Planting miscanthus instead of row crops may increase the productivity and economic performance of farmed potholes

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Abstract
Climate change projections indicate that precipitation events in the central United States are expected to become more intense, more frequent in the spring, and less frequent in the summer. Such a precipitation shift could adversely impact crop yields, especially in subfield areas known as farmed potholes, which are highly susceptible to flooding and ponding, and crop death is more likely to occur, particularly early in the growing season. This suggests that planting alternative crops, such as more flood tolerant perennials, in these areas may be a more profitable option. Using observations of crop growth and yield along with ponding depth of a specific field and farmed pothole in the central United States, we developed a spatially explicit version of the agroecosystem model Agro-IBIS to estimate water depth and crop yield. After evaluating the model, we conducted a case study for a specific farmed pothole with a range of future precipitation scenarios with Agro-IBIS to simulate the effects of contemporary (2002–2016) and future precipitation on a conventional corn/soybean (Zea mays L. and Glycine max Merr.) rotation and an alternative perennial miscanthus (Miscanthus × giganteus Greef et Deu.) cropping system. The depth and frequency of ponding increased under most future precipitation scenarios. The corn/soybean rotation had greater total loss (i.e., no yield) on average (>30%) for all scenarios in comparison to miscanthus (<10%). Under one future precipitation scenario with increased spring precipitation, both the corn/soybean rotation and miscanthus simulations showed an increase in yield. A simple budget analysis indicated that it is more profitable to plant miscanthus instead of corn or soybeans where yields in farmed potholes are consistently poor. Our findings show that potholes can be individually modeled, and their influence on yield can be quantified for use in future management decisions dictated by change in climate.

KEYWORDS
Agro-IBIS, Corn Belt, crop modeling, miscanthus, potholes, Prairie Pothole Region, water stress
1 INTRODUCTION

Closed surface depressions in agricultural fields (i.e., farmed potholes) are subfield scale topographic features where temporary, seasonal, or semipermanent ponds may form (Martin et al., 2019; Stewart & Kantrud, 1971; Upadhyay et al., 2018). These depressions characterize the Prairie Pothole Region (PPR) of the Upper Midwest United States, which extends from central Iowa, northwest to Alberta, Canada, and covers more than 70 Mha, with individual depressions ranging anywhere from 1 to over 6 ha in size (Martin et al., 2019; Miller et al., 2009; van der Valk, 2005; van Meter & Basu, 2015). Within the agriculturally dominated Des Moines Lobe of Iowa, these depressions account for more than 2000 km² (7.3%) of the total 31,000 km² study region, with approximately five depressions every square kilometer (McDeid et al., 2019).

Potholes are often areas of low productivity compared to the high yielding land common across the PPR due to conditions such as poor soil quality, erosion, and waterlogging (Muth & Bryden, 2012). Even though the nature of ponding in potholes during the growing season is ephemeral, these areas are still used for agricultural production with projections for the area of farming to increase as more grassland is converted to cropland (Lark et al., 2020; Logsdon, 2015; Rashford et al., 2011). However, sustained periods of flooding within potholes can lead to crop failures and significant economic losses ranging between 15% and 75% (Fey et al., 2016). In the United States, excess water is second behind drought for the largest cause of corn production loss, totaling up to $10 billion in damages from 1989 to 2016 (Li et al., 2019). In 2011 alone, floods in farm fields of the Midwestern United States resulted in $1.6 billion worth of losses in corn and soybean production (Bailey-Serres et al., 2012).

It is likely that losses could become larger in the future in the PPR because precipitation patterns are projected to both increase during the growing season and shift to earlier in the Spring (Easterling et al., 2017; Karl et al., 2009; Takle & Hofstrand, 2015). Dai et al. (2016) documented the trends of increasing early season precipitation occurring for locations in the Midwest United States. Inter-annual variability of yields from rainfed crops is driven strongly by precipitation and more rainfall during the planting season can delay planting dates and reduce yields, as the number of workable field days become reduced (Hatfield et al., 2018; Lobell et al., 2011; Rosenzweig et al., 2002; Walthall et al., 2013). However, a potentially more severe impact of wetter springs may be the increased risk of recently planted or emerging crops experiencing waterlogged soils or flooding, especially in field depressions. Thus, identifying strategies to increase flood tolerance will be critical to sustain production, as increased precipitation and extended wet periods result in more ponding within farmed potholes.

Evidence suggests that perennial crops perform better in potholes compared to corn (Zea mays L.) and soybean (Glycine max) crops (Bailey-Serres et al., 2012; Mann et al., 2013), and therefore, may help to minimize or eliminate losses in flood-prone pothole areas. Corn and soybean have a low tolerance to prolonged durations of oxygen deficiency, resulting in low survival rates and decreased yield in the presence of ponded surfaces or waterlogged soils (Bailey-Serres et al., 2012; Fukao & Bailey-Serres, 2004; Pasley et al., 2020). Corn has been observed to survive waterlogging up to 10 days (Zaidi et al., 2003) and soybean between 2 and 4 days (Rhine et al., 2010). Even though starchy seeds such as corn are able to germinate under reduced oxygen, developing seedlings are more sensitive to this stress post germination (VanToai et al., 1995). Rhizomatous perennials may prove a more resilient alternative because of their ability to tolerate flooded conditions due to the rhizome acting as a nutrient reserve from which the plant can regrow after prolonged low-oxygen conditions (Mann et al., 2013; Rau et al., 2019).

