate change). Appropriate crop management strategies to improve CWP should be taken into account with these different factors and their potential interactions. Furthermore, in order to improve CWP, we need to reveal the cause– effect relationships between variables such as evaporation, transpiration, percolation or capillary rise, and biophysical variables such as dry matter and grain yields under different eco-hydrological conditions. Studying different factors and their interactions affecting CWP and measurements of the required hydrological variables under field conditions are difficult, time consuming, expensive and need sophisticated instrumentation. To overcome these problems, simulation model offers the opportunity to gain detailed insights into the system behavior in space and time. Models make it possible to evaluate the effects of different yield-affecting factors simultaneously in order to identify optimal water and nutrient regimes (optimal crop management options) for specific scenarios. They also make it possible to examine water and nutrient balance which can be useful when attempting to develop optimal water and nutrient management strategies to achieve higher CWP.

Assessing yield, returns and WP of crops and cropping systems under existing agro-climatic, crop management and socio-economic conditions prevailing in a region along with quantification of cause – effect relationship among different variables which affects WP are prerequisite to develop and/or identify suitable management options for improving CWP. As the information pertaining to yield, returns and WP of crops and quantification of different variable determining yield and WP are scarce for IGNP command area of India; the present project (Study or experiment) was undertaken during 2011 – 2012 and 2012 - 2013 in Indira Gandhi Nahar (Canal) Project (IGNP) Command area of North western Rajasthan, India with following objectives:

i) Assessing yield, returns and water productivity of crops (cropping systems);

ii) Calibration and verification of or Validation and performance evaluation of Crop-syst model for different crops. (cropping systems)

iii) Developing set of recommendation for water, nutrient and crop management to get higher land and water productivity (if scenario analysis available);

iv) Capacity building of researchers (in case of project report)

An overview of study area

The Indian hot arid region covers 31.7 million ha, and is characterized by low (100 - 400 mm y^{-1}) and erratic (CV > 50%) rainfall, high evapotranspiration (1600 - 2000 mm y^{-1}) and high wind speed (Rao and Singh, 1998). Soils are coarse textured, deficient in organic matter and nitrogen (N) and have poor moisture retention capacities (Gupta *et al.*, 2000).Water resources and vegetation cover are therefore low and the average productivity of crops in this region is very low (<0.5 t ha^{-1}). High biotic pressure (human and livestock numbers have increased from 5.87 million and 13.80 million in 1950 to 22.50 million and 27.50 million in 2001, respectively) has resulted in the overexploitation of resources and poses a serious threat to the sustainability of the region (Gupta and Narain, 2003).

IGNP is one of the largest irrigation projects in the world, and was conceived to transform the dreary and desolate Thar Desert into a land of prosperity and plenty. The project had laudable objectives of "drought proofing, provision of drinking water, industrial and irrigation facilities, creation of employment opportunities, settlement of human population of thinly populated desert areas; improvement of fodder, forage and agriculture facilities, check spread of desert area and improve ecosystem through large-scale afforestation, develop road network and provide requisite opportunities for overall economic development" (IGNB 2002). The project has been divided into two stages (Figure 1):

Stage – I: It comprises of 204 km long feeder from Harike Barrage in Punjab to Masitawali in Hanumangarh (Rajasthan), and 189 km long main canal from Masitawali to Chattargarh in Bikaner district. It has 3454 km long distribution system to serve a CCA of 0.553 M ha. It has one lift canal system (Lunkaransar lift scheme).

Stage – II: It consist 256 km long main canal from Chhatargarh to Mohangarh (Jaisalmer), with 5606 km long distribution system to serve a CCA of 1.41 Mha. It has six "Lift canal": Sahwa, Gajner, Kolayat, Bangarser, Phalodi and Pokaran lift scheme (Gupta A.K. *et al.*, 2002).

By 2004-05, 559,000 ha irrigation potential was created under Stage I and 510,000 ha under Stage II. The transformation brought about by the project in poverty alleviation, improving agricultural productivity, providing livelihood, settling people and providing drinking water etc. has been remarkable (Kavadia and Hooja, 1994). While the IGNP opened up vast possibilities for development, it has simultaneously posed several intriguing environmental, management and social challenges (Ramanathan and Rathore, 1994; Mac Donald and Dalal, 1999; MacDonald *et al.,* 1999).

Rapidly increasing water table which leads to water logging, development of secondary soil salinity, low crop yield and input use efficiency in crop production are some of the serious concerns in IGNP command area. The proper management of water in command area is essential to augment water productivity and minimizing adverse effects of water logging, salinity etc. associated with faulty water management practices followed in the IGNP command area.

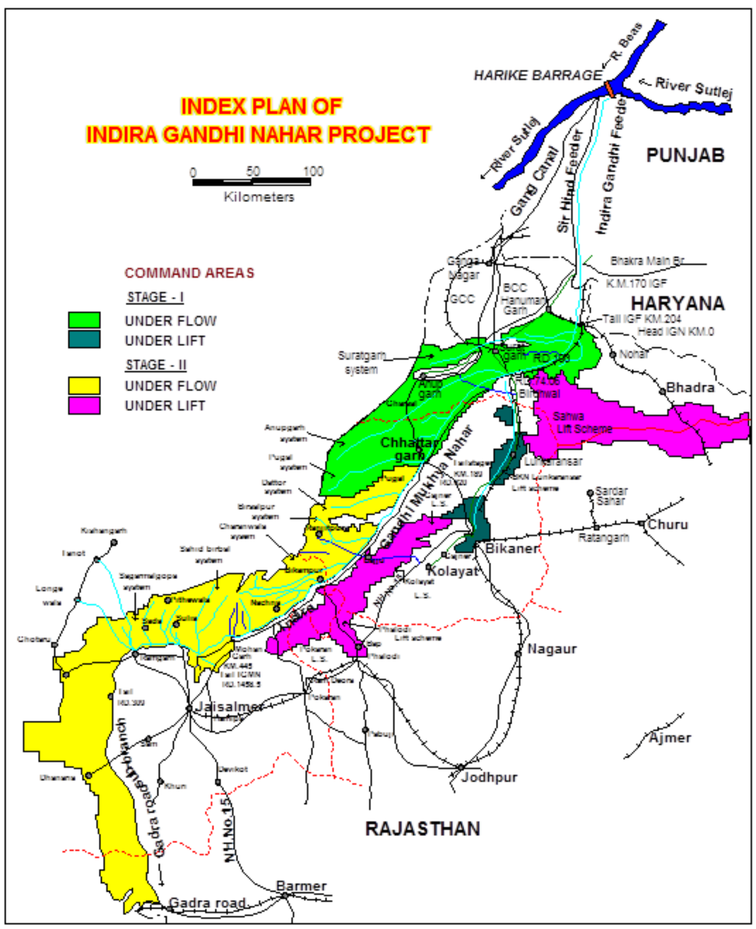

Figure 1 : Index plan of Indira Gandhi Nahar Pariyojna (IGNP)

