MAUSAM, **57**, 2 (April 2006), 307-314

551.586 : 633

Use of PNUTGRO model for optimization of sowing date and plant spacing to maximize yield of groundnut (*Arachis hypogaea* L.)

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(*Received 31 March 2004, Modified 15 February 2005*)

सार – पीनटग्रो (पी. एन. यू. टी. जी. आर. ओ.) मॉडल की प्रामाणिकता सिद्ध करने के लिए 1987 - 90 के दौरान आनंद, गुजरात में क्षेत्रीय प्रयोग किए गए हैं। इस मॉडल का उपयोग मूँगफली की फीनोलॉजी, बढ़ोतरी, विकास और पैदावार का पूर्वानुमान लगाने के लिए किया गया है। मूँगफली के प्रतिरूपित पुष्पन, पेगिंग, फली बनने और फली पकने की तिथियों, पर्णी क्षेत्रफल सूचकांक (एल. ए. आई.) जैवभार, शैलिंग का प्रतिशत तथा पैदावार की तुलना तीन पद्धतियों नामतः जी. ए. यू. जी. 10, जी. ए. यू. जी. 2 और आर. ओं. - 33 - 1 से प्राप्त हुए प्रेक्षित मानों के साथ की गई है। प्रतिरूपित घटनाक्रम से पुष्पन के लिए एक दिन कमी तथा पाँच दिन की बढ़त का, पेगिगं के लिए 2 से 6 दिनों की बढ़त, फली बनने के लिए 3 दिन की कमी तथा 6 दिनों की बढ़त का और फली पकने के लिए 6 दिन की कमी तथा 5 दिन तक की बढ़त का अंतर पाया गया है। वास्तविक मानों की तुलना में इस मॉडल से पर्णी क्षेत्रफल सूचकांक 91.8 से 105.8 प्रतिशत और शैलिंग का प्रतिशत 81.5 से 109. 8 पाया गया है। इस मॉडल से मूँगफली की पैदावार प्रेक्षित मानों की तुलना में 88.5 से 112.7 प्रतिशत तक पाई गई है। इस मॉडल से प्राप्त परिणामों के आधार पर पर लगातार चार फसलों और ऋतुओं के संबंध में मूँगफली की फीनोलॉजी, बढ़ोतरी, विकास और पैदावार के बारे में पूर्वानुमान संतोषजनक पाया गया है। मूँगफली की प्रेक्षित और प्रतिरूपित पैदावार के बीच 11 प्रतिशत की घटबढ़ पाई गई है जिससे पता चलता है कि मॉडल के आधार पर किया गया पूर्वानुमान संतोषजनक है। एल. ए. आई. को छोडकर वास्तविक मानों और प्रेक्षित मानों में अंतर (डी.) 0.03 और 1.77 के बीच रहा है जिससे मॉडल के संतोषजनक कार्य करने का पता चलता है। प्रतिरूपण अध्ययनों के परिणामों से पता चलता है कि जब अधिक वर्षा होने की संभावना हो तो मूँगफली के बीजों की सामान्य दूरी तथा बुवाई के सामान्य समय की अपेक्षा बीजों को अधिक पास–पास बोकर तथा बुवाई लगभग एक सप्ताह पहले करके मूँगफली की अधिक पैदावार प्राप्त की जा सकती है।

ABSTRACT. Field experiments were conducted at Anand, Gujarat during 1987-90 to validate the PNUTGRO model. The model was used to predict phenology, growth, development and yield of groundnut. The simulated flowering, pegging, pod formation and pod maturity dates, leaf area index (LAI), biomass, shelling % and pod yield of groundnut were compared with the observed values for three cultivars *viz*., GAUG 10, GAUG 2 and Ro-33-1. The simulated phenological events showed a deviation of –1 to +5 days for flowering, +2 to +6 days for peg formation, -3 to +6 days for pod formation and –6 to +5 days for pod maturity of the crop. The model estimated leaf area index within 91.8 to 105.8% and shelling percentage within 81.5 to 109.8% of the actual values. The model simulated the pod yields within 88.5 to 112.7% of the observed values. The results obtained with the model for the four consecutive crops and seasons revealed satisfactory prediction of phenology, growth, development and yield of groundnut. The percent error between observed and simulated pod yield was 11% which indicated satisfactory prediction by the model. The degree of agreement (d) ranged between 0.03 and 1.77 except for LAI indicating satisfactory performance of the model.

