Soil Nitrogen

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Freshwater nitrogen (N) pollution is a significant sustainability concern in agriculture. In the U.S. Midwest, large precipitation events during winter and spring are a major driver of N losses. Uncertainty about the fate of applied N early in the growing season can prompt farmers to make additional N applications, increasing the risk of environmental N losses. New tools are needed to provide real-time estimates of soil inorganic N status for corn (Zea mays L.) production, especially considering projected increases in precipitation and N losses due to climate change.

Keywords: smart farming ; DSSAT ; decision support tool ; soil mineral nitrogen ; nitrogen management ; nitrogen losses ; corn ; Illinois ; U.S. Midwest

1. Introduction

Nutrient losses from agriculture are a significant concern from tile-drained landscapes in the U.S. Midwest [1][2]. Building on the work and recommendations of the Mississippi River/Gulf of Mexico Watershed Nutrient Task Force over the past two decades (https://www.epa.gov/ms-htf/history-hypoxia-task-force, accessed on 16 December 2020), individual states have developed nutrient loss reduction strategies outlining the most effective in-field and edge-of-field practices for reducing nitrogen (N) leaching losses from agriculture and other sources. Among the different recommendations, changes in N management are particularly important because of the combined influence on crop yields and water quality. Moreover, compared to other practices, there is potential for immediate impact through voluntary adoption because changes in N management can result in cost savings and have relatively greater stackability (the ability to pair management practices) and trackability (the ability to track practice implementation) [3]. By avoiding excessive N inputs, multiple studies have highlighted the opportunity to optimize crop yields while decreasing N losses [4][5].

A major factor influencing efforts to reduce N losses is precipitation [6]. Particularly in tile-drained fields, large precipitation events contribute to higher drainage volumes, consequently increasing nitrate export [7]. Studies at both the field-level [4][5] and regional-level [8] have highlighted the combined negative influence of increased precipitation and N inputs on water quality. More recently, using a dataset across the entire U.S. to develop empirical models, the variables of precipitation, land use, and N inputs explained nearly 70% of the variation in annual N loading to waterways [9]. Of concern is that precipitation is expected to become more variable and extreme under climate change in the U.S. Midwest, further increasing N losses [10]. One study estimated that N inputs would have to decrease by more than 30% to offset the anticipated increase in riverine N loading due to changes in future precipitation patterns, including extreme precipitation events [11].

There is an urgent need for site-specific N management tools to ensure sufficient soil N supply while minimizing the risks of N losses [12]. Soil N concentration is a key variable to monitor when trying to match soil N supply with crop demand, especially early in the growing season before the major period of crop N uptake. For example, the late spring soil nitrate test is used in Iowa to quantify the amount of soil N available relative to an established threshold, helping guide in-season N fertilizer management decisions [13]. In a modeling study comparing many different N management strategies, Mandrini et al. [14] found that soil N concentration at V5 corn growth stage was the most influential variable influencing the economic optimum N rate relative to other climate or soil factor. Meanwhile, increasing amounts and intensity of precipitation during springtime, which are becoming more frequent with climate change, can decrease soil N concentrations. Puntel et al. [15] reported that excess precipitation during early season corn establishment and growth (April–June) led to exponential increases in N losses through leaching and denitrification, thereby reducing soil N supply. In addition, excessive precipitation has been shown to negatively influence regional crop yields [16].

In the U.S. Midwest, farmers sometimes respond to wet weather early in the season by applying additional N fertilizer to corn, believing that some of the N previously applied was lost to leaching or denitrification. Thus, uncertainty in soil N supply can lead to unnecessary increased N inputs, directly conflicting with farm profitability and environmental goals. Model-based decision support tools which have the potential to estimate soil N concentration could reduce this uncertainty, while avoiding the high costs and time requirements associated with manual soil sampling [12][17]. Yet, simulating soil N concentration during the growing season is challenging due to weather uncertainties and interactions with many soil-crop processes [18]. Several modeling tools have been developed in the private sector and are available to farmers, but these are proprietary products, and there is a lack of published information describing the modeling mechanisms or validating model performance. We are currently unaware of an online, user-friendly, publicly available tool allowing farmers to enter management information and estimate soil N concentration for their fields in this region, which would be especially useful after periods of wet spring weather. Another benefit of public tools is the transparency in describing the steps of model development, calibration and validation, and assessment of uncertainty and limitations.