2. MATERIALS AND METHODS

2.1 Study site

Village Mainawali (74° 20’34” - 74° 20’60” E longitude and 28° 37’62” N - 29° 21’39” N latitude; 235 m asl) in district Hanumangarh (Figure 2), Rajasthan having 28 farmer household were selected. The study site has area of 187 ha receiving water from a common water distributary of IGNP stage - I. The climate of experimental site is hot arid with an average annual precipitation of 281 mm; the mean maximum and minimum temperature are 43.03 and 5.05 ˚C, respectively (Ram and Chauhan, 2002). More than 85% of the total annual rainfall is received during the south-west monsoon season (July to September). The weather data for the crop growing seasons during the two-year experiment are presented in Figure 3.

The soil has following key properties for the 0- to 15-cm layer: pH (soil/H2O, 1:2.5): 8.1, organic carbon: 1.3 g kg $^{-1}$ (Walkley–Black method), available NO_3 – N: 20.2 kg ha^{-1}; available NH_4 – N: 55.6 kg ha^{-1}; texture was loamy sand, with sand (2000–50 μm), silt (50–2 μm) and clay (<2 μm) content: 678, 21 and 11 g kg^{-1} respectively.

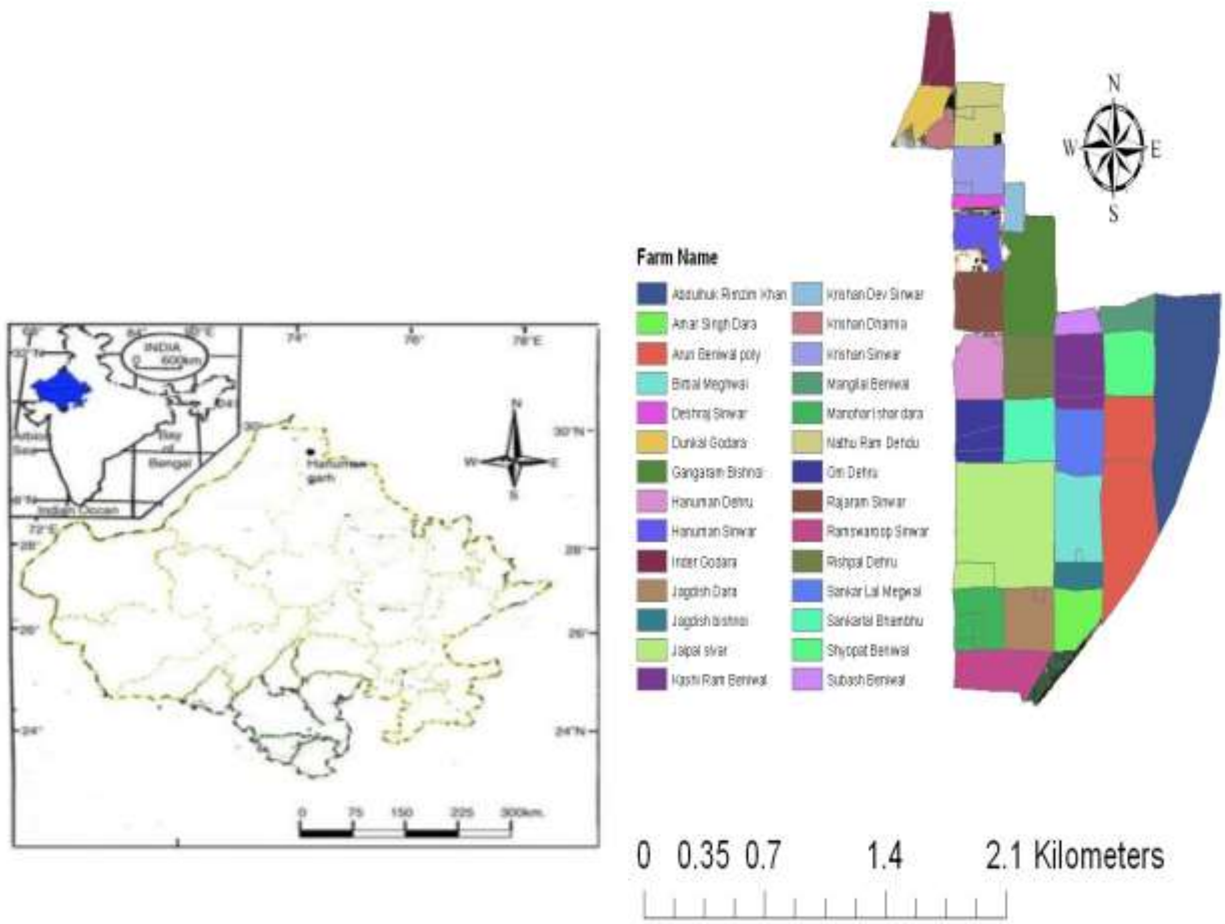

Figure 2. Study location and land holding of different farmers

2.2. Assessment of yield, returns and water productivity of crops

Out of total 28 farms of Village, 15 farms were selected randomly to assess agronomic and economic performance of crops/ cropping systems. The detailed information regarding cultivar used, tillage operations (time, frequency and type of implements used), nutrient management (time, rate and source of nutrient), sowing (time, method, seed rate), plant protection measures (time, method, and rate of application of pesticides), harvesting and threshing were collected by personal interview method (The detail of crop management practices for each farmer is appended as Annexure 1). The amount of irrigation application was measured by using V notch weir.