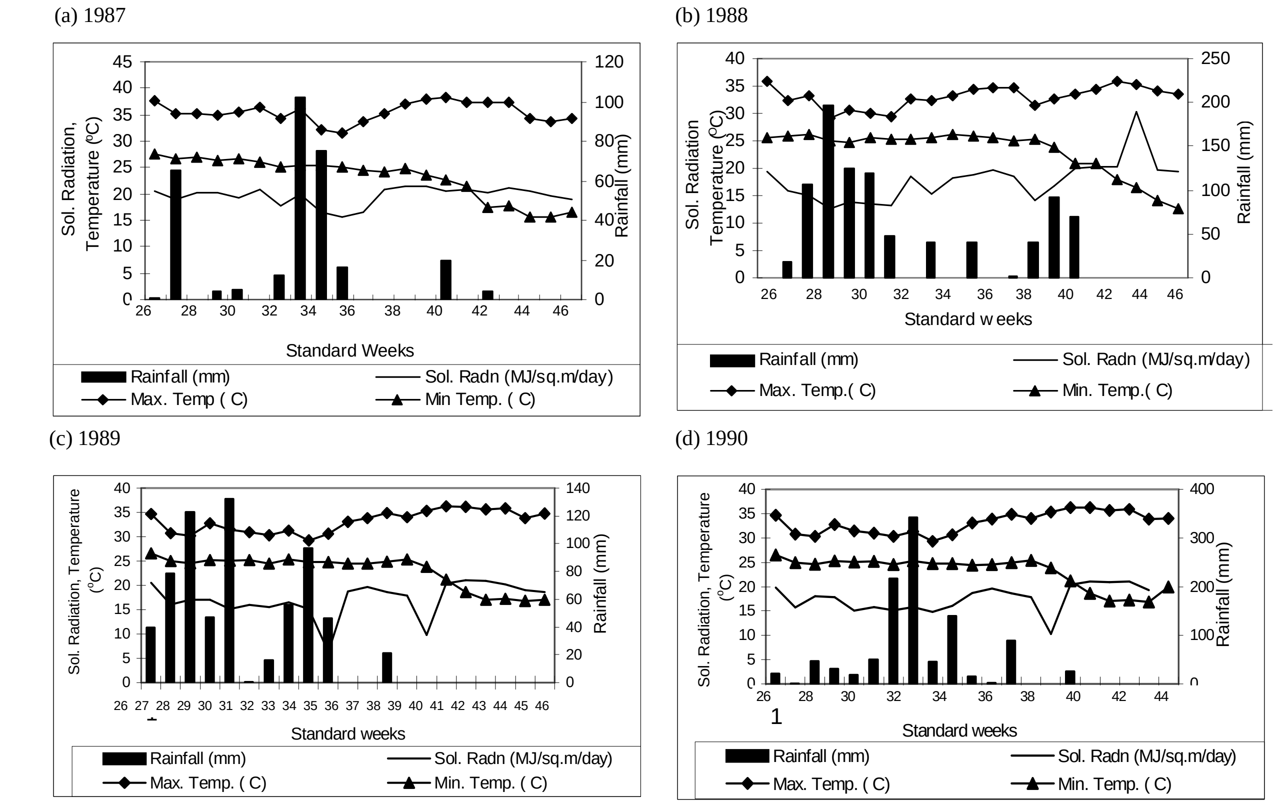
Results of simulation studies indicated that when there is a possibility of high rainfall higher pod yield can be achieved by adopting closer spacing and early sowing (one week earlier than normal date of sowing) compared to normal spacing and date of sowing.

Key words – Validation, Growth, Yield, Groundnut, PNUTGRO model, Simulation.

