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Predicting cotton production using Infocrop-cotton simulation model, remote sensing and spatial agro-climatic data

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A methodology is described to predict cotton production on a regional basis using the integrated approach of remote sensing (RS), geographic information system (GIS) and a crop simulation model, i.e. Infocrop-cotton model. This model is based on an indigenous crop growth simulator called Infocrop. The Infocrop-cotton model was calibrated and validated to simulate the effect of diverse weather, soil, and agronomic management practices on growth, development and yield of cotton varieties and hybrids using results of several diverse field experiments (60 datasets). These experiments were conducted during 2000–01 to 2004–05 in major cotton-producing states of India across locations spreading from Hisar (29°10′N, 75°46′E) to Coimbatore (11°00′N, 77°00′E) with varying management practices, weather and soil. The model satisfactorily simulated the trends in leaf area, dry matter growth, days to flowering and seed cotton yield. The simulated time to flowering and maturity varied between 54 and 80 days as well as 136 to 193 days, with an RMSE value of 3 and 8.5 days respectively. Total biomass and seed cotton yield showed an accuracy of 86 and 89% respectively. The model also precisely simulated water deficit and N stress, the two important abiotic constraints for dryland cotton production.

The Infocrop-cotton model was used in conjunction with RS and GIS techniques for developing an integrated approach for deriving cotton production estimates. Resourcesat-1 LISS III data of October/November months corresponding to peak vegetative stage of cotton crop were used to derive spatial distribution of cotton crop. The study area was classified as polythesian polygons based on pedo-climatic variables, namely soil type, soil depth and rainfall pattern using GIS. Cotton yields for each of these polygons were simulated using the crop model and were aggregated to determine the total production of the district. The prediction of cotton production was more accurate to the partially irrigated or irrigated districts and not for the rainfed districts. The utility of the integrated approach in prediction of cotton production at the regional level has been discussed.

Keywords: Cotton, crop simulation model, production, remote sensing.

COTTON is an important commercial crop and a widely traded commodity across the world. Its yield is sensitive to weather, soil as well as management practices. India and China, where cotton is predominantly cultivated under dryland conditions, are two of the five largest cotton-producing countries in the world accounting for 42% of the world's cotton production[1]. In these countries, abiotic and biotic constraints such as declining soil fertility, frequent water and nutrient stresses, outbreaks of insect pests, uncertainties in rainfall and other environmental hazards cause large year-to-year fluctuation in yield[2]. The present production estimations by different agencies based either on the crop area sown, crop-cutting experiments or market arrivals show wide variability because of their inability to capture the indeterminate nature of the crop and its response to weather conditions. The unreliability and delay in the present production estimations are posing serious problems to planners to take timely import–export decisions. Reliable prediction methods are therefore needed to help planners and policy makers take strategic decisions to safeguard national interest.

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Crop simulation models, which account for daily variation in weather, are being used to predict the year-to-year fluctuation in yield[3,4]. However, crop simulation models, when run with input data from a specific field site, produce a point output. Their scope can be extended to a regional scale by providing spatially varying inputs (soil, weather, crop management practices) using a geographic information system (GIS). The interfacing of models with GIS facilitates the temporal and spatial analysis of yield on a regional scale as crop behaviour has a spatial dimension and simulation models produce a temporal output[5]. Recent developments in GIS technology allow capture, storage and retrieval, and visualization and modelling of geographic data. Earlier there were few attempts to integrate crop models with GIS. In the European Union, the WOFOST model has been integrated with GIS for operational yield forecasting of important crops[6]. The crop growth monitoring system (CGMS) of the MARS (monitoring agriculture with remote sensing) integrates crop growth modelling (WOFOST), relational database ORACLE and GIS with the system's analytical part for yield forecasting[7]. In India, simulation model WTGROWS was integrated with GIS to simulate potential and water-limited wheat yields for 219 weather locations[8].

With the availability of multi-spectral (visible, near infrared) sensors on polar orbiting earth observation satellites, remote sensing (RS) data have become an important tool for crop-yield modelling[9–11]. In indeterminate crops like cotton, the poor relationship between leaf area index (LAI) and vegetation indices (VI) is one of the constraints for direct adoption of this approach for cotton-yield modelling[12]. However, remote sensing technology has immense potential for estimation of pre-harvest crop acreage and its distribution. The spatial distribution of the crop can be integrated with different pedo-climatic variables using GIS. The crop yield under different pedo-climatic variables can be estimated using crop simulation models. Thus, integration of crop simulation models with RS and GIS is useful for crop monitoring, modelling and forecasting of crop production.

A simple generic model, Infocrop, has been found to satisfactorily simulate the growth and yield of rice and wheat[3] and a number of other crops such as potato, pearl millet, soybean, maize and sorghum in the tropical and sub-tropical environments[13]. It simulates the effects of weather, soil, agronomic management practices (planting, nitrogen, residues and irrigation) and major pests on crop growth, yield, soil carbon, nitrogen, water and greenhouse gas emissions. Because of its simplicity, requirement of a limited number of easily measurable/available plant and soil parameters, and easy availability of the source code, it is found to be amenable for integration with GIS and RS. This article describes the results of our study on the calibration and validation of Infocrop to simulate the growth and yield of cotton, and a methodology to predict cotton production on a regional basis by integrating RS, GIS and Infocrop-cotton simulated yields. The detailed methodology is illustrated for Nagpur District and the results of other cotton-growing districts are also given.