Miscanthus × giganteus Greef et Deu. (referred to hereafter as miscanthus) is a perennial, rhizomatous grass with the C₄ photosynthetic pathway. It is a strong biomass energy crop candidate (Clifton-Brown et al., 2015; Heaton et al., 2008; Somerville et al., 2010) not only because it requires fewer inputs and produces more biomass than corn (Beale & Long, 1997; Dohleman & Long, 2009), but also because it has been found to improve water quality and reduce nitrate leaching (Ferin et al., 2021; Hussain et al., 2019; Johnson et al., 2008). Comparing the thresholds of corn, soybean, and miscanthus survival following extreme flood stress suggests that miscanthus is more tolerant to longer durations of increased soil moisture (Mann et al., 2013; Rhine et al., 2010; Zaidi et al., 2003). One of the parents of miscanthus is the riparian species M. sacchariflorus that has high flood tolerance, suggesting that miscanthus may have mechanisms that aid in increasing this tolerance (Sacks et al., 2013). In a glasshouse study, established and propagule cohorts of miscanthus under flood stress performed just as well as, if not better than, the non-moisture stress control group after 8 and 16 weeks, respectively (Mann et al., 2013). Therefore, transitioning particularly flood vulnerable portions of the PPR landscape from the conventional cropping systems to less susceptible perennial systems like miscanthus is one potential adaptation to changes in precipitation intensity and variability.

Even though there is strong evidence to suggest that conventionally managed potholes, or potholes managed the same way as the field around them, are susceptible to frequent losses, many are still managed this way due to a number of factors. While not all factors are known, some involve limited known alternatives and risk management strategies with respect to the timing and intensity of in-season precipitation events. With the building consensus that precipitation patterns are changing, and will likely continue to change (Dai
et al., 2016; Groisman et al., 2012), the uncertainty in the projections of these dynamics creates challenges for multi-year yield predictions within farmed potholes. Wetter springs that result in more pothole flooding can drown out newly planted or younger crops. However, should the upcoming growing season be anomalously dry or as the frequency of rain-free days increases, farmed potholes can better support crops compared to the surrounding field. For example, in drier years, it has been observed that potholes have greater yields than their surroundings (Zipper et al., 2016). To better manage risk, more information is needed to understand how an alternative crop will react with a changing climate to quantify yield and profit implications of the management change to perennials relative to current practice.

Our overall goal was to develop a framework to assess the viability (i.e., profitability) of planting miscanthus in farmed potholes under varying precipitation patterns and ponding conditions, and to improve the understanding of how traditional and alternative crops within farmed potholes may react to a changing climate. We hypothesized that under the current and projected climate, the conventional land management of the corn/soybean rotation will have larger and more frequent losses in yield due to ponding relative to miscanthus. To test this hypothesis, we adapted the land surface and ecosystem Agricultural Integrated Biosphere Simulator Variably Saturated Flow (AgroIBIS VSF) model to simulate ponding and the resulting impacts of excess moisture stress (Carr, 2014; Soylu et al., 2014; Zipper et al., 2015) on the current corn/soybean rotation (i.e., control) that dominates the region relative to the perennial treatment (i.e., miscanthus). Simulations were run with contemporary (2002–2016) precipitation patterns, and future scenarios were developed where changes in precipitation occur due to either shifts in intensity or frequency while still keeping annual rainfall totals within 2.5% of the observed. To support the model analysis, we conducted a field-based study and incorporated data into the model collected across scales ranging from the leaf to the field. Our study is novel because, to the authors’ knowledge, it is the first to combine a physically based, mechanistic model with spatially explicit data at the field, canopy, and leaf scale in order to generate a spatially explicit simulation of the impact farmed potholes have on yield due to ponding and excess soil moisture.

2 | MATERIALS AND METHODS

This study collected spatially explicit data that quantified the effects of soil, management, and weather on crop productivity from the field and combined those data with a process-based model that was configured to run on an elevation-dependent subfield grid. Model simulations were then driven by a combination of historical, site-specific weather data, as well as a range of scenarios intended to capture the future variability in precipitation for central Iowa. To calibrate and evaluate model simulations, biomass, leaf area index (LAI), grain yield, and weather data were collected. Future precipitation scenarios were derived by systematically adjusting the observed weather dataset to reflect a range of projections. Simulations were driven with these precipitation scenarios to analyze the effect of variable ponding conditions on crop production and profitability.

2.1 | Field sites and observations

Crop yield data from combine yield monitors and hand harvests were collected from two study sites in Ames, IA: Bennett Farm and Sorensen Farm (approx. 41.9890°N, −93.6823°W; and 42.0145°N, −93.7435°W, respectively;
Figure 1a). Combine yield data were collected at 1 s intervals using a factory installed yield monitor on a John Deere S670 combine. The yield monitor mass flow sensor and moisture sensor were calibrated prior to treatment data collection according to the manufacturer specifications. Bennett Farm has been in a corn/soybean rotation since at least 2004, with corn planted every even year. This farm also contains a previously studied farmed pothole known as Lettuce pothole (Figure 1b; Martin et al., 2019) where in-season ponding depths were collected at its lowest elevation using pressure transducers (Solinst Levelogger Edge Model 3001, Solinst Barologger Edge Model 3001, Solinst Canada Ltd). Subsurface drainage was added to the pothole after the 2015 growing season at roughly 50 ft spacing and no surface inlet. To supplement and compare the odd years of modeled data, yield data were taken from a bordering farm south of Bennett (Been Farm, approx. 41.9833°N, −93.6832°W, Figure 1a), which had soybean planted every even year. Both crops were planted with a 30-inch row spacing, with fall tillage after corn harvest and field cultivation in the spring.

Sorensen Farm (42.0130°N, −93.7430°W, Figure 1a) is one of three sites used in the Long-term Assessment of Miscanthus Productivity and Sustainability (LAMPS) field experiment (see Tejera, 2019 for full description). Blocks of miscanthus were established over three planting years (2015, 2016, and 2017) and treated with five different nitrogen application rates (0, 112, 224, 336, and 448 kg/ha). Leaf and stem biomass (hereby referred to as yield for miscanthus), specific leaf area, and max carboxylation rate (vmax) from the 2-year-old stand age planted in 2015 with 0 kg/ha nitrogen application rate were collected and measured to set up and validate model runs (Tejera, 2019).

