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Analysis of a precision agriculture approach to cotton production☆

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Abstract

The hope of precision agriculture is that through more precise timing and usage of seed, agricultural chemicals and irrigation water that higher economic yields can occur while enhancing the economic production of field crops and protecting the environment. The analyses performed in this manuscript demonstrate proof of concept of how precision agriculture coupled with crop simulation models and geographic information systems technology can be used in the cotton production system in the Mid South to optimize yields while minimizing water and nitrogen inputs. The Hood Farm Levingston Field, located in Bolivar County, Mississippi, next to the Mississippi River, was chosen as the test sight to obtain a one hectare soil physical property grid over the entire 201 ha field. The 1997 yield was used as a comparison for the analysis. Actual cultural practices for 1997 were used as input to the model. After the 201 simulations were made using the expert system to optimize for water and nitrogen on a one hectare basis, the model predicted that an increase of 322 kg/ha could be obtained by using only an average increase of 2.6 cm of water/ha and an average decrease of 35 kg N/ha. Published by Elsevier Science B.V.

Keywords: Precision agriculture; Simulation; Geographical information systems; Decision support; Crop management; Crop model

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1. Introduction

Production agriculture has experienced dramatic changes during the past few years. Not long ago, US agriculture was organized around small farms. Economic pressures and production technology have changed this traditional organization. Today, large farms dominate production agriculture. Investments in equipment and labor costs now have an increasingly greater impact on the economic success of a farm enterprise. The result of these transitions is the current predominant management strategy of uniform applications of crop inputs despite the presence of many heterogeneous soil and environmental conditions. This type of management results in, as Schug et al. (1998) wrote, 'a side by side over and under supply.' Currently, low commodity prices and increases in production costs challenge these current farm management strategies.

These realities are the context in which the concept of precision agriculture was born. Precision farming, also known as 'site-specific farming,' 'site-specific crop management,' 'prescription farming,' is the name given to an application of a host of modern technologies geared specifically toward agricultural production. With the use of technology, it seems possible to manage large fields as if they were numerous small fields. The use of computers, global positioning systems (GPS), variable rate technology farm implements, geographic information systems (GIS), machine guidance and remote sensing provide farm managers with unprecedented levels of information. Site specific information available on every square meter of the farm is now being used to reverse the practice of uniform inputs to large fields.

Management practices are moving away from conglomeration, back to small individually managed units. This shift back to the management of small-scale units has brought about the new challenge of managing tremendous amounts of information (Jallas et al., 1999). This information management problem can quickly escalate beyond a person's ability to handle and digest for decision-making purposes. Psychologists have determined experimentally that the average person can, at most, consider seven things concurrently, with rare individuals being able to consider eight and maybe nine independent things.

Since cotton is intensively managed within season (multiple fertilizer applications, multiple plant growth regulator applications, multiple irrigation potential applications, and multiple pesticide applications), the decision process is already complicated with the management of entire fields as a single unit. When precision agriculture technology is applied to this management process, hopefully to maintain or improve yields while minimizing resource inputs, this already complex management process can quickly be inundated with cascading decisions and amounts of data 10–100 times the levels digested previously. For example, consider a 400 ha field with ten soil types which in the past has been managed as a single unit. With precision agriculture techniques described herein, we now have the opportunity to manage the crop response to each of these ten soils. The response of crops to soil properties is well known. There is as much variation within a soil series as there is between soil series. Now in our example there could be easily ten different requirements for nitrogen. The crop could also call for ten different irrigation rates and/or dates. There may be an opportunity to match differing varieties to these ten soil types. Using these hypothesized three requirements we now have at least 30 times the information load a single management unit would require. Now add the requirement to develop a crop growth regulator schedule for these ten areas of this field. Now suppose that this is a large operation with 30 fields very much like this one. How would a farm manager cope with this scenario?

One solution to manage this information is the use of an integrated crop model decision support system coupled with geographic information system (GIS) software to estimate, based on environmental conditions, the impact of the cultural practices on production and to manage the huge information/data base generated. Computers are ideal tools that have been developed for precisely the purpose of managing tremendous quantities of data. Not only would the software system manage this large amount of data, it would also generate the area-based prescriptions for nitrogen timing and amount, irrigation timing and amount, variety planted, timing and amount of plant growth regulator, and so forth. These prescriptions would be downloaded into variable rate technology controllers mounted on the application equipment.

The objective of this study was to evaluate the potential for using the GOSSYM-COMAX decision support system (DSS) (McKinion et al., 1997) integrated with the ESRI ARCView geographic information system[2] (ESRI Education Services, 1996) for the micro-management of nitrogen fertilization and irrigation as a proof of concept for precision agriculture.

2. Background

Over the past twenty years, crop models have been used to help growers manage their crops. The CERES-Miaze (Jones and Kiniry, 1986), CROPGRO-Soybean (Wilkerson et al., 1983), and the GOSSYM/COMAX (Hodges et al., 1997) models are prime examples of the state-of-the-art simulators for corn, soybean and cotton crop production. These models were typically applied to simulate a whole field, and not parts thereof. Irrigation, fertilization, plant density, and crop termination were typically handled by these models. As computer technology improved and additional information technologies became available over time, the complexity and capabilities of these models continued to evolve.

