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Study of Cotton crop yield optimization in Telangana using Crop Simulation models and GIS techniques

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ABSTRACT

To delineate the potential crop production zones of cotton and strategies to improve the lower potential zones in Telangana through experimental means is labororious and cumbersome, so the present study aimed at the application of calibrated and validated crop simulation models for delineation of potential production zones by using GIS techniques in Telangana State. Model application through seasonal analysis the optimum plant density and nitrogen level for the MRC 7201 cultivar was 1,11,111 plants ha^{-1} at 60 cm x 15 cm spacing with 120 kg N ha^{-1} The simulated average potential non-water-limited yield decreased from the western to the eastern parts of Telangana, varying between 3,717 kg ha^{-1} and 3,891 kg ha^{-1} across different sowing dates (15 June to 30 July). Water-limited yields showed a decreasing trend from the northern to the southern parts of Telangana, ranging from 2,642 kg ha^{-1} to 3,029 kg ha^{-1}. The potential yield of cotton was highest when sowing occurred on July 22 and July 30. A strategic irrigation application at the flowering stage for crops sown on June 15 in the Maktal mandal (Mahabubnagar district) led to a maximum simulated yield increase of 2,500 kg ha^{-1}. A maximum yield increase of 1738 kg ha^{-1} was simulated at the Eturunagaram Mandal in the Warangal district with strategic irrigation applied at the flowering and boll development stage in crop sown on 06 July.

Keywords: *Seasonal analysis, crop simulation, growth model, phenology, water limitation, GIS, CROPGRO-Cotton*

INTRODUCTION

The Decision Support System for Agrotechnology Transfer (DSSAT) crop models are complex, as they require many input parameters to provide in-depth assessments of crop growth and development and water and nutrient dynamics [1]. Crop models are extensively used in tactical and strategic decision support for crop productivity enhancement [2], including the impact of weather variability, crop management practices, and selection of genotypes in specific environments [3]. The cropping system model (CSM) CROPGRO-Cotton model simulates crop growth and development in response to weather conditions, soil properties, cultivar characteristics, and crop management practices. The DSSAT is a platform that encompasses 42 crop growth models covering fruit crops, vegetable crops, fiber crops, cereals, legumes, oil crops, and root crops. Each crop model simulates crop growth and development in response to weather conditions, soil properties, cultivar characteristics, and crop management data.

The use of a seasonal analysis tool in the CROPGRO-Cotton model indicated that higher aboveground biomass, seed cotton yield, and nitrogen productivity were obtained when irrigation was scheduled for 40% depletion of available soil moisture [4]. Modeling cotton growth in the Texas Rolling Plains, revealed successful deficit irrigation strategies for producing a relatively new crop in western Kansas [5]. All the studies reported the importance of calibrating the CSM-CROPGRO-Cotton model for particular cultivars and growing regions for successful model implementation. Model parameterization using detailed and wider ranges of quality data from field experiments is still lacking across the globe for cotton. In addition, no studies have tested models for cotton growth, development, and yield response to various plant densities and nitrogen dosages. The above-discussed review highlighted the significance of CSM-CROPGRO-Cotton model calibration for a particular genotype under specific environmental conditions and its application in decision support. Hence, there is a need to provide optimum plant populations and nutrient management strategies for cotton producers using crop simulation models through the validation of experimental data for estimating potential and water-limited yields in Telangana State. The objectives of the present study were as follows: 1. To delineate potential cotton production zones in Telangana using the CROPGRO-Cotton model and GIS technique. 2. Strategies for yield improvement in low-yield potential zones were identified by using the CROPGRO-Cotton model.

MATERIALS AND METHODS

Description of the CSM-CROPGRO-Cotton model

The Telangana region, encompassing 33 districts, lies in the

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southern part of India (Fig. 1). For this study, the CSM-CROPGRO-Cotton model was chosen due to its successful application for different cropping systems under different climatic conditions by various researchers across the globe. The DSSAT is a platform that integrates the database management systems (soil, climate, and management practices), crop models, and various application programs including sensitivity analysis and spatial analysis [2] by bringing together a diverse array of crop models in a single platform. The DSSAT, version 4.6, is equipped with over 28 crop growth simulation models [6]. Each crop growth model incorporated into DSSAT predicts crop growth, development and yield, soil water balance, evapotranspiration, soil moisture, and carbon and nitrogen processes over time based on weather, soil, crop management, and crop cultivar information.