Crop yields were determined at the maturity stage from five randomly selected 2 × 2 m^2 area (in case of cotton the 4 picking from selected area is used) . Economic and straw yields were separated manually after harvesting. Sub-samples of economic yield (seed and seed cotton in case of cotton) and by-products (straw) were oven-dried to a constant weight at 70 °C and expressed as kg ha^{-1}.

Total biomass yields (BY) were measured by totaling the EY [seed / (seed cotton in case of cotton)] and straw yields (SY) of the individual crops. Costs of cultivation (CC) and returns of crops were calculated on the basis of prevailing market prices for inputs and outputs. Net returns were calculated by subtracting CC from the gross value of the produce (main and by-products) for each of the crops:

$$NR = \{(EY)(Pe) + (SY)(Ps)\} - \{CC\} \quad (1)$$

For individual crop, WP was determined by dividing yields (EY, BY) and returns by amount of water applied (rainfall + irrigation) as follows:

$$WP = Y\ (EY \text{ or } BY) \text{ or } NR\ /\ TW \quad (2)$$

where Y is the yield (EY or BY in kg ha^{-1}) and TW is the total water applied (mm) to crop.

2.3. Validation and performance evaluation of CropSyst model

2.3.1. Model used:

CropSyst (Cropping Systems Simulation Model) is a multiyear, multi-crop, daily time step crop growth simulation model, developed with emphasis on a friendly user interface, and with a link to GIS software and a weather generator (Stockle et al., 1994, 2003; Stockle and Nelson, 1999).

The model is intended for crop growth simulation over a unit field area (m^2). Growth is described at the level of whole plant and organs. The water budget in the model includes precipitation, irrigation, runoff, interception, water infiltration, and water redistribution in the soil profile, crop transpiration, and evaporation. Water redistribution in the soil is handled by a simple cascading approach or by a finite difference approach to determine soil water fluxes. CropSyst offers three options to calculate grass reference ET. In decreasing order of required weather data input, these options are: the Penman–Monteith model, the Priestley–Taylor model, and a simpler implementation of the Priestley–Taylor model, which only requires air temperature. Crop ET is determined from a crop coefficient at full canopy and ground coverage determined by canopy leaf area index. The nitrogen budget in CropSyst includes N transformations, ammonium sorption, symbiotic N fixation, crop N demand and crop N uptake. Nitrogen transformations of net mineralization, nitrification and denitrification are simulated. The water and nitrogen budgets interact to produce a simulation of N transport within the soil. Crop development is simulated based on thermal time required to reach specific growth stages. Daily crop growth is expressed as biomass increase per unit ground area. The model accounts for four limiting factors to crop growth: water, nitrogen, light, and temperature. The increase of leaf area during the vegetative period, expressed as leaf area per unit soil area (leaf area index, LAI), is calculated as a function of biomass accumulation, specific leaf area, and a partitioning coefficient. Leaf area duration, specified in terms of thermal time and modulated by water stress, determines canopy senescence. Root growth is synchronized with canopy growth, and root density by soil layer is a function of root depth penetration. The prediction of yield is based on the determination of harvest index (grain yield/aboveground biomass). The harvest index is determined using the unstressed harvest index as base, a required crop input parameter, modified according to crop stress (water and nitrogen) intensity and sensitivity during flowering and grain filling.

2.3.2Input parameters

Four input data files are required to run CropSyst: Location, Soil, Crop, and Management files. A Simulation Control file combines the input files as desired to produce specific simulation runs.

The Location file includes information such as latitude, weather file code name and directories, rainfall , and local parameters to generate daily solar radiation and vapor pressure deficit (VPD) values.

The Soil file includes surface soil CEC and pH, required for ammonia volatilization, parameters for the curve number approach (runoff calculation), surface soil texture (for erosion calculation), and five parameters specified by soil layer: layer thickness, field capacity, permanent wilting point, bulk density, and bypass coefficient.

The Management file includes automatic and scheduled management events. Automatic events (irrigation and nitrogen fertilization) are generally specified to provide optimum management for maximum growth. Management events can be scheduled using actual date, relative date (relative to year of planting), or using synchronization with phenological events (e.g., number of days after flowering). Scheduled events include irrigation (application date, amount, chemical or salinity content), nitrogen fertilization (application date, amount, source - organic and inorganic), and application mode - broadcast, incorporated, injected), tillage operations (primary and secondary tillage operations), and residue management (grazing, burning, chopping, etc.).

The Crop file allows users to select parameters to represent different crops and crop cultivars using a common set of parameters. This file is structured in the following sections: phenology (thermal time requirements to reach specific growth stages, modulated by photoperiod and vernalization requirements if needed), morphology (maximum LAI, root depth, specific leaf area and other parameters defining canopy and root characteristics), growth (transpiration-use efficiency normalized by VPD, light-use efficiency, stress response parameters, etc.), residue (decomposition and shading parameters for crop residues), nitrogen parameters (defining crop N demand and root uptake), harvest index (unstressed harvest index and stress sensitivity parameters), and salinity tolerance.

2.3.3 Output parameters

Main simulated output by CropSyst are harvest date, planting dormancy date, emergence date, maturity date, yield, above ground biomass, soil water drainage, actual ET, total N uptake and N leached.

2.3.4 Data collection

Dates of important crop specific phenological events (i.e. emergence, panicle initiation, flowering and physiological maturity) were observed and thermal time for those stages was calculated as growing degree-days. Observations were taken for green area index (GAI); dry weight of stem, leaf and grain; N content in stem, leaf and grain; number of tillers and leaves at four different crop growth stages. The soil parameters required for models were estimated at sowing of the crop. Soil texture was estimated by hydrometer method (Bouyoucos, 1927), soil pH was determined by Piper's 1:2 (soil: water) method (Jackson, 1973). Gravimetric method (Jackson, 1973) was followed for estimating bulk density. Field capacity and permanent wilting point was estimated by pressure plate method (Richards and Weaver, 1964). Available N in the form of $NO_3^{\ -}$ and NH_4^+ was determined by Bremner's KCl extraction method (Bremner, 1965). Organic carbon was determined by wet acid digestion method (Walkley and Black, 1934). The weather parameters were taken from the weather station of ARS, Sriganganagar.

