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OPTIMIZING COVER CROP ROTATIONS FOR WATER, NITROGEN AND WEED MANAGEMENT

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OPTIMIZING COVER CROP ROTATIONS FOR WATER, NITROGEN AND WEED MANAGEMENT

THESIS

A thesis submitted in partial fulfillment of the requirement for the degree of Master of Science in the College of Agriculture, Food and Environment at the University of Kentucky

by

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Lexington, Kentucky

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ABSTRACT OF THESIS

OPTIMIZING COVER CROP ROTATIONS FOR WATER, NITROGEN AND WEED MANAGEMENT

Winter cover crops grown in rotation with grain crops can be an efficient integrated pest management tool (IPM). However, cover crop biomass production and thus successful provisioning of ecosystem services depend on a timely planting and cover crop establishment after harvest of a cash crop in the fall. One potential management adaptation is the use of short-season soybeans to advance cover crop planting date in the fall. Cover crops planted earlier in the fall may provide a greater percentage of ground cover early in the season because of higher biomass accumulation that may improve weed suppression. However, adapting to short-season soybeans could have a yield penalty compared to full-season soybeans. In addition, it is unclear if further increasing cover crop growing season and biomass production under environmental conditions in Kentucky could limit nitrogen and water availability for the next cash crop. This thesis combines the use of field trials and a crop simulation model to address the research questions posed.

In Chapter 1, field trials evaluating yield and harvest date of soybean maturity group (MG) cultivars from 0 to 4 in 13 site-years across KY, NE, and OH, were used to calibrate and evaluate the DSSAT crop modeling software (v 4.7). The subsequent modeling analysis showed that planting shorter soybean maturity groups (MG) would advance date of harvest maturity (R8) by 6.6 to 11 days per unit decrease in MG for May planting or by 1 to 7.3 days for July planting. The earliest MG cultivar that maximized yield ranged from MG 0 to 3 depending on the location, allowing a winter-killed cover crop to accumulate between 257 to 270 growing degree days (GDD) before the first freeze occurrence when soybean was planted in May, and between 280 to 296 GDD when soybean was planted in July. Winter-hardy cover crops could accumulate 701 to 802 GDD following soybean planted in May and 329 to 416 GDD after soybean planted in July.

In Chapter 2, a two-year field trial was conducted at Lexington, KY to evaluate the effect of a soybean – cover crop rotation with soybean cultivars MG 1, 2, 3 or 4 on cover crop biomass and canopy cover, and on weed biomass in the fall and the following spring. Results showed that having cover crops was an efficient management strategy to reduce weed biomass in the fall and spring compared to no cover treatment. Planting cover crops earlier in the fall after a short-season soybean increased cover crop biomass production and percentage of ground cover in the fall, but not the following spring. Planting cover crop earlier after a short-season soybean did not improve weed suppression in the fall or spring compared to a fallow control with full-season soybean. Having a fall herbicide application improved weed control when there was a high pressure of winter annual weeds. By the spring, delaying cover crop termination increased cover crop biomass but also did weed biomass.

In Chapter 3, a soybean – cover crop – corn rotation was simulated to evaluate the effect of different soybean MG and cover crop termination, as well as year to year variability on water and nitrogen availability for the next corn crop in Lexington, KY. Simulations showed that when cover crops were terminated early, they did not reduced soil available water at corn planting. However, introducing a non-legume cover crop reduced total inorganic nitrogen content in the soil profile by 21 to 34 kg ha^{-1} implying 15 to 30 kg ha^{-1} less in corn nitrogen uptake. Cover crop management that was able to maintain similar available water values than fallow treatment while minimizing nitrogen uptake differences was cover crops planted after soybean MG 4 with an early termination. However, the best management strategies that will maximize ecosystem services from cover crops as well as cash crop productivity may need to be tailored to each environment, soil type, irrigation management, and must consider year-to-year variability.

KEYWORDS: model calibration, DSSAT, soybean maturity group, cover crops, weed control, nitrogen balance, water balance, corn.

Cintia Soledad Sciarresi
October 17th, 2019

OPTIMIZING COVER CROP ROTATIONS FOR WATER, NITROGEN AND WEED MANAGEMENT

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Chapter 1: Evaluating short-season soybean management adaptations for cover crop rotations with a crop simulation model.

ABSTRACT

Cover crop fall biomass production and thus successful provisioning of ecosystem services depend on the previous cash crop harvest date. Late cover crop plantings may not allow sufficient biomass accumulation. Hence, with this study, we wanted to explore short-season soybean as a management adaptation to advance cover crop planting date. We used a process-based eco-physiological model to investigate the potential of short-season soybean maturity groups (MG) to extend the cover crop growing window while achieving yields similar as full-season MG cultivars. The DSSAT – CROPGRO model was calibrated with data from soybean MG cultivars 0 to 4 grown during 13 site-years (in 2017 and 2018) across Kentucky, Nebraska, and Ohio. The model was efficient in predicting differences in harvest maturity date (R8; Model efficiency [ME] = 0.61; Root Mean Square Error [RMSE] = 7.4 days) and yield (ME=0.38; RMSE = 0.452 Mg ha^{-1}) across the range of MG cultivars in the study. After calibration, a multi-factor sensitivity analysis across 30-yr of historical weather data revealed that MG selection was responsible for a relatively low percentage of yield variability. Yield was most sensitive to planting date under irrigated conditions, and soil type and precipitation patterns under rainfed conditions. Adapting cultivar selection to shorter-season MG would advance the date of R8 by 6.6 to 11 days per unit decrease in cultivar maturity when planted on May 15, or by 1.0 to 7.3 days when planted on July 1. The earliest MG cultivars that maximized yield (MG 0 to 3 cultivars dependent on the location) would provide a cover

crop growing window following harvest and before the first freeze in the fall of 34 to 51 days or 186 to 670 growing degree days (GDD; base 4.4 ºC) when soybean was planted on May 15. For a July 1 planting date, this cover crop growing window was reduced to 11 to 25 days or 45 to 167 GDD. Establishment of a winter-hardy cover crop would increase the fall growing window to 432 to 819 GDD following soybean planted in May, and to 238 to 353 GDD after soybean planted in July. The potential to further lengthen the cover crop growing window by adapting to shorter season cultivars was greatest for planting dates in May and the warmest locations in our study region, but would have a yield penalty of 0.20 – 0.60 Mg ha^{-1} per unit decrease in cultivar maturity. Our analysis provides a useful framework to apply crop simulation models to identify management adaptations that can facilitate rotations with cover crops.

ABREVIATIONS

DUL: drainage upper limit; RMSE: Root mean squared error; ME: Model efficiency; GDD: growing degree days; $GDD_{R8\text{-}FREEZE}$: growing degree days from soybean harvest date until first freeze occurrence; $GDD_{R8\text{-}END}$: growing degree days from soybean harvest date until the end of the year; MG: Maturity Group; rMG: relative maturity group.

1. INTRODUCTION

Soybean (*Glycine max* (L.) Merr.) maturity group (MG) selection could be used as a management adaptation strategy to increase resource use efficiency and ecosystem services. The MG classification is based on the length of the cultivar's growing cycle, which depends on the response to temperature and photoperiod (Cober et al., 2001; Summerfield et al., 1998). Further, gradations within each MG (1 to 10) are also commonly noted by adding a decimal to the MG number to get a relative MG (rMG) number (Alliprandini et al., 2009). Soybean is classified in 13 MGs that range from 000 to 10, with short-season or early-season MG, cultivars being best adapted to higher latitudes, and full-season or late-season MG, cultivars to lower latitudes with longer potential growing seasons (Mourtzinis and Conley, 2017; Zhang et al., 2007). However, producers can usually choose from a range of MGs well-adapted and commercially available for a given location.

Relatively early MG cultivars for a given location have a shorter growing season and can have the advantage of reducing irrigation requirements compared to later MGs (Purcell et al., 2007). In addition, early soybean MGs planted after wheat (*Triticum aestivum* L.) harvest in a double-crop system can increase the overall productivity of a given environment (Egli, 2011). A less studied soybean MG adaptation is the rotation of early soybean MGs followed by winter cover crops. Planting earlier in the fall after short-season soybean MGs can lengthen the cover crop growing window and increase biomass production (Mirsky et al., 2011; Webster et al., 2016). Greater biomass production can improve cover crop benefits for weed control (Haramoto, 2019; Sarrantonio and Gallandt, 2003; Teasdale and Mohler, 2000), reduce nitrogen leaching (Di and Cameron, 2002; Reeves, 2017; Salazar et al., 2019), and increase soil aggregation and water infiltration (Fageria et al., 2005; Hargrove, 1986; McVay et al., 1989). However, the use of early-season soybeans that would allow cover crops to be established in a crop rotation might result in a yield penalty depending on the location, soil type, annual weather variability, and management practices.

Several researchers have evaluated yield differences across soybean MG choices for a given environment (De Bruin and Pedersen, 2008; Egli and Cornelius, 2009; Salmerón et al., 2016). Late soybean MGs have a longer growing season and thus greater cumulative intercepted solar radiation compared to early soybean maturities, which is often associated with higher yields (Edwards et al., 2005; Egli, 1998; Salmeron et al., 2014). However, in some instances early MG cultivars can provide yields that are similar to late MGs. Under rainfed conditions in central Argentine Pampas, MG 3 had similar yields to MG 5 cultivars planted in November and December (i.e., mid to late spring) as a result of a higher resource uptake and irradiance during R1-R5 period for the MG 3 cultivars (Santachiara et al., 2017). Under irrigated conditions in Kentucky, MG 2 cultivars planted in May attained yields similar to MG 3 and 4 cultivars (Egli and Bruening, 2000). Similarly, under irrigated conditions in Missouri and Tennessee, MG 3 cultivars had yields similar to MG 4 cultivars, and higher than MG 5 and 6 (Salmerón et al., 2016). One explanation for the relatively high productivity of early MG cultivars under irrigated conditions is that reproductive stages start earlier in the season allowing them to grow under more optimal environmental conditions (i.e., higher solar radiation intensity) compared to late MGs (Egli and Bruening, 1992; Kantolic et al., 2013), and avoid end of season low temperatures and frost damage (Heatherly, 1999).

