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Site-specific modeling of corn yield in the SE coastal plain

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Abstract

When site-specific agriculture became technologically feasible, existing crop models made computer simulation a natural choice for predicting yield under various combinations of soil, weather, and management. However, modeling for site-specific farming may require both greater accuracy and sensitivity to more parameters than current models allow. The objective of this paper was to evaluate the DSSAT V3.5 corn model, CERES-Maize, for sensitivity to parameters important to site-specific farming. The model was unexpectedly insensitive to inputs for soil type, depth to clay, nitrogen, and plant population, suggesting areas for attention. Although it was appropriately sensitive to rainfall, indicating sensitivity to soil water content is generally correct, there are known problems with the curve number procedure that calculates runoff. The runoff routine needs improvement, and a separate routine may be needed to accommodate within-field redistribution of runoff. The model also responded to maximum air temperature, but since crop temperature varies more than air temperature, perhaps crop temperature should be calculated from air temperature and water stress. Model accuracy issues aside, accommodating spatial inputs and model runs requires enhanced interfaces. These and other suggested enhancements to the model would improve its applicability for site-specific agriculture. © 2000 Published by Elsevier Science Ltd. All rights reserved.

Keywords: Corn yield; Site-specific; Computer simulation

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1. Introduction

Site-specific agriculture became technologically feasible in the late 1980s and early 1990s, at which time the capabilities of the equipment exceeded the information needed to operate it. To accelerate the development of site-specific recommendations for fertilizer and other inputs, researchers looked to crop growth models, which used as inputs soil and cultural parameters and had been widely used to simulate crop growth for different soils in the county soil survey databases. However, the models were neither developed nor tested with the objective of describing within-field variation. The procedures developed and included in the models placed important constraints on eventual uses of the models. To set a context for the current work, we first examine the particular needs of site-specific modeling, then discuss candidate variables to which a model should be sensitive if it will be used in site-specific agriculture.

1.1. Requirements of models

To be fully functional for use in site-specific agriculture, models need to be able to use and produce spatial data, need to account for and describe the processes that are important to site-specific agriculture, and need to be sufficiently accurate that their results can be reliable. Whether or not models successfully address all these issues will determine their value in the long term. A description of the 1995 state of the art of modeling for site-specific agriculture was given by Sadler and Russell (1997), and steady progress has been made since then. Here, the authors examine several issues that appear critical for success under conditions common to the SE USA Coastal Plain and similar regions of the world.

1.1.1. Interface issues

Nearly all modeling work has been done using the assumption of 1-dimensional vertical processes. Site-specific agriculture requires the addition of the two horizontal dimensions. Rather than completely restructure models to do this, most work has applied 1-D models at multiple points in space. This appears both to be efficient and to have potential for success, but causes some difficulties accounting for some processes that inherently occur in the spatial dimensions, such as surface runoff, discussed in a later section.

Managing spatial data is most efficiently done using geographic information systems (GIS). Merging GIS tools with models appears to be a logical solution to the combined problem of spatial data management and spatial modeling. Most applications of modeling to site-specific agriculture have combined the 1-D models with a GIS or have built some GIS features into the model's user interface. Examples range from very simple models that run entirely within the GIS (Ambuel et al., 1994) to specialized interfaces to pass data between the model and GIS (Engel et al., 1995). Several examples of this work were summarized by Sadler and Russell (1997).

1.1.2. Process issues

Model developers start by describing the relationships that are both tractable and important to the model objectives, and incrementally add other modules as possible. Therefore, embodied in every model is a suite of assumptions about what factors and processes are important enough to include. These assumptions constrain the proper application of a model to conditions for which the assumptions are justified. For instance, a crop growth and yield model is likely to have less technical rigor in the computation of nitrate leaching than would a groundwater loading model. This would make the former less attractive than the latter for studying water quality. Though trivially obvious to the developers, these differences in objectives are sometimes ignored by, or are even unknown to, users.

Development of 1-D models understandably placed less emphasis on processes inherently important only to the horizontal dimensions. One such process rarely addressed except externally to 1-D models is the horizontal transfer of water via runoff or flow along subsoil horizons. This may be significantly important to site-specific modeling. Also, the opportunity for site-specific pesticide use may ultimately make predation and competition effects very important to site-specific modeling. Another example is livestock feeding patterns, which may be distinctly spatial for reasons known only to the livestock, and which may be critical for models used in site-specific forage management. Many such examples have been listed (Sadler and Russell, 1997). No consensus seems to be in sight as to what constitutes an important process.

1.1.3. Accuracy issues

Accuracy of models has been both an objective and a stumbling block for model developers and model users. One reason is that accuracy requirements are as varied as model objectives. For example, if one desires to create a fertilizer recommendation map using a model to optimize nitrogen applications, then the model must accurately simulate the effect of nitrogen on yield for all combinations expected for a range of soil, weather, and nitrogen. This implies that if a model does not account for a factor, the real system's sensitivity must be independent of that factor. A working definition, then, of accuracy requirements is that models must be appropriately sensitive to all important parameters (Sadler and Russell, 1997). Appropriately sensitive means that both the average value and derivative with respect to the managed input must be accurate within tolerances appropriate for the objective.

1.1.4. Working pattern for a site-specific model

In summary, a model applicable to site-specific agriculture should (1) easily accommodate spatial data, (2) account for all factors considered important or manageable, and (3) be accurate enough to make reliable decisions.