2.3.5. Model calibration

Model calibration or parameterization is the adjustment of parameters so that simulated values compare well with observed values. For parameterization of CropSyst the heat sums for different phenological stage (emergence, peak LAI, flowering, grain filling and physiological maturity) were estimated from the base temperature, cutoff temperature and daily mean temperature (Stockle and Nelson, 1996). Then other crop parameters were derived manually by changing 5% of the default value of each crop parameter till a satisfactory level of agreement between predicted and observed value of yield, biomass was achieved. For calibration the data from the first year of experiment was considered.

2.3.6. Validation and evaluation of models

Before any model can be used with confidence, adequate validation or assessment of the magnitude of the errors that may result from their use should be performed. Model validation, in its simplest form, is a comparison between simulated and observed values.

To determine model performance, we compared simulated and measured economic yield (EY), above-ground biomass yield (ABY) and nitrogen uptake (NU) root mean square error (RMSE), relative root mean square error (RRMSE), correlation coefficient (CC) (or the coefficient of determination (r2)) and the index of agreement (IoA). (Willmott, 1982; Legates and McCabe, 1999; Yang et al., 2000). In this study, the EY, ABY and NU parameters in CropSyst were calibrated against the experimental data for the 2012–2013 growing season and the resulting model was validated by comparing the model's output to experimental data for the 2013 - 2014 growing season.

The RMSE is calculated using the following expression:

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(P_i - O_i)^2}{n}}$$

RRMSE is calculated using the following expression:

$$\mathbf{RRMSE} = \sqrt{\frac{\sum_{i=1}^{n} (P_i - O_i)^2}{n}} \cdot \frac{100}{\bar{O}}$$

Where n is number of observations, Pi is value predicted by model, Oi is measured value, and Ō is the mean of measured values. The RRMSE provides a measure (%) of the relative difference between the simulated and observed results. The quality of the simulation is considered to be excellent if the RRMSE is less than 10%, good if it is between 10% and 20%, fair if it is between 20% and 30%, and poor if it is above30% (Jamieson et al., 1991).

The index of agreement (IoA)

$$= 1 - \left(\frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} (|P_i - O| + |O_i - O|)^2} \right)$$

Provide adequate nomenculture and judging criterion for the IoA.

vhere n is the number of samples, P_i and O_i are the predicted and bserved values, and O is the mean of the observed data. The closer he value of root mean square error ($RMSE$) is to 0, the more accurate s the model. Modeling efficiency (E) ranges from $-\infty$ to 1. An effi-

The RRMSE is calculated as:

RRMSE =

Where n is number of observations, Pi is value predicted by model, Oi is measured value, and Ō is the mean of measured values. The

(3) Agreement index (d) (Willmott, 1981)

$$d = 1 - \left(\frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} (|P_i - O| + |O_i - O|)^2} \right)$$

ter predictor than the model. Agreement index (d) represents the ratio of the mean square error and the potential error. A perfect match between prediction and measurement results in $d = 1$. Based on Van Liew and Garbrecht (2003), an acceptable simulation should have $E > 0.36$ and $d > 0.7$.

3. Results and Discussion (Salient findings)

3.1. Weather conditions:

The weather conditions during cropping seasons (kharif: June to October, rabi: November to May) is presented in Figure 3. The 2012 – 2013 cropping year received higher rainfall (415 mm) compared to 2013 – 2014 cropping year (326 mm). The total rainfall during Kharif season was 308 mm in 2012 – 2013 and 228 mm in 2013 – 2014. There are distinct temporal variations in rainfall during Kharif season between the two years. In 2012 – 2013 the highest rainfall received during September (185 mm) and July (74 mm), whereas in 2013 – 2014 highest rainfall received during August (114 mm) and July (80 mm). Thus the August was relatively drier in 2012 – 2013 and September was drier in 2013 – 2014. The evaporation and temperatures did not vary considerably during 2012 – 2013 and 2013 – 2014.

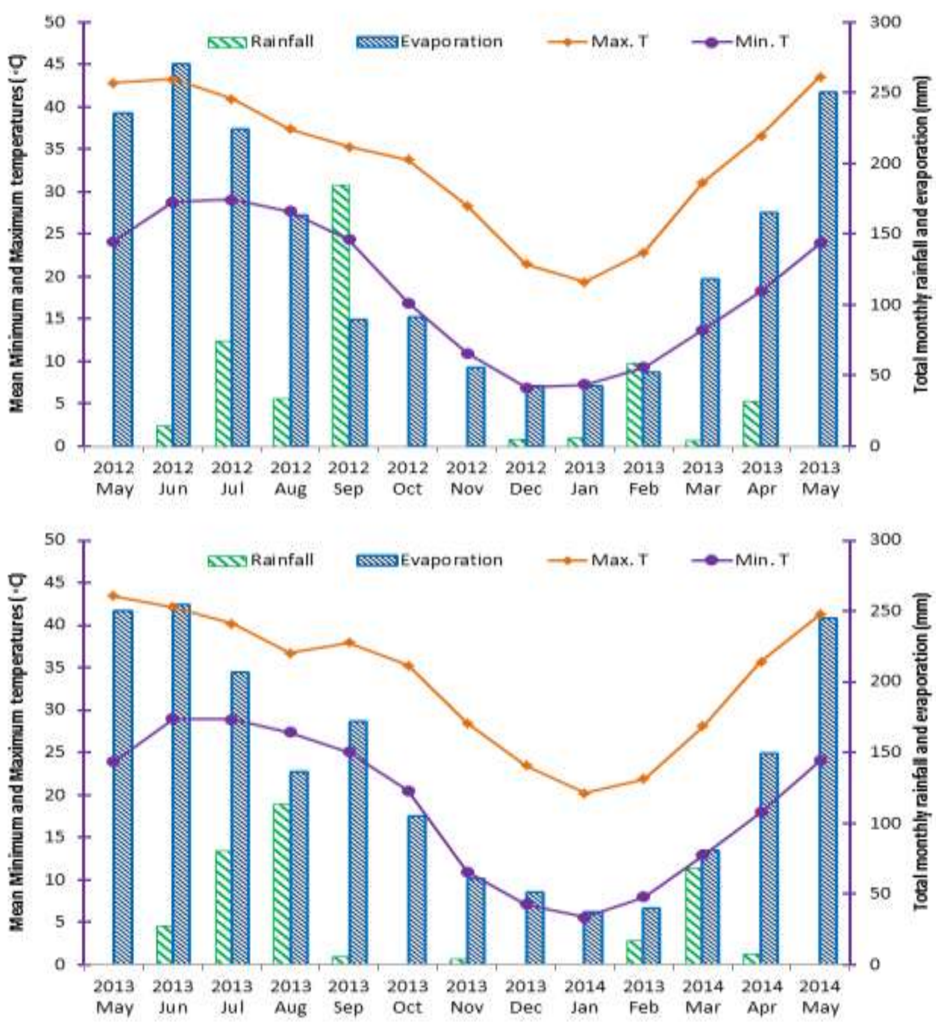

Figure 3. Weather conditions during 2012 – 2013 and 2013 – 2014 crop growing season In IGNP Stage – I, Hanumanagarh, India

