J. Agronomy & Crop Science (2009) ISSN 0931-2250

HEAT, CHILLING AND FREEZING STRESS

Analysis of Water Non-limiting and Water Limiting Yields and Yield Gaps of Groundnut in India Using CROPGRO-Peanut Model

V. S. Bhatia[1], P. Singh[2], A. V. R. Kesava Rao[2], K. Srinivas[2] & S. P. Wani[2]

1 National Research Centre for Soybean (ICAR), Indore, Madhya Pradesh, India
2 Global Theme on Agroecosystems, International Crops Research Institute for the Semiarid Tropics (ICRISAT), Patancheru, Andhra Pradesh, India

Keywords
actual yield; CROPGRO-Peanut; India; water limiting yield; water non-limiting yield; yield gaps

Correspondence
V. S. Bhatia
National Research Centre for Soybean,
Khandwa Road, Indore, Madhya Pradesh
452 017, India
Tel.: +91 731 2760987
Fax: +91 731 2470520
Email: bhatia_virender_singh@hotmail.com

Accepted July 17, 2009

doi:10.1111/j.1439-037X.2009.00392.x

Abstract

To assess the scope for enhancing productivity of groundnut (*Arachis hypogaea L.*) in India, well-calibrated and validated CROPGRO-Peanut model was used to assess potential yields (water non-limiting and water limiting) and yield gaps of groundnut for 18 locations representing major groundnut growing regions of India. The average simulated water non-limiting pod yield of groundnut for the locations was 5440 kg ha^{-1}, whereas the water limiting yield was 2750 kg ha^{-1} indicating a 49 % reduction in yield because of deficit soil moisture conditions. As against this, the actual pod yields of the locations averaged 1020 kg ha^{-1}, which was 4420 and 1730 kg ha^{-1} less than the simulated water non-limiting and water limiting yields, respectively. Across locations, the simulated water non-limiting yields were less variable than water limited and actual yields, and strongly correlated with solar radiation during the crop season ($R^2 = 0.62$, $P \leq 0.01$). Simulated water limiting yield showed a significant positive, but curvilinear relationship ($R^2 = 0.73$, $P \leq 0.01$) with mean crop season rainfall across locations. The relationship between actual yield and the mean crop season rainfall across locations was not significant, whereas across seasons for some of the locations, the association was found to be significant. Total yield gap (water non-limiting minus actual yields) ranged from 3100 to 5570 kg ha^{-1}, and remained more or less unaffected by the quantity of rainfall received across locations. The gap between simulated water non-limiting and water limiting yields, which ranged from 710 to 5430 kg ha^{-1}, was large at locations with low crop season rainfall, and narrowed down at locations with increasing quantum of crop season rainfall. On the other hand, the gap between simulated water limiting yield and actual farmers yield ranged from 0 to 3150 kg ha^{-1}. It was narrow at locations with low crop season rainfall and increased considerably at locations with increasing amounts of rainfall indicating that type of interventions to abridge the yield gap will vary with the rainfall regimes. It is suggested that improved agronomic management (such as high yielding cultivars, balance crop nutrition and control of pest and diseases) in high rainfall regimes and rainfall conservation and supplemental irrigations in low rainfall regimes will be essential components of the improved technologies aimed at abridging the yield gaps of groundnut.

Introduction

Groundnut is the major oilseed crop in India grown traditionally by small and marginal farmers under rain-fed conditions. The crop is grown in diverse agro-climatic environments in a latitudinal belt of 7–30°N. Rainfall in these regions varies from 400 to 1500 mm during the crop season and the soils range from low water holding capacity Alfisols to high water-holding capacity Vertisols and associated soils. Though the crop can be grown throughout the year, the major area under the crop is during rainy season (June–November) which accounts for about 85 % of total groundnut production in India. The rainy season crop is spread over the entire country and is grown as rain-fed. The rest 15 % of the total groundnut production comes from post-rainy (10 %) and summer (5 %) season crops, which are largely grown under irrigated conditions (Talawar 2004). Though, India has been the leading country in the world in terms of area and production of groundnut, the average productivity of the crop has remained more or less stagnated at 1000 kg ha^{-1}, which is well below its potential and the world average.