1. Introduction

Groundnut (*Arachis hypogaea* L.) is cultivated in India in diverse agroclimatic environments characterized by spatial and temporal variations in rainfall and by soils of various water retention capacities (Singh *et al*., 1994). The crop is often subject to various patterns and intensities of water deficits during the season causing year-to-year variation in its production.

System approach nowadays becomes important tool in agricultural research, as conventional field experiments



Figs. 1 (a-d). Weekly weather data of Anand for the standard weeks 26-46 during 1987-90

are costly and time consuming. The PNUTGRO model developed by Boote *et al*. (1986 and 1987) effectively predicts growth and yield of groundnut. This model dynamically responds to daily weather inputs, soil water deficits, cultural practices and cultivar choice. It also considers crop carbon balance – inputs from photosynthesis, its conversion into crop tissue and carbon losses due to growth and development. Management options of the model include prediction of growth and yield of groundnut in response to date of sowing, spacing, etc. This model was selected for the validation of growth and yield of groundnut in Gujarat.

It is needed to evaluate the performance of the models, because models in its original conception related to temperate environments, where the climatic conditions that simulate crop growth and development are very different from Indian environment. The agro-ecological variability is also high in our country, thus it is essential that before the models put in use for the prediction of growth and yield in India, it needs to be validated against crop performance under field conditions.

PNUTGRO model was validated by many modelers in the world. But in India, very few modelers evaluated the performance of the model under varying weather conditions. Singh *et al*. (1994) conducted multilocational trials in groundnut and evaluated the model for its response to date of sowing and row spacing. Kaur and Hundal (1999) forecasted groundnut yield using the PNUTGRO model in Punjab.

Crop simulation models are increasingly used to evaluate the variations in management options and associated yield response. Jones (1993) concluded that crop simulation models can be put in use in research yield forecast and taking strategic and tactical decision making. In the present study, the main focus was on optimizing farm management strategies using PNUTGRO model particularly by altering date of sowing and population.

2. Methodology

Field experiment was conducted at Gujarat Agricultural University, Anand (72° 55′ N and 23° 35′ E, 48 m a.m.s.l.). The soil at Anand is deeper (2 m) and has a higher water retention capacity (300 mm) in the root zone. Three varieties of groundnut, *viz*., GAUG 10, GAUG 2 and Ro-33-1 were chosen and model performance was evaluated for the period 1987-90.

TABLE 1

Observed and simulated phenology of groundnut

Year and variety	Sowing day (Julian day)	Days to flowering			Days to peg formation			Days to pod formation			Days to pod maturity		
		O	S	D	O	S	D	O	S	D	O	S	D
1987													
GAUG 10	183	29	31	2	37	40	3	49	46	-3	115	117	2
GAUG 2	183	23	27	4	32	36	4	40	45	5	113	116	3
Ro-33-1	183	29	30	1	37	39	2	50	48	-2	110	113	3
1988													
GAUG 10	184	23	26	3	33	38	5	48	49	1	121	118	-3
GAUG 2	184	22	27	5	31	37	6	40	45	5	110	114	4
Ro-33-1	184	24	27	3	32	36	4	48	53	5	110	113	3
1989													
GAUG 10	183	27	26	-1	33	38	5	50	52	2	138	132	-6
GAUG 2	183	22	27	5	30	36	6	42	48	6	122	127	5
Ro-33-1	183	22	26	4	32	37	5	46	51	5	130	128	-2
1990													
GAUG 10	183	28	27	-1	33	37	4	52	49	-3	128	126	-2
GAUG 2	183	23	26	3	31	35	4	42	47	5	118	123	5
Ro-33-1	183	24	25	1	33	36	3	45	49	4	127	129	2
Mean	-	24.2	27.1	2.4	32.8	37.1	4.3	46.0	48.5	2.5	120.2	121.3	1.2
S.D.	-	2.7	1.7	1.9	2.1	1.4	1.2	4.0	2.5	0.3	8.8	6.6	3.4

O – Field observed, D – S-O
S – Model simulated, S. D. – Standard deviation

Meteorological data for the crop growing period (June – November) for 1987-90 were collected from the agromet observatory, Anand, Gujarat. Daily weather data on solar radiation (MJ m^{-2} day^{-1}), maximum temperature (°C), minimum temperature (°C) and rainfall (mm) were collected and utilized for the study. Weather data are presented in Figs. 1 (a-d).