3.2. Productivity and profitability of crops:

The EY (economic yield) and ABY (above ground biomass yield) varied considerably amongst studied crops (Table 1). Amongst Kharif season crops, the EY varied from 1946 kg ha^{-1} to 2212 kg ha^{-1}; and ABY varied from 5844 kg ha^{-1} to 8077 kg ha^{-1}. Averaged across years, cotton had 32 % higher EY and 29 % higher ABY than that of clusterbean (Figure 4A and B). Amongst rabi season crops the EY varied from 1940 kg ha^{-1} to 4182 kg ha^{-1}, and ABY varied from 5844 kg ha^{-1} to 8077 kg ha^{-1}.Wheat had highest yield (EY : 4180 kg ha^{-1} , ABY : 9981 kg ha^{-1}) followed by barley (EY :4021 kg ha^{-1}, ABY : 9861 kg ha^{-1}) and Indian mustard (EY : 1938 kg ha^{-1} , ABY : 5898 kg ha^{-1}). Averaged across years, the bread wheat had 2.2 and 1.7 folds higher EY and ABY compared to Indian mustard. Thus, yields of crops varied substantially and among kharif season crops cotton had higher yields than clusterbean; and bread wheat had higher yields than other *rabi* season crops (Figure 4 A).

Table 1. Yields, cost of cultivation and net return of crops in IGNP stage – I, Hanumangarh, India.

Crop	**EY (kg ha^{-1})**	**ABY (kg ha^{-1})**	**CC (Rs ha^{-1})**	**NR (Rs ha^{-1})**
		2012 - 2013		
Kharif season				
Cotton	1946 ± 228	7359 ± 846	43118 ± 2386	53580 ± 11348
Cluster bean	1530 ± 231	5844 ± 951	24386 ± 2175	213680 ± 35669
Rabi season				
Bread wheat	4182 ± 180	9833 ± 286	27630 ± 2152	50058 ± 3577
Indian mustard	1940 ± 309	5952 ± 901	21524 ± 1729	31421 ± 6606
Barley	4051 ± 152	9794 ± 411	29600 ± 2124	50420 ± 3671
		2013 -2014		
Kharif season				
Cotton	2212 ± 111	8077 ± 294	40479 ± 1174	90423 ± 5023
Cluster bean	1612 ± 109	6089 ± 398	23824 ± 482	63452 ± 4391
Rabi season				
Bread wheat	4178 ± 201	10128 ± 800	32042 ± 1214	56152 ± 4082
Indian mustard	1936 ± 143	5844 ± 378	25019 ± 1032	41985 ± 4607
Barley	3991 ± 138	9928 ± 162	28524 ± 664	33893 ± 814

Values are mean ± standard deviation
Cotton *: Gossypium hirsutum* ; Clusterbean : *Cyamopsis tetragonoloba* ; Bread wheat : *Triticum aestivum*; Indian mustard : *Brassica juncea*; Barley : *Hordeum vulgare*; Chick pea : *Cicer arietinum*
Where EY : economic yield, ABY : above-ground biomass yield; CC : cost of cultivation; NR : net return and NC : not cultivated

Under non-stressed conditions, yield of crop at any given location is determined by the product of the available light energy and by the genetically determined properties: efficiency of light capture [which is function of LAI and canopy architecture (radiation interception coefficient, k)] , the efficiency of conversion of the intercepted light into biomass [i.e. radiation use efficiency (RUE)], and the proportion of biomass partitioned into grain [harvest index (HI)], each describing broad physiological and architectural properties of the crop (Long *et al.*, 2006) ; and variations in these efficiencies leads to variations in yields of crops. The higher ABY of cotton compared to clusterbean, and wheat compared to Indian mustard in present study might be explained by longer duration (greater light energy available over crop duration) and higher RUE of cotton and wheat compared to other crops in their respective seasons. The reported value of RUE (1.70 – 1.92 g MJ $^{-1}$) for cotton (Sardas and Wilson, 1997) is higher compared to RUE (1.33 g MJ $^{-1}$) for clusterbean (Khicahr et al., 2012). Similarly, the value of RUE (2.8 g MJ $^{-1}$) for wheat (Kiniry et al. 1989.) is higher compared to RUE (1.25 – 1.45 g MJ $^{-1}$) for Indian mustard (Jha et al., 2012). High ABY does not necessarily translate into higher EY, when we compare different crops. The difference in HI reflected in variations in EY for crops, for instance the average HI for wheat and barley (0.4) was higher than Indian mustard (0.3). Thus higher EY for wheat and barley compared to Indian mustard can be attributed to both greater ABY (due to longer crop duration and higher RUE) and HI than that for Indian mustard.