Material and methods

Model description

Infocrop is a generic model to quantify the interactions of weather, variety, soil, N, water and pests on crop growth and yield. The basic model is written in Fortran Simulation Translator programming (FST/FSE; Graduate School of Production Ecology, Wageningen, The Netherlands), a language also adopted by the International Consortium for Agricultural Systems Applications (ICASA) as one of the standard languages for systems simulation[14]. A user-friendly version of the model has also been developed to expand its applications in agricultural research and development by the stakeholders not familiar with programming. The user-interface of this software is written using Microsoft.Net framework, while the back-end has FSE models and databases in MS-Access[13].

In Infocrop, the basic crop growth and yield processes follow Penning de Vries *et al.*[15] and Aggarwal *et al.*[16]. It simulates crop development, growth, yield and N accumulation in response to temperature, photoperiod, soil water and N supply. It uses a daily time-step, and is designed to predict yield, crop biomass, crop nitrogen uptake and partitioning within the crop. Brief descriptions of some of the well-established genetic coefficients which were used in the model development[17–22], are presented in Table 1. Details about the basic crop model are given by Aggarwal *et al.*[3].

Model calibration

Data collected from field experiments conducted during the season of 2002–03 at the Central Institute for Cotton Research (CICR), Nagpur farm on a fine, smectitic hyperthermic Typic Haplusterts were used to calibrate the model. The treatments involved were three sowing dates (15 June, 2 and 20 July) and three nitrogen doses (0, 45 and 90 kg ha^{-1}) arranged in a split-plot design with dates of sowing as main plots and fertilizer levels as sub-plot treatments. A long-duration intra-hirsutum hybrid, NHH 44 and a popular variety, LRA 5166 were grown at a spacing of 60 × 60 cm. Each treatment was replicated three times in plots of size 10 m × 8 m. Half dose of N and complete dose of P_2O_5 and K were applied 20 days after sowing. Rest of the N was applied in two equal splits at squaring and flowering. Plots were weeded manually and intercultural operations were done at regular intervals in the early growth stages until the canopy was closed. Insecticides

Table 1. Genetic coefficients set for the model calibration of a hybrid and a variety

Genotypic constant	Units	Hybrid	Variety	Reference
Base temperature	°C	15	15	4
Thermal time for				
Germination	Degree-days	70	70	Field experiments
Germination to anthesis (range)	Degree-days	800–900	700–800	
Anthesis to maturity (range)	Degree-days	1600–1900	1500–1700	
Optimum temperature (°C) for seedling emergence, squaring, flowering and boll development	°C	28	28	4, 17
Specific leaf area (SLA)	$dm^2 mg^{-1}$	0.0022	0.0020	Field experiments
Relative growth rate of leaves during early stage	$(°C\text{-}d)^{-1}$	0.0095	0.009	3, field experiments
Radiation use efficiency (range)	$g MJ^{-1} day^{-1}$	1.5–1.8	1.4–1.6	18
Extinction coefficient of leaf at flowering	ha soil ha^{-1} leaf	0.80	0.70	3, 18
Contribution of bracts and capsules to photosynthesis	Per cent	15	15	19
Potential boll weight	mg $boll^{-1}$	5000	4000	Data from All-India Coordinated Cotton
Potential boll load	Million bolls/ha	1.4–1.6	1.2–1.4	Improvement Project
Root extension growth rate	mm day^{-1}	12	12	20
Biomass partitioning				
At emergence seed biomass in				
Root	Fraction	0.6	0.6	4
Above ground		0.4	0.4	
At early seedling				
Root		0.35	0.35	4
Above ground		0.65	0.65	
Squaring				
Leaf		0.7		Field experiments
Stem		0.3		
Flowering				
Leaf		0.4		
Stem		0.6		
Early boll development				
Leaf		0.1		
Stem		0.2		
Seed rate	kg/ha	2.5	5.0	Recommended
Sensitivity to flooding (between scale 1.0 and 1.2)		1.0	1.0	21
Index of greenness of leaves (between scale 0.8 and 1.2)		1.0	1.0	Field experiments
Photosensitivity	–	Commercially grown cultivars are photoinsensitive		4, 22

were used according to the recommendations to control sucking pests, *Helicoverpa armigera* and *Pectinophora gossypiella*. Sampling was done at every 15-day interval. Plants from 1 m^2 area were cut above the soil surface from the inner four rows of each plot. Each sample was partitioned into leaf (lamina), stem (including petioles), squares, green bolls and open bolls. Leaf area of a few representative leaves was measured using leaf area meter (LICOR-3000, Lincoln, USA) and their dry weight was recorded. Using this area : weight relation the leaf area of the whole plant at each of the sampling dates was calculated for all the treatments. The shed plant parts such as leaves, squares, flowers and bolls were collected at regular intervals and added to the weight of the respective plant parts.