Under rainfed conditions, the year-to-year variability in the timing and intensity of water stress can influence yield across cultivars of different maturities. However, some MG choices can reduce the risk of water stress and increase yields depending on precipitation patterns at different locations. For instance, midsouth producers may avoid late-season drought by selecting earlier MG cultivars, as MG 3 and 4 cultivars planted early (April/ May) have greater yields compared to MG 5 to 7 in irrigated conditions, suggesting their yield potential is similar if drought stress is avoided (Bowers, 1995). On the other hand, for later planting dates (in late May and June), late MG cultivars usually provide greater yields compared to early MG cultivars by avoiding summer drought and benefiting from precipitation in the fall (Purcell et al., 2003).

Although there are many studies evaluating yield differences across different MG choices, there is limited research on early MG cultivars providing better adaptability for rotations with cover crops or double- cropping. In addition, studies conducted in U.S. regions with a high percentage of rainfed acreage have not investigated the interaction of MG selection with water availability and soil characteristics. Under similar environmental conditions, soils with different physical properties (i.e., water holding capacity, texture, bulk density) will influence the crop available water (Afyuni et al., 1993; Doraiswamy et al., 2004; Wright et al., 1990) and final crop yield (Miller et al., 1988; Stone et al., 1985). Thus, the selection of MG cultivars that can optimize yield and resource use efficiency is likely to depend on the location, specific environmental conditions, water availability, and soil type. However, exploring all these different scenarios with field trials is often not feasible due to financial and time limitations. Process-based crop models offer the advantage of exploring a number of management strategies across a range of environmental conditions, provided they have been adequately calibrated (Boote et al., 1996; Kovács et al., 1995; Royce et al., 2001; Ruíz-Nogueira et al., 2001; Salmerón et al., 2014).

The Decision Support System for Agrotechnology Transfer (DSSAT) (Hoogenboom et al., 2015; Jones et al., 2003) is a software system comprising many crop models that can be used to evaluate management options. The CROPGRO-Soybean model in DSSAT (K. J. Boote et al., 1998; Wilkerson et al., 1983) has previously demonstrated its applicability to predict soybean crop growth and development in a wide range of locations in the U.S. (Ma et al., 2005; Nielsen et al., 2002; Salmerón and Purcell, 2016; Salmerón et al., 2017) and used to explore effects of management and environmental conditions on yield (Curry et al., 1995; Egli and Bruening, 1992). However, before models can be used to study different scenarios, they require calibration and evaluation with field data from the environment(s) of interest (Jones et al., 2011; Timsina and Humphreys, 2006). Calibration of cultivar coefficients requires detailed in-season growth data (i.e. crop biomass over time; Boote and Jones, 1988) that is difficult to collect for a large number of cultivars and environments. Further, calibration of cultivar specific coefficients short-lived because it is necessary to calibrate new cultivars as they are released every year. As a result, there has been an increasing use of alternative approaches to obtain cultivar coefficients based on MG or on low input data (phenology, yield, and yield components) across many sites with an acceptable level of uncertainty that makes these models suitable for most agronomic applications (Archontoulis et al., 2014; Irmak et al., 2000; Mavromatis et al., 2001; Salmerón and Purcell, 2016; Salmerón et al., 2017; Setiyono et al., 2007). We hypothesized that DSSAT-CROPGRO-Soybean cultivar coefficients obtained based on the cultivar's MG will provide similar accuracy to cultivar specific calibration.

The objectives of this study were: (i) to calibrate and evaluate the DSSAT - CROPGRO v 4.6.1.0 to predict soybean harvest date and yield of MG cultivars 0 to 4 using data from two years (2017 and 2018) across experimental sites in Kentucky, Nebraska, and Ohio; ii) to determine whether MG specific coefficients could substitute for cultivar specific coefficients in DSSAT-CROPGRO-Soybean model calibration; and (iii) to quantify the potential use of early soybean MGs as a management adaptation to advance harvest date and consequently advance cover crop planting date with DSSAT-CROPGRO model.

2. MATERIALS AND METHODS

2.1. Field experiments for model calibration and evaluation.

Experimental data for model calibration and evaluation were obtained from a multi-state project across Nebraska, Ohio and Kentucky (USA). Experiments were conducted in six locations in 2017 and seven locations in 2018 (Table 1.1). At each location 16 commercial soybean cultivars ranging from MG 0 to 4 were evaluated at each location, except in Custar and South Charleston, OH, where MGs ranged from 0 to 3 and 1 to 4, respectively. Some cultivars changed from one year to another due to seed availability but cultivars were replaced with a similar rMG. Soybean was planted at 37 seeds m^{-2} from May 8 to June 8 in 0.38 or 0.76 m row spacing depending on the year and location. Details on the experimental design and methods can be found in Proctor et al. (in preparation). All locations were rainfed in 2017 except the North Platte, NE, site which was irrigated. In 2018, an additional irrigated location was included in Concord, NE, and both irrigated and rainfed water management sites were added in Lexington, KY. The date of key developmental stages was recorded at all locations based on Fehr and Caviness, (1977). These stages included onset of flowering (R1), physiological maturity (R7), and harvest maturity (R8) across sites and years. Yield and yield components (individual seed weight and the number of seeds per unit area) were obtained by harvesting 4.9 meters of the four center rows in each plot except for the Nebraska locations where yields were obtained from only two center rows.

2.2. DSSAT – CROPGRO model description.

DSSAT v.4.6.1.0 (Hoogenboom et al., 2015; Jones et al., 2003) is a software program comprising several crop models such as CROPGRO-Soybean, which was used in our study for the simulation of soybean growth and development. DSSAT-CROPGRO is a dynamic and process-based model that simulates crop growth and development, as well as carbon, nitrogen, and water balance (K. J. Boote et al., 1998; Hoogenboom et al., 2015; Jones et al., 2003). To perform model simulations management, weather, soil, and genotype input data is required. The hourly leaf-level, hedgerow photosynthesis option in CROGPRO was selected to simulate photosynthesis (see detailed description in Boote and Pickering, 1994). Reference evapotranspiration was calculated based on the FAO-Penman approach (Allen et al., 1998), and soil evaporation with the CERES-Ritchie soil method (described in Jensen et al., 1990). A water stress index in the model is calculated as the ratio of the potential daily water uptake and the crop potential evapotranspiration (Ritchie, 1998). The model was run with biological N fixation activated, which is driven by the crop N demand, and influenced by temperature, soil water, and plant age (Boote et al., 1998).

2.3. Model inputs.

Daily weather inputs for estimation of potential evapotranspiration based on the FAO-Penman method are maximum and minimum air temperature, precipitation, solar radiation, average wind seed, dew point temperature and/or relative humidity. For KY, daily weather data was obtained from the UK Ag Weather Center (http://www.agwx.ca.uky.edu), in NE from the HPRCC (https://hprcc.unl.edu/), and in OH from the OARDC Weather System (http://www.oardc.ohio-state.edu/weather1/). One exception was daily solar radiation in Ohio and Kentucky obtained from NASA – Power (https://power.larc.nasa.gov). To obtain soil input parameters for Nebraska and Ohio, percent clay and silt, drainage class, runoff potential, curve number, soil albedo, percent slope, percent organic carbon, CEC, and pH in water were gathered from USDA – NRCS (2018) whereas bulk density (BD), saturated hydraulic conductivity (Ks), and drainage upper limit (DUL), lower limit (LL),saturation (SAT) were estimated with the DSSAT pedotransfer functions (Rawls and Brakensiek, 1985; Saxton et al., 1986). For Kentucky, drainage class, runoff potential, curve number, soil albedo, percent slope, were gathered from USDA – NRCS (2018). Percent organic carbon, CEC, pH in water, percent clay and silt, bulk density (BD), drainage upper limit (DUL), lower limit (LL), and saturation (SAT) were obtained from direct field measurements. Saturated hydraulic conductivity (Ks) was estimated with DSSAT pedotransfer functions. On a later step, DUL was then adjusted between ± 8 to 28% DUL to improve model predictions. A summary of the final soil input parameters can be found in Table 1.1. Finally, common genotype model inputs that describe cultivar differences consist of eighteen crop cultivar coefficients (see Table 1.2) that were obtained as described in the following section.

2.4. Calibration of DSSAT-CROPGRO-Soybean cultivar coefficients.

Five common cultivars, one within each MG 0 to 4, were consistently used across all years and locations for the purpose of calibration, which will be referred from now on as the *calibration* cultivars. The remaining 11 cultivars at each location changed between years or across locations and will be referred to as the *evaluation* cultivars. First, cultivar coefficients for the five calibration cultivars were obtained with the following steps: i) calibration of phenology coefficients with data across all locations, and ii) calibration of growth coefficients using data from sites under no water stress. Second, crop cultivar coefficients for the evaluation cultivars were estimated based on cultivar maturity (Table 1.2).

The phenology and growth cultivar coefficients for the five calibration cultivars were optimized with the DSSAT - GLUE tool (Generalized Likelihood Uncertainty Analysis) (Jones et al., 2011). Details on the input coefficients and their units are provided in Table 1.2. The GLUE tool uses a Bayesian method based on a random parameter search method called Monte Carlo that compares simulated and observed variables, selecting the set of parameters that minimizes root mean squared error (RMSE) between simulated and observed variables (Jones et al., 2011). As a first step, due to the relatively small range of environmental conditions tested, most phenology coefficients (XFRT, PODUR, THRSH, SDPRO, and SDLIP) were estimated as a function of rMG based on Grimm et al (1994, 1993) and Salmerón and Purcell (2016) or standard coefficients by MG in DSSAT v 4.6 (Table 1.2) and fixed prior to the GLUE optimization. Subsequently, coefficients CSDL and SD-PM were optimized by performing 5000 runs across all sites and years (n = 13) for each coefficient. Next, coefficients FL-SH and FL-SD were recalculated assuming that the changes in duration of different developmental stages are not independent from each other and will increase/decrease proportionally (see Table 1.2 for more details). Lastly, cultivar coefficients LFMAX, SLAVR, SIZLF, WTPSD, SFDUR and SDPDV were calibrated simultaneously by conducting 200,000 runs with GLUE across the non-water stressed sites to optimize prediction of yield and yield component data. To determine non-water stressed sites, we performed crop simulations deactivating the water balance from the model. Sites under water stress were not included in the calibration because we wanted to obtain coefficients that approximate to crop yield potential. Coefficients for the remaining cultivars in the study (*evaluation* cultivars) were then obtained based on each cultivar rMG as described in Table 1.2 (total of 42 different cultivars of rMG 0.3 to 4.5). Similarly, cultivar coefficients for MG 0 to 4 (rMG 0.5, 1.5, 2.5, 3.5, and 4.5) were obtained with the same approach and were used to conduct the subsequent sensitivity analysis.