Information on latitude of the site, soil profile properties, planting date, planting depth, population, fertilizer application and amount were used in the model. Regular crop management practices were followed and data were collected from the field experiments conducted during the period 1987-90. 12 data sets comprising three varieties for four years (1987-90) were collected to compare observed and predicted values. Data on crop phenology, LAI, biomass and yield were compared with model predicted values.

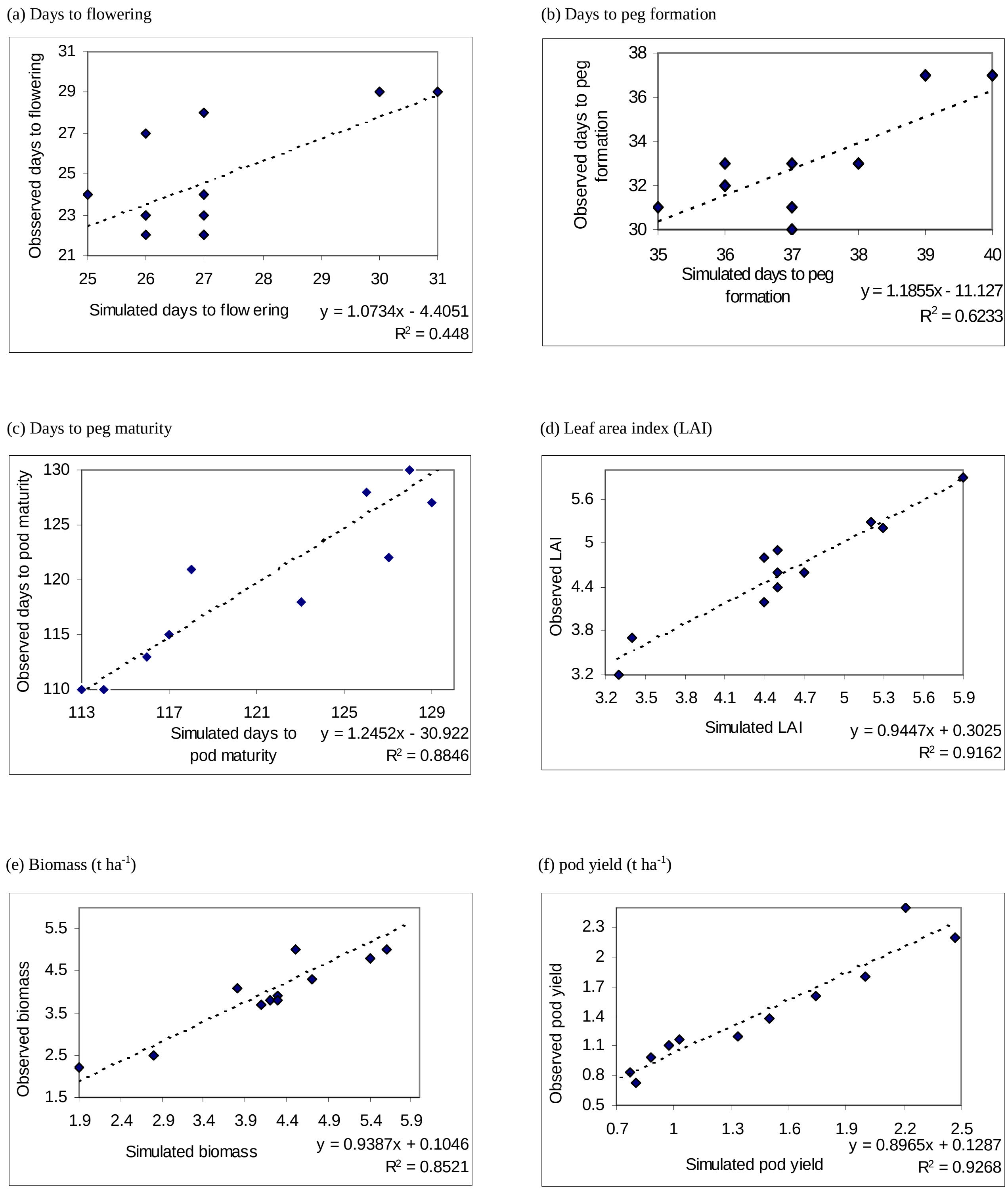
The groundnut crop was sown on 2nd or 3rd of July with a spacing of 30 × 10 cm (*i.e.*, 33.3 plants m^{-2}). The cultivars *viz.*, GAUG 10, GAUG 2 and Ro-33-1 normally take 120, 100 and 110 days respectively, to reach physiological maturity.