Before sowing, the soil profile was examined and horizon-wise soil samples were analysed for texture, soil reaction, EC, bulk density, soil moisture constants, saturated hydraulic conductivity, organic carbon, $CaCO_3$, exchangeable cations, CEC, initial ammonical N, nitrate N, available P and available K.

Model parameters such as radiation use efficiency (RUE), light extinction coefficient, root growth rate and mobilization of reserve carbohydrate of cotton, which are relatively stable, were obtained from the literature. With the incorporation of the above weather, soil and crop parameters, the model was run to simulate the phenology, growth and yield of normal and late-sown hybrid and variety at different 'N' levels.

Model validation

Datasets collected from similar experiments as described above (involving date of sowing and nitrogen level) conducted under the Technology Mission on Cotton Project funded by the Government of India were utilized for model validation. Field experiments were conducted dur-

Table 2. Experiments and their details used for model validation under water-limited and nitrogen-limited environments. Treatments differed in location, genotypes, irrigation, date of sowing and nitrogen levels

Location	Latitude/ Longitude	Agro-eco region	Year	Genotype	Hybrid or variety	Sowing in Julian days		N level (kg/ha)	No. of treat-ments	Temperature range (°C)		Solar radiation (MJ m^2/day)*	Rain-fall (mm)*
						Rainfed	Irrigated			Maxi-mum	Mini-mum		
Coimbatore	11°00′N, 77°00′E	Hot semiarid	2003	LRA 5166	Variety	–	221, 231, 261	0, 60, 90, 120	12	26.5–34.7	14.0–25.0	22.1–28.8	500–700
Dharwad	15°27′N, 75°05′E	Hot semiarid	1996	Abadhita	Variety	178, 198,	–	90	3	22.8–31.9	10.9–21.5	8.2–22.1	400–600
			1997	Abadhita	Variety	218, 198,	–	90	2				
			1997	Abadhita	Variety	216, 218	–	90	1				
Nagpur	21°09′N, 79°09′E	Hot dry sub-humid	2001	NHH 44	Hybrid	187, 202, 217	–	90	3	23.8–40.5	12.2–28.4	6.4–19.0	700–900
			2002	NHH 44	Hybrid	166, 183, 201	–	0, 45,	12				
							–	90, 135					
			2003	NHH 44	Hybrid	175, 191	175, 191	90	4				
				LRA 5166	Variety	175	175	60	2				
			2004	NHH 44	Hybrid	192	192	90	2				
Surat	21°12′N, 72°52′E	Hot semiarid	2001	GCOT Hy 10	Hybrid	–	183, 198, 213	120, 240, 360	9	24.7–39.0	12.5–28.0	9.5–26.5	700–900
			2002	GCOT Hy 10	Hybrid	–	182	120, 240	2				
			2003	GCOT Hy 10	Hybrid	171, 191	171, 191	240	4				
Hisar	29°10′N, 75°46′E	Hot typic arid	2001	H 1098	Variety	–	132	40, 80,	3	25.4–45.5	11.9–32.5	10.0–28.0	
			2002	H 1098	Variety	–	123, 141, 156	120	3				
								80					

*Values are ranges during the crop growth period.

ing 2000–01, 2002–03, 2003–04 and 2004–05 seasons in different cotton-growing states of India, spreading from Hisar (29°N) in the north to Coimbatore (11°N) in the south (Table 2). There was a wide variation in temperature, solar radiation and rainfall across these regions. Cotton was grown under rainfed conditions at Nagpur and Dharwad, and irrigated condition at Coimbatore and Hisar. At Surat, one or two protective irrigations were given. At each location the popular variety or the hybrid was selected for the experiment (Table 2).

Digital analysis of satellite data

Standard digital analysis technique employing complete enumeration approach using in-season ground truth information was followed for deriving information on spatial extent of cotton crop in Nagpur, Dharwad, Bharuch and Sirsa districts. The IRS LISS-III satellite data of 24 m resolution of October/November months corresponding to the optimal bio-window of cotton crop was used in the study. In-season ground truth information on land use/land cover was collected and marked on LISS-III false colour composite prints. Based on the ground truth, training areas for different agricultural land use/cover classes were defined and signatures were generated in terms of mean, variance and co-variance matrices. These signatures were used in the classification of satellite data employing supervised maximum likelihood algorithm to derive the spatial distribution of cotton crop of the district by overlaying the administrative boundary.

Spatial integration of crop, soil and weather parameters with Infocrop simulation model

The distribution of cotton crop derived from satellite data was spatially integrated with pedo-climatic variables, viz. soil type, soil depth and rainfall using GIS techniques. The soil map 1 : 50,000 scale developed by the National Bureau of Soil Survey and Land Use Planning (ICAR), Nagpur[23] was digitized in an Arc GIS environment. This shape file was further integrated with soil parameters, viz. soil depth (six classes – extremely shallow, very shallow, shallow, moderately shallow, moderately deep and deep) and six textural classes (fine clay, clay, fine loamy, loamy, coarse loamy and loamy skeletal). Using long-term rainfall data of 14 rain gauges located in Nagpur District, nine homogenous thessien polygons were identified. Unified soil maps (depth and texture) were overlaid to identify homogenous units for running the model. Similar exercise was undertaken for Dharwad (Karnataka), Bharuch (Gujarat) and Sirsa (Haryana) districts. The district maps were prepared from the soil re-