2.5. Sensitivity analysis.

A multi-factor sensitivity analysis was conducted with model simulations for 30 years of historical weather data (1987 - 2017) at four selected locations in our study (Lexington, KY; Custar, OH; and Havelock and North Platte, NE). Across the seven sites in our study, these four sites provided the widest variation in weather data and predicted model outputs (data not shown). The treatment factors investigated were two water managements (irrigated vs. rainfed), two planting dates (May 15 and July 1), soybean cultivars of MG 0 to 4, and three levels of soil water holding capacity (unmodified soil, -20% and +20% change in drainage upper limit) using a common silty clay loam soil across all sites (Table 1.1). The purpose of including a common soil type was to compare results across locations without the confounding effect of soil types for each site. Overall, the sensitivity analysis included a total of 7200 simulations (30 years x 4 locations x 5 MG cultivars x 2 water managements x 2 planting dates x 3 soils).

2.6. Statistics for model evaluation and data analysis.

Model performance during calibration and evaluation was assessed by computing the RMSE between the observed and simulated date of R7 and R8 developmental stages and grain yield. In addition, the model efficiency (ME) was computed as:

$$\mathrm{ME} = 1 - \frac{\sum_{c=1}^{N}(S_c - O_c)^2}{\sum_{c=1}^{N}(O_c - O_{av})^2} \tag{1}$$

where O_c is the observed value for R7, R8, or yield for a given cultivar, S_c is the simulated value, O_{av} is the mean of the environment, and N is the number of observations for each cultivar. The ME ranges from -∞ to 1, with 1 being the optimal value. ME values between 0 and 1 indicate the model is more efficient in describing observed values than using the mean of the environment, while values <0 indicate that the observed mean is a better predictor than the model. Yield data from some MG 3 cultivars in Lexington, KY, during 2018 were omitted for model calibration and evaluation based on field notes reporting unusual stunted growth and final low yields.

Simulated results from the multi-factor sensitivity analysis across the 30 years were analyzed with an analysis of variance. The PROC GLM procedure in SAS (v. 9.4, SAS Institute, Cary, NC) was used to test the effect of the different factors evaluated on yield. The assumptions of the model, including normality and homogeneity of variances, were met. Fixed factors were MG, soil type, planting date, and location, while year was treated as a random factor. This analysis was performed for rainfed and irrigated conditions separately. The relative effect of the different factors and interactions on yield was quantified as the sum of squares for each factor obtained from the analysis of variance, divided by the total modeled sum of squares, and expressed as a percentage. The LSMEANS procedure was used to identify MG cultivars with greatest yields within each location, planting date, irrigation management, and soil type.

The potential to advance the cover crop planting window with early-season soybean maturities was investigated with the predicted dates of R8 by the model. In addition, cumulative thermal time or growing degree days (GDD) were calculated from the date of R8 until the first frost (GDD_{R8-F}), and from R8 until the end of the year (GDD_{R8-E}). The first frost date is based on daily minimum temperature ≤ -4°C, and on the condition that 80% of freeze damage occurs in winter killed cover crops (i.e., oat (*Avena sativa* L.; Webb et al., 1994). The base temperature for computing cumulative thermal time for over-wintering cover crops was set to 4.4 °C based on previous work on cereal rye (*Secale cereal* sp.), a widely used cool season cover crop (Nuttonson, 1957).

3. RESULTS

3.1. Model Calibration and Evaluation.

After calibration of cultivar specific coefficients for the five common cultivars across locations, the model was able to predict date of R7 and R8 with a RMSE of 3.5 to 7.4 days, and yield with a RMSE of 0.219 to 0.540 Mg ha^{-1} (Table 1.3). When cultivar coefficients were derived based on rMG for the remaining cultivars, the RMSE for the predicted R7 date changed from a 1.8 day decrease to a 3 day increase for MG 2. Similarly, the RMSE for the predicted R8 date changed from a 2.5 day decrease for MG 0 to a 0.3 day increase for MG 2. Finally, the yield RMSE changed from a 0.185 Mg ha^{-1}

decrease for MG 2 to a 0.341 Mg ha^{-1} increase for MG 1 when coefficients were derived based on rMG compared to cultivar specific calibration (Table 1.3). Although changes in RMSE depending on the source of the cultivar coefficients (calibrated or based on rMG), were relatively small, the overall reduction in ME with the evaluation cultivars indicated that the model was less efficient with cultivar coefficients derived from rMG (Table 1.3). However, the positive overall ME regardless of the source of the cultivar coefficients indicates that the model was still efficient in predicting differences across MG cultivars (ME = 0.72, 0.61 and 0.53 for prediction of R7, R8 and yield, respectively).

To evaluate the overall model accuracy to predict yield differences across MG, statistics were calculated by location and year, including water-stressed sites and cultivars used for both calibration and evaluation (Figure 1.1 to 1.3). In Lexington, KY, observed yields increased with MG, and the model was able to predict this trend in all cases with a RMSE of 0.340 to 0.456 Mg ha^{-1} (Figure 1.1). In both years, the model was able to mimic the yield trend. However, the model under-predicted MG 0 in 2017 and MG 4 in 2018 under rainfed and over predicted MG 2 in 2018 in both rainfed and irrigated conditions. When looking at yield simulations under an automatic irrigation, there was a yield gap in 2017 and 2018 in rainfed environments due to water stress (Figure 1.1).

For the sites in Nebraska, the model predicted yield with a RMSE ranging from 0.053 to 0.712 Mg ha^{-1} depending on the year and location (Figure 1.2). The lowest model efficiency (- 7.4) occurred at Havelock in 2017, but the model still predicted the observed yield trend with a RMSE of 0.321 Mg ha^{-1} (Figure 1.2c). Simulations when the water balance was deactivated indicated that there was a yield gap due to water stress in Mead and Havelock (rainfed) (Figure 1.2 a-d), but not at North Platte and Concord (irrigated) (Figure 1.2 e-g). It is interesting to note that the model was efficient at predicting differences across MGs in locations that did not experience significant water stress (ME= 0.58 – 0.65; Figure 1.2 f,g), with the exception of North Platte in 2017 (ME = - 0.29). In contrast, the model was less efficient in two site years with significant water stress (ME = - 4.69 and - 7.39) (Figure 1.2 c,d).

In Ohio, the model predicted yield with a RMSE of 0.00025 to 0.680 Mg ha^{-1}, with South Charleston 2018 being the least accurate (RMSE = 0.680 Mg ha^{-1}) (Figure 1.3 a-d). In this location, yield of MGs 2 to 4 was over-predicted. The over predictions might be due to the lack of measured soil data for this site which made it extremely difficult to accurately estimate soil parameters. When comparing yield simulations for non-water stress and water stress production system, there was a larger yield gap in South Charleston 2017 and in Custar 2018, than in South Charleston 2018 and Custar 2017. Sufficient precipitation during the growing season produced yields closer to the no-water-stress simulation scenarios at these particular sites.

3.2. Analysis of simulation scenarios.

3.2.1. Multi-factor sensitivity analysis.

Analysis of variance (ANOVA) results on the impact of different management, environmental, and soil factors on simulated soybean yield grown under rainfed or irrigated conditions, and partitioning of sums of squares, are shown in (Table 1.4). Under rainfed conditions, the soil main effect explained the greatest percentage of the yield variability (35.5 % of the model sum of squares), and its interactions with location and planting date explained 0.4 and 2.8% more of the yield variability, respectively. The planting date main effect explained 20.7% of the yield variability, and its interactions with location explained an additional 0.4%. Not surprisingly, year to year variability represented 12.9% of the yield variability. Location main effect explained 19.6% of the yield variability and its interaction with MG an additional 3.6%. Interestingly, the MG main effect explained only 2.9% of the yield variability, and the interaction of MG with other factors only added up to 4.2% (Table 1.4).

The factors that explained yield variability were largely different under irrigated conditions. Planting date explained the greatest percentage of the yield variability (66.8%), with an additional 1.2 and 0.7% when interacting with location and MG, respectively. Year–to-year variability explained only 7.1% of the yield variability. The MG main factor explained 7.1% of the yield variability, and its interaction with other factors added up to 8.2%. Thus, MG cultivar explained a larger percentage of the yield variability compared to rainfed conditions, but was still relatively low. Location main effect explained 9.4% of the total yield variability. As expected, the soil main effect explained fewer yield changes under irrigated conditions (0.1%), and there were no interactions with other factors.

3.2.2. Effect on soybean harvest date and cover crop planting window.

The simulated date of harvest maturity (R8) for 30-yr of historical weather data was plotted by MG to investigate the potential to advance the cover crop planting date when switching from late to earlier MGs (Figure 1.4). The median date at each location when the minimum daily temperature reached -4 °C based on 30-yr of historical weather data is shown in Figure 1.4 with a red solid horizontal line. Thus, the time difference from soybean harvest to this horizontal line provides an estimated cover crop planting and growth window before freezing damage or mortality may occur in the fall. We considered that frost-sensitive cover crop species like oats and oilseed radishes would start to senesce and stop accumulating additional biomass after this date. Only data from simulations under irrigation or under rainfed conditions with a 20% reduction in DUL were included in Figure 1.4, since they provided the largest variation in water availability and differences in predicted date of R8. Results from MG 4 cultivars planted in July are not presented for Custar, OH and Havelock and North Platte, NE since this cultivar experienced late season freeze in > 80% of the simulations at these locations.