Assessment of potential yield and yield gaps can help in identifying the yield limiting factors and in developing suitable strategies to improve the productivity of a crop (Aggarwal and Kalra 1994, Lansigan et al. 1996, Naab et al. 2004, Bhatia et al. 2008). Identifying the yields at different production levels for a crop grown in diverse environments and quantifying the yield gaps through field experiments may involve many years of data collection to make meaningful inferences. Besides being time consuming and expensive, total elimination of factors other than the ones governing growth and development and their interactions for a given production level may not be possible in these field experiments. Alternate approach is to use process-based dynamic crop simulation models that have been developed to predict crop growth, development and yield using systems approach that integrate knowledge of the underlying processes and interaction of different components of crop production (Boote et al. 1996). These simulation models are being increasingly used in the yield gap analysis by assessing the water non-limiting potential, water limiting or nutrient limiting yields for a particular region with given environmental conditions that characterize the factors that define crop growth and development (He et al. 1998, Verdoot et al. 2003, Naab et al. 2004, Bhatia et al. 2008, Audebert and Fofana 2009).

The CROPGRO-Peanut is one such model, which has been developed to simulate vegetative and reproductive development, growth and yield as function of crop characteristics, climatic factors, soil characteristics and crop management scenarios. It is part of a suite of crop growth models available in the software named Decision Support System for Agrotechnology Transfer (DSSAT) (Jones et al. 1998). The model has been in use for the past 20 years by researchers world wide (Hoogenboom et al. 2003). It has also been evaluated across a wide range of soils and climate conditions and used for various applications in India (Singh et al. 1994a,b, Bhatia et al. 2008). Although updated version of this model with new added features became available during the course of the study, we preferred to use version 3.5 as it has been evaluated earlier and satisfied the requirements of this study. The objectives of the study were to estimate potential water non-limiting and water limiting yields and yield gaps of groundnut for selected locations varying in rainfall and soils in the major groundnut growing regions of India.

Materials and Methods

CROPGRO-Peanut model

Crop growth simulation models, which share a common input data and format, have been developed and embedded in a software package called DSSAT (Jones et al. 1998). For this study, we used CROPGRO-Peanut model v3.5, which is part of the DSSAT v3.5. The major components of the peanut model are vegetative and reproductive development, carbon balance, water balance and nitrogen balance. It simulates groundnut growth and development using a daily time step from sowing to maturity and ultimately predicts yield. The physiological processes that are simulated describe the crop's response to major weather factors, including temperature, precipitation and solar radiation and include the effect of soil characteristics on water availability for crop growth. Daily photosynthesis is a function of light interception and the pool of carbohydrates available for growth is reduced by daily maintenance and growth respiration. The remaining carbohydrates are partitioned to vegetative and reproductive growth as a function of the development stage (Boote et al. 1998). The soil water balance is a function of precipitation, irrigation, transpiration, soil evaporation, runoff from the soil surface and drainage from the bottom of the soil profile and is calculated on a daily basis. Soil water is distributed among different soil layers with depth increments specified by the user. The water content of any soil layer can decrease by soil evaporation, root absorption, or flow to an adjacent layer (Ritchie 1998). Actual plant water uptake and transpiration is a function of potential demand and potential supply and is the minimum of either demand or supply. If potential transpiration demand is higher than potential supply by the root system, a water-stress factor is calculated. Water stress causes a reduction in photosynthesis and canopy abscission of plant material, depending on the timing and severity of the stress.

Model input

Minimum data set required to run the model for a location are described by Jones et al. (1998). Briefly, it includes site characteristics (latitude, longitude and elevation), daily weather data (solar radiation, maximum and minimum air temperatures and precipitation), basic soil profile characteristics by layer (saturation limit, drained upper limit and lower limit of water availability, bulk density, organic carbon, pH, root growth factor, runoff and drainage coefficients) and management data (cultivar, sowing date, plant population and row spacing, sowing depth, and dates and amounts of irrigation and fertilizers applied). The weather data were collected from each location for which simulations were carried out. The soil data were collected from the respective locations as well as from the data base published by the National Bureau of Soil Survey and Land Use Planning, Nagapur (Lal et al. 1994). The management data for calibration and validation experiments were collected from the locations used for calibration and validation of model (Singh et al. 1994a,b). For simulating the water non-limiting and water limiting yields, recommended agronomic practices were followed. The details of weather data used in the study and soil characteristics are presented in Table 1.