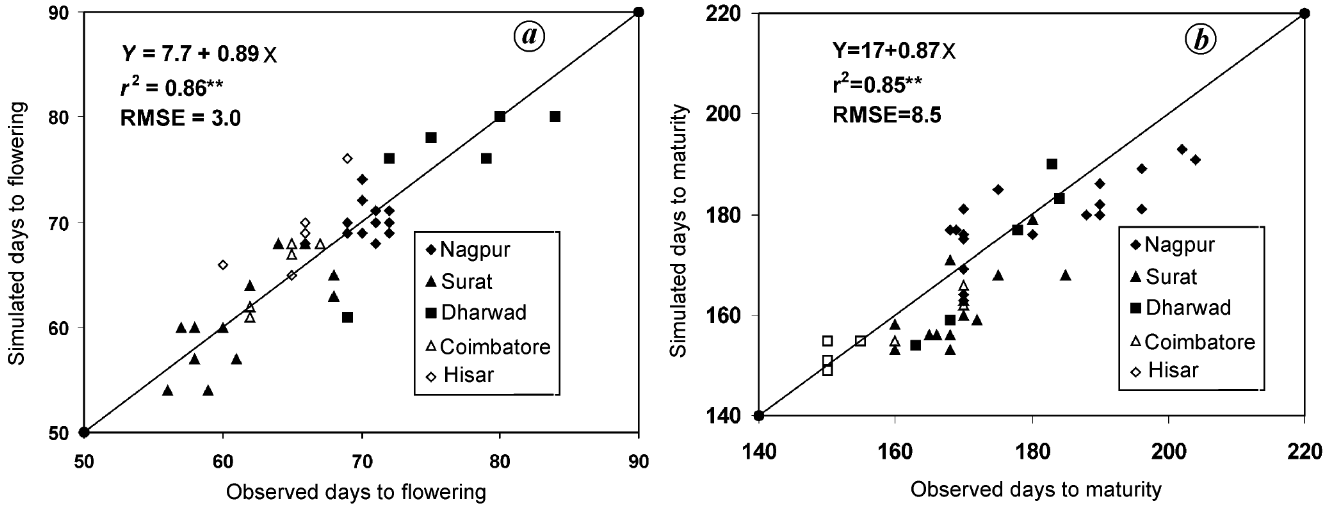

Figure 1. Simulated and measured duration to (*a*) flowering and (*b*) maturity across datasets varying in location, year, season, weather, N management, sowing date and genotype. The 1 : 1 line is also presented.

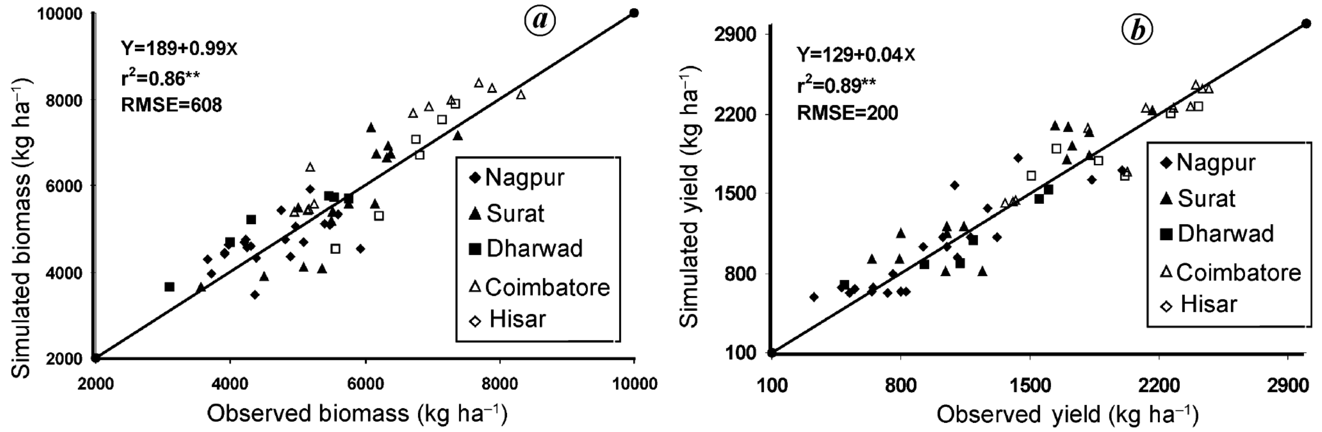

Figure 2. Simulated and observed (*a*) biomass and (*b*) seed cotton yield across datasets varying in location, year, season, weather, N management, sowing date and genotype. The 1 : 1 line is also presented.

source maps (1 : 50,000) of Karnataka[24], Gujarat[25] and Haryana[26].

The cotton crop map in vector format was integrated with soil map for estimating the proportion of cotton crop cultivated under different soil depth and texture classes for each of the nine-thessien polygons. For each polygon class, the Infocrop model was run and the yield was computed for two sowing dates (20 and 30 June) for different soil depth and soil texture combinations using daily weather data. The mean yield (over sowing dates) was multiplied with the area under cotton in each polygon (the chosen polygon is unique, with uniform soil depth and texture parameters) to provide the production at disaggregated level.