3. Model calibration

Before using any model in an area, it is necessary to calibrate that model for that area (Jagtap *et al.*, 1993 and Dent and Blackie, 1979). The PNUTGRO model requires variety specific genetic coefficients. The file, GENETICS PN9. of the model was used for the purpose. This file defines cultivar sensitivity to daily weather inputs at different growth stages. The PNUTGRO model includes 11 phenological coefficients and 12 growth coefficients (Kaur and Hundal, 1999). The values of these 23 genetic coefficients were calibrated to validate growth and development of groundnut.

In addition to validation, *i.e*., comparison of both simulated and observed values, the model performance was also evaluated by statistical measures like coefficient of determination (R^2). Wilmott (1982) pointed out that the main problem of this analysis is that the magnitude of R^2 is not consistently related to the accuracy of prediction where accuracy is the degree to which model predictions approach the magnitude of their observed values.

In this case test criteria are separated into two groups, *viz.*, summary measures and difference measures. Summary measures include the mean of observed and



Figs. 2 (a-f). Relationship between observed and simulated parameters (days to flowering, days to peg formation, days to pod maturity, leaf area index, biomass and pod yield) of groundnut (broken line – regression line).

TABLE 2

Observed and simulated growth and yield of groundnut

Year and variety	Maximum LAI			Biomass (kg ha^{-1})			Shelling %			Pod yield (kg ha^{-1})		
	O	S	D	O	S	D	O	S	D	O	S	D
1987												
GAUG 10	5.2	5.3	0.1	6533	5925	-608	65.22	64.41	-0.81	722	803	81
GAUG 2	5.9	5.9	0.0	4963	4541	-422	64.73	69.45	4.72	735	683	-52
Ro-33-1	5.3	5.2	-0.1	4831	5416	585	65.68	72.11	6.43	842	767	-75
1988												
GAUG 10	4.2	4.4	0.2	5034	5598	564	65.81	60.22	-5.59	1375	1544	169
GAUG 2	4.6	4.7	0.1	3904	4259	355	66.47	64.34	-2.13	1169	1035	-134
Ro-33-1	4.9	4.5	-0.4	4092	3826	-266	66.26	67.98	1.72	1588	1740	152
1989												
GAUG 10	3.2	3.3	0.1	3801	4238	437	64.62	67.39	2.77	982	881	-101
GAUG 2	4.6	4.7	0.1	2223	1950	-273	64.18	69.19	5.01	1084	967	-117
Ro-33-1	4.6	4.8	0.2	2548	2818	270	64.81	68.24	3.48	1222	1336	114
1990												
GAUG 10	3.7	3.4	-0.3	4267	4715	448	59.78	65.10	-5.32	1783	1998	215
GAUG 2	4.8	4.4	-0.4	3663	4125	462	63.23	64.74	1.52	2192	2470	278
Ro-33-1	4.4	4.5	0.1	3848	4290	442	66.62	68.01	1.39	2454	2218	-236
Mean	4.6	4.5	0.03	4096	4352	171	64.80	66.80	1.10	1345.6	1370.2	11.1
S.D.	0.7	0.0	0.21	998	1123	412	1.80	3.00	3.70	560.1	615.2	157.9