1.2. Candidates for 'important' variables

A basis for judging importance of variables for site-specific agriculture can be obtained from both a consideration of observations and of technical capabilities of variable-rate technology (VRT) equipment. The former provides candidates for causes of yield variability, and the latter provides candidates for management. The candidates for causal factors include soil type, depth to clay horizon, and canopy temperature (especially its effect on phenology). For rainfed culture, water supply is a candidate cause, and under irrigation, is a candidate for site-specific management. The most common candidates for site-specific management are fertilizer application and seeding rate. Therefore, it is important that models demonstrate both accuracy and appropriate sensitivity to these variables if the models are to be used to explain effects or to develop site-specific recommendations for the variables.

1.2.1. Soil map unit

For soils in the southeast region, soil map unit classification is a logical first choice as a candidate for a causal factor, both because data are available in the county soil surveys and because expected yields vary markedly among map units, as reflected in the soil survey productivity rating. However, within-field yield maps and soil map units are not always highly correlated. The poor correlation may result from a mismatch between the scale of the county soil survey and the scale of the yield mapping effort.

The national soil survey was not intended as a within-field, site-specific agriculture tool (Mausbach et al., 1993). Not surprisingly, within-field yield variation has seldom been well described using the 1:24 000 county-level soil survey, usually because of yield-affecting inclusions that are too small to include at that scale. Correlation can be improved two ways, either by getting yield maps over a larger area, or by surveying at a finer scale in a small area, such as a field. Although no success was observed describing within-field yield variation using 1:24 000 soil survey classes, the correlation improved when the scale of the yield mapping effort (multiple thousands of hectares) increased to approach the scale of the county soil survey (Sadler et al., 1999). For within-field work, finer scales appear to be appropriate. For a survey conducted at 1:1200 scale, Karlen et al. (1990) presented 5 years of significant correlations between mean yield and map unit classification. However, later work on the same site was less conclusive (Sadler et al., 1995b), suggesting that the series of weather years reported by Karlen et al. (1990) may not have been representative. Steinwand et al. (1996) compared 1:3305 and 1:15 840 scales in Iowa and reported success describing mean yield by map unit at the latter scale. For a review of scale requirements for site-specific agriculture in the Atlantic Coastal Plain, see Sadler (1998).

1.2.2. Depth to clay

Success correlating yield with surface soil depth has been well documented in Missouri claypan soils (Sudduth et al., 1996, 1997). In the Atlantic Coastal Plain, the depth of the transition from sandy to clayey layers is a prominent determinant of the soil mapping unit, so it is a logical and easily measured candidate for describing within-map-unit variability. Further, the geostatistical parameters (sill and range) for depth to clay were comparable to those of yield data (Sadler et al., 1998). These results support further examination of depth to clay as a cause of yield variation.

1.2.3. Water supply

For rainfed agriculture, within-field variation in soil water content is usually obvious even to the casual observer. However, difficulties in measuring it spatially have hindered its acceptance as a candidate for cause or for management of spatial variability in crop yield. Remotely sensed images showing severe variation in crop temperature indicate a close link between soil water content and crop temperature and, therefore, support the existence of severe variation in soil water content. The few examples of spatial measurements (e.g. Lascano et al., 1999) also show such variation in surface-60-mm soil water content. In the Coastal Plain, spatially sparse soil profile water content measurements (Sadler et al., 1995a, 2000) support water relations as an additional candidate for study.

Despite the evidence supporting its inclusion in this sensitivity analysis, it is not obvious which parameter to test. While the ultimate objective is to vary water stress, interactions among rainfall, runoff, infiltration, drainage, rooting depth, and the various soil water storage parameters together describe water available to the plant. Seasonal dynamics further complicate the choice and may compromise variation in the variable to be tested. For instance, varying the curve number parameter may or may not cause a variation in the soil water content, and thus water stress, because rainfall totals may be either below that required for runoff for the range of curve numbers, or the antecedent soil water content may be high enough that much of the water runs off or drains. Similarly, changing the upper or lower limits of soil water storage, or the difference between the two, interacts with infiltration, drainage, and possibly even rooting depth to provide unpredictable variation in soil water content.

The most-nearly direct link to soil water content, and thence to crop water stress, appears to be via manipulating infiltration. However, as mentioned earlier, varying curve number does not provide an unequivocal nor predictable variation in soil water content. Further, we have observed probable errors calculating infiltration for our conditions (Stone and Sadler, 1991). One example was for a 92-mm storm that occurred in 52 min during the 1986 drought. Simulation results indicated 72 mm of infiltration. In this extreme event, it is highly unlikely that more than one third of the rainfall was retained, as indicated using dynamic infiltration models.

1.2.4. Crop temperature

Variation in crop temperature became readily apparent when infrared thermometers (IRT) became available (Aston and van Bavel, 1972). These and more recent instruments have documented variable canopy temperatures for a wide variety of crops, soils, and conditions (Moran and Jackson, 1991; Norman and Kustas, 1996). In the southeastern Coastal Plain, IRT measurements on transects at four dates during a drought showed severe variation in canopy temperature on a short spatial scale (Sadler et al., 1995a); these data had the most extreme variation of the entire dataset examined by Sadler (1998). While an argument could be made that canopy temperature is a crop response, as is yield, temperatures have known effects on crop development and physiology. Further, correlation existed between final crop yield and IRT temperatures for the two more-stressed dates (Sadler et al., 1995a). Therefore, crop temperature was selected as a candidate for examination.

