Proceedings of the Integrated Crop Management Conference

Proceedings of the 27th Annual Integrated Crop Management Conference

Dec 1st, 12:00 AM

Forecasting yields and in-season crop-water nitrogen needs using simulation models

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Introduction

Forecasting crop yields and water-nitrogen dynamics during the growing cycle of the crops can greatly advance in-season decision making processes. To date, forecasting approaches include the use of statistical or mechanistic simulation models, aerial images, or combinations of these to make the predictions. Different approaches and models have different capabilities, strengths, and limitations. System-level mechanistic simulation models (crop and soil models together) usually offer more prediction and explanatory power at the cost of extensive input data. In contrast, statistical approaches or aerial images can be more robust than mechanistic models but their applicability and prediction/explanatory power is limited. The combination of these technologies is viewed as a very promising tool to assist Midwestern agriculture, but in general, all of these technologies are in their initial stages of implementation and more time is needed to prove their potential. Here we present results from a pilot project that aimed to forecast weather, soil water-nitrogen status, crop water-nitrogen demand, and end-of-season crop yields in Iowa using two process-based mechanistic simulation models.

Materials and methods

We combined a climate model (WRF, http://www.wrf-model.org/index.php) that provided a 14-day weather forecast with the capabilities of APSIM (Keating et al., 2003; Holzworth et al., 2014) to create in-season forecasts. The project focused on 8 cropping systems: 2 crops, corn and soybean; 2 sites, central and northwestern Iowa; and 2 planting dates, early and late. In this article we present information for corn. The crops were managed using typical crop management practices for the Midwestern US. High resolution measurements were taken from replicated plots. Measurements included hourly soil water and temperature at three depths, hourly groundwater table measurements, weekly soil NO_3-N and NH_4-N measurements, and 10 in-season destructive crop harvests to estimate phenology, biomass production and partitioning, tissue N concentration, and leaf area index. During the growing reason eight forecasts were released bi-weekly via a website (http://agron.iastate.edu/CroppingSystemsTools/) to a group of Iowa State University Extension faculty and staff to evaluate the project and make use of the in-season information. In each forecast, we provided both in-field measurements and model predictions. The forecast included information for seven major topics: a) climate, b) crop staging, c) crop biomass and leaf area index (LAI), d) soil water, temperature and nitrogen; e) 14-day forecast of crop demand and soil supply of resources; and finally f) end of season grain yield forecast. To forecast the end of season crop yields we used synthetic meteorological files which included: actual weather data up to the forecast date, WRF model one week ahead forecasted weather, and then we filled the rest of the growing season with historical years (1980 to 2014; 35 years). The APSIM software platform was central to this project as it was used to synthesize soil-crop-climate information and create the in-season forecasts. To set up APSIM (model initial conditions, cultivars, etc.) in the experimental plots, we leveraged results from previous modeling studies in Iowa (Archontoulis et al., 2014a,b; 2015a; Dietzel et al., 2015). APSIM predictions accounted for water and nitrogen limitations to crop growth but do not account for pest and diseases. For more information on APSIM we refer to the cited references and model's website (www.apsim.info).

Results

Forecasting end-of-season grain yields and accuracy

The uncertainty with the end-of-season yield prediction (10%, 50%, and 90% chance of yield being above) was large at the beginning of season, became smaller during the season, and converged to a single value at crop maturity (Figure 1). We obtained both combine and hand measured yields to validate the end-of-season predictions. In general, across all corn based cropping systems (n=4), APSIM predictions compared to hand measured yields had an error from 1.6% to 6.1%, while when APSIM predictions were compared to combine measured yields the error ranged from –5% to +10.4%. So, the first year results (2015) showed that the model predicted corn yields reasonably well with an overall error of ± 10%, which is very promising.