Other classes of models to handle cumulative effects of cropping systems on soils have evolved. The EPIC and NTRM models were developed for these purposes (Cole et al., 1987). However, these models, because of their simple crop model component, proved to lack sensitivity needed to enable them to be used for analysis

[2] Use of trade names is for information purposes only and does not represent an endorsement of the USDA-ARS.

of risk or simulation of performance at specific location and seasons (Williams et al., 1989; Steiner et al., 1987).

The GOSSYM model represents the best part of these two model groupings. GOSSYM is a detailed simulator of the physiological processes involved in crop growth, development, and yield (Sequeira and Jallas, 1995). GOSSYM also has a very significant soil submodel which simulates all major soil processes down to a depth of two meters. These processes include rainfall or irrigation water infiltration into the soil profile. Irrigation by center pivot, line move, furrow and even subsurface systems have been addressed. The soil submodel also accounts for subsurface water tables. Soil water uptake by the crop and subsequent soil water redistribution by horizon is accounted for by solution of the two-dimensional D'Arcy partial differential equation for flow through porous media.

Weather information, some cultural practices and genetic characteristics drive the plant model. Plant development is limited by water and nitrogen supply. When the plant grows its shade limits soil water evaporation. The plant sub-model includes two important concepts: 'materials balance' and the use of different stresses (N, H_2O, C) to regulate plant growth. The model runs on a daily basis. Each day, the model first calculates carbohydrate supply based on external factors (light, temperature, water supply, etc). Second, the system calculates the carbohydrate demand for growth, respiration and plant maintenance based on external factors and plant status. Third, the system partitions the carbohydrate supply to the different organs based on their demand and priority levels with fruit having the highest priority and storage the lowest. GOSSYM requires information on soil, variety, cultivation practices, and weather. Its reports includes number and weights of individual organs (leaves, branches, flowers, and fruit), in addition to nitrogen and water concentration and stress indices.

When expert systems technology became available in the mid-1980's, the GOSSYM model developer team added the COMAX (Crop MAnagement eXpert), a rule-based system, to the crop model (McKinion and Lemmon, 1985). Dr Susan M. Bridges, Computer Science Department, Mississippi State University, (Personal communication) later re-engineered this expert system which today provides users with expert decision support (Baulch et al., 1996). The decision support system uses an expert system rule base to determine the optimal actions to perform, given a projected weather scenario. The decision support system is associated with the GOSSYM model in order to make recommendations to the farmer. When the user invokes the COMAX decision support system, COMAX monitors the GOSSYM simulation runs in order to detect stress symptoms. If COMAX detects stress, it may recommend different practices to relieve the stress. The COMAX decision support system provides recommendations for irrigation, nitrogen use, and for the application of plant growth regulators.

Beginning in the early 1990s, new technology in the area of geographical positioning systems (GPS), geographical information systems (GIS), and precision equipment for seeding, irrigation, and chemical applications started to become available to agricultural production. The ARCView GIS system (ESRI Education Services, 1996) was one of the first software packages that became available to use on a high-end PC. It was simple enough for non-GIS experts to use while powerful enough to allow the development of precision agriculture applications. The real key to precision agriculture, though, was the development availability of accurate and low-cost GPS sensors which make variable rate technology possible.

Also during this time (early 90s to present), site specific irrigation through center pivots or linear move machines became available (Duke and Sadler, 1992; McCann and Stark, 1993; Camp and Sadler, 1994). The resolution of these machines is built into the machine design. Better resolution means increased cost due to more discrete sprinkler with smaller wetted radii and more control requirements. This also implies more pressure regulators, more valves, etc. These requirements must be matched to the soil variability involved and the use to which the machine is made (Sadler et al., 1998). Resolutions built into these three known site specific machines are 30 m (McCann and Stark, 1993), 20 m (Duke and Sadler, 1992), and 10 m (Camp and Sadler, 1994).

The development of variable rate technology (VRT) equipment for seeding, fertilizer, and chemical applications has progressed such that it is commercially available for all major row crops (Duke et al., 1997; Ellis, 1997; Ferguson et al., 1997). However, now the challenge is when and how much should be applied to specific sites in a field. A number of efforts in this regard is under way (Zhang et al., 1999; Acock and Pachepsky, 1997; McCown et al., 1996; Matthews and Blackmore, 1997; Lu and Watkins, 1997).

The remainder of this paper focuses on the use of the GOSSYM/COMAX cotton crop decision support system to develop a site-specific nitrogen and irrigation management system. The GOSSYM/COMAX system was integrated into the ARCView GIS system to allow the evaluation of strategies using a one hectare soil grid of soil physical properties as the basis of precision agriculture management system.