The known dependence of phenology on crop temperature suggests another comparison using this particular sensitivity test. When visual contrast between developing plants is maximized, such as with height variations or with emergence or tasseling, spatial variation in development can be readily apparent. However, there is very little published information on spatial causes of this variation. Sadler et al. (1995a) described both spatial variation in plant height on transects and also variation in phenology at 11 sites in a field. Repeated observations by the authors of areas that have advanced crop development within experimental fields suggest that this variation bears further examination, if only to ascertain the causes of small-scale variation.

1.2.5. Fertilizer

Since the original patent (Ortlip, 1986) and commercial development of the site-specific dry granular fertilizer spreader, the primary candidate for variable-rate management in rainfed agriculture has usually been fertilizer application. In areas with sandy soils, such as the southeastern Coastal Plain, site-specific application of leachable nutrients, particularly N in nitrate form, presents a potential for both economic and environmental benefits. Thus, sensitivity of the model to nitrogen application is critical for crop growth modeling's successful use in site-specific agriculture.

1.2.6. Seeding rate

In rainfed agriculture, variable-rate seeding (VRS) is one of the few management options to alter water relations on a site-specific basis. Commercial availability of VRS planting equipment indicates that there must be some acceptance of VRS seeding in the farm as well as the research communities. The economic profitability of VRS planting is not yet proven, but the theoretical response curve for plant population suggests some potential (Bullock et al., 1998).

The present study examined the sensitivity of the crop growth model CERES-Maize in DSSAT version V3.5 (Hoogeboom et al., 1999) to soil map unit, depth to clay layer, water supply, crop temperature, fertilizer nitrogen, and seeding rate. The results of these analyses will establish, to a large part, the suitability of the model for application to site-specific agriculture in the sandy, stratified soils of the SE USA Coastal Plain and similar regions.

2. Materials and methods

Since 1985, researchers at the USDA-ARS Coastal Plains Soil, Water, and Plant Research Center in Florence, SC, have mapped field crop yields on a 6-ha field with soil variation typical of the region. A detailed description of the soils and research history can be found in Karlen et al. (1990) and Sadler et al. (1995b). To date, the inherent variability in the field has been documented using conventional, whole-field culture. In the 13 years, seven corn, one grain sorghum, five wheat, and four soybean crops have been mapped, initially with stop-and-weigh techniques, and since 1996 with a combine yield monitor. Detailed soil water use and other measurements were made during the 1987 wheat and 1993 corn seasons (Sadler et al., 1995a). The 7 years of corn yield maps and collateral data were used here to evaluate model sensitivity. These years were 1985, 1986, 1988, 1992, 1993, 1995, and 1997. Of these, 1986 and 1993 were severe, and 1988 moderate, droughts. Other years had better growing conditions and correspondingly higher yields.

The CERES-Maize corn growth and yield model (Jones and Kiniry, 1986; Tsuji et al., 1994) in DSSAT V3.5 (Hoogenboom et al., 1999) was used to simulate corn yield after the fact. Weather data were taken from an on-site automated station. Soil files were constructed to match typical pedon descriptions for the specific soils in the field (USDA-SCS, 1984). These were supplemented by literature values where available (Long et al., 1969; Peele et al., 1970) or local measurements for physical parameters (Busscher, personal communication). For some soil map units, variation in horizon depth was the only difference, and for others, similarity to soils with published parameters was exploited.

The current advice is to obtain in situ measurements of the upper and lower limits, citing effects of soil structure that is destroyed when laboratory methods are used. The effects of using laboratory or in situ measurements for the soils used in this study were reported by Sadler et al. (1999). In general, the agreement between measured and simulated yield was not noticeably improved, even when using in situ measurements taken from the specific year being simulated.

Best estimates of all parameters were used to make baseline runs to compare to runs with varied parameters (Table 1). These four representative soils were used for the bulk of this work. These covered the range of variation seen in the field for texture, depth to clay, runoff curve number, and other soil characteristics, as well as final yield. The sensitivity for soil map unit was also conducted for all other map units in the field, but the input database is not given here because of length. All runs for the map unit sensitivity were made using the best-estimate, baseline soil files.

For the sensitivity analyses of the other variables, all but the subject variable were held at baseline values, and the subject variable was varied over the range of values expected in the field, except where the range was extended to test an extreme case. For instance, depth to clay was varied over the range observed for each soil type in the field. Because of the considerations discussed previously, the sensitivity to water supply was tested by reducing runoff curve number to an arbitrarily low value to eliminate runoff, and then varying rainfall from 50 to 150% of the observed value. Because canopy temperature is not an input to the model, air temperature was the variable tested. Further, because nighttime radiative forcing is essentially neutral to water stress, the effect of water temperature on canopy temperature would presumably be limited to the maximum temperature experienced. Therefore, the approach used was to vary maximum air temperature from observed −4°C to observed +6°C. In addition to the effects on yield, the effects on crop development and maturity were also examined using the runs in which maximum air temperature was varied. Total applied nitrogen was varied from 0 to 220 kg ha^{-1}, where the recommendation for rainfed corn is 134 kg ha^{-1}. Population was varied from 0 to 15 plants m^{-2}, with the recommended (and average) population ranging from 5 to 5.5 m^{-2}.