Model calibration and validation

The CROPGRO-Peanut model available in DSSAT v 3.5 was calibrated and validated for groundnut cultivar Robut 33-1 using phenology, crop growth, yield and soil water dynamics data from the large number of experiments carried out between 1987 and 1992 at four diverse locations in India. These locations ranged in latitude from 11°00′N to 22°35′N, longitude 72°55′E to 78°16″E, and elevation 48–545 m. The cultivar Robut 33-1 has the same yield potential as the more recent cultivars of similar duration. The management and environmental factors evaluated in these multi-location studies were planting dates, plant population, row-spacing and water availability in different cropping seasons. The results showed that changes in vegetative growth, total dry matter accumulation, growth of pods and seeds and soil moisture changes were predicted accurately by the model in different environments. Predicted pod yields were significantly correlated ($R^2 = 0.90$) with the observed yields. The details of above calibration and validation are described in detail by Singh et al. (1994a,b). The calibrated and validated model was used for simulation of water non-limiting and water limiting yields of groundnut across major growing regions in India using cultivar Robut 33-1.

Simulation for potential yield of groundnut

The study was confined to a latitudinal belt of 11°N (Thanjavur) to 27°N (Jaipur) encompassing the states of Tamil Nadu, Karnataka, Andhra Pradesh, Gujarat, Maharashtra, Madhya Pradesh, and Rajasthan together contributing to 95 % of groundnut area in India. Long-term simulations for potential yield were carried out for 18

Table 1 Geographical details, period of weather data used and soil characteristics of the locations selected for simulation of potential yields of groundnut in India

Location	Latitude (°N)	Longitude (°E)	Period	No. years	Rainfall (mm)	Soil depth (cm)	Extractable soil water capacity (EXSW) (mm)
Jaipur	26.92	76.82	1994–2004	11	560	170	155
Jhansi	25.43	78.58	1994–2003	10	840	140	179
Kota	25.18	75.83	1976–1996	21	660	188	224
Jhabua	22.77	74.60	1969–1996	16	790	78	91
Dhar	22.60	75.30	1973–1993	19	880	78	91
Rajkot	22.30	70.78	1994–2004	11	600	156	105
Junagadh	21.31	70.36	1985–1995	11	720	165	198
Akola	20.50	77.17	1969–2007	39	670	180	212
Pune	18.53	73.87	1985–2001	17	590	120	144
Warangal	18.00	79.83	1990–2000	10	770	145	198
Patancheru	17.38	78.87	1975–2007	33	710	145	141
Bijapur	16.67	75.92	1983–2007	25	420	176	141
Raichur	16.20	77.37	1986–1996	11	600	150	182
Kurnool	15.48	78.48	1984–2007	24	620	174	141
Dharwad	15.43	75.12	1975–2002	28	460	170	189
Anantpur	14.68	77.62	1977–2006	30	370	180	129
Coimbatore	11.00	76.97	1985–1998	14	340	68	71
Thanjavur	10.80	79.15	1971–1998	28	500	120	152

locations (Table 1) under two scenarios i.e. water non-limiting and water limiting. Depending on the availability of weather data, the simulations were carried out for 10–39 years. The locations selected for simulation of potential yields have either Alfisols or Vertisols and associated soils representing the major soil orders on which groundnut is grown in India.

For long-term simulation of potential yield and water balance components of groundnut, the CROPGRO-Peanut model v3.5 coupled with seasonal analysis program of DSSAT was used. For water non-limiting potential yield, the simulated crop was sown on 21st June every year taking into account the recommended optimum planting time and onset of rainy season for major peanut growing region of India (Talawar 2004). The water, nutrient and pest controls switches of the model were kept off. For simulation of water limiting yield, only the water balance switch of the model was activated. Due to rain-fed nature, its planting totally depends on the onset of rains (monsoon), which varies across years and locations. The normal arrival time of monsoon in target region is from 1st June to 30th June. The optimum planting time for rainy season groundnut in most parts of India is reported to be between first week of June to last week of July (Talawar 2004). However, farmers particularly in southern parts of India, do plant rainy season groundnut up to 15th August in case of delayed arrival of monsoon (Gadgil et al. 2002). Taking into account the time of onset of monsoon, inter-annual variation in its arrival and farmers practices in a given region, the sowing window for simulation of water limiting potential yield was kept between 1st June and 15th August. However, the model simulations were initiated on 15th May every year and the soil profile was considered to be at the lower limit of water availability (SLL) on that day. The simulated crop was sown on the day when the soil moisture content in the top 30-cm soil depth reached at least 40 % of the extractable water-holding capacity during the sowing window. The plant population of 30 plants m^{-2} at 30 cm row-spacing was considered throughout the simulation study. A soil fertility factor of 1.0 was used for all sites to simulate the crop yield without any soil fertility limitations.