Statistical analysis

Data from the field experiments were analysed using split-plot design. Comparisons were made between the simulated (Y) and observed (X) data with regression analyses of the form $Y = a + bX$. Measures of accuracy were made with the adjusted coefficient of determination (r^2) and the root mean squared error (RMSE) between simulated and observed values.

Results and discussion

Model validation

Phenology: In the datasets used for model validation, large variation was seen for time to flowering and maturity. The former ranged from 56 to 84 days, whereas the latter ranged from 150 to 204 days. Year-to-year fluctuation was more under rainfed compared to irrigated condition. The simulated time to flowering ranged between 54 and 80 days, with an RMSE value of 3 days (Figure 1 *a*), whereas time to maturity ranged between 136 and 193 days with an RMSE of 8.5 days (Figure 1 *b*). In most parts of India, cotton at early growth stages suffers from intermittent drought, waterlogging and insect attack and at later stages, owing to its indeterminate growth habit produces multiple flushes of squares and bolls. This complicates the determination of exact time to physiological maturity, causing poor relationship between phenology and heat unit under adverse conditions. This might partially explain the discrepancies between observed and simulated phenology[27,28].

Biomass and yield: Data depicted in Figure 2 *a* and *b* indicate that there was a close relationship between the simulated and observed biomass, and seed cotton yield across all treatments comprising location, season, genotype, sowing date and N level. Measured biomass and seed cotton yield ranged from 3096 to 8319 kg ha^{-1} and 590 to 2466 kg ha^{-1} respectively. Though there is a good correlation between vegetative growth and fruit load in cotton[29], this is offset by the loss of fruiting forms caused by biotic and abiotic factors under rainfed condition. Despite the above complexities the model-simulated yield showed an accuracy of 89%, with an RMSE of 200 kg ha^{-1}. Simulated biomass on the other hand, showed 86% accuracy with an RMSE value of 608 kg ha^{-1}. The difficulty in recording of biomass lost as litter (leaves, squares and bolls) between observations could partly explain the relatively larger variance between simulated and observed biomass.

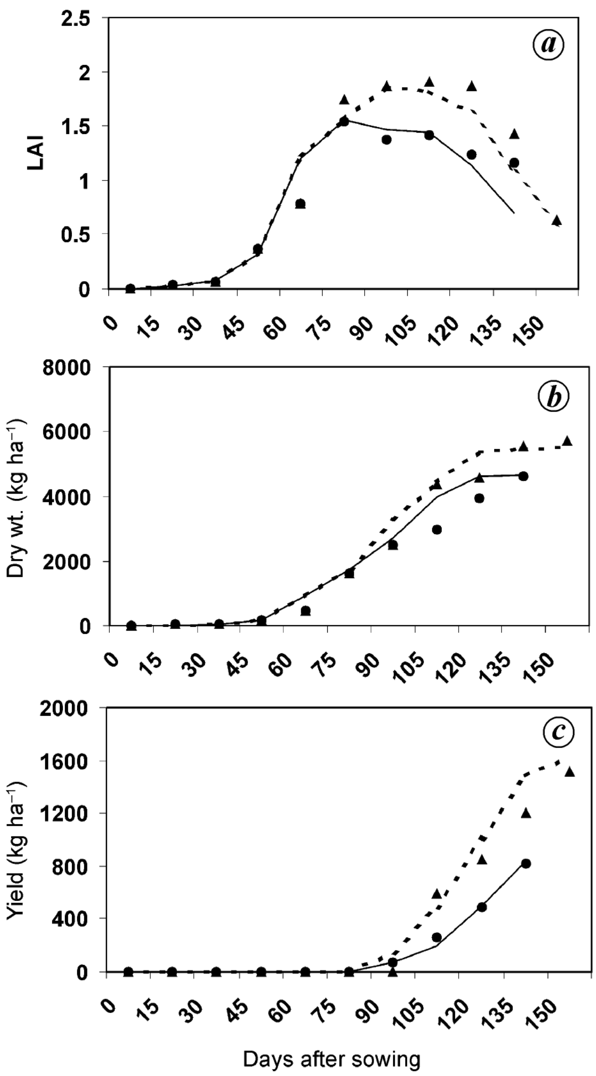

Figure 3. Observed (symbols) and simulated (line) (*a*) LAI, (*b*) biomass and (*c*) seed cotton yield in a dryland (observed (•) and simulated (–)) and irrigated (observed (▲) and simulated (-----)) experiment with intra-hirsutum hybrid (NHH 44) sown on 22 June 2004 on a vertisol at CICR Farm, Nagpur.

Effect of water stress: Water deficit is an important constraint in dryland cotton production. Cotton crop which is sown with the onset of monsoon, experiences intermittent drought owing to uneven distribution of rainfall, or terminal drought because of its early cessation. Figure 3 depicts the capability of the model to simulate the water-deficit effects on cotton (cv. NHH44) sown in 2004 at CICR farm, Nagpur without irrigation. In this experiment, the crop experienced a terminal drought and a single irrigation at early boll development significantly increased the LAI, biomass and seed cotton yield. The response to irrigation depicted in Figure 3 shows that the model could capture increased growth and yield with irrigation. The model also precisely simulated the crop duration, which was extended (as seen in Figure 3 with irrigation), with the application of irrigation.