Leaf area index (LAI) was collected using an LI-COR LAI-2200C Plant Canopy Analyzer (LI-COR Biosciences) which archives data geospatially using a global position system (GPS). Gridded maps of LAI were generated by taking measurements walking on foot in parallel transects with c. 3 m spacing through the Bennett Field site on August 16, 2016, specifically where the flooding in Lettuce pothole affected the 2016 crops. These data were then analyzed using ArcGIS (ArcMap Release 10.5.1, Environmental System Research Institute; kriging) to interpolate LAI values between measured points. The georeferenced LAI values were also aligned with the elevation of the potholes as determined from 3 m resolution LIDAR data taken from the Iowa DNR Natural Resources Geographic Information Systems Library (https://programs.iowadnr.gov/nrgislibx/).

### 2.2 Agroecosystem model

The agroecosystem model AgroIBIS VSF is a coupling of AgroIBIS and Hydrus-1D (Soylu et al., 2014). AgroIBIS is a process-based model that runs at an hourly time step, driven by the following meteorological data: temperature, precipitation, relative humidity, solar radiation, and wind speed (Kucharik, 2003). The hourly time step offers an advantage in our study over models that use a daily time step in that it allows for a more explicit representation of meteorological events, such as extreme precipitation, which can be limited to occurring within an hour or two. Daily time step models would require a correction to capture the effects of precipitation intensity as opposed to just total rainfall. Hydrus-1D is a model used to analyze the vertical water flow and solute transport in variably saturated porous media by numerically solving the mixed-based Richards’ equation in terms of pressure head (Simunek et al., 2009). Past studies have used AgroIBIS VSF to study the influence of groundwater on corn water use and productivity (Soylu et al., 2014) and the effects of shallow groundwater and soil texture on subfield scale yield (Zipper et al., 2015).

#### 2.2.1 Model modifications

The AgroIBIS miscanthus module developed and tested in AgroIBIS (Ferin et al., 2021; VanLoocke et al., 2010, 2012, 2017) was implemented into AgroIBIS VSF for this study. Furthermore, a drowning function was developed to simulate the impact of ponding water on crops. This drowning function is derived from an existing freeze kill function and uses the depth and duration of ponded water simulated by the model to determine when a crop will die and stop accumulating biomass. Different drowning thresholds were created for corn, soybean, and miscanthus (Table 1).

Corn and soybean thresholds were based on studies of corn and soybean tolerance to soil waterlogging (Rhine et al., 2010; Zaidi et al., 2003). Two drowning thresholds were parameterized for miscanthus: A high threshold where miscanthus was simulated to be more resilient to drowning, and a low threshold to make it more susceptible to drowning. A high threshold for tolerance of drowning durations was taken from Mann et al. (2013). Because the Mann et al. (2013) research institute; kriging) to interpolate LAI values between measured points.

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**TABLE 1** Drowning thresholds of simulated crops

| Crop       | Hours ponded above crop | Hours ponded | Minimum depth (mm) |
|------------|-------------------------|--------------|--------------------|
| Corn       | 24                      | 72<sup>a</sup> | 10                 |
| Soybean    | 24                      | 72<sup>b</sup> | 10                 |
| Miscanthus Low | 42            | 139          | 30                 |
| Miscanthus High | 1344       | 1344<sup>c</sup> | 30                 |

Hours indicate consecutive accumulation.

<sup>a</sup>Zaidi et al. (2003).
<sup>b</sup>Rhine et al. (2010).
<sup>c</sup>Mann et al. (2013).
values were observed under a glasshouse setting, which may provide optimal conditions for the growth, a lower threshold was defined in attempt to represent the effect of ponding if miscanthus is more susceptible to drowning under open environment and non-optimal conditions. While the miscanthus from the Mann et al. (2013) study did not drown, they observed that after 3 days of exposure to ponded conditions, the growth of miscanthus temporarily stopped, resuming after about a week. To simulate this observation by Mann et al. (2013), after 72 consecutive hours of ponding, miscanthus carbon assimilation was simulated to cease, allowing it to remain dormant and accumulate no biomass. After 7 days, miscanthus was allowed to recover if not drowned during that timeframe.

AgroIBIS VSF applies oxygen stress to crops through the use of the piecewise Feddes function (Feddes et al., 1978; Soylu et al., 2014). Soil pressure head values that drive the piecewise Feddes function had to be added for miscanthus and soybean to apply oxygen stress to the respective crop. Miscanthus pressure head values were chosen and adjusted based on grassland values from Taylor and Ashcroft (1972) and Booth and Loheide (2010), and soybean values were taken from Taylor and Ashcroft (1972) and can be found in Table S1.

A puddle algorithm exists within AgroIBIS VSF that is a function of precipitation amount, rate, and soil properties. This algorithm creates a ponded source of water when sufficient precipitation occurs, from which evaporation and infiltration values are calculated. If the depth of water exceeds the maximum puddle parameter set in the model, excess water is apportioned to runoff. To incorporate the effect of topography, which would alter the rate of surface runoff, we developed an empirical model for ponding depth and calibrated it to the case study pothole. The empirical model was derived from 2016 observed daily precipitation data (discussed below) and ponding depths from Lettuce pothole to simulate ponding depths and conditions during model runs (Equation 1; Figure 2). If precipitation in a 24 h period summed to greater than 19 mm, an empirically derived threshold, the pond was calculated from the following equation:

\[
\text{Depth of ponding (mm)} = (24 \text{ h precip}) \times 0.7377 + 125.04
\]  

An additional step was necessary to introduce the effect of the topography of the pothole into AgroIBIS VSF, as it is a 1D model and does not explicitly account for changes in elevation, which effects ponding depth. For any increase in elevation within the domain relative to the lowest point, this increase was subtracted from the depth of ponding. For example, if the lowest point had a ponding depth of 0.5 m, a point with an elevation increase of 0.2 m would see a ponding depth of 0.3 m. Drainage from the pond occurred at a constant decrease of 1.46 mm/h based on the observed rate.