2. Development of an Online Decision-Support Tool

2.1. Weather Data and Methods

Based on the validated DSSAT model, we developed an online Internet tool that provides user-friendly interfaces and operations for predicting SMN availability, while requiring minimal user inputs. Our project was built on the premise that such information could help support in-season N management decisions by understanding the risk of soil N losses, thereby improving the economic and environmental sustainability of N management in the U.S. Corn Belt. An important first step was to incorporate an improved weather data source compared to the previously published studies abovementioned [19][20]. This earlier version was driven by data inputs from local weather stations and soil parameters from the Gridded Soil Survey Geographic (gSSURGO) dataset [21]. The soil dataset has a spatial resolution of 10 m. In the original model, weather parameters such as daily solar radiation, maximum and minimum air temperature, rainfall amount, and relative humidity were obtained from 19 weather stations in the Illinois Climate Network (http://www.isws.illinois.edu/warm/datatype.asp, accessed on 16 December 2020). Below we describe how datasets for real-time weather were integrated with field-level management and soil information into an online platform to track soil N status during the growing season in cornfields throughout Illinois.

Inputs to the online tool include soil property data, daily weather data, soil conditions before planting, and crop management information (planting date, N application dates, and N rate). Soil property data were directly extracted from the gSSURGO dataset [21]. The drained upper and lower limits, saturation, drainage coefficients, and runoff curve number were estimated based on soil profile properties [22].

The online tool uses the National Weather Service (NWS) weather data (Real-Time Mesoscale Analysis, 2.5 km, and 1 h resolution) downloaded automatically to the server daily. The data are saved on the server and processed to CSV format daily to decrease processing time when users request to run the tool. The data include hourly 2 m air temperature, 10 m wind speed and direction, cloud cover, and precipitation. The DSSAT needs daily total solar radiation, daily maximum and minimum air temperature, rainfall, longitude, latitude, elevation, long-term average air temperature, and amplitude of the warmest and coolest monthly long-term average temperatures, and wind height and temperature data.

Total solar radiation is calculated using equations in [23] based on longitude, latitude, elevation, and cloud cover. The longitude and latitude are input data from the online tool user. Elevation data of 1 km resolution is obtained from MOD03 data (MODIS satellite) (https://modaps.modaps.eosdis.nasa.gov/services/about/products/c6/MOD03.html, accessed on 16 December 2020).

The server contains NWS data from 2005 to the present. The amplitudes of warmest and coolest monthly long-term average temperatures are calculated from these historical data.

Crop management information is provided by the user and includes hybrid maturity in growing degree days, planting date, date of N fertilizer application, and rate. In most cases, the user will be the farmer; hence this information is readily available.

In addition to soil property and weather data, DSSAT requires information about initial soil conditions (soil moisture and N content) at the site. This information is not readily available, however. We used initial soil N conditions for seven sites across Illinois each year from 2015 to 2018 [20] to set the initial conditions, using the nearest site to the user’s location. This information can also be updated later as more data become available.

2.2. Online Tool Structure

The online tool tracks real-time (daily frequency) SMN content (in lb N acre^{-1} = kg ha^{-1} × 0.89) in cornfields for user-defined locations in Illinois (flowchart in Figure 1). As highlighted above, SMN concentration is considered a useful indicator to guide crop management decisions. It is the net balance of multiple processes governing crop response to N fertilizer, including SOM mineralization, N fertilizer transformations, crop N uptake, and environmental losses.