Actual yields

The district yields represent the average productivity of the crop in diverse farmers' fields and are the product of climate of the area and management practices adopted by different farmers. The average productivity of the rainy season crop is about 1000 kg ha^{-1} and the post-rainy and summer season groundnut crops, which are generally irrigated, have higher productivity (1500 kg ha^{-1}, pod yield) (Talawar 2004). However, no separate yield data of rainy, post-rainy and summer season groundnut at district level was available. Therefore, the actual yields reported for these locations could be relatively higher than the ones realized by the farmers during cultivation of rainy season groundnut in India. The district pod yields of last 10 years (1995–2004) (Damodaram and Hegde 2007) for each location for which simulation were carried out were averaged out and used as actual yields and were compared with simulated pod yields to quantify present yield gaps of groundnut across location in major crop growing regions of India. The duration for which actual yields of each location were averaged out was long enough to capture the wide seasonal variability observed in groundnut yields in India and short enough to eliminate the impact of technology changes if any on actual crop yields. For calculation of association between rainfall and actual yield across season at each selected locations, long-term available data on actual yields and corresponding season's rainfall were taken into account.

Results and Discussion

Simulated water non-limiting potential yield of groundnut

Depending on climatic conditions, considerable spatial and temporal variability in simulated water non-limiting yield was observed (Table 2). When averaged over locations, the water non-limiting pod yield was 5440 kg ha^{-1} with a coefficient of variation of 14.5 %. Among locations, mean simulated pod yield ranged from 4030 kg ha^{-1} (Raichur) to 6350 kg ha^{-1} (Dhar). Similarly, there was a wide variability in minimum and maximum pod yields recorded over the simulation period at each location. The coefficient of variation for this temporal variability ranged from 2.1 % to 17.7 % among these locations. The average minimum pod yield of these locations (4500 kg ha^{-1}) was 26 % less than the average maximum simulated pod yield (6120 kg ha^{-1}).

Yields obtained in these simulations were governed only by climatic conditions of solar radiation and temperatures. The long-term mean solar radiation for crop growth period of these locations ranged from 11.9 to 19.0 MJ m^{-2} day^{-1} (Fig. 1). Being a rainy season crop, depending upon the monsoon activity over locations and years, large fluctuations are observed in solar radiation during the crop growth period. The mean simulated water non-limiting pod yields of selected locations showed a significant positive association ($R^2 = 0.62$, $P \le 0.01$) with mean crop season solar radiation (Fig. 1). Simulated water non-limiting pod yields across locations as well as over years at these locations did not show any significant association with crop season temperatures

Table 2 Simulated yield (water non-limiting and water limiting), actual yield and yield gaps of groundnut at selected locations across India