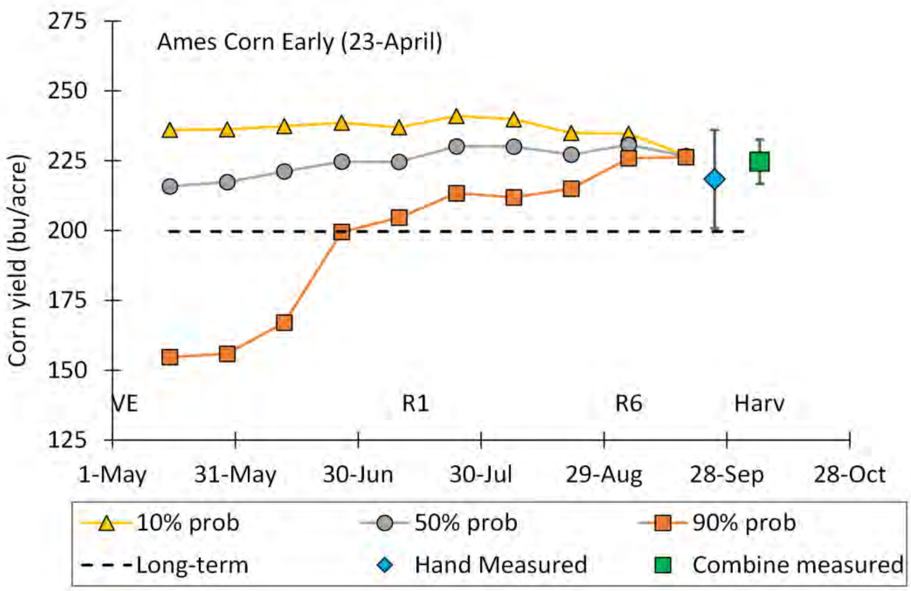

Figure 1. APSIM model predictions of corn grain yield over the growing season of 2015. Yellow triangles, grey circles and orange squares show the probabilities of yield being above that level. Hand measured and combine measured yields are also shown. Dates of emergence (VE), silking (R1), physiological maturity (R6) and harvest are provided along the x-axis. The corn was planted on April 23, at 32,300 seeds/acre and received 150 lbs N/acre at planting. A 107-d hybrid was used. The previous crop was soybean.

Overall model performance

To evaluate whether the model provided the right answer (grain yield) for the right reasons, we compared APSIM predictions to several other soil-crop measurements. We found that the model simulated reasonably well several aspects of the system such as soil water, groundwater table, soil nitrogen dynamics, crop growth and partitioning, and tissue N concentration for all cropping systems. Figure 1 shows model performance for one cropping system. We obtained similar results for the other cropping systems (data not shown).

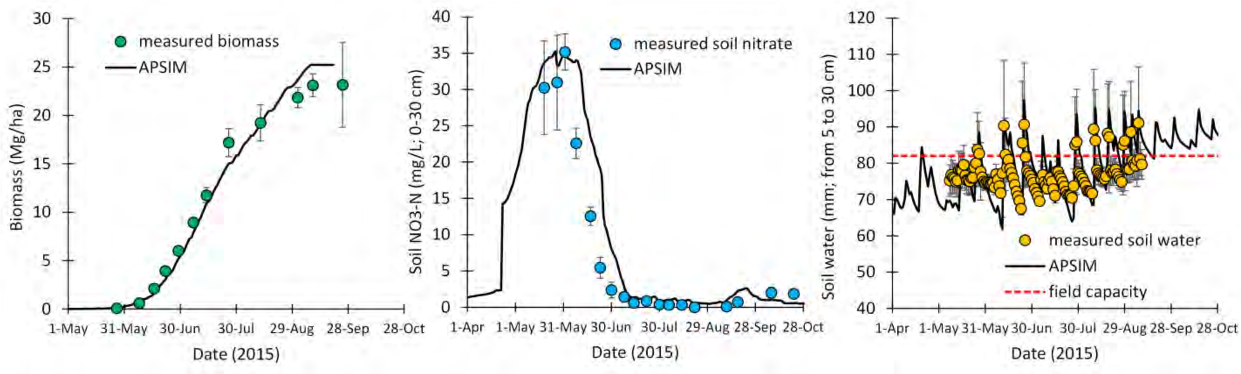

Figure 2: Measured versus predicted crop biomass accumulation, soil nitrate and soil water for the Ames-Corn-Early cropping system. See more management information in Figure 1.