3. Material and methods

3.1. Field conditions

In 1997, cotton (Delta Pine 1330 BR) was planted on the eastern side of Levingston Field on the Kenneth Hood Farm in Bolivar County, MS, USA. The cultural practices applied and the final yield results are given in Table 1. The total actual N applied to Levingston Field in 1997 was 159.4 kg/ha of N. The total amount of irrigation water applied was 8.3 cm in three applications. From May of 1997 through October of 1997 there were 40 actual recorded rainfall events for a total of 75.4 cm of rainfall. PIX is a commercial plant growth regulator (PGR). UAN is a liquid nitrogen mixture containing 43% nitrogen by weight. DEF and DROPP are commercial crop growth termination and defoliant chemicals, respectively. In the fall of 1996 through the spring of 1997, soil profiles were collected using a tractor-mounted Giddings no. 10-T Model GST hydraulic soil sampling and coring machine. This equipment allowed intact soil cores (5 cm in diameter and up to 2 m in depth) to be obtained for physical characterization of soil properties. After processing, profiles (which contained data on sand, silt and clay% content, bulk density and the soil water retention curve, all by soil horizon) were obtained for approximately a one hectare grid for the entire 201 ha Levingston Field. A map showing the location of the soil profiles in Levingston Field is shown in Fig. 1. Each point represents the center of approximately a one-hectare square cell (cell arrangement was arbitrary but encompasses the entire 201 ha field) with soil samples taken at the center and then by soil horizon for determination of soil physical properties. Each transect (a line following the row orientation of the field representing 32 rows) of soil profiles running roughly from the southwest to the northeast were numbered by transect with the westernmost transect being T01 and the easternmost transect being T18. The profile locations (which were determined by a 91.4 m (300 ft.) spacing along the center of each transect) were next identified by the number of the points taken, i.e. P01–P12. Finally the profile taken was labeled by the soil type, CC, CE, CL, and CS for Commerce variants (Aeric Fluvaquents), RA and RL for the two Robinsonville soil variants (Typic Udifluvents) and SL, SO and SS for the three Souva variants (Typic Fluvaquents). Thus, a soil profile could for example be uniquely identified by soil type and location such as CCT11P09 by concatenating the abbreviation for the soil name, the transect number and the profile location along the transect. All weather data for the Hood Farm was collected with a Campbell Scientific CR10 automated weather station. Weather data obtained on a daily basis were total solar radiation, maximum and minimum air temperature, total rainfall, and wind run.

Table 1
Actual cultural practices, rainfall, and final yield for Levingston Field for 1997

Event	Date	Category	Description	Method	Rate	Units	Rainfall month	Rainfall total (cm)
1	02/06/97	Fertilizer	UAN solution	Sidedress	134	kg/ha	May	6.2
2	18/06/97	PGR	PIX	Broadcast	905	ml/ha	June	35.4
3	30/06/97	Fertilizer	UAN solution	Sidedress	90	kg/ha	July	4.7
4	30/06/97	PGR	PIX	Broadcast	680	ml/ha	Aug	5.1
5	04/07/97	PGR	PIX	Broadcast	680	ml/ha	Sept	13.1
6	07/07/97	Fertilizer	Am nitrate	Sidedress	168	kg/ha	Oct	10.9
7	12/07/97	Fertilizer	UAN solution	Sidedress	90	kg/ha		
8	14/07/97	PGR	PIX	Broadcast	680	ml/ha		
9	15/07/97	Irrigation	Sprinkler	Every Row	3.8	cm		
10	01/08/97	PGR	PIX	Broadcast	680	ml/ha		
11	02/08/97	Irrigation	Sprinkler	Every Row	2.5	cm		
12	18/08/97	Irrigation	Sprinkler	Every Row	1.9	cm		
13	20/09/97	Herbicide	Def 6	Broadcast	2.72	l/ha		
14	20/09/97	Herbicide	Dropp 50WP	Broadcast	2.17	l/ha		
15	20/11/97	Harvest			1084	kg/ha		