Table 1
The soil characteristics file contents for the four representative soils used in the sensitivity analyses

*ACFL000001			Best estim		LOSA	200	BnA									
@SITE			Country		Lat		Long	SCS FAMILY								
	SCFL		USA		34.20		79.70	Bonneau- loamy, siliceous, thermic grossarenic paleudults (1)								
@	SCOM	SALB	SLU1	SLDR	SLRO	SLNF	SLPF	SMHB	SMPX	SMKE						
	−99	0.20	7.5	0.26	67.5	1.00	0.00	IB001	IB001	IB001						
@	SLB	SLMH	SLLL	SDUL	SSAT	SRGF	SSKS	SBDM	SLOC	SLCL	SLSI	SLCF	SLNI	SLHW	SLHB	SCEC
	12	−99	0.045	0.121	0.277	0.887	0.15	1.50	−99	2.8	22.7	0.0	−99	6.5	−99	5.3
	25	−99	0.043	0.125	0.279	0.684	0.08	1.50	−99	2.8	22.7	0.0	−99	6.3	−99	5.3
	40	−99	0.047	0.142	0.250	0.517	0.08	1.69	−99	4.6	30.7	0.0	−99	5.8	−99	2.1
	61	−99	0.046	0.143	0.251	0.361	0.01	1.69	−99	4.6	30.7	0.0	−99	5.3	−99	2.1
	76	−99	0.133	0.244	0.311	0.252	0.06	1.65	−99	9.4	29.5	0.0	−99	5.0	−99	2.0
	97	−99	0.150	0.260	0.319	0.176	0.03	1.60	−99	23.1	24.9	0.0	−99	4.9	−99	5.6
	117	−99	0.150	0.260	0.319	0.118	0.03	1.60	−99	23.1	24.9	0.0	−99	4.9	−99	5.6
	144	−99	0.183	0.293	0.344	0.073	−99	1.60	−99	28.8	24.9	0.0	−99	4.9	−99	8.1
	172	−99	0.183	0.293	0.344	0.042	−99	1.60	−99	28.8	24.9	0.0	−99	4.9	−99	8.1
	200	−99	0.183	0.293	0.344	0.024	−99	1.60	−99	28.8	24.9	0.0	−99	4.9	−99	8.1
*ACFL000003			Best estim		LO	222	Cx									
@SITE			Country		Lat		Long	SCS FAMILY								
	SCFL		USA		34.20		79.70	Coxville- clayey, kaolinitic, thermic typic paleaquults (3)								
@	SCOM	SALB	SLU1	SLDR	SLRO	SLNF	SLPF	SMHB	SMPX	SMKE						
	−99	0.14	9.0	0.14	87.5	1.00	0.00	IB001	IB001	IB001						
@	SLB	SLMH	SLLL	SDUL	SSAT	SRGF	SSKS	SBDM	SLOC	SLCL	SLSI	SLCF	SLNI	SLHW	SLHB	SCEC
	10	−99	0.137	0.254	0.336	0.905	0.19	1.57	−99	12.1	47.5	0.0	−99	6.1	−99	14.4
	20	−99	0.132	0.254	0.337	0.741	0.19	1.57	−99	12.1	47.5	0.0	−99	5.5	−99	14.4
	33	−99	0.130	0.254	0.337	0.583	0.05	1.67	−99	20.6	30.0	0.0	−99	5.1	−99	11.7
	64	−99	0.220	0.341	0.386	0.375	0.03	1.60	−99	35.3	25.8	0.0	−99	4.8	−99	10.4
	76	−99	0.220	0.341	0.386	0.247	0.03	1.53	−99	39.1	24.1	0.0	−99	4.6	−99	9.8
	108	−99	0.220	0.341	0.386	0.159	0.02	1.53	−99	37.3	21.5	0.0	−99	4.5	−99	11.2
	132	−99	0.221	0.342	0.386	0.091	0.02	1.53	−99	37.3	21.5	0.0	−99	4.5	−99	11.2
	162	−99	0.240	0.356	0.395	0.053	−99	1.53	−99	48.8	14.8	0.0	−99	4.5	−99	12.0
	192	−99	0.240	0.356	0.395	0.029	−99	1.53	−99	48.8	14.8	0.0	−99	4.5	−99	12.0
	222	−99	0.240	0.356	0.395	0.016	−99	1.53	−99	48.8	14.8	0.0	−99	4.5	−99	12.0

Table 1 (*continued*)

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*ACFL000012            Best estim       LOSA  200   GoA@SITE    COUNTRY           Lat          Long SCS FAMILY
            SCFL       USA                  34.20   79.70  Goldsboro- fine-loamy, siliceous, thermic aquic paleudults (12)
@           SCOM  SALB  SLU1      SLDR  SLRO  SLNF  SLPF  SMHB   SMPX   SMKE
            -99   0.20  8.0       0.17  77.5  1.00  0.00  IB001  IB001  IB001
@           SLB   SLMH  SLLL      SDUL  SSAT  SRGF  SSKS  SBDM   SLOC   SLCL   SLSI  SLCF  SLNI  SLHW  SLHB  SCEC
            9     -99   0.062     0.162 0.270 0.905 -99   1.54   -99    3.9    17.3  0.0   -99   6.3   -99   4.9
            18    -99   0.058     0.168 0.273 0.756 -99   1.54   -99    3.9    17.3  0.0   -99   6.0   -99   4.9
            28    -99   0.059     0.181 0.270 0.631 -99   1.81   -99    11.9   24.2  0.0   -99   5.7   -99   5.4
            38    -99   0.058     0.182 0.270 0.517 -99   1.81   -99    11.9   24.2  0.0   -99   5.3   -99   5.4
            64    -99   0.179     0.293 0.354 0.361 0.05  1.67   -99    26.8   22.3  0.0   -99   5.0   -99   9.8
            81    -99   0.232     0.346 0.366 0.232 0.06  1.52   -99    31.7   23.7  0.0   -99   4.8   -99   11.0
            102   -99   0.241     0.352 0.362 0.159 0.02  1.52   -99    42.4   19.4  0.0   -99   4.8   -99   12.4
            127   -99   0.241     0.352 0.362 0.122 -99   1.52   -99    36.4   14.9  0.0   -99   4.8   -99   12.7
            173   -99   0.241     0.352 0.362 0.050 -99   1.52   -99    35.7   15.3  0.0   -99   4.8   -99   10.1
            200   -99   0.241     0.352 0.362 0.024 -99   1.52   -99    35.7   15.3  0.0   -99   4.8   -99   10.1