Date of R8 showed a positive linear relationship with soybean maturity in all locations, planting dates, and soil types (R^2 >0.85) (Figure 1.4). Under irrigated conditions, using an early MG allowed to advance soybean harvest and lengthen the cover crop planting window by 6.6 to 10.2 days per unit delay in cultivar maturity when planted in May, and by 1 to 7 days when planted in July. Overall, the slope of the relationship between soybean MG and date of R8 increased under rainfed conditions and for the warmest sites in our study. To further evaluate the potential for cover crop growth after soybean harvest in the fall, the thermal time accumulation as a function of cultivar maturity was calculated across sites and planting date treatments under irrigation (Figure 1.5). As expected, adapting to short-season MG cultivars increased GDD_{R8-F} and GDD_{R8-E} and thus the potential cover crop growing window after soybean harvest (Figure 1.5).

3.2.3. Effect on soybean yield.

Simulated yield differences across MG cultivars by location, planting date, and soil type are shown in Figure 1.6. Simulations under irrigation provide an indication of the yield potential at each environment and planting date without water stress. Soybean yields under irrigation and planted on May 15 were the highest at the warmest location

(4.105 Mg ha^{-1} in Lexington, KY), and lowest at the coolest location (2.649 Mg ha^{-1} in North Platte, NE). As expected, delaying planting date to July 1 reduced irrigated yield by 28 to 59% depending on the location and cultivar MG. To compare yield responses across sites under rainfed conditions, the same common silty clay loam soil was used across the four locations in the sensitivity analysis. Overall yield gap from irrigated vs rainfed conditions for soybean planted on May 15 was 50% (North Platte), 26% (Havelock), 21% (Custar) and 16% (Lexington). When planting date was delayed to July 1, the yield gap due to water stress was reduced to 33% (North Platte), 15% (Havelock), 9% (Custar) and 13% (Lexington). When the soil water holding capacity was increased (+20% DUL), planting dates on May 15 would still experience water stress in the North Platte (18% yield gap), Havelock and Lexington (3%), but water stress would be negligible in Custar (1.5%). For planting dates on July 1 and soils with a high water holding capacity (+20% DUL) the yield gap would be minimal across locations (1-3.4%). In contrast, simulations with a soil that had reduced water holding capacity (-20% DUL) had a profound effect on yields and increased the yield gap to 40 to 80 % across locations and planting dates.

The simulated yield data was further analyzed by conducting lsmeans by location, planting date, soil type, and MG cultivar to identify the range of MG cultivars that provided the highest yields or not different from the highest yielding MG (Figure 1.6). In Custar, MG 1 to 3 cultivars had the highest yields for both May and July planting dates, except when DUL was reduced by 20% for a July 1 planting date, where all MG cultivars yielded the same (Figure 1.6 a,b). Similarly, in Havelock, yields were highest with MG 1 to 3 cultivars planted in May, except when decreasing DUL by 20%, when MG 1 to 4 had the highest yields (Figure 1.6 c). However, for July 1 planting dates in Havelock, MG 2 and 3 cultivars yielded the highest under irrigation, and MG 1 to 3 cultivars under rainfed conditions (Figue 1.6 d). In Lexington, MG 3 and 4 cultivars had the highest yields across soil and planting date treatments, excluding irrigated conditions with a July 1 planting date, where the highest yields were only achieved with MG 4 cultivars (Figure 1.6 e f). Finally, MG 0 to 3 cultivars had the highest yields in North Platte under rainfed conditions and a May 15 planting date (Figure 1.6 g). However, only MG 1 and 2 cultivars maximized yields under irrigation at this planting date. Interestingly, when delaying planting date to July 1, there were no yield differences across MG cultivars in North Platte (Figure 1.6 h).

4. DISCUSSION

4.1. Evaluation of crop model applicability.

In this study, five common cultivars across locations in Kentucky, Nebraska and Ohio were used to derive crop cultivar coefficients as a function of rMG for cultivars MG 0 to 4. Our results showed that the model was still efficient at predicting the date of R8 and yield with this simplification. Similar results were obtained with DSSAT-CROPGRO simulations with generic coefficients based on cultivar maturity for MG 3 to 6 in latitudes 30.6 to 38.9°N in the Midsouth (Salmerón and Purcell, 2016; Salmerón et al., 2017). Our study evaluated model simulations with the same simplification but across 39.9 to 42.4 °N latitudes and MG 0 to 4. This approach to obtain cultivar coefficients based on the rMG provided by seed production companies and previously calibrated coefficients in similar environments can increase model application for agronomic purposes and the opportunity to explore management adaptation strategies. Although the model was efficient for the prediction of R7, R8, and yield across the range of MG cultivars in our study, the applicability of the generic crop cultivar coefficients that we obtained is limited to our study region. In addition, calibration of cultivar coefficients with experiments that include different planting dates, more cultivars, and years, would increase the model robustness and regional applicability to study management adaptation strategies.

Our results also indicate a high degree of model sensitivity to the parameterization of soil inputs for simulations under rainfed conditions. Increasing the intensity and quality of soil data collection in agronomic trials would aid in reducing model uncertainty in calibrations with regional data. Further experiments performed under both irrigated and rainfed conditions, and with information on crop growth and soil moisture would be necessary to reduce model uncertainty to study management adaptations that maximize yield productivity and water use efficiency across our study region.

Overall, results from the 30-yr simulations were in agreement with the yield analysis by Proctor et al. (in preparation) from the same data used for model calibration for this study. One exception was the yield analysis at Havelock, where surprisingly, early MG 0 yielded as high as later maturities at a 0.76 m row spacing. In contrast, our model simulations predicted a yield reduction with MG 0 cultivars at this location despite using a narrower row spacing (0.38 m) that could benefit early-season maturities. As expected, the 30-yr sensitivity analysis indicated that the year effect on yield was higher under rainfed compared to irrigated conditions (12.9 and 7.2 % of the total sum of squares, respectively). Thus, results from a limited number of irrigated sites or years would be still relatively robust. In contrast, model simulations might be more necessary to investigate different management options under rainfed conditions, where results from a limited number of sites or years might be less representative of environmental conditions in a region.

4.2. Soybean MG adaptation for cover crop rotations.

The third objective in this study was to use a calibrated crop simulation model to evaluate the potential of early-season soybeans to advance harvest and cover crop planting date to lengthen the growing window without soybean yield penalty. Interestingly, our multi-factor sensitivity analysis from 30-yr simulations revealed that MG selection contributed to a relatively low percentage of the yield variability in both irrigated and rainfed environments. Instead, under rainfed conditions yield variability was mostly explained by soil type, and under irrigated conditions, yield was mostly dependent on the planting date. Hence, early MGs can provide a means to adapt growing season length with relatively low impact on yield potential, compared to other practices such as changing planting date and water supply.

Our simulations indicated that at any location, planting date, water management, and soil type, there was a range of maturities with similar yields (i.e. MG 1-3 yielded the same for May 15 planting dates in Custar, OH). This means that while producers may select from a number of MG cultivars within a location that yields similarly, they could plant relatively early MGs for their location to simplify crop rotations and field operations. These results also have strong implications for increasing water use efficiency with short-season cultivars, as reported in irrigated trials in the Midsouth (Purcell et al., 2007). We found that producers may advance soybean harvest by 6.6 to 11 days per unit decrease in MG when soybean was planted in May. However, advancing harvest in double-crop soybean would be more challenging, with harvest occurring 1 to 7.3 days earlier per unit decrease in MG.

An earlier soybean harvest can be beneficial to advance cover crop planting date, thus increasing biomass production in the fall (Prabhakara et al., 2015; Teasdale et al., 2004; Thapa et al., 2018). However, not only the duration of the cover crop growing window is important for crop planting and field operations, but temperatures during this period are more critical for cover crop growth, and will partially determine the success of a cover crop and the biomass produced in the fall (Mirsky et al., 2011; Webster et al., 2016). Previous studies in the U.S. estimated biomass gains of 1.8 – 5.3 kg ha^{-1} GDD^{-1} in a hairy vetch cover crop (Lawson et al., 2015; Mirsky et al., 2017; Teasdale et al., 2004), 4.1 – 11.0 kg ha^{-1} GDD^{-1} for cereal rye (Lawson et al., 2015; Mirsky et al., 2017), and 6.7 – 7.5 kg ha^{-1} GDD^{-1} in cereal rye-vetch mixtures (Lawson et al., 2015). At Custar and Havelock, the earliest maturity that maximized yields were MG 1 soybeans and provided a growing window of 602-627 GDD before the first frost (at -4°C). Considering a relationship of cover crop biomass with cumulative thermal time of 5 kg ha^{-1} GDD^{-1}, a warm-season cover crop (i.e. oats) would be able to produce above 3000 kg ha^{-1} of biomass before the first frost in these locations. For winter cover crops (i.e. cereal rye and hairy vetch) the growing window after MG 1 soybeans would be extended to 732-819 GDD, and cover crop biomass would increase to 3,658-4,095 kg ha^{-1} (considering 5 kg ha^{-1} GDD^{-1}). At the coolest location in our study (North Platte, NE), yield under irrigated conditions was also maximized with MG 1 cultivars, but due to relatively lower temperatures, a warm-season cover crop may produce 1,495 kg ha^{-1} in the fall, whereas a winter cover crop may produce 2,795 kg ha^{-1} (considering 5 kg ha^{-1} GDD^{-1}). Adapting from MG1 to MG 0 soybeans under irrigation in North Platte would reduce yield by 390 kg ha^{-1} and increase biomass production by 723 kg ha^{-1} on average. Finally, at our warmest site in Lexington, the estimated cover crop biomass produced after MG 3 soybeans would be 3,348 kg ha^{-1} until the first frost, or 4,062 kg ha^{-1} until the end of the year. Adapting to MG 2 in Lexington would reduce yield by 220-440 kg ha^{-1} and increase cover crop biomass by 845 kg ha^{-1} on average. As expected, the growing window for cover crops after a double crop soybean was reduced across all locations. A warm-season cover crop after double-crop soybean when selecting the earliest MG that maximizes productivity would produce 519-1,127 kg ha^{-1}, whereas a winter cover crop would produce 166-2,080 kg ha^{-1}, depending on the location. Adapting to earlier MG at Custar, Havelock or Lexington would reduce yields by 70 – 382 kg ha^{-1} and increase cover crop biomass by 332 – 562 kg ha^{-1}.