When the empirical model predicted no ponding, AgroIBIS VSF’s native ponding feature was used for the top layer soil moisture.

Soil texture values were updated with observations (Carr, 2014; Hall, Iowa State University, personal communication, 2017) taken from the field site at 20 cm depth intervals. These values were passed through the HYDRUS-1D pedo-transfer function to calculate the necessary soil parameter inputs required to run the model, which included saturated hydraulic conductivity, air entry potential, porosity, residual water content, and pore size distribution (n parameter in the Van Genuchten equation). Saturated hydraulic conductivity of the surface layer was calibrated to match ponding observations. These soil values can be found in Table S2.

### 2.2.2 Model setup

To initialize soil carbon and nitrogen in AgroIBIS VSF, a spin-up period was run for the years 1750–1900 using an accelerated procedure to produce realistic levels of soil carbon (e.g., VanLoocke et al., 2010). A second spin-up period was run for the years 1901–2002, simulating the corn/soybean crop rotation. Weather for the period 1901–1947 was generated by randomly selecting years of weather data from 1948 to 2002 (Kucharik et al., 2013), created from the Climate Research Unit (CRU05; Mitchell & Jones, 2005; New et al., 1999) and National Centers for Environmental
Prediction (NCEP) National Center for Atmospheric Research (NCAR) reanalysis dataset (Kalnay et al., 1996; Kistler et al., 2001; VanLoocke et al., 2010). For the years 1948–2002, the respective daily weather data were used for the simulated year.

The thickness of the AgroIBIS VSF soil domain was five meters, divided into 400 soil layers. The surface soil layer depth was chosen to be 0.5 cm, with each subsequent layer increasing in thickness by a constant 0.00376 cm. Simulations were run with free drainage out of the bottom of the domain.

2.3 Weather data

2.3.1 Observed weather data

To generate distributions of pothole dynamics and plant responses, 15 years of weather record (2002–2016) from a local weather station was used. For the Bennett field site, weather data containing hourly measurements of solar radiation, temperature, relative humidity, precipitation, and wind speed were taken from three weather stations located nearby (Figure 1a). The first weather station (Station 1) is located at the Agricultural Engineering and Agronomy Research Farm in Boone, IA (42.0204°N, −93.7738°W; Iowa Environmental Mesonet; https://mesonet.agron.iastate.edu) approximately 8 km northwest of the site. The second weather station (Station 2) is located approximately 5 km southeast of the site (41.9542°N, −93.6406°W; U.S. Department of Agriculture, Agricultural Research Service). The third station (Station 3) is located at Ames Municipal Airport (41.9921°N, −93.6239°W), approximately 5 km east of the field site.

Station 2 was the primary source of hourly weather data input. If a data gap of 1 h was missing, an average for the missing variable was calculated by using data from the hour before and the hour after. For any data gaps longer than 1 h, an average was taken between Station 1 and Station 3 and used to fill that gap. Since Station 3 did not record radiation, those data were taken from Station 1 to fill any radiation data gaps in Station 2.

2.3.2 Future precipitation scenarios

Three precipitation scenarios were created (Low, Middle, High) by multiplying the observed (Control) average accumulated 15 years (2002–2016) of precipitation recorded at Station 2 during the spring (March, April, May) and summer (June, July, August) months by a weighted, randomized factor to increase (Spring) or decrease (Summer) the intensity of precipitation in these months (Table 2; Figure 3). For example, all precipitation data in the month of March were multiplied by 1.58 for the Middle scenario to increase precipitation amounts and by 0.61 in June to decrease precipitation amounts. Average annual accumulated precipitation was kept within 2.5% of the observed and weighted values were based on data from the North American Regional Climate Change Assessment Program (NARCCAP, Mearns et al., 2012). The low scenario simulates drier springs than the control, whereas the middle and high scenarios simulate wetter springs than the control. Two additional precipitation scenarios were created (moderate and aggressive) to simulate increased precipitation frequency in the spring and decreased precipitation frequency in the summer. In the moderate scenario, 9 days of precipitation was randomly taken out of the summer months and randomly placed into the spring months to create an average increase of about one consecutive dry day for the summer. A consecutive dry day is defined as the average number of days receiving less than 1 mm of precipitation. In the aggressive scenario, 15 days of precipitation was randomly taken out of the summer months and placed into the spring months to create an average increase of about three consecutive dry days for the summer, a conservative average based on the trends predicted by the 2014 National Climate Assessment (Melillo et al., 2014).

2.4 Model simulations

For the corn/soybean rotation (corn on even years, soybean for odd), the model was run for 15 years (2002–2016) using the control and five generated precipitation scenarios. As this study focused only on changes in precipitation, all other weather variables used by the model (wind speed, relative humidity, solar radiation, and temperature) were kept the same as the observed record. Miscanthus was modeled under the same weather conditions as the corn/soybean rotation, but with two cases representing two differing drowning thresholds for the plant. The spatial domain was an 81 m by 90 m area surrounding the Lettuce pothole in Bennett field, with crops simulated at a 3 m resolution on a 27 by 30-point grid (Figure 1).

| Scenario | Precipitation factor |
|----------|----------------------|
|          | March | April | May | June | July | August |
| Low      | 0.86  | 0.80  | 0.72| 1.18 | 1.19 | 1.05   |
| Middle   | 1.58  | 1.15  | 1.12| 0.61 | 0.78 | 0.99   |
| High     | 1.96  | 1.40  | 1.28| 0.47 | 0.70 | 0.78   |

Table 2: Precipitation of the listed months from the Bennett field (Station 2) weather record were multiplied by the following factors to create four varying precipitation scenarios.
2.5 | Model evaluation and data analysis

Observed grain yields from Bennett and Been field (available for years 2009–2015) were compared with AgroIBIS VSF simulated grain yields to confirm that the model could capture similar yields when run with weather data from the same region (Figure S1). Simulated miscanthus total yield, stem biomass, leaf biomass, and LAI were compared to 2016 in-season miscanthus values from LAMPS plots planted in 2015 (Figure S2; Table S3).