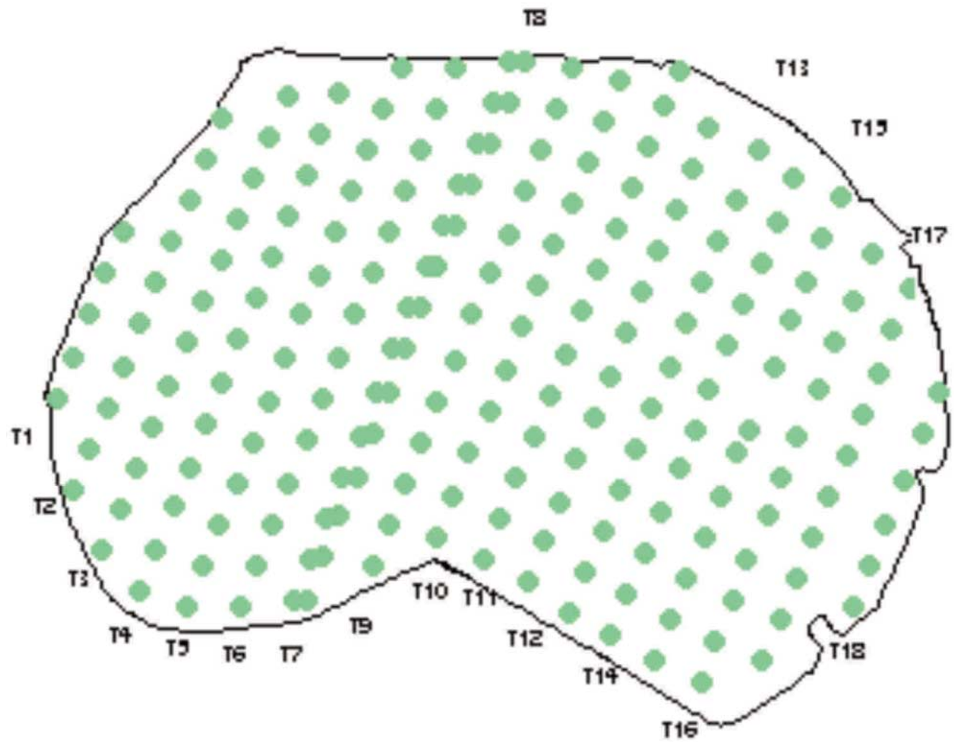

Fig. 1. 201 ha Levingston Field on the Kenneth Hood Farm in Bolivar County, MS, USA. The dots represent the sample points where soil physical property information was collected. The symbols T1–T18 represent transect lines across the field. Samples were taken on a 1 ha grid basis

The soil and weather information was used as the basis for exploring the application of precision agriculture applications on Livingston Field. The Agricultural Research Service's Cotton Model (GOSSYM/COMAX) (Reddy et al., 1997; McKinion et al., 1997) and the Environmental Systems Research Institute, Inc. (ESRI) ARCView GIS system were used in the analysis of actual data from the 1997 growing season and of potential data from simulations to predict crop response to additional applications of nitrogen and water. The model was run using each soil profile for position on the grid and the appropriate weather data and cultural practice information. All analyses were then carried out at spatial resolution of 1 ha or higher.

3.2. The system GOSSYM-COMAX and its integration with a GIS

To facilitate the use of the GOSSYM/COMAX in this research, the model was integrated into the ESRI ARCView geographic information system (GIS). Thus, by being able to point and click using the mouse pointed at single areas of a field, production could be simulated based on real weather data and real or hypothesized cultural practices and results displayed in a map representation. Additionally, from multiple areas to the entire field results could be simulated by selection using the mouse pointing device. The ARCView database mechanism was used to store all information needed to run the model including all spatial information such as soil physical properties, soil nitrogen content, soil water content, etc. which the model could automatically retrieve based on the area being simulated. None of this work required modification of the GOSSYM/COMAX cotton model except how information was provided to the model and how information was displayed by the model.

3.3. Evaluation of nitrogen and water applications experiments

In order to prepare for the use of the cotton model for decision support in making recommendations for nitrogen and water site specific application, a series of benchmark simulations were made to determine the accuracy with which the eastern side of Levingston Field's 1997 crop could be simulated (Boone et al., 1995; McKinion et al., 1989; McKinion and Wagner, 1993). First, a single simulation was made using the historical Commerce silt loam soil file which had been used in the past for managing the entire field as a single management unit. The past strategy was to use the majority soil type in the field to make recommendations for the entire field. This simulation was made without changing any parameters in the model.

The next step was to take the eastern half (88 ha) of Levingston Field and divide this area up into the soil grid as indicated by the soil map in Fig. 2. A single simulation was made for each of the 88 soil profiles identified by each point. The strategy was to take advantage of the knowledge of the 88 soil physical property samples and to make simulations of each of these individual one-hectare locations in the field. Soil fertility for each of these locations was assumed to be the same as the fertility sample for the entire field. The yield results from these simulations are given in Table 2. The column labeled Fname gives the soil physical property name for the location in the field. Column labeled soil type gives the actual soil type for the one-hectare location. The column labeled Irrig.'s gives the total number of irrigations proposed to be applied by the simulation. The column labeled Irrig. Rate gives the total amount of water proposed to be applied by the simulation in centimeters of water. The column labeled no. of fert.'s indicates the number of additional fertilizations recommended by the simulation after the actual fertilizer applied before June 30, 1997. The column labeled Fert. Rate gives the total amount of N recommended to be applied by the simulation in kilograms of N per hectare. The column labeled Iterations gives the number of simulation runs required to arrive at a solution. Index is the tracking number assigned to the row of data. The next two columns of data shows the difference in base yield predicted versus optimized yield in terms of bales per acre and per cent difference. The last two columns show the predicted yield by soil physical properties. The yield_base column shows the predicted yield using only the actual cultural practices and the