The CSM-CROPGRO-Cotton model, which was developed from the CROPGRO-Soybean model, simulates crop growth and development on a daily time scale. It simulates different crop growth stages such as emergence, first leaf, first flower, first seed, first cracked boll, and 90% open boll based on the accumulation of heat units or photothermal time [7]. The CSM-CROPGRO-Cotton model works by calculating various rate variables on a daily time step, integrating the model state variables over time, and finally updating the state variables. A warm-up period can be simulated in the model before planting to establish the soil hydrological conditions. After planting, the model simulates carbon, nitrogen, and water dynamics as well as plant processes such as photosynthesis and respiration. The vegetative phase mostly depends on the supply of carbon and nitrogen [2].

The soil water balance routine in DSSAT simulates daily soil water processes that affect the availability of soil water [8]. Detailed information about the methodologies and processes used in DSSAT can be found in the DSSAT documentation [9].

Application

The accuracy of the model simulations was validated with data recorded against plant densities and nitrogen level treatments during 2015 and 2016 under variable weather conditions. During all these processes, available data on anthesis date, maturity date, yield components, seed cotton yield, and total crop biomass was compared with the simulated values.

If the calibrated models are validated with independent data sets, they can potentially be used as tools to make operational, tactical, and strategic decisions to support on-farm crop management [10]. An analysis was carried out with the CROPGRO-Cotton model for identifying the optimum plant densities and nitrogen levels for cotton production using the seasonal analysis tool DSSATv4.6 CROPGRO-Cotton model to simulate seed cotton yield with 9 plant densities ranging from 18,518 plants ha^{-1} to 1,48,148 plants ha^{-1} and 8 nitrogen levels ranging from 110 kg N ha^{-1} to 180 kg N ha^{-1} under the semiarid environment of Telangana state using 30 years of historical daily weather data from 1986 to 2015.

Biophysical and strategic analysis options were used to compare the results under different options. Seed cotton yield was compared by percentile distribution for each plant density and nitrogen level. The data were analyzed statistically by one-way analysis of variance using SAS. The significance was tested by the 'F' test [11]. The significance of critical differences for examining treatment means was calculated at the 5 percent probability level (P=0.05). To analyse the pattern of difference between means Fisher's least significant difference test (t-test) was employed [12].

Delineation of potential cotton production zones using the CROPGRO-Cotton model and GIS technique

Assessment of potential and water-limited yields can help in identifying yield-limiting factors and in developing suitable strategies to improve the productivity of a crop [13]. At production level one, growth occurs with ample water and nutrient availability throughout plant life. Under such conditions, the growth and productivity of a crop are primarily determined by solar radiation and temperature. The yields obtained at this production level are also referred as the water-nonlimiting potential yields, and their estimation is important for determining the scope of yield improvement [14].

Rainfed or partially irrigated crops with ample nutrients are examples of water-limited production systems. At level two, growth is limited for at least a part of the plant life due to limited water availability, thus decreasing the crop growth rate and yield. At all these levels, it is assumed that biotic factors are not a constraint to growth. The calibrated and validated model was used to predict the potential and water-limited yields of cotton across 584 mandals of Telangana state. The simulations were carried out using historical weather data (1986-2015) collected from the Directorate of Economics and Statistics [15]. The data on the soil characteristics of each of these locations were taken from the database published by the National Bureau of Soil Survey and Land Use Planning. Similarly, different management strategies were also simulated after identifying constraints in low-yield potential zones.

Geographical Information system (GIS) is a very powerful tool for processing, analyzing and integrating spatial data sets. ArcGIS addresses information on the location patterns of features and their attributes. It can be considered a higher order computer-coded map that permits storage, selective dedicated manipulation, display and output of spatial information [16]. The simulation results are linked to a geographic information system for presentation and to contribute to the identification of hotspots for interventions aimed at yield improvements. The simulated potential production, and water-limited yields were kept in the GIS environment and maps were generated for Telangana state. Strategies were used for low yield zones with planting dates and irrigations practices across the state. Irrigation should be applied at peak flowering, and boll development stages as another option to improve the seed cotton yield.

RESULTS AND DISCUSSION

Model application for plant densities

The highest mean seed cotton yield was predicted for P_9 (1,48,148 plants ha^{-1}) which was significantly greater than that for P_1 (18,518 plants ha^{-1}), and P_2 (24,691 plants ha^{-1}),in turn, P_1 (18,518 plants ha^{-1}) had significantly lowest seed cotton yield (Table 1). However, P_1 (18,518 plants ha^{-1}), P_2 (24,691 plants ha^{-1}), P_3 (37,037 plants ha^{-1}), P_4 (37037 plants ha^{-1}) P_5 (55,555 plants ha^{-1}), P_6 (1,11,111 plants ha^{-1}), P_7 (49,382 plants ha^{-1}) and P_8 (74,074 plants ha^{-1}) were on par with each other.