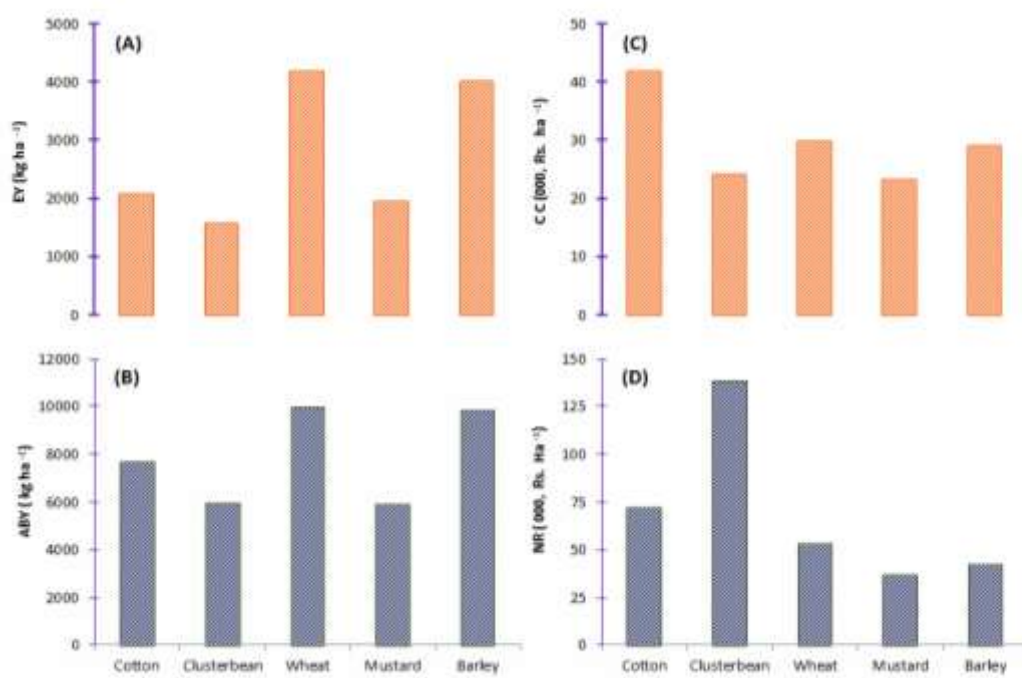

Figure 4. Average (A) economic yield, (B) above ground biomass yield, (C) cost of cultivation, and (D) net return of crops cultivated during 2012 -2013 and 2013 – 2014 in IGNP stage – I, Hanumangarh, India.

The cost of cultivation (CC) of crops varied from Rs. 24386 ha^{-1} to Rs. 43118 ha^{-1}. Averaged across years the cultivation of cotton incurred highest cost (Rs. 41799 ha^{-1}) followed by wheat (Rs. 29836 ha^{-1}), barley (Rs. 29062 ha^{-1}), clusterbean (Rs. 24105 ha^{-1}), and Indian mustard (Rs. 23272 ha^{-1}) (Figure 4 C). The cotton incurred 40, 44, 73 and 80 % higher CC compared to wheat, barley, clusterbean and Indian mustard, respectively. The higher labor, irrigation, and seed costs for cotton compared to clusterbean was responsible for higher CC of cotton .The higher CC of wheat is attributed to higher labor and irrigation costs compared to Indian mustard.

The profitability of crops measured in terms of net return (gross return – cost of cultivation) varied from Rs. 33893 ha^{-1} to Rs. 213680 ha^{-1} (Table 1) Averaged across both the years, the clusterbean had greatest NR (Rs. 138566 ha^{-1}) followed by cotton (Rs. 72002 ha^{-1}), wheat (Rs. 53103 ha^{-1}), barley (Rs. 42157 ha^{-1}) and Indian mustard (Rs.36703 ha^{-1}) (Figure 4D). Amongst the kharif season crops, cotton earned 1.9 times higher profit than clusterbean. Amongst Rabi season crops, wheat was most profitable and it earned 1.3 and 1.4 folds higher NR than barley and Indian mustard, respectively. The clusterbean despite having lower yields (EY and ABY) than cotton, was more profitable than cotton. This can be explained by higher selling price and lower cost of cultivation for clusterbean than that for cotton. In contrast, despite higher selling price of Indian mustard compared to wheat, it earned minimum NR due to lower EY.

3.3. Water use and water productivity:

The total amount of water applied for different crops varied from 315 mm to 676 mm, being highest for cotton, followed by wheat, barley, clusterbean and Indian mustard (Table 2). The amount of irrigation water applied had range : 92 – 470 mm. Averaged across both the years, the mean amount of irrigation water applied were highest for cotton (402 mm) followed by barley (318 mm), Indian mustard (252 mm) and clusterbean (92 mm) (Figure 5A). Amongst the kharif season crops, the amount of irrigation water applied for cotton was 4.4 folds higher than that for clusterbean. In case of rabi season crops, the amount of irrigation water applied for wheat were 1.5 and 1.8 times higher than for barley and Indian mustard, respectively.

The water productivity of total water applied measured in terms of economic yield (WP_{TWY}) varied from 0.27 kg m^{-3} to 1.00 kg m^{-3} (Table 2). Averaged across the years, the WP_{TWY} for cotton, clusterbean, Indian mustard, wheat and barley were 0.31, 0.45, 0.62, 0.75 and 0.98 kg m^{-3}, respectively (Figure 5C). Thus considering WP_{TWY}, the clusterbean was 1.4-times more water productive than clusterbean, and among rabi season crops, barley was 1.3- and 1.6- times more water productive than wheat and Indian mustard, respectively. The water productivity of total water applied measured in terms of return (WP $_{TWR}$) varied from 7.4 Rs. m^{-3} to 52.7 Rs. m^{-3}. Averaged across the years, the WP $_{TWR}$ for cotton, clusterbean, Indian mustard, wheat and barley were 10.9, 36.4, 12.0, 9.5 and 10.3 kg m^{-3}, respectively (Figure 5D). Thus considering WP $_{TWR}$, the clusterbean was 3.3-times more water productive than clusterbean, and among rabi season crops, Indian mustard was 1.2- and 1.3- times more water productive than barley and wheat, respectively. Thus, considering WP measured for total water applied in terms of economic yield and return the clusterbean was more water use efficient than cotton. Among the rabi season crops, barley had greatest WP $_{TWY}$ and, Indian mustard had greatest WP $_{TWR.}$

Table 2. Water applied and water productivities of crops in IGNP stage -I, Hanumangarh, India.