LAI – Leaf area index D – S-O
O – Field observed S.D – Standard deviation
S – Model simulated

simulated values, the standard deviation of observed values and simulated values. In addition, a degree of agreement (*d*) (Wilmott, 1982) was calculated as follows :

$$d = \left[\sum_{i=1}^{n} (P_i - O_i)^2 / \sum_{i=1}^{n} \left(\left| P_i' \right| + \left| O_i' \right| \right)^2 \right], \; 0 \le d \le 1$$

where, P_i and O_i are the predicted and observed values,

$$P_i' = P_i - P \text{ and } O_i' = O_i - O$$

While summary measures describe the quality of simulation, difference measures try to locate and quantify errors. The latter includes mean absolute error (MAE), the mean bias error (MBE), the root mean square error (RMSE) and per cent error (PE) (Wilmott, 1982). They are calculated as below :

$$\text{MAE} = \sum_{i=1}^{n} \left(\left| P_i' - O_i' \right| \right) / n$$

$$\text{MBE} = \sum_{i=1}^{n} (P_i' - O_i') / n$$

$$\text{RMSE} = \sqrt{\sum_{i=1}^{n} (Pi - Oi)^2 / n}$$

$$\text{PE} = \text{RMSE} / \overline{O}$$

MAE and RMSE indicate the magnitude of the average error. MBE describe the direction of the error bias. PE less than 10% indicates matching of predicted and observed values, more than 10% and less than 25% indicates matching of predicted and observed values fairly. PE more than 25% indicates predicted and observed values do not match.

4. Application of model

In order to study the crop yield response to different dates of sowing and plant densities, yields were simulated with the following sets of treatments using historic weather data. Effect of date of sowing and spacing was simulated for high and low rainfall years, *i.e.*, 1990 and 1987, respectively.

Date of sowing : One week earlier (D_1)
Normal date (D_2)
(*i.e.*, 2nd or 3rd July)
One week later (D_3)

Spacing : 25 × 10 cm (40 plants m^{-2}) (S_1)
30 × 10 cm (33.3 plants m^{-2}) (S_2)
30 × 15 cm (22.2 plants m^{-2}) (S_3)

5. Results and discussion

The model predicted growth characters *viz.*, crop phenology, LAI, biomass and yield of groundnut in close

TABLE 3

Summary measures and difference measures for the data sets of groundnut

Parameters	Unit	Summary measures					Difference measures			
		Observed*	Simulated*	S.D. (O)	S.D. (S)	*d*	MAE	MBE	RMSE	PE
Flowering	Days	24.7	27.1	2.7	1.7	0.59	2.75	2.42	3.12	12.63
Peg formation	Days	32.8	37.1	2.1	1.4	1.77	4.60	4.67	4.40	13.41
Pod formation	Days	46.0	48.5	4.0	2.5	0.47	3.80	2.50	4.12	8.91
Pod maturity	Days	120.2	121.3	8.8	6.6	0.10	3.30	1.16	3.46	2.93
LAI	-	4.6	4.5	0.7	0.7	12.29	0.18	-0.03	4.80	104.31
Biomass	Kg ha^{-1}	4096	4352	998	1123	0.003	427.6	12.90	10.60	0.3
Shelling %	%	64.8	66.8	1.8	3.0	0.57	1.85	1.05	3.87	6.0
Pod yield	Kg ha^{-1}	1345.6	1370.2	560.1	615.2	0.06	11.98	3.33	158.00	11.7

* mean of 12 values
S.D. (O) – Standard deviation (observed)
S.D. (S) – Standard deviation (simulated)
MAE – Mean Absolute Error
PE – Percent Error
MBE – Mean Bias Error
RMSE – Root Mean Square Error
d – degree of agreement

association with field observed values. They are described under the following heads:

5.1. *Crop phenology*

The data on days to flowering, peg formation, pod formation and pod maturity (both observed and simulated) are presented in Table 1 and in Figs. 2 (a-c). The results indicated that the model simulated the time of flowering closely to that of observed values in all the 4 years. The simulated days varied from –1 to + 5 days in all the years. The variation in weather parameters during the trial is attributed to this deviation. The simulated days varied more in 1988 than other years. The lowest variation was observed in 1990 as rainfall was the highest among all the other years.

There was no much difference between observed and simulated values on time of peg formation. The model predicted the time of pegging 2-6 days late in all 4 years. The variation in predicted days for pegging was the maximum in 1989 and lowest in 1987 when compared with other years.