The graphical representation of the simulation scenarios showed that the median yield increased consistently with increasing plant density. The box plots showed that the crops grown at plant densities of P_9 (1,48,148 plants ha^{-1}) and P_6 (1,11,111 plants ha^{-1}) were considerably less variable than those grown at all other plant densities (Fig. 2), as the smaller variance was associated with the average yield. Furthermore, the reduced variability in Fig. 3 shows the least downside risk (risk of achieving minimum yields) with 90% (27 years out of 30) of

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the years with yields always exceeding the range of 1393 to 1425 kg ha^{-1} if the cotton crop was raised with a plant density of 1,11,111 plants ha^{-1} at a spacing of 60 x 15 cm to 1,48,148 plants ha^{-1}at a spacing of 45 x 15 cm.

Model application of Nitrogen levels

The results of the statistical analysis of the different levels of nitrogen in the simulations are presented in Table 2. The highest mean seed cotton yield was predicted for N_8 (180 kg N ha^{-1}), which was significantly greater than that for N_5 (150 kg N ha^{-1}), N_4 (140 kg N ha^{-1}), N_3 (130 kg N ha^{-1}), N_2 (120 kg N ha^{-1}) and N_1 (110 kg N ha^{-1}),in turn N_1 (110 kg N ha^{-1})had significantly the lowest seed cotton yield. However, N_1 (110 kg N ha^{-1}), N_2 (120 kg N ha^{-1}), N_3 (130 kg N ha^{-1}), N_4 (140 kg N ha^{-1}) and N_5 (150 kg N ha^{-1}) were on par with each other. N_8 (180 kg N ha^{-1}), N_7 (170 kg N ha^{-1}), N_6 (160 kg N ha^{-1}), N_5 (150 kg N ha^{-1}), N_4 (140 kg N ha^{-1}), N_3 (130 kg N ha^{-1}) and N_2 (120 kg N ha^{-1}) were on par with each other.

The graphical representation of the simulation scenarios showed that the median yield increased consistently with increasing nitrogen levels. The box plots in Fig. 4 show that the crop response to nitrogen level of 180 kg N ha^{-1} was considerably less variable than that to all other nitrogen levels, as the smaller variance was associated with the average yield. Furthermore, the reduced variability in Fig. 5 shows the least downside risk (risk of achieving minimum yields), with 90% (27 years out of 30) of the year yields always exceeding the range of 1379 to 1426 kg ha^{-1} if the cotton crop is raised with a nitrogen level of 150 kg N ha^{-1}to a nitrogen level 180 kg N ha^{-1}.

The response to nitrogen Fig. 4 shows a classic response curve in which the yield increasedin response to the first 120 kg N ha^{-1}to130 kg N ha^{-1}, however, the yield decreased in response to each additional 10 kg N ha^{-1}to 180 kg N ha^{-1}. The response to N addition beyond 120 kg N ha^{-1} was unlikely to be economically beneficial. The spread of the whiskers on the box plots indicates that, yield variability increased with each increase in N application.

Delineation of potential production zones of cotton in the Telangana state

The applicability of models can be extended to a much broader spatial scale by combining them with a Geographic Information System (GIS). GIS provides a framework to facilitate the storage manipulation, analysis, and visualization of spatial data. Using the CROPGRO-Cotton model, potential and water-limited yields were simulated for each mandal (584) polygon across Telangana state. Potential yield mapping was developed based on historical climate data, with the aim of defining the best suitable sowing dates to lower the probability of yield losses due to water deficit during reproductive cotton phases.

The simulated average potential nonwater-limited yields of Telangana state varied between 3717 kg ha^{-1} and 3891 kg ha^{-1} across different sowing dates, *i.e*., 15 June to 30 July (Fig. 6). The potential yield of cotton was greater on July 22 and July 30 sown crop. At the mandal level, Peddakodapgal in the Kamareddy district had the highest potential yield of 4201 kg ha^{-1}. However, Vemsoor Mandal in the Khammam district had the lowest potential yield of 3165 kg ha^{-1}. At the district level, Peddapally had the highest average potential yield of 3984 kg ha^{-1}and the lowest average potential yield of 3614 kg ha^{-1} was simulated at Medchal-Malkajgiri for the crop sown on 06 July (Fig. 6).