Crop	**Water applied (I + R) (mm)**	**WP (kg m^{-3})**	**WP (Rs m^{-3})**	**WP$_{IW}$ (kg m^{-3})**	**WP$_{IW}$ (Rs m^{-3})**
			2012 - 2013		
Kharif season					
Cotton	408.2 + 318.5	0.27	7.4	0.48	13.1
Cluster bean	91.6 + 314.1	0.38	52.7	1.67	233.3
Rabi season					
Bread wheat	451.2 + 104.3	0.75	9.0	0.93	11.1
Indian mustard	270.8 + 82.0	0.55	8.9	0.72	11.6
Barley	300.0 + 106.0	1.00	12.4	1.35	16.8
			2013-2014		
Kharif season					
Cotton	396.4 + 228.1	0.35	14.5	0.56	22.8
Cluster bean	91.8 + 222.1	0.51	20.2	1.76	69.1
Rabi season					
Bread wheat	470.4 + 88.8	0.75	10.0	0.89	11.9
Indian mustard	234.1 + 42.8	0.70	15.2	0.83	17.9
Barley	315.8 + 99.2	0.96	8.2	1.26	10.7

Values are mean
Cotton *: Gossypium hirsutum* ; Clusterbean : *Cyamopsis tetragonoloba* ; Bread wheat : *Triticum aestivum*; Indian mustard : *Brassica juncea*; Barley : *Hordeum vulgare*; Chick pea : *Cicer arietinum*
Where I : irrigation, R : rainfall; WP : water productivity ; WPIW :irrigation water productivity

The water productivity of irrigation water applied measured in terms of economic yield (WP $_{IWY}$) varied from 0.48 kg m^{-3} to 1.76 kg m^{-3} (Table 2). Averaged across the years, the WP $_{IWY}$ for cotton, clusterbean, Indian mustard, wheat and barley were 0.52, 1.71, 0.77, 0.91 and 1.31 kg m^{-3}, respectively (Figure 5 E). Thus considering WP $_{IWY}$, the clusterbean was 3.3-times more water productive than clusterbean, and among rabi season crops, barley was 1.4- and 1.7- times more water productive than wheat and Indian mustard, respectively. The water productivity of irrigation water applied measured in terms of return (WP_{IWR}) varied from 10.7 Rs. m^{-3} to 233.1 Rs. m^{-3}. Averaged across the years, the WP_{IWR} for cotton, clusterbean, Indian mustard, wheat and barley were 18, 151, 15, 12 and 14 Rs. m^{-3}, respectively (Figure 5F). Thus, considering WP_{IWR}, the clusterbean was 8.4-times more water productive than clusterbean. Among rabi season crops, Indian mustard had 7 % and 28 % higher WP_{IWR} than barley and wheat, respectively. Thus, considering WP measured for irrigation water applied in terms of economic yield and return the clusterbean was more water use efficient than cotton. Among the rabi season crops, barley had greatest WP_{IWY} and, Indian mustard had greatest WP_{IWR}.

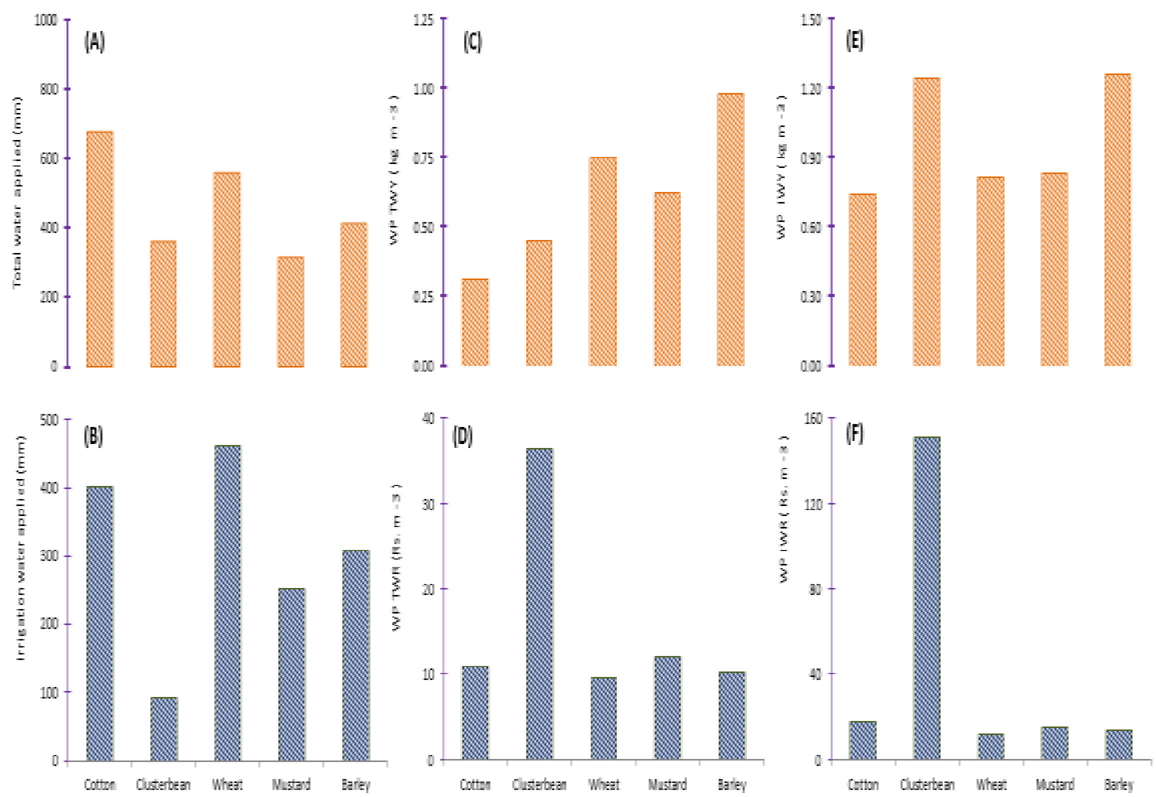

Figure 5. Average (A) total water applied, (B) irrigation water applied, (C) physical water productivity for total water applied (D) economic water productivity for total water applied (E) physical water productivity for irrigation water applied, and (F) economic water productivity for irrigation water applied of crops cultivated during 2012 -2013 and 2013 – 2014 in IGNP stage – I, Hanumangarh, India.