Fig. 2

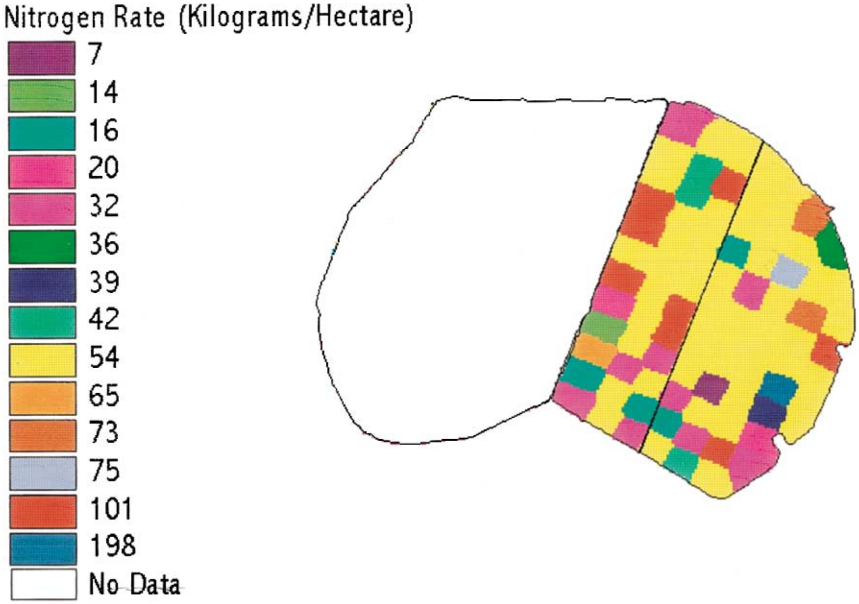

Fig. 3

Fig. 2. Soil types in the eastern half of Levingston Field. CC, CE, CL, and CS are Commerce soil variants, RA and RL and Robinsonville soil variants, SL, SO and SS are Souva soil variants. The Commerce soils are Aeric Fluvaquents, Robinsonville soil types are Typic Udifluvents, and Souva soils are Typic Fluvaquents.

Fig. 3. Distribution of optimized nitrogen rates for eastern half of Levingston Field.

Table 2
Summary of the number of simulations needed to optimize each soil grid location for nitrogen and irrigation application along with predicted yields for base simulation and optimized simulations

Fname	Soil type	Irrig.'s	Irrig. Rate (cm)	No. of fert.	Fert. rate (kg/ha)	Iterations	Index	Diff. (kg/ha)	% Diff.	Yield _base (kg/ha)	Yield _opt (kg/ha)
CCT11P01	CC	4	10	2	32	5	1	129	11.33	1139	1268
CCT11P03	CC	4	10	3	65	4	2	342	33.15	1032	1374
CCT11P04	CC	1	3	2	15	6	3	−73	−5.91	1234	1161
CCT11P05	CC	4	10	2	20	7	4	−6	−0.50	1133	1127
CCT11P08	CC	3	8	4	101	3	5	404	31.30	1290	1694
CCT11P09	CC	4	10	4	101	3	6	499	41.98	1189	1688
CCT11P10	CC	6	15	3	54	4	7	415	44.85	925	1341
CCT11P11	CC	6	15	3	54	4	8	466	47.43	982	1447
CCT12P02	CC	3	8	3	54	4	9	258	20.54	1256	1514
CCT12P03	CC	3	8	2	32	5	10	56	4.46	1256	1313
CCT12P07	CC	7	18	3	54	4	11	438	42.86	1021	1458
CCT12P08	CC	2	5	3	54	4	12	443	39.50	1122	1565
CCT12P09	CC	4	10	3	54	4	13	286	24.06	1189	1475
CCT12P10	CC	5	13	3	43	5	14	264	21.86	1206	1470
CCT12P11	CC	5	13	3	43	4	15	320	29.84	1071	1391
CCT13P01	CC	2	5	2	32	5	16	0	0.00	1251	1251
CCT13P02	CC	1	3	2	16	6	17	−56	−4.39	1279	1223
CCT13P07	CC	4	10	3	54	4	18	331	28.23	1172	1503
CCT13P10	CC	5	13	3	54	4	19	314	28.28	1111	1425
CCT13P12	CC	4	10	3	54	4	20	174	14.16	1228	1402
CCT14P02	CC	3	7	2	16	6	21	−107	−8.52	1251	1144
CCT14P03	CC	4	10	3	32	5	22	34	2.80	1200	1234
CCT14P04	CC	3	8	3	54	4	23	252	20.27	1245	1498
CCT14P06	CC	6	15	3	54	4	24	348	31.79	1094	1442
CCT14P07	CC	6	15	3	54	4	25	426	45.24	942	1369
CCT14P08	CC	7	17	3	54	4	26	365	33.68	1083	1447
CCT14P09	CC	2	5	2	16	6	27	−28	−2.22	1262	1234
CCT14P10	CC	5	13	3	54	4	28	381	33.66	1133	1514
CCT15P01	CC	6	15	3	43	4	29	415	37.56	1105	1520
CCT15P02	CC	3	7	2	32	5	30	17	1.30	1290	1307
CCT15P03	CC	6	15	3	54	4	31	325	29.29	1111	1436
CCT15P07	CC	7	17	3	54	4	32	527	67.14	785	1313
CCT15P08	CC	2	5	2	32	5	33	−28	−2.27	1234	1206
CCT15P09	CC	6	14	3	54	4	34	443	39.11	1133	1576
CCT15P10	CC	5	13	3	54	4	35	320	30.16	1060	1380
CCT15P11	CC	5	13	3	54	4	36	359	30.62	1172	1531
CCT15P12	CC	5	13	3	54	4	37	337	32.79	1026	1363
CCT16P01	CC	5	13	3	54	4	38	353	32.14	1099	1453
CCT16P02	CC	4	10	4	101	3	39	482	39.45	1223	1705
CCT16P04	CC	5	13	3	54	4	40	337	29.27	1150	1486
CCT16P06	CC	6	15	3	54	4	41	454	44.51	1021	1475
CCT16P07	CC	6	15	3	54	4	42	370	34.38	1077	1447
CCT16P08	CC	4	10	3	54	4	43	331	27.19	1217	1548
CCT16P09	CC	4	10	3	75	5	44	331	29.65	1116	1447
CCT16P10	CC	5	12	3	54	4	45	348	30.54	1139	1486
CCT17P05	CC	5	13	3	54	4	46	359	33.16	1083	1442