The potential nonwater-limited yield decreased gradually from the western parts of Telangana to the eastern parts across all sowing dates related to temperature and solar radiation during the crop season.

These results are based on mean weather data; therefore, small deviations in these estimates are possible at some locations due to climatic variability [17].

The potential nonwater-limited yield can be interpreted as the upper limit that can be achieved by the current varieties in a non-constrained environment. Adequate water and nutrient supply and the absence of all yield-reducing factors, such as pests and diseases, characterize the production system. The typical values of potential yield were greater than those of water-limited yields. If the genetic traits of a cultivar and atmospheric CO_2 are kept constant, as was done during the present investigation, potential yields are a function of solar radiation and temperature and are not dependent on soil properties, because it is assumed that both nutrient and water availability are nonlimiting. The potential seed cotton yields are location-specific due to climate variability [17].

Spatial variation in potential water-limited yield

The simulated average potential water-limited yields of Telangana state varied between 2642 kg ha^{-1} and 3029 kg ha^{-1} across different sowing *i.e.*, 15 June to 30 July (Fig. 7 to 10). On 22 and 30 July (Fig. 9 and 10) sowing simulations resulted in higher potential water-limited yield of cotton. At mandal level, Adilabad rural in Adilabad district had the highest potential water-limited yield of 3029 kg ha^{-1}. However, Warangal in the Warangal district had the lowest potential water-limited yield of 446 kg ha^{-1}. At the district level, Adilabad had the highest average potential yield of 2524 kg ha^{-1} on July 22 (Fig. 9), and the lowest average potential yield of 1907 kg ha^{-1} was simulated at Medchal-Malkajgiri for the 15 June sown crop (Fig. 7a). The potential water-limited yield decreased gradually from the north to southern parts Telangana across all sowing dates (Fig. 7a, 8b, 9 and 10). The lower water-limited yields in southern parts of the state may be due to limited soil moisture as rainfall is the most important climatic determinant for rainfed crop production conditions [18].

The yield which is limited only by water availability in the soil, is limited by water availability [19]. It is thus influenced by the soil water holding capacity, rainfall, evapotranspiration, surface slope and crop sensitivity to water deficit [20]. The estimates of potential water-limited yield provide a yardstick for possible improvements in the region. The water-limited (rainfed) seed cotton yield had a significant positive correlation (r = 0.52) with rainfall during the crop simulation period, which was expected because rainfed cotton production in Vertisols is primarily a function of the quantity and distribution of rainfall [17].

Management strategies for improving yield in low-yield zones

The yield gap (difference between potential yield and water-limited yield) of cotton can be reduced by adopting management strategies such as the application of irrigation water at critical stages of soil moisture stress (flowering and boll development). The average seed cotton yield of cotton increased to the maximum extent with the strategic application of irrigation water at the flowering and boll development stages across all sowing dates in Telangana. A maximum yield increase of 2500 kg ha^{-1} was simulated in the Maktal mandal of Mahabubnagar district with strategic irrigation applied at the flowering stage for the 15 June sown crop (Fig. 7b). Moreover, a maximum yield increase of 1738 kg ha^{-1} was simulated at the Eturunagaram mandal in the Warangal district with strategic irrigation applied at the flowering and boll development stage in crop sown on 06 July (Fig. 8b).

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Cotton is very tolerant to water deficit, but is sensitive to water stress during yield formation, *i.e.*, peak flowering to peak boll development stages [21]. Critical plant growth stages have been identified in cotton. The peak flowering to peak boll development stages are very critical and if, irrigation is not provided at this stage, the seed cotton yield declines drastically by approximately 5 to 8 q ha^{-1}, depending upon the soil, genotype, and management level [22]. It can be concluded that early sowing (15 June) of cotton achieved maximum yield improvement with strategic irrigation. Cotton yield can be improved by strategic irrigation during boll development if only one irrigation event is available, and the application of irrigation water during flowering and boll development is beneficial if two irrigations are available.

CONCLUSION

Model application through seasonal analysis identified the optimal plant density and nitrogen level for MRC 7201 cotton in semi-arid Telangana as 111,111 plants ha^{-1} with 60 cm x 15 cm spacing and 120 kg N ha^{-1}. Sowing on July 22 and 30 yielded higher water-limited cotton yields. Key production zones are in western Telangana, with higher non-water-limited yields in Peddapally (3,984 kg ha^{-1}) and higher water-limited yields in Adilabad (3,029 kg ha^{-1}). Strategic irrigation, especially during boll development or both flowering and boll development, can enhance yields. The CSM-CROPGRO-Cotton model effectively simulated cotton yields and will be used to assess climate change impacts and optimize management practices in future studies.