Spatial distribution of cotton crop in Nagpur District: The classified Resourcesat-1 LISS-III satellite data showing spatial distribution of cotton crop are given in Figure 4, with cotton crop depicted in green colour and area of cotton crop estimated as 72,587 ha. Cotton crop in Nagpur District is mostly concentrated in the western part, as indicated in red colour on the satellite data. The integrated soil and crop analysis showed that about two-third of cotton crop in Nagpur District is grown in deep soils. Though very shallow soils are not congenial for cotton cultivation[30], about 22% of cotton is being cultivated in such soils (Figure 4 *a*). Similarly, about two-third of cotton cultivation is on fine-textured clayey soils and nearly 20% is distributed on coarse textured soils (Figure 4 *b*). Area of cotton crop under different soil depth and soil type regimes, individually and across all combinations for each of the nine-polythesian triangles of Nagpur District is presented in Table 3. A unique polygon id was given for a unique combination of station, soil type and soil depth, thus generating about 58 unique polygons. The number of unique polygons may vary from year to year based on the distribution of the cropped area.

The rainfall in different polygons during 2004 ranged from 510 to 763 mm and this was received over 35–43 rainy days (days with > 2.5 mm rainfall). Considerable

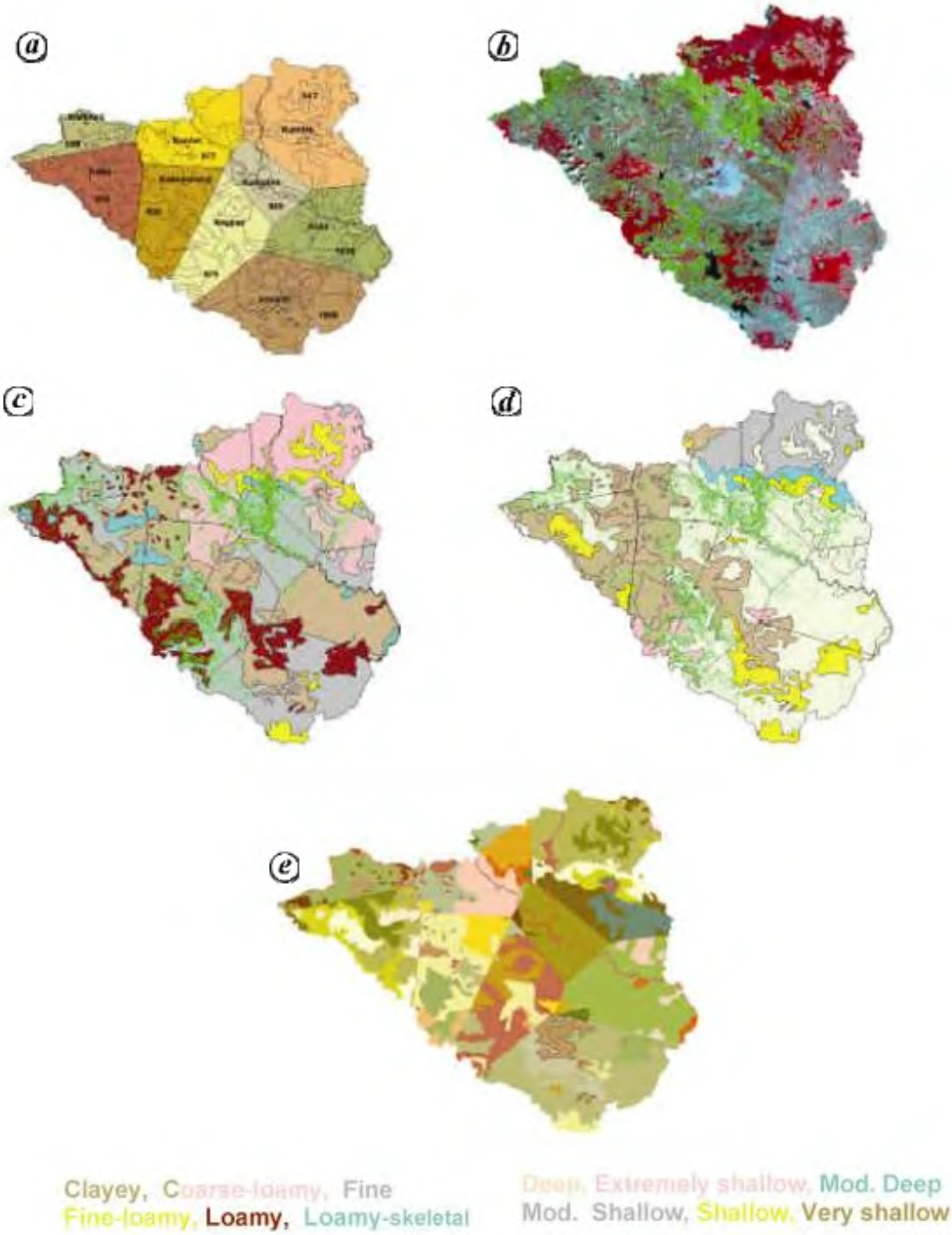

Figure 4. ***a***, Unified soil resource map with rain gauge network. ***b***, Classified crop map showing spatial distribution of cotton crop in Nagpur District (green colour). ***c***, ***d***, Soil texture map and soil depth map of Nagpur District with distribution of cotton overlaid. ***e***, homogenous polygons with station, soil type and soil depth.