The application of a calibrated crop model combined with the analysis of GDD after soybean harvest provided a means to investigate the potential for growth of cover crops in our study region. This approach could be further investigated by considering different cover crop sensitivity to frost injury, as well as different baseline temperatures for growth. However, additional information on cover crop responses to cumulative thermal time in our study region is necessary to reduce uncertainty in cover crop biomass estimations. Moreover, while this simple approach may be sufficient to evaluate the potential to grow cover crops under different sites and MG management options, a more mechanistic eco-physiological model where growth is a function of radiation (and temperature) and that considers water stress may provide more accurate cover crop biomass estimations.

5. CONCLUSION

Our study demonstrates that DSSAT-CROPGRO model calibrated with cultivar coefficients derived from rMG was efficient predicting date of harvest maturity and yield across MG 0 to 4 cultivars and latitudes 39.9 to 42.4°N. However, calibration with data obtained from a wider range of planting dates, cultivars, and years would improve the robustness of the cultivar coefficients and reduce uncertainty in model predictions in the study region. Our multi-factor sensitivity analysis revealed that under rainfed and irrigated conditions, MG selection was responsible for a relatively low percentage of yield variability. Instead, under rainfed conditions yield variability was mostly explained by soil type and variability in precipitation patterns, and planting date was the main factor influencing yield under irrigated conditions. Given the high sensitivity of model predictions to factors that influence water availability, more detailed data collection under water stress conditions is required to simulate management adaptations in our study region, where soybean is mostly grown under no irrigation.

This study provides a simple framework to apply crop simulation models to identify management adaptations that can facilitate cover crop establishment after a grain crop. Overall, our results indicate that it was possible to adapt soybean maturity selection and reduce MG by 0 to 3 units without a yield penalty, depending on the site, planting date, and water availability. The cultivars that maximized yield ranged from MG 0 to 3 across our sites for a planting date in May, and could provide sufficient cover crop growing window for both winter and warm season cover crops. However, the cover crop growing window after a double-crop soybean planted in July was not sufficient for warm-season cover crops, and provided less potential for cultivar maturity adaptation than when soybean was planted in May. An analysis of environmental conditions in the fall with specific temperature sensitivities for different cover crop species would help improve best cover crop management recommendations for our study region.

6. CHAPTER 1: TABLES AND FIGURES

Table 1. 1. Summarized soil properties at each experimental site and year, and for the common soil utilized for the sensitivity analysis. Soil hydrological parameters include the soil lower limit (LL), drained upper limit (DUL), and saturated volumetric water content (SAT), saturated hydraulic conductivity (Ks), and bulk density (BD).

Location	Year	Soil name	Depth (cm)	Clay (%)	Silt (%)	LL (m^3m^{-3})	DUL (m^3m^{-3})	SAT (m^3m^{-3})	K_s (cm h^{-1})	BD (g cm^{-3})
Mead NE	2017	Tomek Silt loam	0 - 60	26.5	67.5	0.22	0.43	0.63	0.68	1.20
			60 - 140	37.0	57.0	0.23	0.41	0.59	0.15	1.36
			140 - 200	27.0	66.0	0.18	0.36	0.57	0.68	1.42
Mead NE	2018	Yutan Silty clay loam	0 - 60	34.6	57.1	0.21	0.35	0.46	0.15	1.35
			60 - 109	24.4	62.3	0.15	0.29	0.47	0.68	1.32
			109 - 200	19.3	63.3	0.13	0.27	0.49	0.68	1.27
Havelock NE	2017	Butler Silt loam	0 - 38	22.7	53.0	0.19	0.38	0.54	0.68	1.12
			38 - 86	50.0	28.0	0.30	0.44	0.48	0.06	1.29
			86 - 152	38.7	54.0	0.23	0.41	0.46	0.15	1.37
Havelock NE	2018	Butler Silt loam	0 - 30	23.0	53.0	0.19	0.37	0.52	0.68	1.12
			30 - 86	50.0	28.0	0.30	0.43	0.47	0.06	1.29
			86 - 152	39.0	54.0	0.24	0.41	0.45	0.15	1.33
North Plate NE	2017	Cozad Silt loam	0 - 30	19.0	60.0	0.15	0.40	0.62	0.68	1.14
			30 - 46	18.3	49.7	0.14	0.28	0.56	1.32	1.29
			46 - 200	13.0	46.0	0.10	0.28	0.54	1.32	1.34
North Platte NE	2018	Cozad Silt loam	0 - 30	19.0	60.0	0.15	0.41	0.64	0.68	1.14
			30 - 46	18.3	49.7	0.14	0.35	0.58	1.32	1.29
			46 - 200	13.0	16.0	0.10	0.28	0.56	1.32	1.34
Concord NE	2018	Moody-Leisy Complex	0 - 40	21.8	41.0	0.18	0.35	0.49	1.32	1.24
			40 - 132	27.3	49.5	0.19	0.37	0.41	0.23	1.20
			132 - 152	27.3	58.0	0.17	0.34	0.49	0.15	1.28
Lexington KY	2017	Armour Silt loam	0 - 60	21.7	68.7	0.17	0.28	0.39	0.68	1.44
			60 - 90	36.5	53.6	0.20	0.29	0.39	0.15	1.51
			90 - 120	40.3	48.7	0.23	0.31	0.39	0.09	1.51
Lexington KY	2018	Maury Silt loam	0 - 60	22.4	66.5	0.17	0.36	0.49	0.68	1.59
			60 - 90	39.5	48.5	0.21	0.37	0.47	0.15	1.62
			90 - 175	43.2	41.2	0.24	0.41	0.47	0.09	1.56
South Charleston OH	2017 & 2018	Strawn-Crosby Complex	0 - 23	19.8	59.0	0.16	0.29	0.53	0.68	1.14
			23 - 55	35.5	41.5	0.21	0.29	0.48	0.23	1.31
			55 - 203	21.8	38.5	0.14	0.30	0.44	1.32	1.43
Custar OH	2017 & 2018	Hoytville Clay loam	0 - 89	35.7	38.0	0.26	0.47	0.56	0.23	1.19
			89 - 145	44.7	37.0	0.26	0.44	0.52	0.06	1.33
			145 - 190	38.7	38.7	0.23	0.40	0.51	0.23	1.34
Common soil	1987-2017	Silty clay loam	0 - 30	30.0	60.0	0.21	0.41	0.49	0.15	1.27
			30 - 90	30.0	60.0	0.20	0.40	0.48	0.15	1.29
			90 - 150	30.0	60.0	0.19	0.37	0.46	0.15	1.35

Table 1. 2. Cultivar crop coefficients for DSSAT-CROPGRO by cultivar relative maturity group (rMG) obtained after calibration and used in the sensitivity analysis.

Coefficient	Unit	rMG 0.5	rMG 1.5	rMG 2.5	rMG 3.5	rMG 4.5	Equation for parameter prediction	Source
CSDL	h	13.76	13.56	13.36	13.16	12.96	y = -0.201 x + 13.90	Calibrated in this study
PPSEN	h^{-1}	0.206	0.223	0.239	0.255	0.271	y = 0.016 x + 0.20	(Hoogenboom et al., 2015; Jones et al., 2003)
EM-FL	PTD	17.5	17.5	17.5	17.5	17.5	-	Salmeron and Purcell, (2016)
FL-SH	PTD	6.3	6.5	6.6	6.8	8.1	$(FLSH/SDPM)_{MG}$ * $SDPM_{CALIBRATED}$	Mavromatis et al., (2001); Salmeron and Purcell, (2016)
FL-SD	PTD	13.7	14.1	15.0	15.9	17.4	$(FLSD/SDPM)_{MG}$ * $SDPM_{CALIBRATED}$	Mavromatis et al., (2001); Salmeron and Purcell, (2016)
SD-PM	PTD	32.4	34.2	35.9	37.6	39.3	y = 1.724 x + 31.58	Calibrated in this study
FL-LF	PTD	26.00	26.00	26.00	26.00	26.00	-	(Hoogenboom et al., 2015; Jones et al., 2003)
LFMAX	mg CO_2 m^{-2} s^{-1}	0.94	1.02	1.10	1.17	1.25	y = 0.076 x + 0.91	Calibrated in this study
SLAVR	cm^2 g^{-1}	337.0	352.4	367.7	383.0	398.3	y = 15.317 x + 329.40	Calibrated in this study
SIZLF	cm^2	138.2	139.0	139.7	140.5	141.2	y = 0.752 x + 137.84	Calibrated in this study
XFRT	-	1.00	1.00	1.00	1.00	1.00	-	(Hoogenboom et al., 2015; Jones et al., 2003)
WTPSD	g	0.181	0.175	0.169	0.163	0.157	y = 0.006 x + 0.18	Calibrated in this study
SFDUR	PTD	24.2	24.6	24.9	25.3	25.6	y = 0.343 x + 24.08	Calibrated in this study
SDPDV	# pod^{-1}	1.83	1.94	2.05	2.16	2.27	y = 0.109 x + 1.77	Calibrated in this study
PODUR	PTD	10.00	10.00	10.00	10.00	10.00	-	(Hoogenboom et al., 2015; Jones et al., 2003)
THRSH	%	77.0	77.0	77.0	77.0	77.0	-	(Hoogenboom et al., 2015; Jones et al., 2003)
SDPRO	-	0.405	0.405	0.405	0.405	0.405	-	(Hoogenboom et al., 2015; Jones et al., 2003)
SDLIP	-	0.205	0.205	0.205	0.205	0.205	-	(Hoogenboom et al., 2015; Jones et al., 2003)

PTD: Photothermal days; CSDL: critical short day length below which reproductive development progresses with no daylength effect; PPSEN: slope of the relative response of development to photoperiod with time; EM-FL: time between plant emergence and flower appearance; FL-SH: Time between first flower and first pod; FL-SD: Time between first flower and first seed; SD-PM: Time between first seed and physiological maturity; FL-LF: Time between first flower and end of leaf expansion; LFMAX: Maximum leaf photosynthesis rate at 30 C, 350 vpm CO2, and high light; SLAVR: Specific leaf area of cultivar under standard growth conditions; SIZLF: Maximum size of full leaf; XFRT: Maximum fraction of daily growth that is partitioned to seed and shell; SFDUR: Seed filling duration for pod cohort at standard growth conditions for the crop; SDPDV: Average seed per pod under standard growing conditions; PODUR: Time required for cultivar to reach final pod load under optimal conditions for the crop; THRSH: Threshing percentage; SDPRO: Fraction protein in seeds; SDLIP: Fraction oil in seeds.