Future scope of the study: In near future, there is need for monitoring the changes in land quality over time in response to land management options adopted using models sustainably. To assess the impact of climate change on cotton growth and productivity and further for identifying the possible mitigation strategies under changing climatic scenarios and pest incidence.

Conflict of interest: The authors declare that they have no conflict of interest.

Acknowledgments

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Table 1. Tukey's tests (HSD) for mean seed cotton yield (kg ha^{-1}) of cotton at varied plant densities.

Plant densities	Mean seed cotton yield (kg ha^{-1})	Tukey's Grouping	
P_9 (45x15cm)	2760		A
P_6 (60x15cm)	2721	B	A
P_8 (45x30cm)	2714	B	A
P_7 (45x45cm)	2692	B	A
P_5 (60x30cm)	2689	B	A
P_4 (60x45cm)	2654	B	A
P_3 (90x30 cm)	2508	B	A
P_2 (90x45cm)	2478	B	
P_1 (90x60 cm)	2442	B	

**Note: Means with the same letter are not significantly different*

Table 2. Tukey's tests (HSD) for mean seed cotton yield (kg ha^{-1}) of cotton at varied nitrogen levels.

Nitrogen levels	Mean seed cotton yield (kg ha^{-1})	Tukey's Grouping	
N_8- 180 kg N ha^{-1}	2760		A
N_7- 170 kg N ha^{-1}	2735		A
N_6-160 kg N ha^{-1}	2713		A
N_5-150 kg N ha^{-1}	2682	B	A
N_4-140 kg N ha^{-1}	2626	B	A
N_3-130 kg N ha^{-1}	2563	B	A
N_2-120 kg N ha^{-1}	2508	B	A
N_1-110 kg N ha^{-1}	2442	B	

**Note: Means with the same letter are not significantly different*

Fig. 1. Spatial extent of Telangana State in India and location of Agro Climate Research Station, Rajendranagar

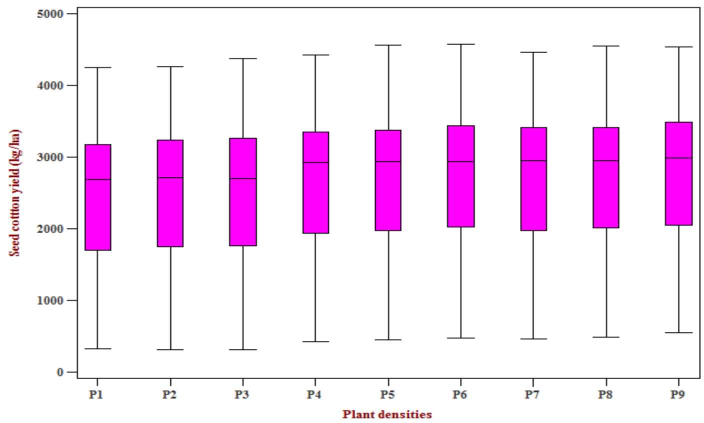

Fig. 2. Simulated seed cotton yield for cotton under varied plant densities. Box limits represent the 25th and 75th percentiles, box central line represents the median, and whiskers represent the minimum and maximum values.

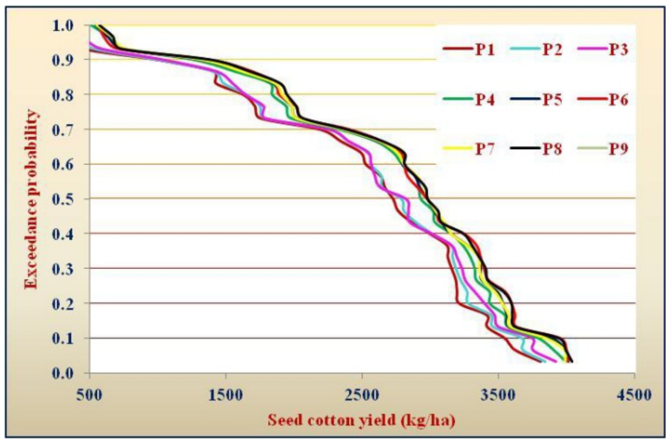

Fig. 3. Exceedance probability of seed cotton yield (kg ha^{-1})of cotton under varied plant densities.