	Simulated potential yield (kg ha^{-1})									Yield gaps (kg ha^{-1})		
	Water non-limiting				Water limiting							
Locations	Minimum	Maximum	Mean (A)	CV	Minimum	Maximum	Mean (B)	CV	Actual yield (kg ha^{-1}) (C)	Due to water limitation (A-B)	Due to factors other than water availability (B-C)	Total (A-C)
Jaipur	5080	6010	5480	6.0	50	5180	3490	53.5	1180	1990	2310	4300
Jhansi	5730	6670	6310	6.5	2060	5830	4000	30.5	860	2310	3140	5450
Kota	3110	6000	4960	13.2	520	5120	2600	55.0	1120	2360	1480	3840
Jhabua	3540	6480	5390	13.3	250	4710	2850	51.1	750	2540	2100	4640
Dhar	4340	6800	6350	11.0	760	5480	3870	34.5	780	2480	3090	5570
Rajkot	3160	5280	4640	13.1	230	4390	2430	54.6	970	2210	1460	3670
Junagadh	4620	6090	5460	6.5	60	5180	3010	53.2	1550	2450	1460	3910
Akola	4960	6640	6020	7.0	290	5760	3140	48.5	830	2880	2310	5190
Pune	5700	6640	6160	4.5	730	5130	3300	44.4	1280	2860	2020	4880
Warangal	3170	5070	4130	17.7	2230	4100	3420	20.0	1030	710	2390	3100
Patancheru	5050	6590	5810	6.5	2150	5920	4420	25.5	1270	1390	3150	4540
Bijapur	3840	6850	5330	16.7	30	4770	1720	69.2	500	3610	1220	4830
Raichur	3490	4690	4030	8.6	1000	4180	2420	48.2	680	1610	1740	3350
Kurnool	5790	6510	6110	3.1	610	5700	2620	55.1	900	3490	1720	5210
Dharwad	3790	5400	4570	9.1	110	4650	2380	52.3	730	2190	1650	3840
Anantpur	3600	5130	4570	7.1	60	3950	1140	98.1	700	3430	440	3870
Coimbatore	6290	6740	6330	2.1	0	3040	900	101.3	1390	5430	0	4940
Thanjavur	5660	6550	6240	3.5	0	4380	1790	76.4	1790	4450	0	4450
Average	4500	6120	5440		620	4860	2750		1020	2690	1730	4420
CV	23.7	11.4	14.5		123.4	15.8	34.7		33.3	41.2	53.9	16.5

CV, coefficient of variation (%).

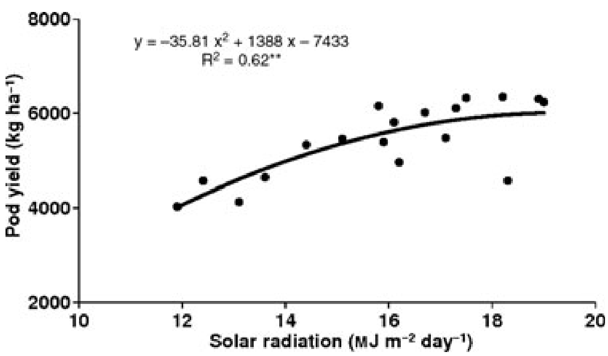

Fig. 1 Association of long-term mean simulated water non-limiting potential yield with mean crop season solar radiation among selected locations across India.

(Data not presented). Thus, the spatial and temporal variability in simulated water non-limiting groundnut pod yields across selected locations in India was largely governed by the spatial and temporal variability in crop season solar radiation. Using present day and future climatic data generated through the GCM models as input to the general large area model for simulating annual crops, Challinor et al. (2007) reported that in India, high temperature stress was not a major determinant to simulated groundnut yields in the current climate. However, temperature may become an important factor in parts of the northern and southern parts of India under changed climatic scenario of 2071–2100 (A2 scenario of IPCC) (IPCC, 2001).

Simulated water limiting yield of groundnut

The average simulated planting time at the selected locations was 20th June with a coefficient of variation of 1.4 % indicating that by and large the crop was planted within an optimum time period. Among these locations, the mean planting time ranged from 10th June to 10th July. The coefficient of variation for temporal variability in planting time at selected locations ranged from 4 % to 13 %.

Under water limiting conditions, the average simulated pod yield of groundnut was 2750 kg ha^{-1} with a coefficient of variation of 34.7 % (Table 2). Among these locations, the water limiting yield of the crop ranged from 900 kg ha^{-1} (Coimbatore) to 4420 kg ha^{-1}

Table 3 Water balance components of simulated groundnut at selected locations across India