Table 1. 3. Root mean square error (RMSE) and model efficiency (ME) in the prediction of days from planting to physiological maturity (R7), to harvest maturity (R8), and dry grain yield (Mg ha^{-1}) in soybean.

Cultivar Maturity Group	n	R7		R8		Yield	
		RMSE (days)	ME	RMSE (days)	ME	RMSE (Mg ha^{-1})	ME
Calibration cultivars							
0	11	4.2	0.60	5.4	0.51	0.540	0.34
1	14	4.6	0.50	6.3	0.59	0.219	0.85
2	13	3.5	0.74	7.4	0.36	0.255	0.84
3	14	5.7	-0.45	7.4	0.46	0.477	0.46
4	12	7.1	-0.74	6.1	0.32	0.423	0.40
All cultivars	64	5.1	0.80	6.6	0.78	0.396	0.68
Evaluation cultivars							
0	12	5.7	-3.47	7.9	0.08	0.198	0.73
1	39	5.2	0.20	6.4	0.48	0.383	0.40
2	42	5.3	0.32	7.0	0.18	0.440	0.23
3	43	5.0	-0.10	8.1	0.11	0.403	0.45
4	15	4.1	0.69	8.4	0.19	0.350	0.41
All cultivars	151	5.1	0.72	7.4	0.61	0.391	0.53

Table 1. 4. Analysis of variance for simulated rainfed and irrigated soybean yields from 30-yr of historical weather data. Year was considered a random factor, and fixed factors were location (Custar, OH, Lexington, KY, Havelock and North Platte, NE), planting date (15 May, 1 July), soybean maturity group (MG) (MG 0, 1, 2, 3, and 4), and soil type (unmodified, -20, and +20 % change in soil drainage upper limit).

Factor	Rainfed		Irrigated	
	p	% Sum of squares	*p*	% Sum of squares
Year	<.0001	12.9	<.0001	7.1
Location	<.0001	19.6	<.0001	9.4
Planting date	<.0001	20.7	<.0001	66.8
MG	<.0001	2.9	<.0001	7.1
Soil	<.0001	35.5	<.0001	0.1
Planting date*Location	<.0001	0.4	<.0001	1.2
Planting date*Soil	<.0001	2.8	0.7661	< 0.1
MG*Planting date	0.014	0.2	<.0001	0.7
MG*Location	<.0001	3.6	<.0001	7.6
MG*Soil	0.0005	0.4	0.0745	< 0.1
Location*Soil	<.0001	0.4	0.6677	< 0.1
Location*Planting date*Soil	0.1148	0.1	0.9747	< 0.1
Location*Planting date*MG	0.8497	0.1	0.1746	< 0.1
Location*Soil*MG	0.6233	0.3	1	< 0.1
Planting date*Soil*MG	0.9158	< 0.1	0.9414	< 0.1
Location*Planting date*Soil*MG	1	< 0.1	1	< 0.1

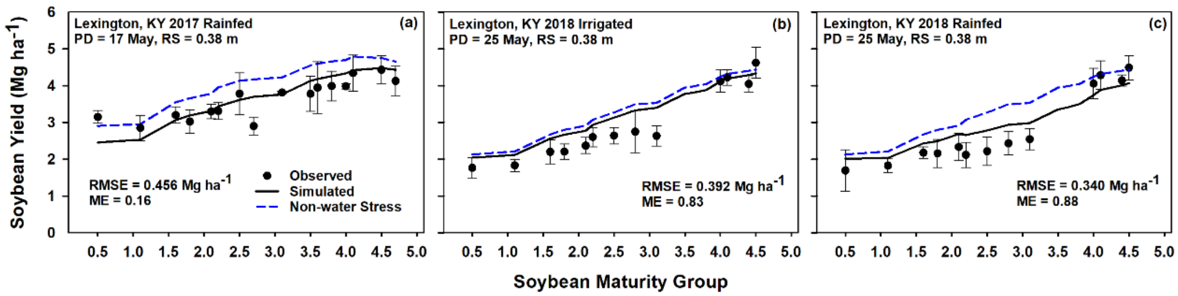

Figure 1. 1. Observed and simulated soybean yields by cultivar relative Maturity Group in experimental sites in Kentucky. Dots indicate observed values with error bars, black line indicates simulated values and blue dashed line indicates non-water stress simulations performed deactivating the water balance from the model. Planting density (PD), row spacing (RS), root mean squared error (RMSE) and model efficiency (ME) to evaluate the model accuracy are indicated in the figure.

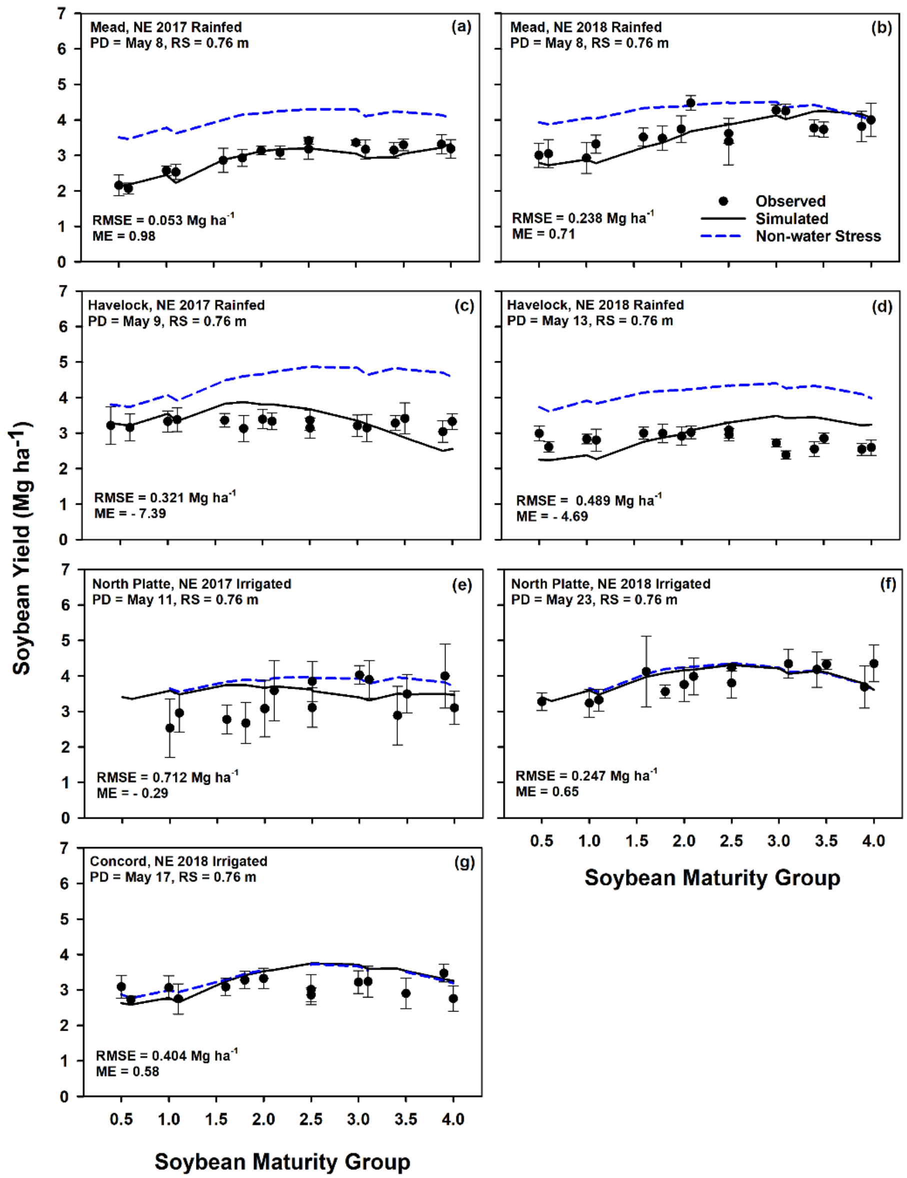

Figure 1. 2. Observed and simulated soybean yields by cultivar relative Maturity Group in experimental sites in Nebraska. The root mean squared error (RMSE) and model efficiency (ME) to evaluate the model accuracy are indicated in the figure.

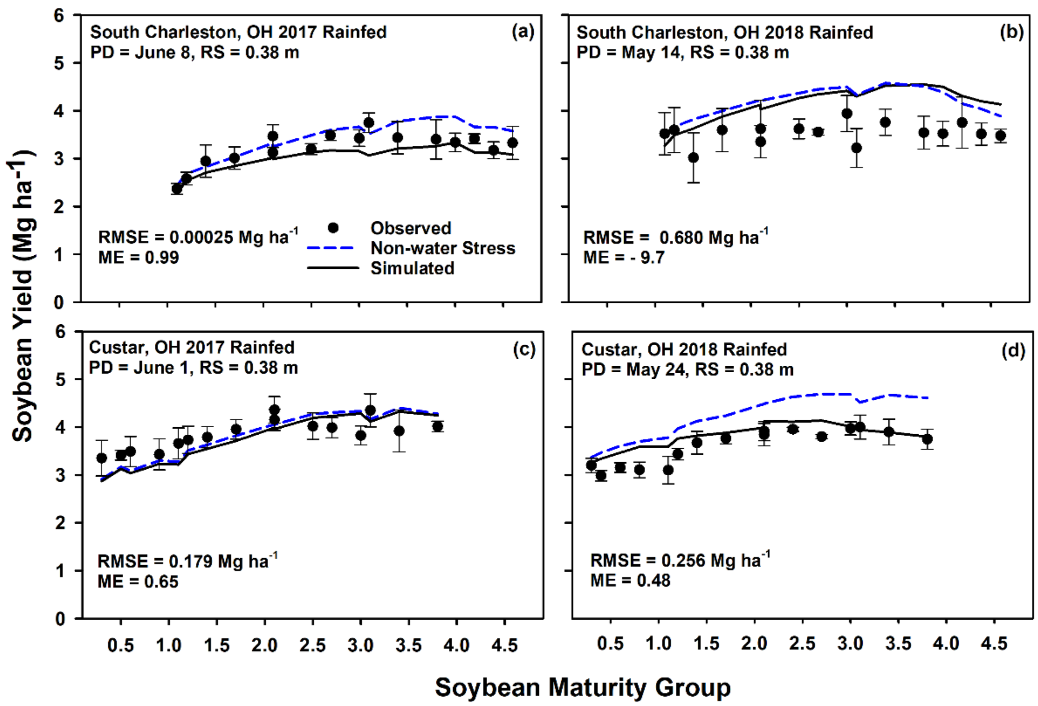

Figure 1. 3. Observed and simulated soybean yields by cultivar relative Maturity Group in experimental sites in Ohio. The root mean squared error (RMSE) and model efficiency (ME) to evaluate the model accuracy are indicated in the figure.