Table 2 (*Continued*)

Fname	Soil type	Irrig.'s	Irrig. Rate (cm)	No. of fert.	Fert. rate (kg/ha)	Iterations	Index	Diff. (kg/ha)	% Diff.	Yield _base (kg/ha)	Yield _opt (kg/ha)
CCT17P06	CC	5	13	3	54	4	47	387	34.67	1116	1503
CCT17P08	CC	5	13	3	54	4	48	342	32.62	1049	1391
CCT17P09	CC	4	10	3	54	4	49	286	23.83	1200	1486
CCT18P04	CC	4	10	4	101	3	50	292	24.30	1200	1492
CCT18P06	CC	6	15	3	54	4	51	348	33.70	1032	1380
CET15P05	CE	6	15	3	54	4	52	393	36.65	1071	1464
CET15P06	CE	5	13	3	54	4	53	353	34.05	1038	1391
CET16P05	CE	5	13	3	54	4	54	398	39.01	1021	1419
CET16P11	CE	5	13	3	73	5	55	342	33.89	1010	1352
CET17P02	CE	5	11	2	20	7	56	179	18.60	965	1144
CET17P03	CE	6	14	2	39	6	57	297	31.55	942	1240
CET17P07	CE	5	13	3	73	5	58	320	32.76	976	1296
CET17P10	CE	5	13	2	36	6	59	185	18.75	987	1172
CET18P03	CE	6	15	3	54	4	60	443	42.93	1032	1475
CET18P05	CE	7	17	3	54	4	61	353	35.39	998	1352
CLT14P12	CL	4	10	3	54	4	62	275	23.33	1178	1453
CST11P07	CS	5	13	3	54	4	63	337	29.70	1133	1470
CST12P01	CS	2	5	3	54	4	64	174	13.84	1256	1430
CST12P04	CS	3	8	3	54	4	65	208	17.54	1183	1391
CST13P04	CS	4	10	2	32	5	66	56	4.61	1217	1273
CST13P06	CS	5	13	4	101	3	67	522	46.27	1127	1649
CST13P08	CS	4	10	3	54	4	68	297	25.12	1183	1481
CST14P01	CS	6	15	3	54	4	69	471	42.64	1105	1576
RAT11P12	RA	2	5	2	32	5	70	62	4.91	1256	1318
RAT11P13	RA	3	8	2	32	5	71	39	3.30	1189	1228
RAT12P12	RA	0	0	3	54	4	72	275	21.88	1256	1531
RAT13P03	RA	3	8	3	54	4	73	202	17.14	1178	1380
RAT13P09	RA	0	0	3	54	4	74	331	25.76	1284	1615
RAT13P11	RA	3	8	4	101	3	75	544	46.41	1172	1716
RAT14P11	RA	3	8	3	54	4	76	376	28.76	1307	1683
RLT11P02	RL	2	5	2	16	6	77	−101	−7.96	1268	1167
RLT18P01	RL	4	10	3	54	4	78	308	25.70	1200	1509
SLT13P05	SL	3	8	4	101	3	79	365	30.52	1195	1559
SOT14P05	SO	4	10	3	54	4	80	247	22.11	1116	1363
SOT15P04	SO	2	5	1	7	8	81	−112	−9.80	1144	1032
SOT16P03	SO	6	15	3	54	4	82	387	36.70	1054	1442
SOT17P01	SO	4	10	2	32	5	83	22	1.93	1161	1183
SOT17P04	SO	5	13	5	198	5	84	561	106.3	527	1088
SOT18P02	SO	5	13	3	54	4	85	337	33.33	1010	1346
SST11P06	SS	7	17	4	101	4	86	538	54.86	982	1520
SST12P05	SS	6	14	3	54	4	87	387	34.33	1127	1514
SST12P06	SS	4	10	3	54	4	88	280	22.83	1228	1509

Table 3
Comparison of total actual inputs made by grower and inputs recommended by simulation precision agriculture study

	Nitrogen input (kg N/ha)	Irrigation applied (cm H_2O)	Yield (kg/ha)
Actual	159.4	8.3	1088
Simulated	159.4	8.3	1123
Precision	124.3	10.9	1410

actual 1997 weather with the only variable being the soil physical properties for each location. The last column shows the predicted yield using both irrigation and fertilization optimization capabilities of the model. As can be seen in this table some areas call for less water and some for more.