Simulated spatial yield maps for the corn/soybean rotation and miscanthus were normalized by dividing each year within a scenario by that scenario’s total 15-year average yield (Equation 2). Within the context of this paper, drowned is defined as when the simulated crop reaches or exceeds the threshold set by the drowning function.

\[
\text{Drown frequency} = \left( \frac{\text{Pixel drown count}}{15} \right) \times 100. \tag{2}
\]

To calculate the percent increase or decrease in yield of a future scenario relative to its respective management control (corn/soybean rotation, low drown threshold miscanthus, or high drown threshold miscanthus, Equation 3):

\[
\text{Yield percent difference} = \left( \frac{\text{Control scenario} - \text{Future scenario}}{\text{Control scenario}} \right) \times 100. \tag{3}
\]

Any simulated yields less than 1% of the maximum yield within the domain for its respective year was defined as a total loss. This is not to be confused with a drowned crop, for example, drowning can occur after the crop has reached maturity and result in no yield loss.

2.6 | Economic cost analysis approach

To quantify the economic value of miscanthus productivity in context to an Iowa farm, Iowa State University’s Ag Decision Maker tool and costs of crop production were used to create yearly budgets (https://www.extension.iastate.edu/agdm/, see Table 3). A 10-year period of simulated yields from the Control precipitation scenario were chosen (2007–2016) and the budgets were developed for the representative management of: corn following soybean, soybean following corn, and the low drowning threshold miscanthus from this study.

Grain prices and management costs for corn and soybean were held static using the median values from the last 10 years (2010–2019), resulting in $3.76 bu⁻¹, $9.65 bu⁻¹, $707.92 ac⁻¹, and $519.84 ac⁻¹, respectively. Miscanthus prices were held static at $80.00 ton⁻¹, which is a typical price in Iowa energy, bedding, and erosion control markets in 2019 as relayed to the authors by the University of Iowa Biomass Fuel Project (https://www.facilities.uiowa.edu/energy-environment/renewable-energy). Miscanthus planting and establishment costs were amortized evenly across the 10-year period.

3 | RESULTS

3.1 | Observed weather and crop growth

Cumulative annual precipitation was similar in 2016 (907 mm) to the 36-year (1980–2016) climatology (839 mm)
|                          | 2007  | 2008  | 2009  | 2010  | 2011  | 2012  | 2013  | 2014  | 2015  | 2016  | Mean/year
|--------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------| ($/ac)   |
| **Corn/soy**             |       |       |       |       |       |       |       |       |       |       |         |
| Sale price ($/bu)        | 9.65  | 3.76  | 9.65  | 3.76  | 9.65  | 3.76  | 9.65  | 3.76  | 9.65  | 3.76  | 9.65  |
| Yield (bu/ac)            | 16.97 | 34.09 | 44.08 | 27.87 | 20.42 | 68.48 | 14.51 | 55.07 | 12.67 | 125.41 |         |
| Cost ($/ac)              | 519.84| 707.92| 519.84| 707.92| 519.84| 707.92| 519.84| 707.92| 519.84| 707.92| 613.88|
| Profit ($/ac)            | −356.10| −579.90| −94.46| −603.25| −322.79| −450.77| −379.82| −501.12| −397.53| −237.01| −392.28|
| **MxG low threshold**   |       |       |       |       |       |       |       |       |       |       |         |
| Sale price ($/ton)       | 80.00 | 80.00 | 80.00 | 80.00 | 80.00 | 80.00 | 80.00 | 80.00 | 80.00 | 80.00 | 80.00 |
| Yield (ton/ac)           | 4.08  | 8.51  | 6.64  | 7.46  | 8.20  | 8.17  | 7.33  | 7.07  | 5.01  | 8.60  |         |
| Cost ($/ac)              | 124.39| 162.73| 140.15| 150.09| 158.99| 158.64| 148.54| 145.37| 120.64| 163.77|         |
| Establishment amortization ($) | 112.31| 112.31| 112.31| 112.31| 112.31| 112.31| 112.31| 112.31| 112.31| 112.31| 259.64|
| Profit ($/ac)            | 89.52 | 406.09| 278.48| 334.68| 384.95| 382.99| 325.93| 307.98| 168.21| 411.97| 309.08|
| **MxG high threshold**  |       |       |       |       |       |       |       |       |       |       |         |
| Sale price ($/ton)       | 80.00 | 80.00 | 80.00 | 80.00 | 80.00 | 80.00 | 80.00 | 80.00 | 80.00 | 80.00 | 80.00 |
| Yield (ton/ac)           | 4.30  | 10.28 | 6.76  | 7.74  | 9.40  | 10.65 | 9.62  | 9.99  | 8.19  | 9.83  |         |
| Cost ($/ac)              | 127.12| 183.92| 141.69| 153.47| 173.34| 188.46| 176.02| 180.51| 158.84| 178.51|         |
| Establishment amortization ($) | 112.31| 112.31| 112.31| 112.31| 112.31| 112.31| 112.31| 112.31| 112.31| 112.31| 278.50|
| Profit ($/ac)            | 104.91| 525.83| 287.17| 353.77| 466.07| 551.50| 481.22| 506.58| 384.14| 495.26| 415.64|
for Ames, IA. However, relative to climatology, 2016 was drier in spring and summer (March–August) and wetter in the fall (September–November; Figure 3a). Relative to climatology, spring and summer maximum temperatures were slightly cooler than average (−0.1 and −0.3°C), and minimum temperatures were warmer than average (1.2 and 1.0°C; data not shown).