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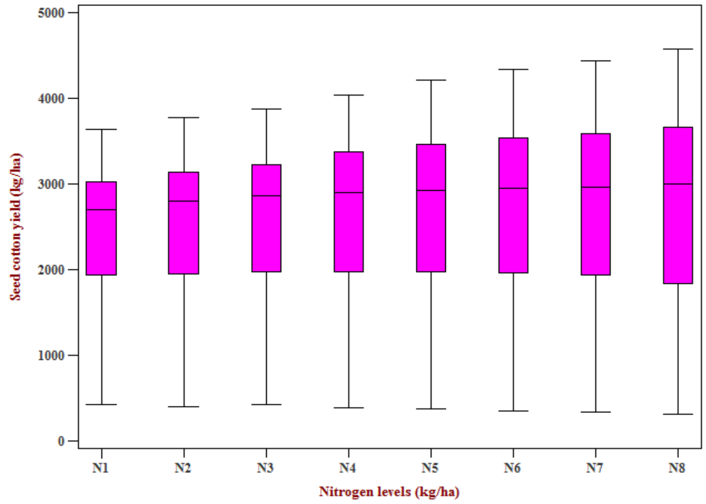


Fig. 4. Simulated seed cotton yield for cotton under varied nitrogen levels. Box limits represent the 25th and 75th percentiles, box central line represents the median, and whiskers represent the minimum and maximum values.

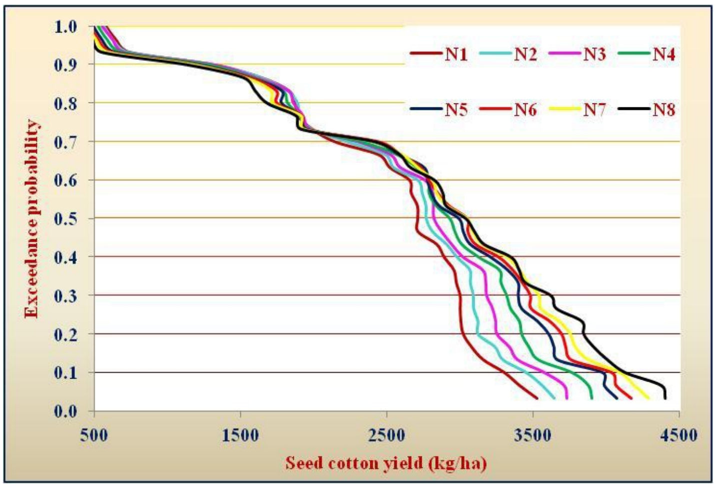
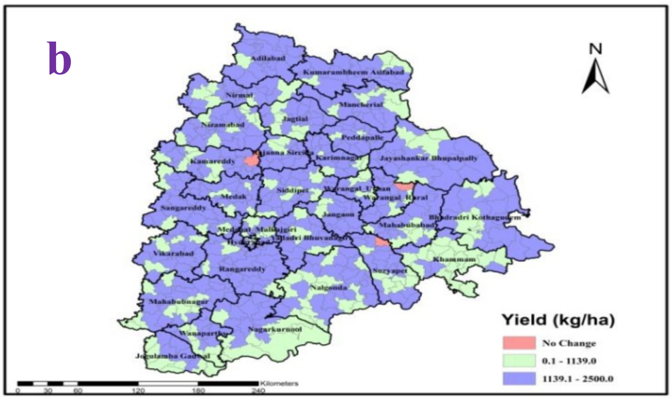
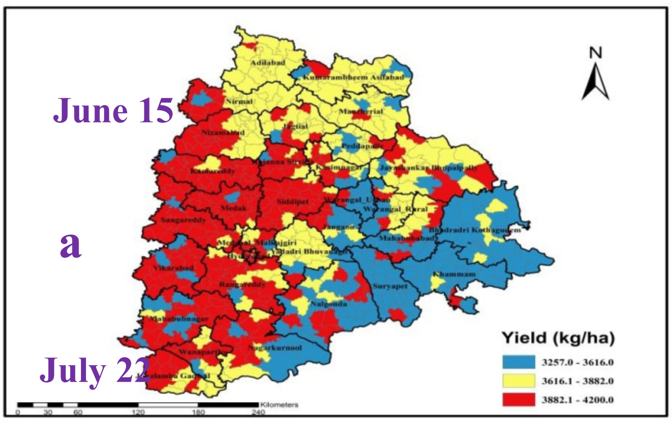
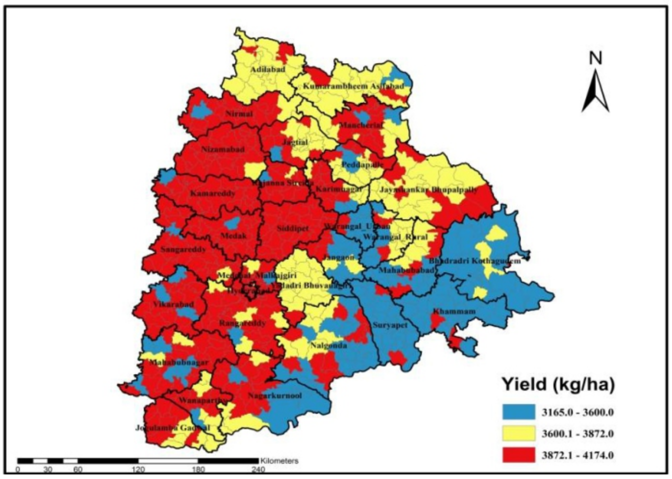
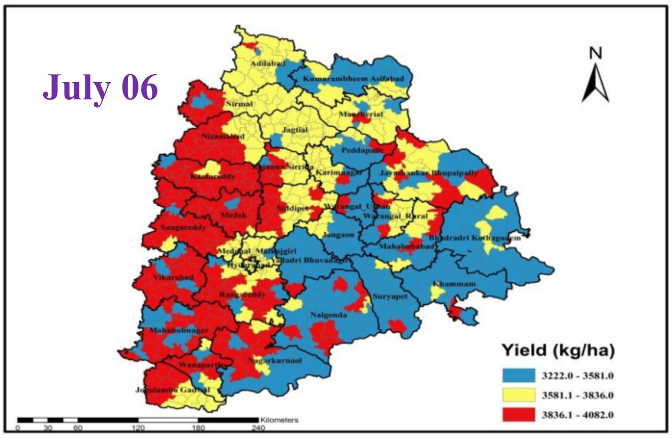