How does the 2015 corn yields compare with other years? – Yield gap analysis

The 2015 growing season was smooth with no major issues regarding water or nitrogen stresses in the forecasting plots. An exception was some water stress that occurred at Sutherland corn plots before silking stage but a 3 inch precipitation event diminished this stress (see Archontoulis et al., 2015b). The estimated from the model yield lost for these plots was around 10 bushels/acre. In general, our model analysis indicated that the 2015 corn crops reached near potential yield levels with a yield gap less than 6% in our plots.

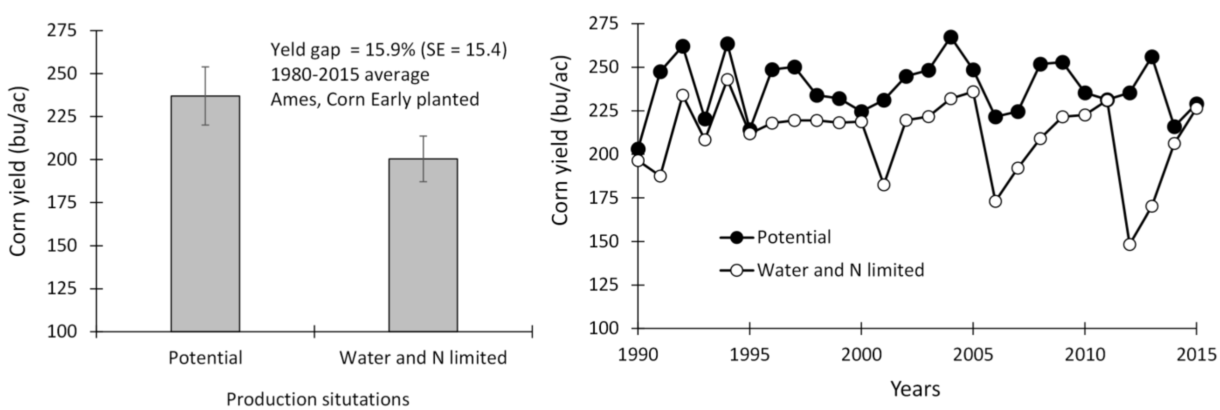

Figure 3: Left panel: Simulated long term average (± SE) potential and water-nitrogen limited production situation for early planted corn in Ames (the difference between potential and water-nitrogen limited yield is a measure of the yield gap); Right panel: Temporal variability in the yield gap. In each yearly simulation we used the same management (23-April planting, 150 lbs N/acre, 32,300 seeds/acre, 107-d hybrid) and model initial conditions (soybean residue, soil water and nitrate). This allowed us to explore the effect of climate on yield potential and the associated yield gap. Every change in the above inputs will affect the yield gap.

The simulated potential yield by the model is determined by solar radiation, temperature, crop physiology, canopy architecture, and crop management (date of planting and plant population). The water-nitrogen limited yield accounts also for water and nitrogen limitations (but not pest and diseases) and is closer related to the actual observed yields (Figure 1). The difference between potential and water-nitrogen limited is a measure of the yield gap in this study (Figure 3). Below, we provide a yield gap analysis for the Ames-corn-early cropping system. Figure 3 shows long term average yields gaps as well as the temporal variability in yield gap across different years. For this analysis we ran the model for different climatic years but in each year used the 2015 management practices, hybrid, and model initial conditions. This analysis showed that on average the yield gap is 15% ± 15 and that the 2015 year was an exceptional year as the gap was minimal. Interestingly, the gap in 2015 did not close because of the chosen management (which was the same every year) but because the potential yield decreased. To shed light onto the factors which decreased the 2015 yield potential, we compared the 2015 year with another year where the yield potential was substantially high (1994). We found that the reasons for the decreased potential in 2015 were: a) less radiation interception due to cloudy/rainy 2015 summer, and b) low temperatures during grain fill period (period August 18 to 28). In terms of numbers the comparison between 2015 and 1994 years showed 7.9% less radiation interception and 4oC lower mean temperatures during the grain fill period. It should be noted that this analysis is specific for this cropping system. A change in management (plant population, hybrid, date of planting) or initial conditions (previous crop residue) will change the estimation of the yield potential and the associated yield gap.