The final test was to use the first 30 days of the cultural practices and the 1997 weather with emergence set for 5/21/97. The ARS Cotton Model was then run in the expert system mode using the plant growth regulator application rates and weather data for the rest of the 1997 growing season. The expert system was then instructed to determine an optimum irrigation schedule in combination with an optimum fertilization schedule with harvest termination set for 10/15/97. This was done for each of the 88 spatial locations in the field. Solutions were found for the above criteria with some taking as few as three iterations and some taking as many as eight iterations of the model. The majority of solutions required five model iterations to come to a solution. The results are shown in Table 3. The first row, called actual, presents the actual results obtained by the grower in 1997. The row called simulated uses the grower's exact inputs to show the accuracy of the simulations on a whole field basis. The precision row shows the predicted yield using the model to optimize water and nitrogen on a per hectare basis. The last study predicted less nitrogen usage by an average of 35 kg/ha, an average increase of 2.6 cm/ha of irrigation water, and an average yield increase of 322 kg/ha. The optimized average yield was predicted to be 1408 kg/ha (2.51 bales per acre) with a standard deviation of 0.264.

4. Discussion

In the first simulation experiment, the model was run using the Commerce soil file, the actual cultural practices used by the grower on the field as listed in Table 1, a mid-season variety file and weather data from the Hood Farm weather station for 1997. A whole field simulation was made which predicted an average yield of 1133 kg/ha (2.02 bales per acre), which was 49 kg/ha (0.084 bales/acre) or 4.3% higher than the actual yield. This single simulation was taken to be the base, uniform treatment for the entire field. The grower's actual yield was 1084 kg/ha (1.94 bales/acre).

Results from the second simulation experiment are given in Table 2. A series of 88 simulations were made using the actual soil physical properties of each of the 88 grid locations. The remaining conditions were the same as in the first simulation experiment. The average yield simulated by the ARS cotton model was 1127 kg/ha (2.01 bales per acre). The model was not recalibrated or changed to produce these results, but it was used simply as delivered to users for 1997. This is remarkably close to the actual picked yield (1088 kg/ha) for Levingston Field for 1997 showing that GOSSYM/COMAX has been optimized for predicting average yield of production units using only information about the majority soil type of the unit. The low yield predicted was 505 kg/ha (0.9 bales per acre) on the Souva soil file located in grid index 84. The high yield predicted was 1284 kg/ha (2.29 bales per acre) on a Robinsonville soil file in grid index 74. The average yield was 1127 kg/ha (2.01 bales per acre) with a standard deviation of 0.216. The range of variation in yields for the 88 hectares in the simulated data was due strictly to the differences in the measured soil physical properties for the nine soil types in the eastern half of Levingston Field (four textures of Commerce, two Robinsonville textures, and three Souva textures) with everything else held constant or the same for each simulation.

The third and last simulation experiment used all of the soil information used in the experiment two plus used the optimization capabilities of COMAX to find best solutions for irrigation and nitrogen applications. Solutions were found in this set of simulations with some taking as few as 3 iterations and some taking as many as eight iterations of the model. The majority of solutions required 5 model iterations to come to a solution. The results are shown in Table 2. The optimized average yield was predicted to be 1407 kg/ha (2.51 bales per acre) with a standard deviation of 0.264 with an increase of over 286 kg/ha (0.51 bales per acre).

A graphical display of the data in Table 2 can be seen in Figs. 2–5 below. Fig. 3 shows the generated rates of nitrogen applications based on using the ARS cotton model, the ARCView GIS system and an expert system to solve for optimum yield, defined as the optimum agronomic yield given these weather conditions and cultural practices. The strategy was to allow the expert system to solve for nitrogen and irrigation schedules based upon the cultural practices for Levingston Field for the first 30 days of the 1997 season and then selecting nitrogen and irrigation timing and amount based upon the 88 hectare grid of soil types and the remaining actual weather for 1997. The plant growth regulator (PIX) schedule the grower actually used was also kept as inputs during this analysis. Thus as far as the ARS cotton model was concerned, the only difference which produced 88 optimized water and nitrogen schedules for these 88 locations were the 88 soil profiles (Fig. 2).

The precision agriculture system recommended application rates from 7.8 to 199 kg/ha of N (7–178 lbs. of N per acre). Further evaluation of the 199 kg application rate is needed and would not be used in practice because of the high rate. The remaining rates from 16.8 to 102 kg/ha are reasonable.