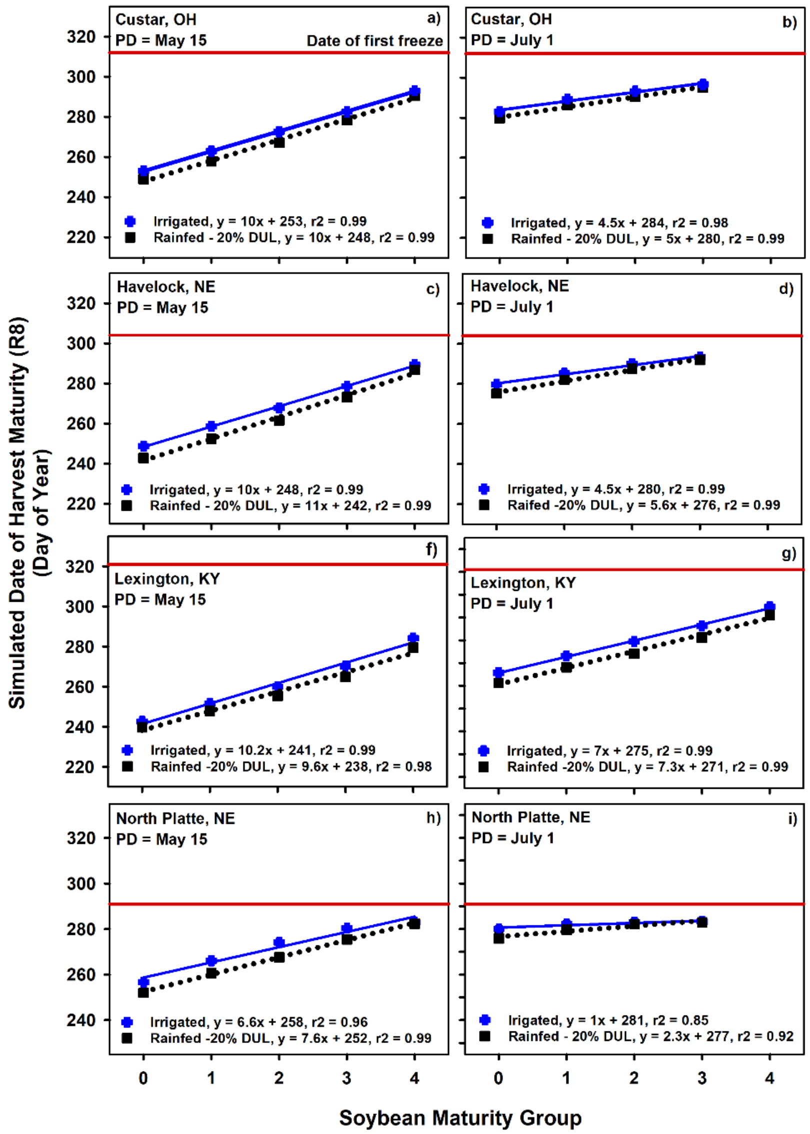

Figure 1. 4. Regression of the predicted soybean harvest maturity date (R8) as a function of cultivar maturity group (MG) for two planting dates (PD; May 15 and July 1), under irrigated (blue symbols) or rainfed conditions (black symbols), and at four select sites. Data averaged across 30-yrs. Red solid horizontal lines indicate the day of the year when freeze damage would occur in frost sensitive cover crops.

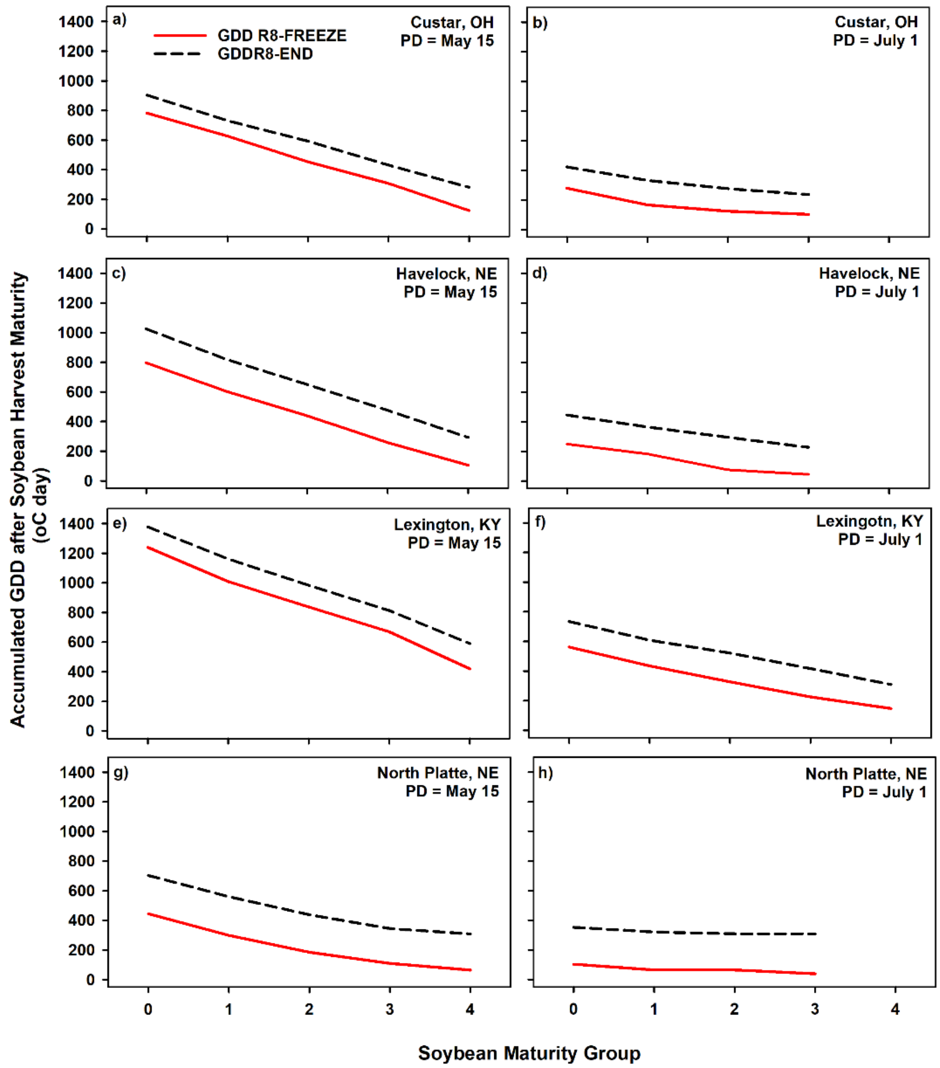

Figure 1. 5. Growing degree days (GDD) accumulated from soybean harvest until the first freeze in the fall ($GDD_{R8\text{-}FREEZE}$) (red solid line) or until the end of the year ($GDD_{R8\text{-}END}$) (black dashed line) at four different locations and two planting dates (PD). Results averaged across 30-yr simulations under irrigation.

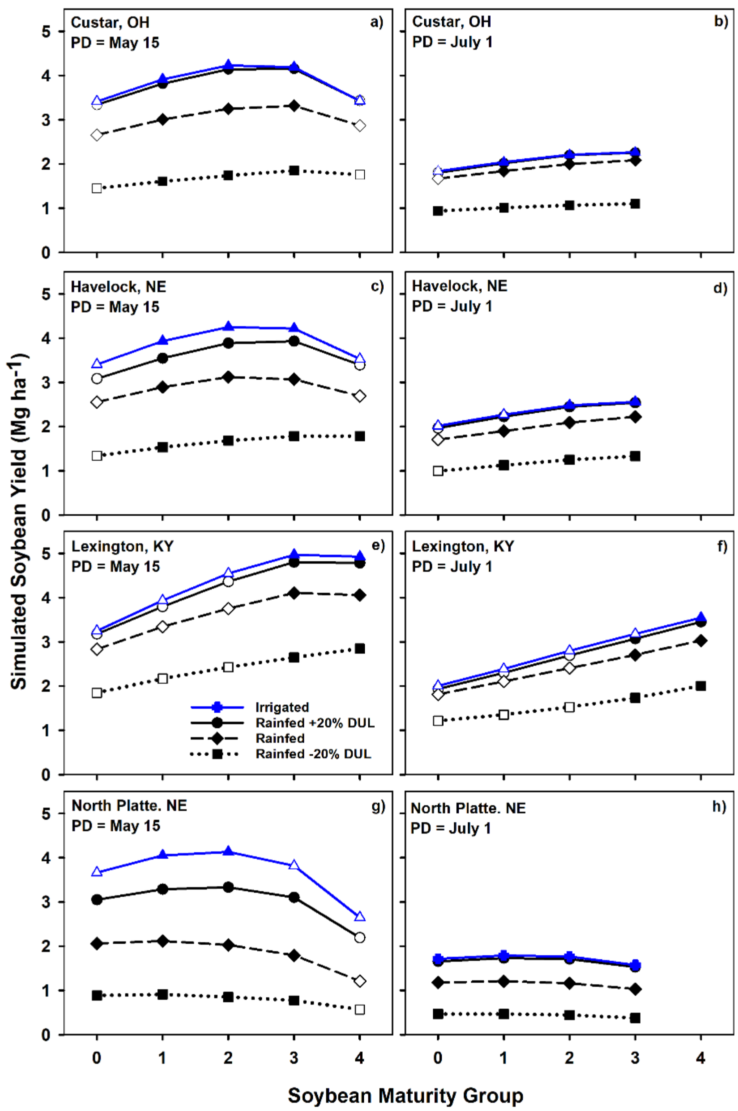

Figure 1. 6. Predicted soybean yield for maturity group (MG) 0 to 4 at four locations and two planting dates (PD). Results obtained from 30-yr simulations under irrigated (blue symbols) and rainfed (black symbols) conditions and with different soil modifications of a common silty clay loam soil (unmodified, -20 and +20 % change in drainage upper limit, DUL). Solid symbols indicate cultivar MG with the highest yield or not significantly different than the highest yielding, within a location, planting date, irrigation management, and soil type.