The average yield for corn in the study area (Been and Bennet Farms, Figure 1a) from 2009 to 2015 was 10.47 Mg ha⁻¹ (167 bu ac⁻¹) and the average yield for soybean from 2009 to 2015 was 3.11 Mg ha⁻¹ (46 bu ac⁻¹; Figure S1). Corn had the highest yield in 2015 (10.87 Mg ha⁻¹, 173 bu ac⁻¹), and soybean had the highest yield in 2014 (3.26 Mg ha⁻¹, 48 bu ac⁻¹). In 2016, corn yields in Bennett field (12.93 Mg ha⁻¹) were similar to the Story County average (13.3 Mg ha⁻¹; USDA), but varied substantially at the subfield scale, with values ranging from 0 to 16.3 Mg ha⁻¹ (0–260 bu ac⁻¹, data not shown). Lower yields, indicated by dark brown colors in Figure 5b, coincided with where the extent of ponding occurred (Figure 4a). Areas of higher yield existed around the border of the pothole. At Sorensen, miscanthus yielded 16.55 Mg ha⁻¹ on average when measured in 2016 (Table S1).

Elevation contours were compared to interpolated measurements of LAI taken across the Lettuce pothole in 2016 (Figure 4a). The lowest elevations of the domain are found within the center of the pothole, with approximately 0.7 m of relief in surface elevation. Elevation and LAI were found to be positively correlated (Figure 4a; $R^2 = 0.53$, $p < 0.05$). Bold contours indicate the extent of flooding that could occur if the depth of ponding in the center of the pothole reached 0.12, 0.20, and 0.56 m. The depth of 0.12 m occurred on July 18, 2016 and drained by July 21, 2016 with one precipitation event in between. The 0.20 m depth occurred on
September 8, 2016 and depth 0.56 m occurred on September 25, 2016 and were the result of compounding precipitation events where the pothole did not fully drain until October 9, 2016 (data not shown).

The 2016 Lettuce pothole LAI measurements (Figure 4a) reflect the same spatial pattern observed in the 2016 yield map (Figure 4b). The spatial pattern in observed LAI correlated with yield ($R^2 = 0.45, p < 0.05$) at both high and low values, for example, from higher yielding areas along the border of the pothole (LAI $\geq 3.0 \text{ m}^2\text{ m}^{-2}$) as well as low yielding areas (LAI $- 1.0 \text{ m}^2\text{ m}^{-2}$) in the center of the pothole. LAI values ranged from 0.0 $\text{ m}^2\text{ m}^{-2}$ in the center of the pothole to 4.0 $\text{ m}^2\text{ m}^{-2}$ at the edge, with corresponding yield ranges from 0 to 14.3 Mg ha$^{-1}$ (Figure 4). In general, there was an increase in observed yield with elevation, especially when the elevation raised the crops high enough to be outside the influence of the pothole.

### 3.2 Model evaluation

Average simulated corn yield was similar ($\pm 4.8\%; p > 0.05$) to the average observed corn yield and average simulated soybean yield was similar ($\pm 1.9\%; p > 0.05$) to the average observed soybean yield (Figure S1). The 2014, 2015, and 2016 simulated spatial corn and soybean yields (Figure 5a–c) also reflected not only similar yields to the observations (Figure 5c–e) but also captured the shape of the pothole, suggesting that pothole dynamics and influence on crops were well represented.

Simulated miscanthus LAI for the 2016 growing season captured the early season increase and the start of the late season decrease, with maximum LAI slightly greater than the observed (9.00 and 8.65 $\text{ m}^2\text{ m}^{-2}$, respectively; Figure S2). Simulated total (stem and leaf) miscanthus yield (18.78 Mg ha$^{-1}$) was within 13.5% of the average observed miscanthus yield (16.55 Mg ha$^{-1}$ $\pm 1.38$ standard error; Table S1). Simulated stem yield (14.28 Mg ha$^{-1}$) was similar to observations (within 8.9%), whereas simulated leaf yield (4.54 Mg ha$^{-1}$) was significantly greater than observed (427.9%). It is worth noting observed miscanthus harvest data were collected in March of 2017 after stand senescence and considerable leaf drop had occurred, whereas the model harvests at the end of the 2016 calendar year.

### 3.3 Precipitation scenarios

Twelve years of simulated corn and soybean yields using the control precipitation scenario illustrates temporal changes in
The size of the pothole (indicated by the area of lowest yields) varied across the 12 years, from a small-scaled feature in the drought year 2012 (Figure 6k), to one that dominates the entire domain in 2013 (Figure 6l). The 15-year average simulated yield for the corn/soybean rotation, low threshold miscanthus, and high threshold miscanthus under the control scenario varied spatially across the domain (Figure 7a–c, respectively). Even though the difference in the magnitude of yield is large between the corn/soybean and miscanthus, the relative effects of the pothole are still visibly evident between cropping systems.

Across precipitation scenarios, lower yields were consistently found within the center of the pothole (lowest elevations) for all crops, and yields increased with elevation as the effect of the pothole diminished. This reflects that the drowning of crops is a common occurrence within the pothole; however, the extent of drowning is influenced by the amount of precipitation that occurs within a growing season (Figures 8 and 9). To note, drowning (defined here as the death of the crop) does not necessarily result in zero yield, as drowning can occur at different crop stages or anytime throughout grain fill. In these results, the timing of the drowning relative to crop stage dictated amount of yield loss. Miscanthus with the higher drowning thresholds were never drowned, and thus, drowning frequency is not shown. In the corn/soybean rotation, the same areas of the pothole (lowest elevations) experienced 100% drowning across all six scenarios (Figure 8). While miscanthus never reached 100% drowning in any scenario for any given pixel, drowning within the pixels located at the lowest elevations of the pothole occurred 14/15 (i.e., 93%) of the years for each scenario (Figure 9). In general, there was a higher frequency of drowning for the corn/soybean rotation than miscanthus.