The irrigation totals range from 0 to 17.6 cm of water (Fig. 4). The number of irrigations called for varied from 1 to 7 (Table 2). Obviously, growers will not be able to apply water on a per hectare basis as addressed in this analysis, but the

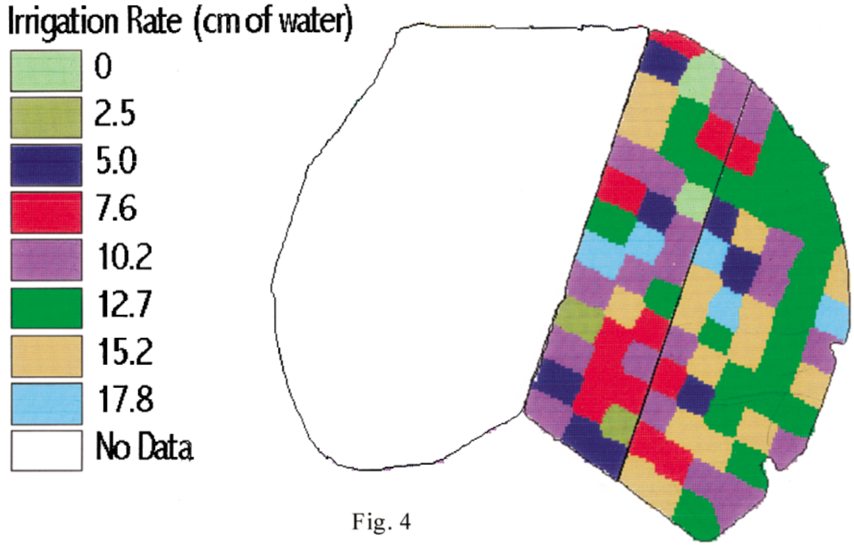

Fig. 4

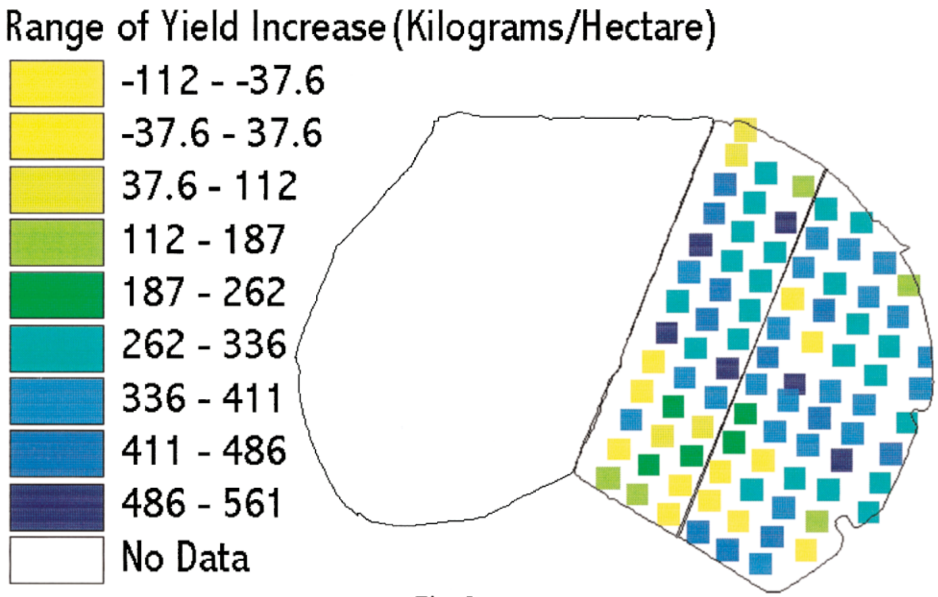

Fig. 5

Fig. 4. Distribution of optimized irrigation amounts for eastern half of Levingston Field.
Fig. 5. Distribution of predicted changes in yield for simulations that used actual soil parameters and model optimized water and nitrogen inputs compared to simulations using actual soil parameters and actual grower inputs for 1997.

numbers are included here to show the range in variability with just having soil type information as a variable.

The yield predictions are shown as difference between the precision agriculture optimized yield and the yield predicted using the grower's actual cultural practices (Fig. 5). The yield differences range from −112 to 560.9 kg/ha (−0.2 to 1 bale/acre) across the field. The negative values show that the expert system is not infallible. When an event like this occurs, the user should conduct manual simulations to determine if improvements can be made. As can be seen in Table 2, this should be in a very small minority of cases. However, the amount of computer work and data analysis likely would be prohibitive in terms of the user's time for making decisions on a per acre basis. The predicted yield improvement using the precision agriculture tool shows that the grower could expect an increase of 286 kg/ha (0.51 bales/acre) for this field even with the few negative results.

The study shows dramatically that there is potential for both increasing yields and decreasing the use of agricultural chemicals by the adoption of precision agriculture technology. A tool such as demonstrated in this study for generating the irrigation and nitrogen rates by soil type and/or soil site sample can be used to automate the calculation of optimum water and N rates.

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