*ACFL000018            Best estim       LOSA  199   NkA lfs Dpw
@SITE                  Country              Lat     Long SCS FAMILY
            SCFL       USA                  34.20   79.70  Norfolk- fine-loamy, siliceous, thermic typic pale (18)
@           SCOM  SALB  SLU1      SLDR  SLRO  SLNF  SLPF  SMHB   SMPX   SMKE
            -99   0.20  7.5       0.39  77.5  1.00  0.00  IB001  IB001  IB001
@           SLB   SLMH  SLLL      SDUL  SSAT  SRGF  SSKS  SBDM   SLOC   SLCL   SLSI  SLCF  SLNI  SLHW  SLHB  SCEC
            9     -99   0.054     0.123 0.260 0.905 -99   1.52   -99    2.0    15.4  0.0   -99   7.2   -99   3.3
            17    -99   0.052     0.127 0.261 0.771 -99   1.52   -99    2.0    15.4  0.0   -99   6.7   -99   3.3
            30    -99   0.061     0.162 0.260 0.619 -99   1.71   -99    2.0    15.4  0.0   -99   5.7   -99   3.3
            51    -99   0.162     0.271 0.353 0.440 -99   1.42   -99    30.5   19.1  0.0   -99   5.3   -99   8.2
            81    -99   0.175     0.283 0.332 0.267 -99   1.42   -99    30.5   19.1  0.0   -99   5.4   -99   8.2
            122   -99   0.173     0.283 0.332 0.130 -99   1.42   -99    30.5   19.1  0.0   -99   5.4   -99   8.2
            132   -99   0.171     0.283 0.332 0.079 -99   1.42   -99    30.5   19.1  0.0   -99   5.4   -99   8.2
            165   -99   0.171     0.283 0.332 0.051 -99   1.42   -99    32.4   16.1  0.0   -99   5.4   -99   10.5
            199   -99   0.171     0.283 0.332 0.026 -99   1.42   -99    32.4   16.1  0.0   -99   5.4   -99   10.5
```

3. Results and discussion

Before the results for the sensitivity analysis can be interpreted, one must recognize the general ability of the model to explain the greatest source of variation, which is usually year-to-year variability in rainfall and other weather parameters. Fig. 1 shows variation from year to year, with the error bars representing variability from map unit to map unit within years.

3.1. Soil map unit

As can be seen from the relatively narrower vertical than horizontal spread in Fig. 1, the model functions better as a central tendency estimator than it does as a variance estimator, both within and among years and within soils. The lack of vertical spread suggests that the causes of yield variation were not represented by either or both of the inputs and processes of the models for these conditions. While these causes remain undetermined, this result suggests that further work will be needed to achieve full success in site-specific applications.

3.2. Depth to clay layer

To create the soil profiles with varied depth to clay layers, the typical pedon description was copied and the thickness of the E horizon was varied to achieve the range observed in the field. Fig. 2 shows the sensitivity of simulated corn yield to depth to clay for the NkA soil. Particularly striking is the nearly absolute insensitivity to this parameter, with only 1986 yields deviating from essentially flat, and