Across the six precipitation scenarios, mean total loss (simulated yields less than 1% of the highest) over the 15-year simulation of the pothole domain for miscanthus was <10% and mean total loss for the corn/soybean rotation was >30% (Figure S3). The scenarios with the highest and lowest mean total loss for both the corn/soybean rotation and low drown threshold miscanthus were the high (47.9%, 7.3%) and low (35.7%, 1.5%) scenarios, respectively. The corn/soybean rotation also experienced more pixels in the domain with total losses in yield compared to miscanthus. The corn/soybean rotation experienced areas of total loss across all years and scenarios, whereas miscanthus experienced multiple years with no pixels of total loss across varying scenarios. This result indicates that while corn, soybean, and miscanthus are all vulnerable to yield losses, corn and soybean are much more susceptible within the pothole. For the corn/soybean rotation, the difference between scenario means were not significant (p > 0.05). Means were significantly different (p < 0.05) between the low and high precipitation scenarios for low drowning threshold miscanthus.

Under the middle precipitation scenario, the corn/soybean rotation and miscanthus yields increased in comparison to the control (p > 0.05 for corn/soybean and low threshold miscanthus; p < 0.05 for high threshold miscanthus; Figure S4). Within the high and moderate scenarios, the miscanthus with the lower drowning threshold had greater yield losses (−13.6% and −7.4%; p < 0.05) than the corn/soybean (−8.8% and −2.1%; p < 0.05 and p > 0.05, respectively) compared to

![Figure 7](image-url) The 15-year total average yield for corn and soybean (a), low drown threshold miscanthus (b), and high drown threshold miscanthus (c) for 2002–2016 under the Control scenario. Yield mean for the domain of interest is listed in the subplot corner.
the control. Corn and soybean only experienced greater loss in yield than both the low and high threshold miscanthus for the aggressive scenario (−14.9%; \( p < 0.05 \)). Corn/soybean and high drown threshold miscanthus had the highest average yields across the 15-year simulation under the middle scenario (2.97 Mg ha\(^{-1}\) and 20.49 Mg ha\(^{-1}\), \( p > 0.05 \) and \( p < 0.05 \), respectively; Figure S4). Low drown threshold miscanthus had the highest average yield under the low scenario (18.15 Mg ha\(^{-1}\); \( p < 0.05 \)). Miscanthus with the higher drowning threshold had higher yields than the low threshold miscanthus for all scenarios (Figure S4).

3.4 | Economic cost analysis

Ten years of simulated corn, soybean, and miscanthus yields from the control precipitation scenario were used to complete the 10-year cost analysis for the pothole domain (Table 3). The 10-year average cost for the corn/soybean rotation was $614 ac\(^{-1}\), resulting in a balance of $392 ac\(^{-1}\) in losses. For the low drown threshold miscanthus, 10-year average management cost was $260 ac\(^{-1}\), resulting in a balance of $309 ac\(^{-1}\) in profit. The conventional corn/soybean rotation resulted in a net loss of profit within the pothole for every year, ranging from −$603 ac\(^{-1}\) in 2010 to −$94 ac\(^{-1}\) in 2009. Conversely, the low threshold miscanthus had a net gain of profit for every year, ranging from $90 ac\(^{-1}\) in 2007 to $411 ac\(^{-1}\) in 2016.

4 | DISCUSSION

Here, we present a study in which we modeled a corn/soybean rotation and perennial grass miscanthus with varying precipitation scenarios to quantify the impact farmed potholes have on crops. In order to determine if an alternative crop would be more viable to farm in these locations, a novel modeling approach was used to generate spatially explicit simulations that could replicate observed pothole dynamics in response to shifting precipitation patterns. Results indicate that across the majority of simulated scenarios, miscanthus outperformed the corn/soybean rotation in terms of yield when compared to
contemporary (control) precipitation patterns both spatially within the domain and across the 15-year simulation.

The corn/soybean rotation had areas of total loss more frequently than miscanthus. All 15 years and scenarios of corn/soy management experienced areas of total loss with greater than 35% of the domain area experiencing total loss on average (Figure S3a). Miscanthus only had 9 years that experienced total loss for each scenario (Figure S3b), and less than 7.3% of the domain area with total loss on average, supporting our hypothesis in part that the corn/soybean rotation will have more frequent loss relative to miscanthus across scenarios. Whereas the high threshold miscanthus had no total loss because it did not drown in any scenario. While our results indicate that miscanthus is much less susceptible to drowning and total losses relative to corn/soybean, it is important to consider that the drowning of a perennial crop may have much different impacts than the drowning of an annual crop. This is because if a perennial crop drowns shortly after planting, and does not recover in subsequent years, the loss may be considered effectively permanent for the lifetime of that stand. Whereas an annual crop can be replanted either later that year or the following year.