variation was observed in simulated productivity (Table 3) and this could be assigned to differences in the soil (depth and texture) and rainfall distribution pattern across stations. The integrated approach offers details on productivity estimates across stations combined with soil type and depth, which can be examined for further improvement in productivity. The integrated approach has been validated to a few more years at Nagpur District and other cotton-growing districts of Dharwad, Bharuch and Sirsa (Table 4). RS estimated cotton area at an accuracy of above 95% to the above cotton-growing districts, except Dharwad where cotton is grown both in kharif and rabi seasons; in this observation, RS captured only kharif cotton. The prediction of cotton production using the integrated approach was found to be more accurate in the irrigated cotton belt of Sirsa District and the partially irri-

Table 3. Polygon features and estimated area, production and productivity of cotton in Nagpur District

Polygon	Rainfall (m) June–December	Rainy days (no.)	Composite soil unit (no.)[a]	Dominant soil unit	Area (ha)	Area under dominant soil unit (ha)[b]	Productivity (kg/ha)[c]	Production (bales)*
On station basis								
Kalmeshwar	751	42	6	Clay, 18 cm	9693	4728 (49%)	361	20,587
Kamptee	742	35	4	Fine clay, 120 cm	9483	8996 (95%)	497	27,723
Katol	540	36	5	Clay, 18 cm	4412	1494 (34%)	397	10,307
Kuhi	590	38	6	Fine clay, 120 cm	759	404 (53%)	473	2940
Nagpur	672	39	6	Fine clay, 120 cm	11745	6883 (58%)	313	21,653
Narkhed	533	37	4	Fine clay, 120 cm	7950	6396 (80%)	392	18,326
Ramtek	750	37	7	Fine clay, 120 cm	11004	4728 (43%)	630	40,749
Saoner	737	42	9	Coarse loamy, 120 cm	14587	9458 (65%)	577	49,480
Umred	763	43	7	Fine clay, 120 cm	2956	2627 (89%)	441	7659
Total					72589		465	198,594

[a]Soil depth and texture combination; [b]Percentage of total area in polygon; [c]Simulated yield (mean over 170 and 180 Julian days).
*Bale = 170 kg lint fibre.

On soil-type basis

Soil type	Area (ha)	Productivity (kg/ha)	Production (bales)
Clay	11244	150	9941
Coarse loamy	16220	698	66,553
Fine	33192	482	94,084
Fine loamy	3729	729	15,982
Loamy	8014	249	11,724
Loamy skeletal	188	281	311

On soil-depth basis

Soil depth (cm)	Area (ha)	Productivity (kg/ha)	Production (bales)
18	18,890	188	20,854
45	1629	363	3476
60	749	463	2039
90	2049	643	7754
120	49,271	567	164,471

gated Bharuch District, while the discrepancies between the official and estimated values were high in the rainfed tracts of Nagpur and Dharwad. In most cases the integrated approach over-estimated productivity because at this juncture the model did not account for the loss due to insect pests. At Sirsa and Bharuch cotton is mostly monocropped. However, nearly 20% of cotton area under Nagpur District is intercropped with pigeon pea. In Dharwad also cotton is intercropped with onion and chillies in replacement series and the actual area planted under cotton is less. If the above losses and discrepancies were accounted for in the model, the predicted yield would be more accurate with the observed yield in Nagpur as well as Dharwad districts. Since the difference is considerable, there is need for a closer look at the official estimates (large discrepancy between Ministry of Textiles and State Government estimates) as well as simulated productivity values. A calibrated and validated model like the one described above, would offer a better choice than the black-box approach of official estimates, which does not furnish information on productivity at a lower level than a district. Thus there is little scope to verify the simulated productivity estimates across rainfall stations within a district. One possible solution could be to carry out a sample survey for productivity estimates across soil types and stations, and compare the same with the simulated values. Further, the model-based estimates can be made available before the end of the crop season. The integrated approach offers an insight into the production potentials within a district for crop production, considering the available resources.

Conclusion

This article reports a crop-simulation model for cotton, a widely cultivated commercial crop in the tropics and subtropics. Infocrop, a generic model was used to simulate cotton growth and yield under rainfed as well as irrigated conditions by modifying certain genetic coefficients based

Table 4. Cotton area, production and productivity estimated by the integrated approach, official values and their deviation for Nagpur, Dharwad, Bharuch and Sirsa districts