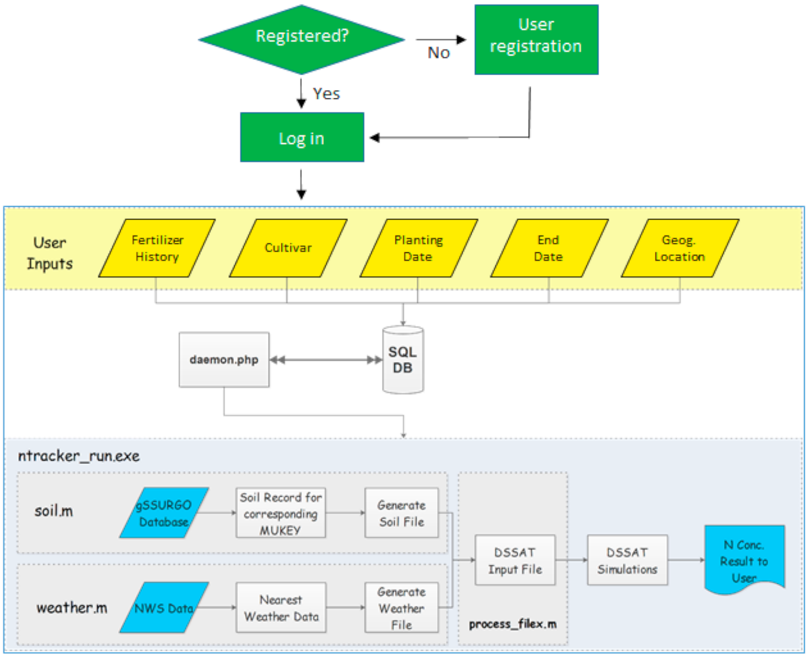

Figure 1. General flowchart of the online tool. Green processes: registration and log in; yellow: user inputs; blue: server downloaded and processed data; gray: server-side processing. Daemon.php: the program checks if there is a user simulation request on SQL DB; ntracker_run.exe is the main program on the server to run a simulation that includes soil.m, weather.m, process_filex.m, and output programs; soil.m prepares soil profile data for DSSAT; weather.m prepares weather data for DSSAT; process_filex.m integrates and formats weather and soil data to DSSAT input files.

The online tool can be accessed at http://rsetserver.sws.uiuc.edu/ntrack (accessed on 16 December 2020). A user registers first (name and email address). After logging in, the user can inquire about SMN availability in real-time for their field by inputting N application (fertilizer history), crop information (growing degree days for maturity, planting date), simulation end date (default: current day), and location (latitude and longitude or by clicking on Googlemap) (Figure 2). In Illinois, because precipitation is usually sufficient, most cornfields are rainfed; therefore, the interface does not include irrigation as a management option. Each request is stored in a queue, and the online tool is ready to receive other requests. The queued requests are processed on a first-in, first-out (FIFO) basis.