Contrary to our hypothesis that the corn/soybean rotation would have greater relative loss in yield compared to miscanthus, in the high and moderate scenarios, the miscanthus with the lower drowning threshold actually had greater relative yield losses than the corn/soybean. While the relative miscanthus losses were greater for some precipitation scenarios, simulated miscanthus had greater overall production than the corn/soybean rotation, resulting in more harvestable yield. In our simulations, miscanthus experienced a greater area of drowning and loss of yield for some future scenarios compared to the corn/soybean rotation is due to the nature of the drown function and how miscanthus is established. The drown function will track how often a pond is greater than the height of the plant. Because miscanthus is a perennial, its rhizome is susceptible to drowning year round in contrast to corn and soybean that are newly planted each season. Thus, there is a greater chance for a pond to drown a rhizome before it can establish shoots greater than the ponding depth. The effect of the timing of drowning (i.e., during dormancy or
active growth) is important to better determine miscanthus rhizome response. While Mann et al. (2013) find no loss of rhizome viability from ponding on dormant rhizomes in glasshouse conditions, this may change under field conditions, which are much more variable.

The negative effect of excess soil moisture on crop yield in this study is in agreement with Rosenzweig et al. (2002), who used the CERES-Maize crop model to assess the impacts of excess soil moisture from heavy precipitation on corn growth and yield. Nine sites from United States Corn Belt were modeled, one of which was Des Moines, IA. CERES-Maize originally had no stress to crop growth under prolonged conditions of excess soil water, so Rosenzweig et al. (2002) introduced a function that would damage root growth ability after three consecutive days of soil saturation. Similar to our results, Rosenzweig et al. (2002) found that yield decreases were larger under future climate scenarios of increased precipitation and increased frequency of extreme precipitation events than the current climate regime.

Previous studies using AgroIBIS VSF have also explored the effects a modeled water table has on crop growth, performance, and yield. Soylu et al. (2014) found that a water table less than 0.8 m from the surface produced anaerobic conditions that negatively affected plant physiology. Zipper et al. (2015) found that soil texture and in-season weather dictate the interaction between groundwater and yield, and that it is important for all three of these factors (water table depth, soil texture, and weather) to be considered when making management decisions.

Economic assessments should be performed to compare the costs and profitability of each management practice to gauge the investment necessary to convert from the corn/soybean rotation to perennial miscanthus in farmed potholes. To contextualize the simulated management scenarios and understand the return on investment from growing miscanthus in a farmed pothole, a simple cost analysis was performed. This analysis was not meant as a full-scale economic analysis, but simply as an initial quantification of the miscanthus value proposition to an Iowa farmer. Based on this theoretical analysis for the pothole modeled in this study (Table 3), it is more economically viable to plant miscanthus in farmed potholes than take yearly losses on farming corn and soybean. As potholes have been found to cover between 7% and 12% of the area in the Des Moines Lobe Region of Iowa alone (McDeid et al., 2019; Van Meter & Basu, 2015), there is a considerable amount of land where the planting of miscanthus can be profitably applied if our results are accurate.

The conversion of marginal land into the production of bioenergy crops is also actively being investigated to understand its environmental and economic impacts upon a broader scale (Chen et al., 2021; Khanna et al., 2021).

Management decisions can also be aided by future studies that investigate other species of perennial grasses that may be better suited or adapted for the moisture conditions found in potholes, such as switchgrass (Panicum virgatum L.) or prairie cordgrass (Spartina pectinate Bosc ex Link), or genotypes of miscanthus. While this study focused only on the impact of precipitation, we acknowledge that there are more factors that can affect final yield in a changing climate, such as increasing temperatures, increasing CO₂ concentrations, biotic stresses, and plant diseases. With respect to our specific land form of focus (farmed potholes), precipitation would likely dominate these factors.

There are several limitations in our modeling approach that could be refined in future studies. For instance, compared to observations, the empirical ponding model tended to underestimate larger ponding events due to a faster drainage rate than actually experienced in the field. The model also created ponds that did not exist in the 2016 observed record (i.e., false positives), and missed a pond that did exist for the 2016 observed ponded data (i.e., false negative), showing that modeled ponding events do not perfectly match up with what would be expected. Future studies could couple physically based models of the pothole with AgroIBIS VSF (Nahkala, 2020; Upadhyay et al., 2018).

Another limitation was the treatment of miscanthus when drowned. As currently modeled, miscanthus will regrow in the next growing season based on the nutrients stored in the rhizome if drowned. In reality, if miscanthus is actually killed (not forced into dormancy), it will have to be completely replanted, which is not currently represented in the model. More research must also be performed to better characterize and quantify the effects of water stress on miscanthus, especially under field conditions. While recent studies show that miscanthus is indeed resilient to ponded conditions (De Vega et al., 2021; Kam et al., 2020), its biology is still not as well understood compared to conventional crops (Mitros et al., 2020).

5 | CONCLUSION

This study quantified the effects of multiple future precipitation scenarios on pothole ponding and the resulting yields of a conventional corn/soybean rotation and alternative miscanthus management. To account for uncertainty in future climate change, multiple scenarios were created. It is important to understand the influence of potholes on yield since their extent will grow with a changing climate and increasing precipitation trends in the early growing season. Even though this study was parameterized around one pothole, because our approach involved a physically based model (AgroIBIS VSF), future work could scale up our framework to characterize the effects that farmed potholes of varied size and shape have on yield across the PPR.
A crop such as miscanthus that is more tolerant to flooding and longer durations of waterlogged soils is a proposed alternative to be planted in farmed potholes since yields under the conventional corn/soybean rotation will see a larger decrease under future precipitation scenarios. This study also shows that miscanthus has the potential to be a viable alternative crop to the conventional corn/soybean rotation in farmed potholes, especially under a changing climate, as across all variable scenarios, it had the least percentage loss in yield. The ability to sustain prolonged periods of ponding or soil waterlogging suggests that transitioning potholes away from annuals to perennials may increase crop production within these flood-prone areas. The transition of farmed potholes to either a retired or alternative management can promote positive environmental impacts along with increasing its economic viability.

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DATA AVAILABILITY STATEMENT
The data that support the findings of this study are openly available in DataShare: the Open Data Repository of Iowa State University at https://doi.org/10.25380/iastate.14762355.

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**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section.

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