The time of pod formation was predicted by the model closely with observed values. However, there is a variation of –3 to 6 days, which are within allowable limits. The variation in predicted days for pod formation was the maximum during 1990 when compared with other years. The lowest variation was observed in 1987. There is a –6 to +5 days variation in the simulated pod maturity. The variation in the predicted days for pod maturity was the maximum during 1989 when compared with the other years. The variation was the lowest during 1987. Thus the deviation between observed and simulated phenological stages of groundnut was within the range of variation encountered in field observations for these parameters.

5.2. *Crop growth and yield*

The data on LAI, biomass at maturity, pod shelling % and pod yield (both observed and simulated) are presented in Table 2 and in Figs. 2 (d-f). The maximum LAI ranged from 3.3 to 5.9 for different varieties and years. The model simulated maximum LAI was significantly correlated (R^2 = +0.9) with the observed maximum LAI at harvest. The model estimated the maximum LAI to be within the range of 91.8 – 105.8% of the observed LAI. The variation was the maximum in 1990 and minimum in 1987.

The data revealed that the model predicted the biomass yield closely with observed values. However, there was deviation of –9.3 to +12.6% to that of observed values in all the four years. The variation in the predicted biomass at maturity was the maximum in 1990 with that of observed values. Model predicted pod shelling % closely to that of observed values. Shelling percentage, an important yield attribute ranged from 60.22 to 72.11% with a deviation of –8.5 to + 9.8% to that of observed values. The variation was the maximum in 1987 and minimum in 1990 due to variation in weather parameters.

The model predicted pod yield ranged between 683 to 2470 kg/ha in all the four years. The model simulated pod yield ranged within 88.5-112.7% of the observed values. Simulated pod yield was significantly correlated (R^2 = +0.93) with the observed pod yield. Highest yield

TABLE 4

Simulated pod yield of groundnut cultivars against date of sowing and spacing during 1987 and 1990

Treatments *	1987			1990		
	GAUG 10	GAUG 2	Ro-33-1	GAUG 10	GAUG 2	Ro-33-1
D_1S_1	711	612	698	2178	2665	2306
D_2S_1	655	639	665	2057	2569	2262
D_3S_1	607	619	656	1916	2432	2168
D_1S_2	779	672	789	2116	2568	2284
D_2S_2	803	683	767	1998	2470	2218
D_3S_2	621	651	698	1832	2321	2140
D_1S_3	676	672	724	2019	2494	2251
D_2S_3	639	651	711	1911	2342	2184
D_3S_3	596	640	663	1692	2146	2084

* Treatment details are given in Application of model

was observed in 1990 due to favourable weather conditions and more rainfall in particular than other years and the model also predicted this.

The summary and difference measures for the data sets of groundnut are presented in Table 3. In this study, the degree of agreement (*d*) ranged between 0 and 0.6 except for LAI. Higher *d* for LAI is due to the fluctuations in the simulated and observed values approaching zero. Negative MBE occurs in the case of LAI as almost model predictions are lesser than observed values. The PE values indicate that the model predicted phenology, growth, yield and development of groundnut satisfactorily except for LAI. This perhaps needs further validation and correction of the model, mostly for LAI. Similar results have been reported by Shivsharan *et al.* (2003) and Shivsharan *et al.* (2003a).

5.3. *Model application*

The sensitivity analysis (simulating date of sowing and spacing) option available in the model allowed to evaluate management strategies or to make tactical or strategic decisions by modifying the default values in the planting and field conditions. The results are presented in Table 4.

The results indicated that by adopting a closer spacing of 25 × 10 cm than normal (30 × 10 cm) and carrying out sowing one week earlier than normal date would be beneficial because of higher population and favourable weather conditions in 1990. The model also predicted that when there is a delay of one week of sowing to that of normal and when wider spacing is followed, pod yields were drastically reduced. This is applicable even for a good rainfall year, *i.e.*, for 1990.

But in the year 1987, when a very low rainfall of 283 mm was received, adopting closer spacing and advancing the date of sowing drastically reduced the pod yield. In such low rainfall year, normal date of sowing and spacing would give better yield than closer spacing and advancing the date of sowing.