Location	Rainfall (mm)				Runoff (mm)			
	Minimum	Maximum	Mean	CV	Minimum	Maximum	Mean	CV
Jaipur	135	851	557	41.8	1	331	97	104.1
Jhansi	507	1129	843	27.0	86	509	262	48.9
Kota	306	1011	662	29.3	24	449	197	52.3
Jhabua	294	1411	787	44.6	45	492	228	71.9
Dhar	600	1492	878	26.7	52	589	235	60.4
Rajkot	195	1080	602	40.7	15	425	197	66.0
Junagadh	137	1392	723	51.5	5	555	225	71.6
Akola	277	1173	673	29.6	37	453	189	48.0
Pune	297	908	591	30.6	55	402	174	56.3
Warranagal	411	1350	766	37.6	35	397	201	62.2
Patancheru	398	1293	705	31.0	27	681	165	73.6
Bijapur	128	633	423	34.5	8	234	93	66.0
Raichur	404	860	596	26.0	60	323	124	62.1
Karnool	347	1211	618	38.3	33	543	162	80.0
Dharwad	132	800	463	31.7	7	201	79	62.0
Anantpur	121	757	370	45.4	1	228	55	106.5
Coimbatore	74	708	337	47.5	0	171	46	95.7
Thanjavur	62	868	496	42.1	1	313	112	79.5
Average	268	1051	616		27	405	158	
CV	58.1	25.4	25.4		91.6	35.5	41.5	

CV, coefficient of variation (%).

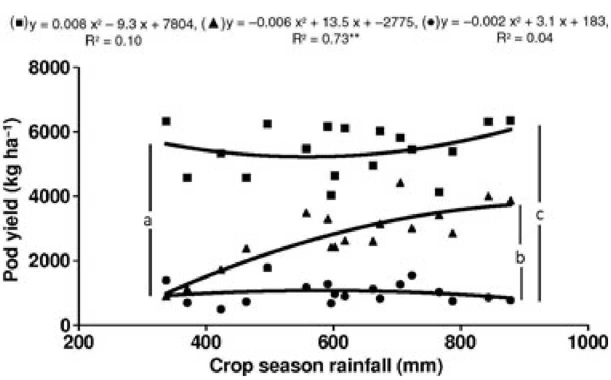

Fig. 2 Association of long-term mean simulated water non-limiting potential yield (■), mean simulated water limiting yield (▲) and actual yield (•) with mean crop season rainfall among selected locations across India (a, yield gap between simulated water non-limiting and water limiting yield; b, yield gap between simulated water limiting and actual yield; and c, yield gap between simulated water non-limiting and actual yield or total yield gap).

(Patancheru). There was a wide variability in minimum and maximum yields recorded over the simulation period at each location. The coefficient of variation for this temporal variability ranged from 20.0 % to 101.3 % at these locations. The average minimum yield of the locations (620 kg ha^{-1}) was 87 % less than the average maximum simulated yield (4860 kg ha^{-1}). As productivity at this level was primarily governed by the water availability (rainfall) besides other elements of weather, both the spatial and temporal variability in simulated water limiting yield was of very high magnitude as compared to simulated water non-limiting yield. In general, high temporal variability in simulated water limited yield at locations such as Coimbatore (CV 101 %), Anantpur (CV 98 %) and Thanjavur (CV 76 %) was associated with low quantum and greater temporal variability in rainfall as compared to other locations (Tables 2 and 3). At two locations (Coimbatore and Thanjavur), the crop failed once to produce any yield during the simulated period, while at four locations (Jaipur, Junagadh, Bijapur and Anantpur) the minimum yields were <100 kg ha^{-1}. For seasons with low rainfall, failure of crop or very low levels of yields particularly in southern parts of India have also been reported by Gadgil et al. (2002). Such large temporal and spatial variations in simulated water limiting yield explain the degree of fluctuations and uncertainty in groundnut productivity under rain-fed conditions in India.

When the mean simulated water limiting pod yield was plotted against the mean crop season rainfall of these locations, a significant positive, but curvilinear relationship ($R^2 = 0.73$, $P \leq 0.01$) (Fig. 2) was observed. The simulated pod yields increased with increasing rainfall from 340 to 880 mm, which was the range of long-term mean crop season rainfall at these locations.