District	Year	Area (ha)		Percentage deviation	Productivity (kg/ha)		Percentage deviation	Production ('000 bales)		Percentage deviation
		Estimated	Official		Estimated	Official		Estimated	Official	
Nagpur	2003–04	78,410	74,300	5	220	264	–20	101.00	115.40	–14
	2004–05	72,587	75,300	–4	465	235	49	198.00	104.30	47
	2005–06	78,490	73,300	7	540	229	58	249.00	98.80	60
	2006–07	68,435	–	–	589	–	–	237.00	–	–
Dharwad	2004–05	159,018	86,480	46	184	139	24	172.00	70.95	59
Bharuch	2004–05	131,526	129,700	1	478	439	8	409.00	335.00	18
	2005–06	138,439	148,000	–7	530	499	6	431.00	485.00	–13
	2006–07	130,233	149,300	–15	495	435	12	379.00	381.00	–1
Sirsa	2005–06	192,000	190,000	1	550	581	–6	622.00	649.00	–4
	2006–07	198,116	194,000	2	535	620	–16	624.00	707.00	–13

on the physiology of the crop. The model was calibrated and later validated using datasets generated through multi-location experiments conducted under diverse climate, soil and management conditions. Despite the relatively simple approach employed, the model gives good predictive capability for cotton phenology, leaf area, biomass, seed cotton yield under diverse growing conditions (dryland and irrigated), cultivars (varieties and hybrids) and management conditions (date of sowing, fertilizer level, irrigation). Since the model is simple and had shown good predictions, it was interfaced with GIS and RS data for the prediction of cotton production in Nagpur, Dharwad, Bharuch and Sirsa districts. The integrated approach prediction of cotton production was found to be more accurate in the irrigated cotton belt of Sirsa and the partially irrigated Bharuch districts, while the discrepancies between the official and estimated values were high in the rainfed tracts of Nagpur and Dharwad. Though the non-inclusion of pest component and the mixed cropping systems could explain the above discrepancies, it still calls for a closer look at the official estimates as well as simulated productivity values.

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Predicting the spatio-temporal variation of run-off generation in India using remotely sensed input and Soil Conservation Service curve number model

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The Soil Conservation Service curve number (SCS CN) model has been used in the GIS environment to compute run-off at spatio-temporal scales using remote sensing-derived rainfall for 2004 and climatic normal (1951–80) rainfall data. The SCS CN model takes into account land use/land cover, antecedent soil moisture condition and hydrological soil groups. Temporal 10-day composite Normalized Difference Vegetation Index images of SPOT–VGT sensor, and daily remote sensing-derived rainfall data at 10 km resolution from the NOAA Climate Prediction Centre have been used to generate the land cover and antecedent moisture condition (degree of saturation) respectively. Hydrological soil groups were prepared using the soil texture and their infiltration and drainage characteristics. Run-off coefficient maps were generated using the CN-based rainfall excess run-off. Wetland rice-growing areas of West Bengal, India were used to calculate threshold run-off coefficient (0.2) to identify run-off potential areas for major river basins of India during the monsoon season (June to September). There was a large difference in the spatial pattern of run-off estimated for the year 2004 compared to using normal climatic rainfall data. Area estimates for run-off potential were also found to vary significantly for the climatic normal and in-season (2004) data. The spatial variability showed high run-off potential in the western India river basins like Mahi, Luni, rivers of Saurashtra and Sabarmati in 2004. Run-off potential areas over India have been found to increase abruptly from June (158,700 km^2) to July (712,300 km^2), and decrease from August (633,400 km^2) to September (142,000 km^2) during 2004.

Keywords: Curve number, remote sensing, river basin, run-off.

INFORMATION about the spatial distribution and temporal variation of run-off potential areas at a regional scale is essential to understand its influence on conservation and development of land and water resources. Conventional techniques (installing stage recorder, current meters, etc.) of point run-off measurement are accurate and useful. However, in most cases such measurements are expensive, time-consuming and difficult. Therefore, rainfall–run-off models (empirical and physically based) are commonly used for computing run-off. There are distributed hydrological models which describe the physical rainfall–run-off processes controlling the transformation of rainfall to run-off[1–3]. The advantage of these models is the accuracy of their predictions. But a major disadvantage is that they require extensive database, time and expertise to be used effectively. A good run-off model includes spatially variable parameters such as rainfall, soil, land use/land cover, etc.[4,5]. Therefore, in this study the Soil Conservation Service curve number (SCS CN) method[6] was used, which is a versatile and popular approach for quick run-off estimation, is relatively easy to use with minimum data and gives adequate results[7–11]. It is used extensively in various hydrologic, erosion and water quality models, including CREAMS[12], EPIC[13], AGNPS[14] and SWAT[15]. Generally, this model is well suited for small watersheds of less than 250 km^2, as it requires details of soil physical properties, land use and vegetation condition[16,17]. Therefore, so far it has been used mostly as lumped (taking the average value of the study area) model at watershed scale[18–23]. However, advances in computational power and the growing availability of spatial data from remote sensing techniques have made it possible to use hydrological models like SCS CN in spatial domain with Geographic Information System (GIS)[24,25]. The SCS CN model has been used extensively on various watersheds of varied sizes. The model has been found to perform well without much calibration.

In the Indian subcontinent, run-off is generated mostly during the monsoon season (June to September) during a year. In this aritcle, the SCS CN model has been used to estimate run-off for major river basins of India at 10 km cell size during the monsoon period of 2004. Run-off coefficient (RC) maps were also prepared considering the wetland rice areas of West Bengal as a mask on the estimated run-off to identify the run-off potential areas.

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