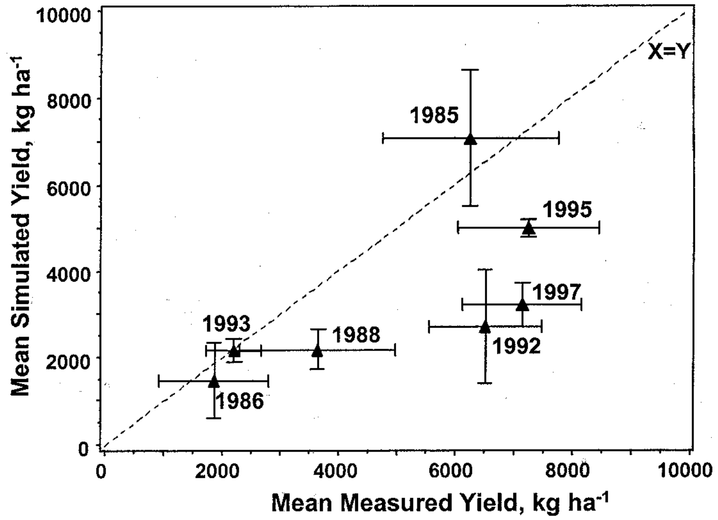

Fig 1. Simulated yield with standard deviation for both measured mean map unit and simulated map unit yields shown for each year.

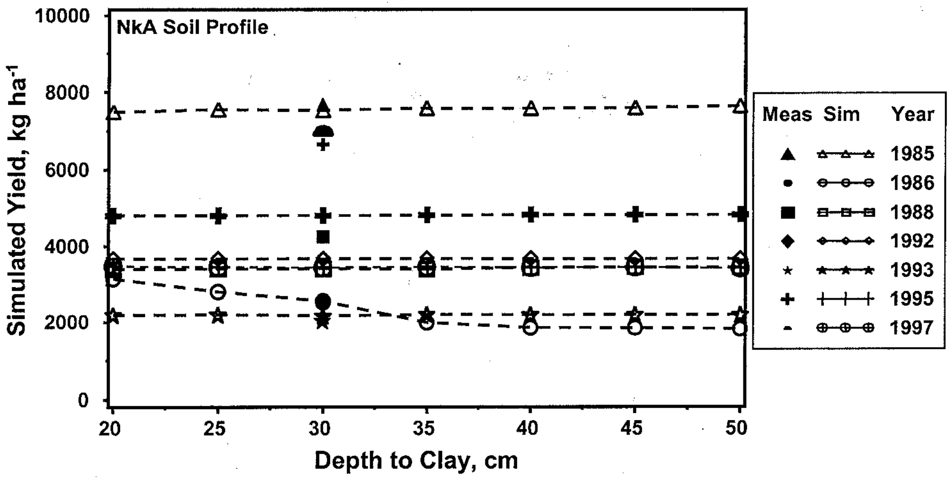

Fig 2. Sensitivity of simulated corn yield to depth of transition from the sandy to clayey layer for the Norfolk soil.

those in an inverse relationship. Historical measured yields (Sadler et al., 1995b) for the Nka and NoA and the similar NcA and NbA map units show a consistent direct benefit to the thicker sandy layer. Regression analysis on 1988 measured corn yields showed a 2.5 kg ha^{-1} increase per 1 cm increase in depth to clay for NkA, and in excess of 100 kg ha^{-1} per 1 cm increase for NoA (Sadler et al., 1995b).

3.3. *Water supply*

Fig. 3 shows the sensitivity of simulated corn yield to rainfall for all years and four soils. The two extremes are demonstrated by 1995, where the water supply had reached a plateau, and by the drought years 1986 and 1993. (The apparently inconsistent increases in 1986 yields with reduced rainfall are explained by delayed germination, causing those scenarios to have discretely different water supply inputs.) Field observations, measurements, and simulations (data not shown) suggest the model overestimates infiltration with the curve number procedure, but CERES-Maize model runs using Green-Ampt infiltration calculations accounted for only half the yield error (Stone and Sadler, 1991). Sensitivity of the corn model shown here suggests a plausible sensitivity to water supply, which is promising. However, known limitations in calculating infiltration and runoff suggest that the procedures to calculate the primary components of the water balance may need examination.

3.4. *Canopy temperature*

Spatial measurements of canopy temperature in 1993 (Sadler et al., 1995a) showed extreme spatial variation, suggesting that within-field variation in crop temperature would merit examination as a cause of differential crop growth and yield. The cause of the variation in crop temperature was assumed to be differential water stress,

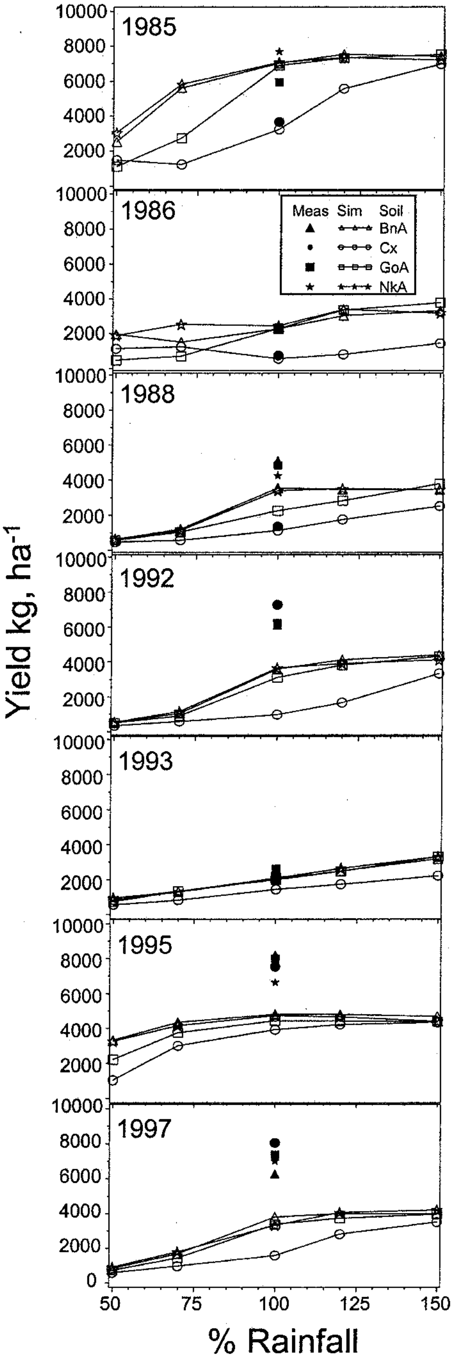

Fig 3. Sensitivity of simulated corn yield to water supply, as controlled by changing the rainfall totals by the ratios indicated, for four soils and all years.

which was markedly variable at eight measured locations (Sadler et al., 2000). Fig. 4 shows the sensitivity of the models to changes in maximum air temperature, which, when combined with the minimum air temperature, drives the crop development calculations. For some years, the sensitivity appears to be sufficient to warrant further examination of the difficulties and benefits that might accrue if a more rigorous canopy temperature routine were added to the model.