Table 4 R^2 values for the association of crop season rainfall with simulated water limiting and actual yields of groundnut over years at different locations in India

Location	Crop season rainfall and simulated water limiting yield	Crop season rainfall and actual yield
Jaipur	0.90**	0.58*
Jhansi	0.82**	0.61*
Kota	0.33*	0.07
Jhabua	0.87*	0.55*
Dhar	0.51*	0.43*
Rajkot	0.57*	0.51*
Junagadh	0.92**	0.83**
Akola	0.62**	0.04
Pune	0.76**	0.55*
Warranagal	0.64*	0.23
Patancheru	0.43**	0.03
Bijapur	0.54**	0.02
Raichur	0.79**	0.12
Karnool	0.70**	0.15
Dharwad	0.72**	0.11
Anantpur	0.63**	0.32*
Coimbatore	0.77**	0.09
Thanjavur	0.50**	0.08

*$P \le 0.05$; **$P \le 0.01$.

However, the rate of increment in pod yield was of greater extent from 340 to ~600 mm, above which the rate of increase in yield in response to increasing rainfall showed a lesser trend. Similar association between the crop season rainfall and simulated pod yield over the years was observed at each location. The R^2 values for this association ranged from 0.33 to 0.92 at the selected locations (Table 4). In contrast to simulated water non-limiting yield, no significant association was observed between mean simulated water limiting yield and mean crop season solar radiation of these locations. This indicated that at this production level, both spatial and temporal variability in groundnut yield across the locations was largely governed by the availability of water. Spatial and temporal variability to the extent of 50–80 % in groundnut yield due to rainfall variability in India has also been reported by several workers (Gadgil et al. 2002, Challinor et al. 2003).

There was a considerable spatial and temporal variability in the crop season rainfall and total runoff of water at selected locations (Table 3). The average crop season rainfall was 616 mm which ranged from 337 (Coimbatore) to 878 mm (Dhar). Among the locations, the loss of water through surface runoff ranged from 14 % to 33 % of the total rainfall received. Total seasonal runoff across locations averaged 158 mm of water, which is 25 % of the average rainfall of these locations. Such high values of runoff are attributed to low permeability of soils at many locations where groundnut is grown. The conservation of this water will not only help in minimizing the loss of fertile soils but could also help in improving the soil moisture availability and providing supplemental water to groundnut crop during the period of drought or to the subsequent post-rainy season crop.

Actual yield of groundnut

The actual average pod yield of these locations (district average yield) was very low (1020 kg ha^{-1}) as compared to simulated water non-limiting (5440 kg ha^{-1}) and water limiting pod yield (2750 kg ha^{-1}) of groundnut (Table 2). The actual yields ranged from 500 kg ha^{-1} (Bijapur) to 1550 kg ha^{-1} (Junagadh) indicating extremely poor levels and a large regional variability in actual groundnut yields harvested by the farmers in India. As one of the reasons cited for poor productivity of groundnut is its rain-fed nature, attempts were made to find out the association of actual yields harvested by the farmers and crop season rainfall across locations as well as across seasons at each selected location. Unlike simulated water limiting yields, the association between actual yields and crop season rainfall across locations was not significant ($R^2 = 0.04$) (Fig. 2). Similarly, the association between actual yield and crop season rainfall over years was found significant only at eight locations with R^2 values ranging from 0.32 to 0.83 (Table 4). The groundnut crop at most of these locations is mainly grown as rain-fed rainy season crop, whereas at rest of the locations, which have not shown any significant association, the crop is also grown during summer/post-rainy seasons with irrigation. This perhaps explains the reasons for poor association between actual yield and crop season rainfall across locations (Fig. 2) and over the years at many of these locations. Nevertheless, as compared to simulated water limiting yields, the low levels of actual yields and their poor association with crop season rainfall clearly indicated that beside water there are other factors, which limit the realization of rain-fed potential of groundnut crop in India. Besides suboptimal availability of soil moisture, the crop management factors such as use of old local genotypes, sub-optimal use of nutrients and planting time, poor plant population, infestation with weeds, pests and diseases limit the productivity of groundnut in India and have been reported by several workers (Gadgil et al. 1996, 2002, Basu 2003).

Yield gaps of groundnut

The simulation of water non-limiting and water limiting yields across large number of locations in major groundnut growing regions of India clearly indicated that there is high yield potential of the crop, which is not presently realized by the farmers. The average actual yield of the farmers (1020 kg ha^{-1}) at these locations was 4420 and 1730 kg ha^{-1} less than the average simulated water non-limiting and water limiting yields indicating a 81 % and 63 % reduction in actual yield as compared to water non-limiting and water limiting yields, respectively.