Fig. 5. Exceedance probability of seed cotton yield (kg ha^{-1}) of cotton under varied nitrogen levels.









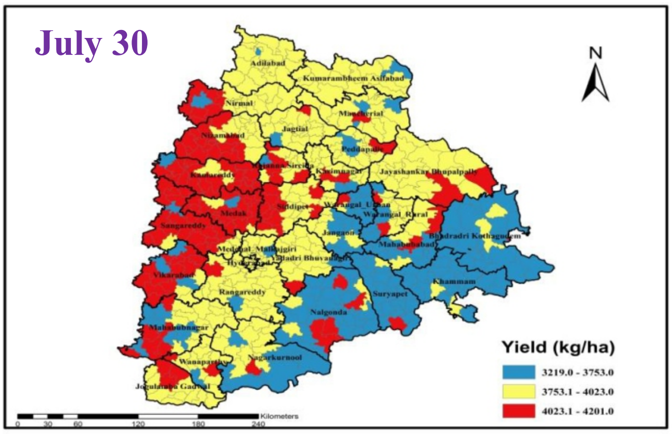


Fig. 6. Simulated potential nonwater-limited seed cotton yield (kg ha^{-1}) of cotton at mandal level under different sowing dates using CROPGRO-Cotton model in Telangana State.

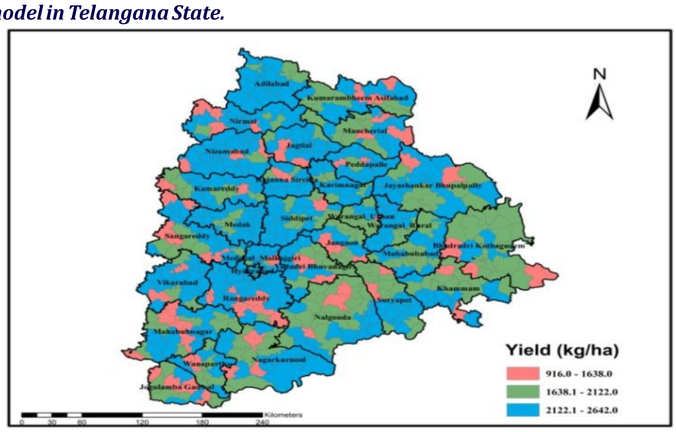


Fig. 7. a) Simulated potential water-limited yields (kg ha^{-1}) of cotton at mandal level on 15 June sown crop using CROPGRO-Cotton model in Telangana State b) increased yield (kg ha-1) of cotton due to strategic irrigation at flowering