Thus crop management options by altering the date of sowing and spacing based on long range/medium range rainfall forecast and adopting proper management practices would help to increase the pod yield of groundnut. Such area specific suggestion can be included in the Agromet Advisory Service bulletin of India Meteorological Department and disseminated among the farmers.

6. Conclusion

The following conclusions are drawn :

(*i*) PNUTGRO model well responded to all varieties in all the years under varying weather conditions.

(*ii*) The results obtained with the model for the four consecutive crop seasons revealed satisfactory predictions of crop phenology, growth and yield of groundnut and hence the model can be used for forecasting groundnut yield in and around Anand region of Gujarat state.

(*iii*) The summary and difference measures indicate that model performed satisfactorily in the prediction of growth and yield of groundnut.

(*iv*) The model can also be applied for making strategic farm management decisions.

(*v*) Using long range seasonal rainfall forecast and the tactical decision developed through the model, it could be possible to advise the farming community for better utilization of resources through Agromet advisory bulletins. Closer spacing and early sowing (one week earlier than normal date of sowing) compared to normal spacing and date of sowing may be advised under normal to excess rainfall condition.

Acknowledgements

The authors express their sincere thanks to Dr. H. P. Das, LACD DDGM (Agrimet) for his encouragement in the present work. They are also thankful to Shri B. I. Karande, Research Associate, CASAM, Pune, for his help in running model. Collection and processing of data by Ms. Gracy John and Ms. S.P. Ransure are also thankfully acknowledged.

References

Boote, K. J., Jones, J. W., Mishoe, J. W. and Wilkerson, G. G., 1986, “Modeling growth and yield of groundnut”, In : Agrometeorology of groundnut. Proc. of an International Symposium, ICRISAT, Sahelian Centre, Niamey, Niger, 21-26, August 1985, 243-254.

Boote, K. J., Jones, J. W., Hoogenboom, G. and Wilkerson, G. G., 1987, “PNUTGRO v1.0, Peanut crop growth and yield model”, Technical documentation. Department of Agronomy and Agricultural Engineering, University of Florida, Gainsville, FL. p121.

Dent, J. B. and Blackie, M. J., 1979, “Systems simulations in agriculture”, Applied Science Publishers Pvt. Ltd., Essex, England, p224.

Jagtap, S. S., Mornu, M. and Kang, B. T., 1993, “Simulation of growth, development and yield of maize in the transition zone of Nigeria”, *Agricultural Systems*, **41**, 215-229.

Jones, J. W., 1993, “Decision support systems for agricultural development”, In : *Systems approaches for agricultural development* (Ed: Penning de Vries, F.W.T., Teng, P.S. and Metselaar, K), Kluwar Academic Publications Inc., The Netherlands.

Kaur, P. and Hundal, S. S., 1999, “Forecasting growth and yield of groundnut (*Arachis hypogaea* L.) with a dynamic simulation model ‘PNUTGRO’ under Punjab conditions”, *Journal of Agricultural Science (Cambridge)*, **133**, 167-173.

Shivsharan, P. N., Sable, R. N. and Varshneya, M. C., 2003, “Validation of DSSAT – 3.5 for summer season pearl millet”, *J. Maharashtra Agric Univ.*, **28**, 2, 173-176.

Shivsharan, P. N., Sable, R. N., Varshneya, M. C. and More, D. B., 2003a, “Validation studies of DSSAT – 3.5 for pearl millet in summer season in the Pune region of Maharashtra state”. *Journal of Agrometeorology*, **5**, 2, 68-72.

Singh, P., Boote, K. J., Rao, A. Y., Iruthayaraj, M. R., Sheikh, A. M., Hundal, S. S., Narangh, R. S. and Singh, P., 1994. “Evaluation of the groundnut model PNUTGRO for crop response to water availability, sowing dates and seasons”, *Field Crops Research*, **39**, 147-162.

Wilmott, 1982, “Validation of the model”, Chapter No. 8 in CERES – Wheat Book draft No. 1, IBSNAT, Univ. of Hawaii, USA.