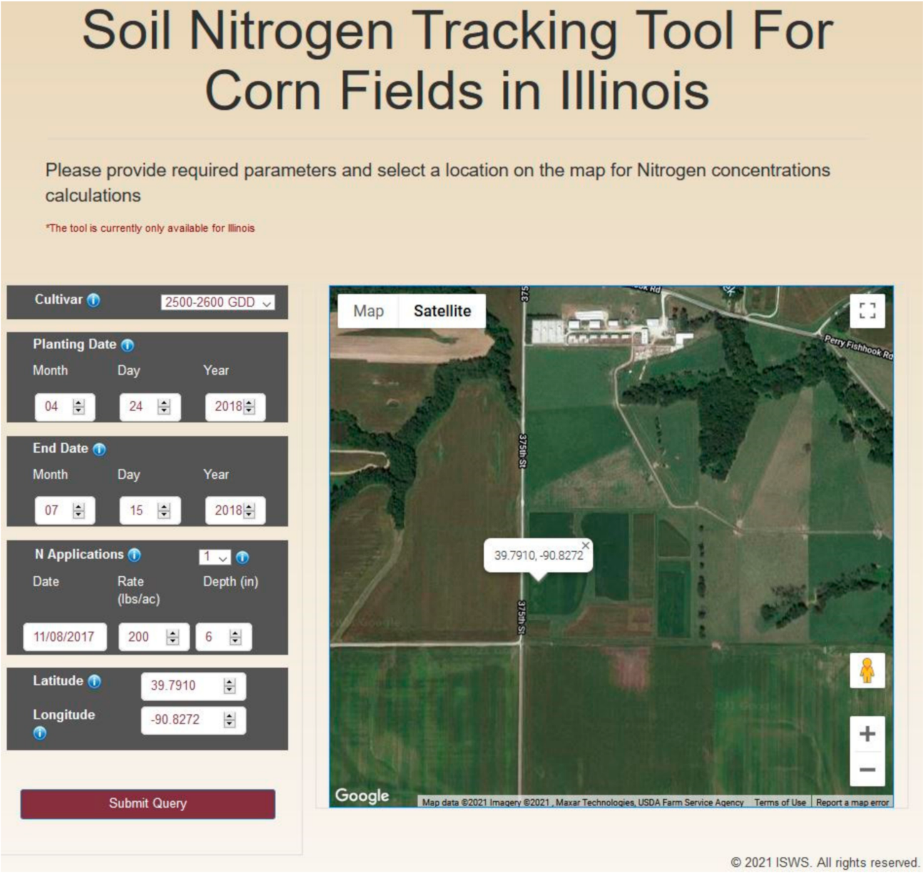

Figure 2. Display of the main screen of the online application tool.

Next, the real-time daily downloaded weather data and soil data are automatically prepared for the DSSAT v4.6 model. The server will assimilate the data and user inputs to simulate plant growth, N uptake, and N loss pathways (including leaching and denitrification) using the DSSAT v4.6 model. The simulation process takes 3–5 min, and the real-time SMN results are provided to the user by email. After successful processing, the request is deleted from the queue.

The simulation results of SMN are provided in a time-series graph with date on the X-axis and SMN content on the Y-axis. Figure 3 shows an example of the simulation results using the crop management information in Figure 2, with starting simulation date 1 November 2017 and end date 15 July 2018, and 200 lbs N acre^{-1} (224 kg N ha^{-1}) applied on 8 November 2017. The results include SMN content (lbs N acre^{-1}) in three depths: 0–1 feet (red line), 1–2 feet (blue line), and 0–2 feet (light blue line) (1 feet = 30.5 cm).

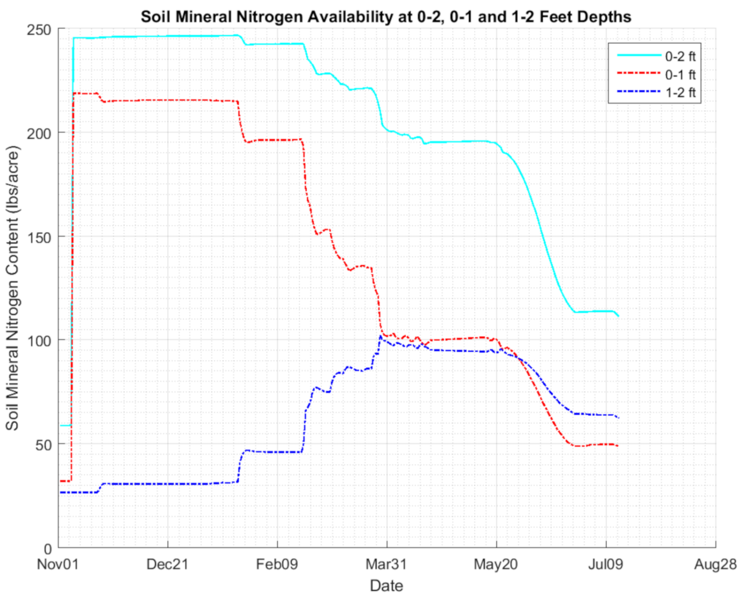

Figure 3. Simulation results of soil mineral nitrogen (N) content at the 0–1 (red line), 1–2 (blue line), and 0–2 feet depths (light blue solid line) (1 feet = 30.5 cm). The simulation start date was 1 November 2017, and the end date was 15 July 2018. N fertilizer was applied on 8 November 2017 at a rate of 200 lbs N acre^{-1} (224 kg N ha^{-1}) at 6 inches depth (1 inch = 2.54 cm).

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