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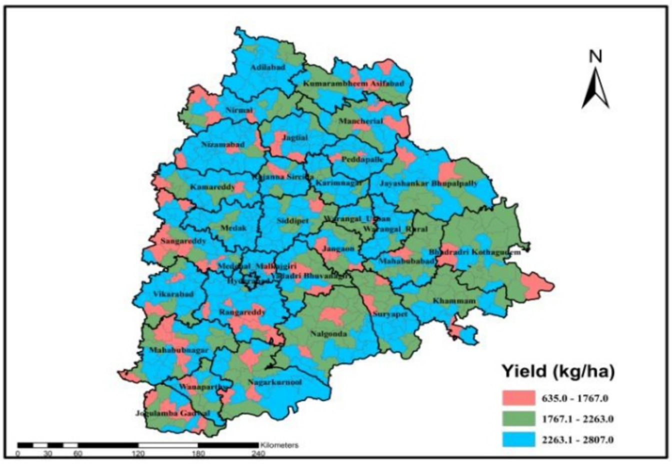
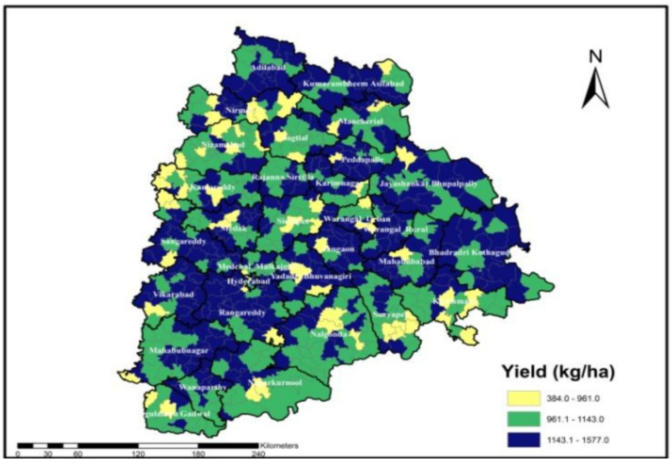


Fig. 8. a) Simulated potential water-limited yields (kg ha-1) of cotton at mandal level on 06 July sown crop using CROPGRO-Cotton model in Telangana State b) increased yield (kg ha^{-1}) of cotton due to strategic irrigation at boll development



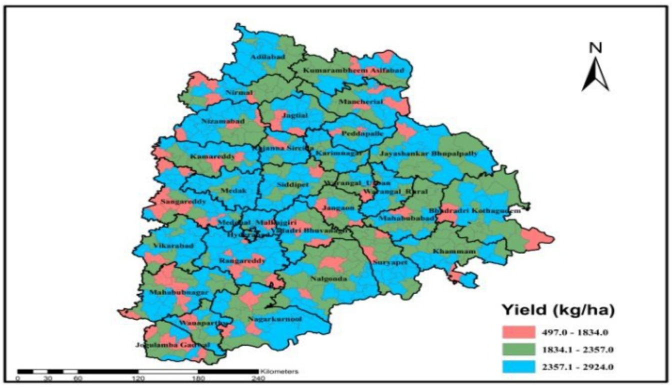


Fig. 9. Simulated potential water-limited yields (kg ha^{-1}) of cotton at mandal level on 22 July sown crop using CROPGRO-Cotton model in Telangana State

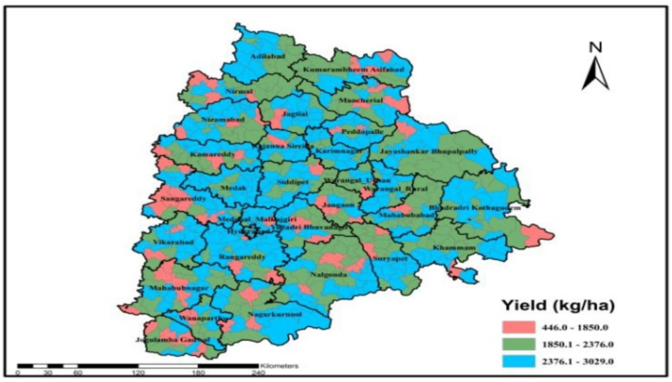


Fig. 10. Simulated potential water-limited yields (kg ha^{-1}) of cotton at mandal level on 30 July sown crop using CROPGRO-Cotton model in Telangana State

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