The known effect of temperature on crop development rates, coupled with the observed spatial temperature variation and the observed variation in tasseling and maturation (Sadler et al., 1995a), required that response of this additional effect of temperature be examined. Increased temperatures accelerated crop development in the simulations (data not shown), as expected from the maturation routine's dependence on growing degree units. However, observations (Sadler et al., 1995a) showed up to 18 days delayed development in areas with higher canopy temperatures. This suggests a routine to account for water stress by temperature interactions may improve the applicability of the models to site-specific agriculture.

3.5. Nitrogen supply

The sensitivity to nitrogen fertilizer was examined using variable fertilizer applications from 0 to 220 kg ha^{-1}, with the actual application and yield indicated (Fig. 5). While the general shape of the rising limb appears reasonable, the point of diminishing marginal returns to nitrogen is shifted well left of the extension recommendations for rainfed corn in the region (134.5 kg ha^{-1} for a target yield of 6.3 Mg ha^{-1}). This suggests either some overstatement of the contribution of residue and organic matter to the available-N pool in the models, some understatement of N losses from the soil profile, or that extension recommendations are particularly conservative.

3.6. Plant population

Sensitivity to varied plant population is shown in Fig. 6. Again, the rising limb shows the expected shape, but at populations $\geqslant 3$ plants m^{-2}, there is relatively little sensitivity to population. The essentially flat response to extremely high populations suggests that competition for water and possibly other resources should be evaluated for inclusion in the model. Mean measured yields for each of the four map units are plotted at the mean population for the field because plant populations were not measured by map unit except in 1993. Simulations for that year showed little effect of map-unit-specific populations on the modeled yield.

4. Summary and conclusions

The performance of the CERES-Maize model under the conditions of these tests was, at best, mixed. The model did not simulate the annual or map unit mean yields particularly well. The sensitivity to soil map unit, which is an extreme multi-parameter

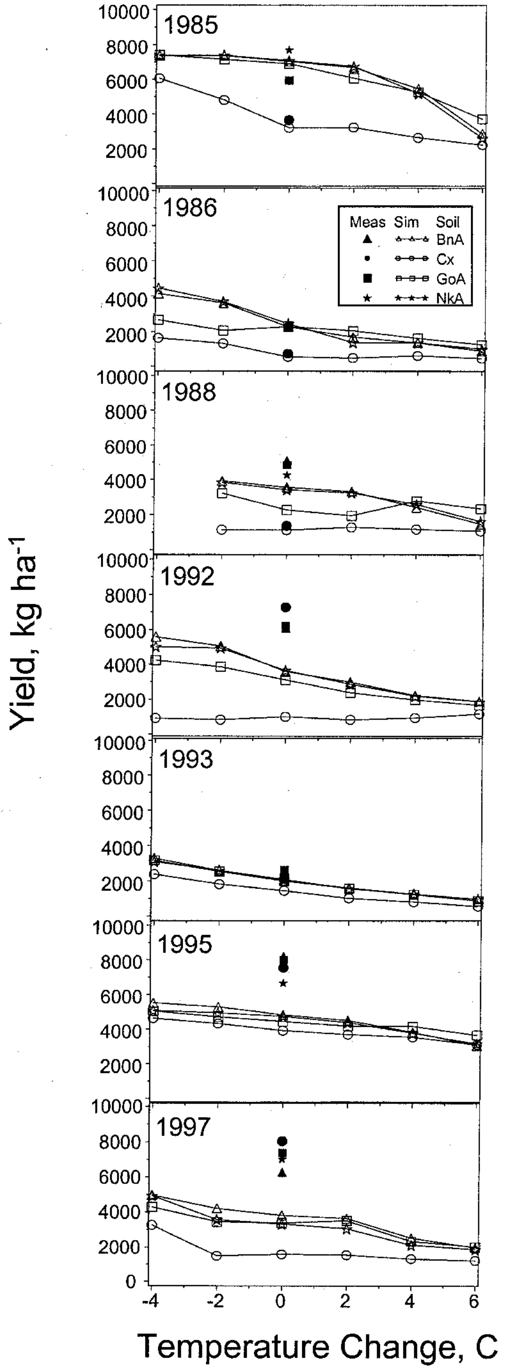

Fig 4. Sensitivity of simulated corn yield to maximum air temperature, used as a surrogate to evaluate sensitivity to canopy temperature, for four soils and all years.