The magnitude of yield loss due to suboptimal water availability as indicated by the difference between simulated water non-limiting and water limiting yields was 2690 kg ha^{-1} (Table 2) and depending on the rainfall received, varied considerably (710–5430 kg ha^{-1}) from location to location. The gap in yield was very large at locations with low rainfall and it narrowed considerably with the increase in rainfall (Fig. 2). As groundnut in India is mainly cultivated under rain-fed conditions, reducing yield losses due to suboptimal water availability may not be possible unless rainfall conservation technologies, supplemental irrigation during moisture stress and cultivars tolerant to drought conditions are developed and adopted.

On the other hand, the gap between actual and simulated water limited yields which ranged from 0 to 3150 kg ha^{-1} (Table 2), were narrow at locations with low rainfall and increased considerably as the quantity of rainfall increased among the locations (Fig. 2). At two locations, which have substantial groundnut area under post-rainy season with irrigation, the actual yields were either marginally higher (Coimbatore) than or equal (Thanjavur) to the simulated water limiting yields. This gap in yield (which reflects the actual yield gap in a rain-fed environment) is mainly caused by non-adoption of improved crop management practices and can easily be reduced if proper interventions are made.

Under simulated conditions, nutrient availability, plant population, weeds, insects and diseases, and other yield limiting factors were not a constraint to groundnut productivity. However, the effectiveness and positive impact of these factors are linked with the soil moisture availability. Therefore, under low rainfall regimes, even simulated yields were low and resultant yield gaps were narrow (Fig. 2). With increasing rainfall, the simulated yield increased significantly whereas the actual yields remained more or less stagnated resulting in larger yield gaps. The association clearly indicates that the farmers are not adopting the recommended practices that include improved genotypes, optimal nutrient application, plant population and adequate weed and plant protection measures. Thus, greater opportunities exist for improving the productivity with proper interventions in areas with high rainfall/soil moisture regimes. For low rainfall regimes, where prolonged dry spells are common during the crop growth period, the conservation of moisture and supplemental irrigation would be essential along with the adoption of improved agronomic practices. The observed large surface runoff of water (Table 3) which on an average accounted for 25 % of the total rainfall received at these locations, provides an opportunity for efficient use of water through adoption of improved soil moisture conservation technologies. Effectiveness of soil moisture conservation techniques such as broadbed-and-furrow, ridge-and-furrow, reduced tillage, residue recycling and mulching in improving the soil moisture availability and improved productivity of crops under rain-fed conditions have been reported by several workers. (Wani et al. 2003, Teklu et al. 2006). These technologies will not only help in improving the productivity in areas with suboptimal rainfall but could also be helpful in areas with high rainfall by improving the land surface drainage.

In conclusion, the simulation studies carried out at large number of location in major crop growing region of India clearly indicate that a high potential of groundnut yield exists as compared with the actual yield harvested by the average farmers. The average gap between simulated water limiting and actual yields was 1730 kg ha^{-1}, which indicates that non-adoption of improved agronomic practices is the major cause of poor productivity in average farmers' field. Similar gaps between the yield harvested by the farmers with their traditional cultivation practices and the yield obtained in on-farm trails conducted with improved agronomic management practices have been reported in India (Reddy et al. 1992). Therefore, if proper interventions are made for adoption of improved agronomic practices, the average productivity of groundnut can be enhanced and existing large yield gaps can be narrowed down in India. However, the gap between simulated water limiting and actual yields were narrow in low rainfall areas and increased considerably as the quantum of rainfall increased indicating that the type of interventions needed to improve the productivity and narrowing of existing yield gap will vary with rainfall regimes. The improved agronomic management (high yielding cultivars, balanced crop nutrition and control of pest and diseases) in high rainfall regimes and rainfall conservation and supplemental irrigation in low rainfall regimes will be essential components of the improved technologies aimed at improving the productivity and abridging the yields' gaps of groundnut in India. Also, the crop growth models such as CROPGRO-Peanut that predict crop growth, development and yield using systems approach can be a useful tool in understanding the underlying constraints to productivity of groundnut with respect to specific location as well as at national level.

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