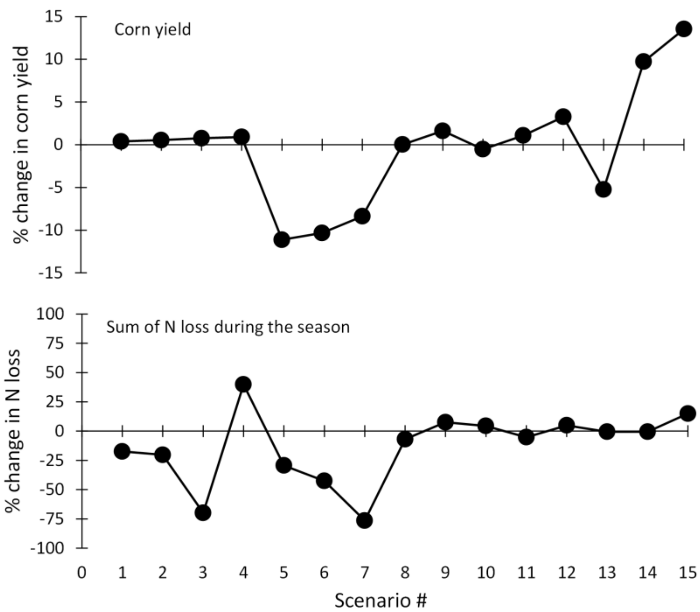

Figure 4: Simulation-based scenario analysis for the Ames-Corn-Early cropping systems. The top panel shows yield change from the control (= management practices followed in 2015; 150 lbs N/acre at planting, 23 April planting date, 107-d maturity hybrid, and population of 32,300 plants/acre.) and the lower panel shows N loss as compared to the control. X-axis numbers shows the scenarios that were explored for the 2015 growing season: 1: Split-N; 2 and 3: apply N later in season; 4: apply additional N at V6; 5, 6 and 7: apply less N at planting or later in season; 8 and 9: increase seeds/acre without or with extra N; 10: decrease seeds/acre; 11 and 12: decrease row spacing without or with extra seeds/acre; 13: use shorter maturity hybrid; 14 and 15: use longer maturity hybrid without and with extra N. The default scenario was: 150 lbs N/acre at planting, 23 April planting date, 107-d maturity hybrid, and population of 32,300 plants/acre.

Post-season model analysis

For each corn-based cropping system we used the model to explore "what-if" questions addressing production and environmental aspects. Here we discuss results for the "Ames Corn Early" cropping system (Figure 4). For that system we ran APSIM to explore 15 different scenarios that included combinations of changes in the time of N application, N-rate, plant population, row spacing and hybrid choice. This analysis showed that a split application or later application could result in the same yield but with less N loss via denitrification and leaching over the growing season. We also found that corn yield in that system could go up if a longer maturity hybrid was chosen. The used hybrid (growing degree days to maturity of 2500) reached maturity the first week of September while there was more time for the plants to grow and for the seeds to dry down this year. This simulation analysis is useful to learn what we could have done better this year but is not valid for next year's recommendations. For decision making, a different type of analysis is needed, where the weather variability needs to included.

Concluding remarks

We followed a mechanistic system-level approach to forecasting soil and crop dynamics which is characterized as difficult. However, this approach allowed us to explore the underlined soil-crop mechanisms in depth and provide answers to critical questions (e.g. yield prediction, yield gap analysis, scenario analysis) that can help us understand the system better and design sustainable corn-based cropping systems in Iowa. This project will be continued next year. The main challenge faced in year 1 was the simulation of shallow groundwater tables, especially for the Ames site where the water table varied from 80 to 150 cm during the growing season. Fully saturated soil layers lack oxygen and this constraints root growth. Inclusion of ground water table improved the simulation of water balance. This in turn improved the simulation of soil N dynamics and N supply. Other challenges faced in year 1 of this pilot project were: a) quality of historical weather data, b) coordination of the information flow (from the field to the computer program and to the website), and c) selection of results to provide publicly.

Acknowledgements

We thank the Iowa State University Department of Agronomy, Iowa State University Extension and Outreach-Agriculture and Natural Resources and the Iowa Soybean Association for sponsoring this project. We also thank Pat Edmonds and Gretchen Rops for their valuable assistance with the field and laboratory measurements.

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