3.4. Model calibration and validation:

Calibration is the process of adjusting parameters values to obtain a good fit between model outputs and observations. The objective is to later apply the model to conditions similar to those characterizing the data used for the calibration. These parameters were calibrated based on field-measured GAI at different phenophases for different crops during 2012 – 2013. We used a direct (grid) search for optimization of the crop parameters by increments of 5% at a time between specified lower and upper bounds, based on literature and default values available. The combination of these parameters with the lowest RMSE in the simulations of EY, ABY, and NU was selected as the final estimates of these parameters. The calibrated genetic coefficients for different crops for CropSyst model are presented in Table 3. The leaf area duration, heat unit required for peak LAI and required for physiological maturity for the different crops varied from 450 – 950, 185 – 310 and 870 – 1100 ˚C – days respectively. The SLA, stem to leaf partitioning coefficient and harvest index fixed varied from 16 – 25 kg m-2, 1.8 – 3.0 and 0.28 – 0.42, respectively.

Table 3. Genetic coefficients derived using Crop Syst for different crops .

Variable	Units	Cotton	Cluster bean	Wheat	Mustard	Barley
Base temperature	˚C	21.0	12.0	4.0	5.0	4.0
Cutoff temperature	˚C	45.0	30.0	30.0	30.0	30.0
Leaf duration	˚C -days	950	750	*670*	450	800
Begin flowering	˚C -days	395	185	310	230	300
Peak LAI	˚C -days		185	275	255	310
Begin grain filling	˚C -days	595	215	430	275	425
Physiological maturity	˚C -days	870	500	700	650	1100
Maximum rooting depth	m	1.4	1.5	1.5	1.3	1.4
Maximum water uptake	mm day^{-1}	14	14	10	10	10
Maximum expected LAI	m^2 m^{-2}	5	4	5	6	5
Fraction of max LAI at physiological maturity	0 – 1	0.55	0.50	0.80	0.80	0.80
Specific leaf area	m^2 kg^{-1}	16	25	22	25	24
Stem / leaf partition coefficient		3.0	1.20	1.8	2.8	2.5
ET crop coefficient at full canopy		1.25	1.35	1.31	1.35	1.23
Light to above ground biomass conversion	g MJ^{-1}	3	3	5	3	3
Leaf water potential at onset of stomata closure	-J kg^{-1}	-1000	-800	-1500	-700	-700
Wilting leaf water potential	-J kg^{-1}	-1600	-1400	-2500	-1600	-1600
Unstressed harvest index		0.28	0.28	0.42	0.32	0.43

Cotton *: Gossypium hirsutum* ; Clusterbean : *Cyamopsis tetragonoloba* ; Bread wheat : *Triticum aestivum*; Indian mustard : *Brassica juncea*; Barley : *Hordeum vulgare*; Chick pea : *Cicer arietinum*

Model provided very satisfactory estimates for the GAI, physiological maturity of crops. Calibrated results are presented in Table 4. The simulated values for EY and ABY matched well with observed values for most of studied crops.

Table 4. Statistical indices derived for evaluating the calibration of CropSyst models in predicting yields and N uptake of crops.

Crop	Parameters	Observed (kg ha^{-1})	Predicted (kg ha^{-1})	RMSE	RRMSE	CC	IoA
Cotton							
	EY	1946	1891	130	7	0.89	0.92
	ABY	7359	7274	366	5	0.94	0.96
	NU	78	80	5	6	0.84	0.89
Clusterbean							
	EY	1530	1532	119	7.8	0.85	0.92
	ABY	5844	5913	369	6.3	0.91	0.95
	NU	74	75	8	11.0	0.79	0.81
Bread wheat							
	EY	4182	4140	124	3.0	0.87	0.90
	ABY	9833	9956	553	5.6	0.76	0.67
	NU	104	100	7	6.5	0.64	0.74
Indian mustard							
	EY	1978	1858	203	10.3	0.82	0.85
	ABY	6064	5670	623	10.3	0.82	0.84
	NU	79.2	87.5	18	23.0	0.75	0.69
Barley							
	EY	4051	4080	29*	0.70**		
	ABY	9794	9487	307*	3.13**		
	NU	94.31	81.8	13*	13.29**		

Cotton *: Gossypium hirsutum* ; Clusterbean : *Cyamopsis tetragonoloba* ; Bread wheat : *Triticum aestivum*; Indian mustard : *Brassica juncea*; Barley : *Hordeum vulgare*; Chick pea : *Cicer arietinum*

Where EY: Economic yield; ABY: Above-ground biomass yield; NU: Nitrogen uptake; RMSE: Root mean square error, RRMSE: Relative mean square error; CC: Correlation coefficient; IoA: Index of agreement

The validation of model was performed using observations of EY, ABY and NU for the different crops. The performance of model was crop and parameter specific.

Table 5. Statistical indices derived for evaluating the performance of CropSyst models in predicting yields and N uptake of crops.

Crop	Parameters	Observed ($kg\ ha^{-1}$)	Predicted ($kg\ ha^{-1}$)	RMSE	RRMSE	CC	IoA
Cotton							
	EY	2212	2275	84.3	3.81	0.86	0.84
	ABY	8077	8750	700.2	8.67	0.88	0.51
	NU	77	86	11.3	14.6	0.87	0.45
Clusterbean							
	EY	1612	1558	95.5	5.93	0.74	0.81
	ABY	6089	5927	388.3	6.38	0.73	0.81
	NU	70	75	6.2	8.90	0.75	0.60
Bread wheat							
	EY	4178	4090	157.8	3.78	0.74	0.81
	ABY	10128	10260	546.3	5.39	0.83	0.90
	NU	96	88	13.4	14.0	0.82	0.54
Indian mustard							
	EY	1936	1866	123.0	6.36	0.83	0.85
	ABY	5915	5764	215.3	4.68	0.87	0.89
	NU	75	82	14.3	19.14	0.90	0.59
Barley							
	EY	3991	4128	151.5	3.79	0.85	0.72
	ABY	9927	10129	374.9	3.78	0.78	0.58
	NU	98	94	4.71	4.81	0.86	0.76

Cotton *: Gossypium hirsutum* ; Clusterbean : *Cyamopsis tetragonoloba* ; Bread wheat : *Triticum aestivum*; Indian mustard : *Brassica juncea*; Barley : *Hordeum vulgare*; Chick pea : *Cicer arietinum*

Where EY: Economic yield; ABY: Above-ground biomass yield; NU: Nitrogen uptake; RMSE: Root mean square error, RRMSE: Relative mean square error; CC: Correlation coefficient; IoA: Index of agreement

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