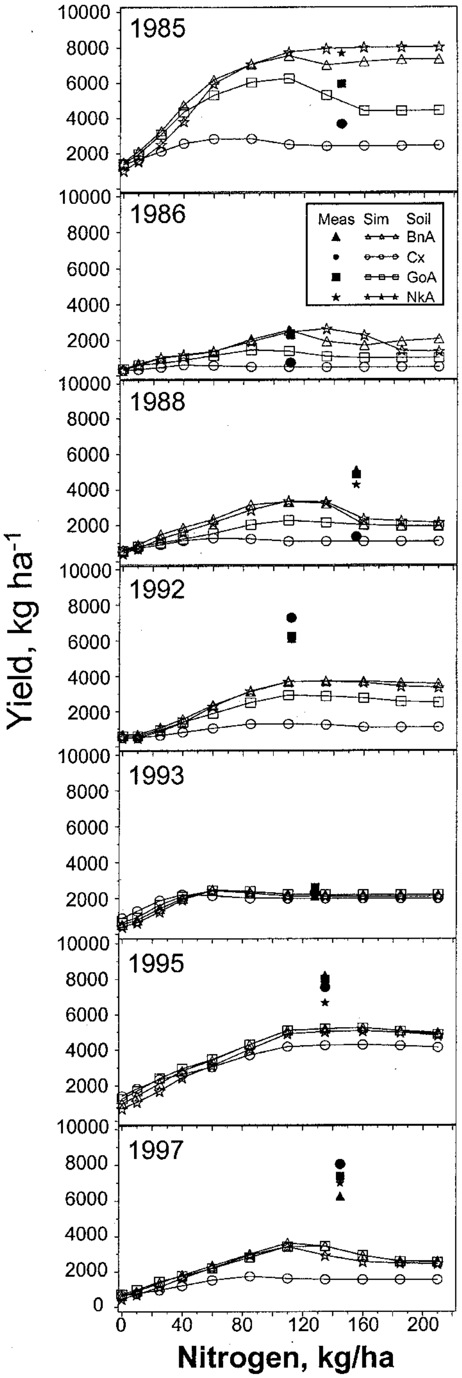

Fig 5. Sensitivity of simulated corn yield to nitrogen applied as fertilizer, for four soils and all years.

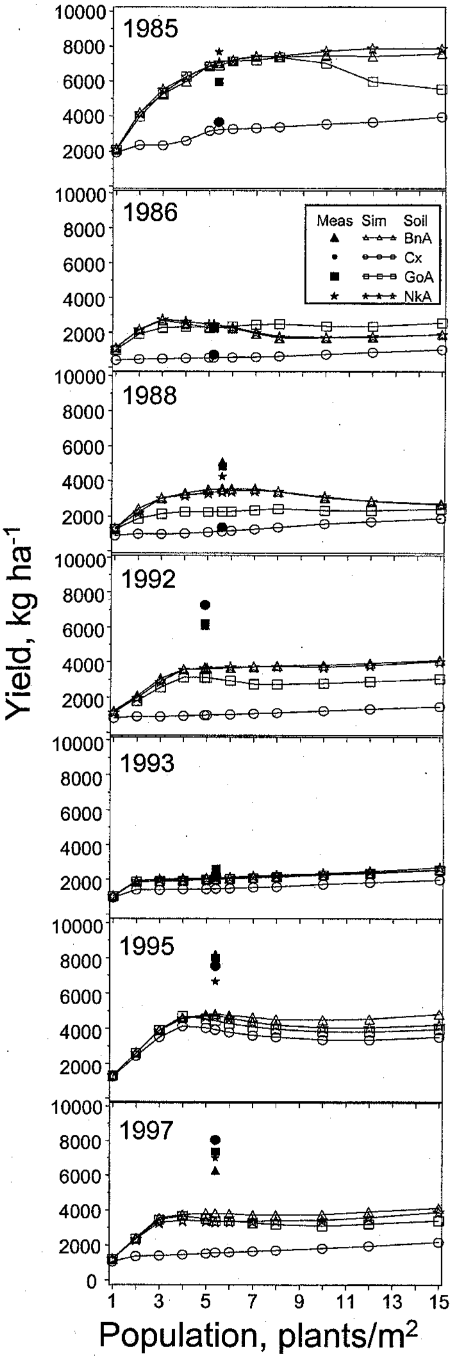

Fig 6. Sensitivity of simulated corn yield to plant population, for four soils and all years.

test, suggested that either of two conditions occurred. One is that the parameters did not adequately describe the soils, for whatever reason. The other is that the processes described within the model did not adequately match those occurring in the field. The truth, were it known, probably lies somewhere within the two extremes. However, for some years (1992, 1995, and 1997), no set of soil parameters caused any modeled yield to approach the mean measured yield, despite the wide variation in soils described. It is interesting that the severe drought years had, at least, the annual mean simulated well.

The model was unexpectedly insensitive to the depth to the clay layer. Although the general shape of the response curves was apparently appropriate for applied nitrogen and seeding rate, the curves were very flat in the regions corresponding to the actual application and population. Again, either the sensitivity to these inputs is understated, or the extension recommendations are somewhat high. No evidence, external to this work, suggests they are set too high, however.

Model sensitivity to several candidate parameters suggests potential directions for model evolution that could improve suitability for use in site-specific agriculture applications. Sensitivity to rainfall indicates that further work improving infiltration, runoff, and within-field surface redistribution would be justified. Sensitivity to canopy temperature suggests that there would be value to a routine that estimates canopy temperature from the energy balance. Phenology results suggest that a temperature by water stress interaction should be examined for the model. Lack of sensitivity to extremely high plant populations suggests that competition for resources could be examined. The location of the point of optimum economic return on the nitrogen sensitivity curve suggests that more empirical data is needed to test and supplement the model.

Although these tests were conducted under conditions common to sandy soils of the SE USA Coastal Plain and similar regions of the world, the theory embodied in the model suggests that the proposed enhancements should apply under many other conditions. Whatever the results, positive or negative, exercises such as those conducted here are critical to the continued improvement of models for use in site-specific agriculture.

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