CHAPTER 2: Optimizing management options in soybean – cover crop rotations for improved weed control.

ABSTRACT

Winter cover crops grown in rotation with grain crops can be used as an integrated pest management tool (IPM) for the management of hard to control weed populations. However, cover crop establishment before the cold temperatures in the fall is challenging. Short-season cash crops that are harvested earlier (e.g., early season soybean [*Glycine max* (L.) Merr.] cultivars) could advance cover crop planting date resulting in a longer growing window and more biomass production that improves weed management. A rotation experiment was planted at Spindletop Farm in 2017 and 2018. The objectives of this study were : (i) to quantify differences in cover crop and weed biomass and ground cover planted after soybean MG cultivars 1 to 4 at two termination times; and (ii) to evaluate weed biomass across different herbicide treatments. Results showed that having a cover crop was an efficient management strategy to reduce weed biomass in the fall and spring compared to a no cover treatment. However, cover crops planted after MG 1 cultivars produced more biomass in the fall and covered the ground sooner, but were not able to reduce weed biomass in the fall and spring compared to cover crops planted after MG 4 cultivars. Having a fall herbicide application improved weed control in one out of two years with higher pressure of winter annual weeds. Delaying cover crop termination increased cover crop biomass but did not reduce weed biomass in the spring.

1. INTRODUCTION

Soybean (*Glycine max* (L.) Merr.) is one of Kentucky's main grain crops with an average yield of 3.5 t ha^{-1} and a harvested area of 805,300 hectares (USDA-NASS 2018). Like other crops, there are environmental and biotic stressors that threaten the ability to increase or maintain productivity for this crop. One major challenge is the increase in the number and frequency of glyphosate-resistant weeds in the USA since glyphosate-resistant soybean introduction in 1996 (Heap, 2014; Owen and Zelaya, 2005). For instance, seven glyphosate-resistant weeds species have been reported in the states of Ohio and Nebraska, and five weed species in Kentucky (ISHRW, 2014). This increase in glyphosate-resistant weeds introduces more competition for resources between weeds and cash crops, and adds more complexity and costs for managing cropping systems. Finding additional and alternative management practices to herbicides for weed control in grain crops is critical.

Cover crops are defined as vegetation that protects the soil surface, and grows between two regular cash crops (Reicosky and Forcella, 1998; Singer, 2008). These cover crops can be legumes (i.e., cowpea, soybeans, clover) or non-legumes/ cereals (i.e., cereal rye, oat, barley, wheat). Among other benefits, cover crops can decrease nutrient leaching (Dabney et al., 2001; Di and Cameron, 2002; Jackson, 2000; Meisinger et al., 1991; Reeves, 2017; Salazar et al., 2019), reduce soil erosion (Dabney, 1998; Langdale et al., 1991; Mutchler and McDowell, 1990), increase soil aggregation and water infiltration (Dapaah and Vyn, 1998; Fageria et al., 2005; Hargrove, 1986; McVay et al., 1989; Meisinger et al., 1991), and increase the natural abundance of beneficial insects (Letourneau et al., 2011; Sunderland and Samu, 2000; Tillman et al., 2004).

Winter cover crops grown in rotation with grain crops can be used as an integrated pest management tool (IPM) for the management of hard to control weed populations, such as glyphosate resistant weeds (Sarrantonio and Gallandt, 2003; Wiggins et al., 2016, 2015). Cover crops with abundant above ground biomass can prevent solar radiation from reaching the soil surface (Upadhyaya and Blackshaw, 2007). Since several weed seeds require light to germinate, this process is inhibited and weeds are suppressed (Haramoto, 2019). However, providing a full ground cover and abundant biomass early in the fall with one single species could be challenging. Indeed, introducing cover crops species mixes, such as oat (*Avena sativa* L.) and cereal rye (*Secale cereale* L.), into the crop rotation might increase cover crops benefits by providing sufficient ground cover over time. While oat has a higher biomass production during fall but winterkills, cereal rye is characterized by its winter hardiness and a rapid regrowth the following spring (Mirsky et al., 2009).

Despite the potential of using winter cover crops as IPM tools in grain cropping systems, one of the biggest challenges for their introduction in grain crop rotations is their timely establishment in the fall (Bich et al., 2014; Hively and Cox, 2001; Johnson et al., 1998; Sarrantonio and Gallandt, 2003). Previous research found that when cover crops are planted earlier, they produce a greater amount of aboveground biomass (Hashemi et al., 2013; Hively et al., 2009; Mirsky et al., 2009). In addition, other studies found that terminating cover later in the spring increased their biomass production (Mirsky et al., 2011; Nascente et al., 2013). Greater cover crop biomass and/or a faster establishment is associated with better weed control (Akemo et al., 2000; Brennan and Smith, 2005; Crutchfield et al., 1986; Mirsky et al., 2011; Mohler and Te Asdale, 1993), reduced N leaching (Di and Cameron, 2002; Meisinger et al., 1991; Salmerón et al., 2010), and increased organic matter (Kuo et al., 1997; Sainju et al., 2005). However, in large parts of the U.S. grain cropping regions, cover crops planted after the harvest of a cash crop (mid-September to late-October) may not have the time to produce enough biomass before the onset of cold temperatures. Finding strategies that ensure an earlier cover crop establishment after grain crops in the fall may enhance their application as IPM management tools and increase other benefits provided by cover crops.

One potential management adaptation is the use of relatively short-season soybean maturities within a region to facilitate earlier soybean harvest and seeding of cover crops in the fall. Short-season soybean maturities would provide a longer fall growing window for cover crops and under better environmental conditions, compared to cover crops planted after full-season soybeans. A recent simulation study across Kentucky, Ohio and Nebraska showed that adapting short- season soybeans maturities into crop rotations could advance soybean harvest by 6.6 to 10.2 days per unit decrease in maturity group without yield penalty for mid-May planting dates (Sciarresi et al., under review). Thus, we hypothesize that planting cover crops earlier after short-season soybeans will increase their biomass production and percentage of ground cover, resulting in a better weed control. We also hypothesize that adding a fall herbicide application will improve weed suppression in the spring.

The objectives of this study were : (i) to quantify differences in cover crop and weed biomass and ground cover planted after soybean MG cultivars 1 to 4 at two termination times; and (ii) to evaluate weed biomass across different herbicide treatments.

2. MATERIALS AND METHODS

2.1. Field experiment – Rotation study.

Field experiments were conducted at Spindletop farm (38° 7' 20" N, 84° 29' 56" W). The fields in both years were adjacent to each other and under a no-till system. In 2017- 2018 the entire field was Lowell – Bluegrass silt loam (Fine, mixed, active, mesic Typic Hapludalfs), while in 2018- 2019 85% of the field was Bluegrass – Maury Silt loam (fine, mixed, active, mesic Typic Peleudalfs) and 15% Lowell – Bluegrass silt loam. Previous crop in 2017 was fescue sod (*Festuca arundinacea* (Schreb.)) while in 2018 was tobacco (*Nicotiana tabacum*).

Experiment consisted of a split-plot design with the rotation type as the main split factor and different herbicide management treatments and cover crop termination times randomized within each sub-plot. The main split-plot treatments consisted of soybean – cover crop – corn rotations with different soybean MG cultivars ranging from 1 to 4 (referred from now on as rotations MG1-C, MG2-C, MG3-C, and MG4-C), and a control with a MG 4 soybean cultivar – fallow – corn rotation (referred from now as MG4-F). This last treatment was considered as the control following current common management practices in Kentucky (Figure 2.1). Each of these main split-plots was 6 m wide by 23 m long and was subdivided into 6 sub plots. Subplots contained a fully factorial combination of two cover crop termination dates and three different herbicide treatments, applied between the fall and early stages of corn development (Figure 2.1). The first herbicide treatment included a fall broadleaf herbicide application plus two herbicide applications in the spring (pre and post corn emergence); the second herbicide treatment included the two herbicide applications in the spring only; and the third herbicide treatment consisted on a single corn post-emergence application. All these herbicide programs included early and late cover crop termination. Further details on the herbicide treatment rates, active ingredients, and application dates, are summarized in table 1.1. The cover crop was chemically terminated using Roundup Powermax (glyphosate 720 g a.e. ha^{-1}) in spring. In 2018, the first termination date was 26 April and the second 3 May; whereas in 2019, the fist termination was 15 April and the second 30 April.

2.2. Crop management.

Soybean was sown on 17 May in 2017 and 24 May in 2018 in 0.38 m rows at a rate of of 37 seeds m^{-2}. Each MG cultivar was harvested on a different date, soon after each cultivar reached harvest maturity (R8) and at approximately 13% grain moisture. In both years, soybean received two herbicide applications. The first application included a soybean PRE emergence herbicide application with Sharpen (saflufenacil 20.8 g a.i. ha^{-1}) and Roundup Powermax (glyphosate 720 g a.e. ha^{-1}) the day after soybean was planted; and a second application with Roundup Powermax (glyphosate 720 g a.e. ha^{-1}) at soybean post emergence (12 June 2017 and 19 June 2018). In addition, soybeans were sprayed for control of Japanese beetle (*Popillia japonica*) with Warrior 2 (lambda-cyhalothrin 14.4 g a.i. ha^{-1}) on 19 July 2017 and 16 July 2018.

A mix of oat and cereal rye at a proportion of 60:40 (weight basis) was used as a cover crop. Seeding rates were 56 kg ha^{-1} for oat and 34 kg ha^{-1} for cereal rye. Cover crops were sown on 0.19 m wide rows using a grain drill immediately after soybean harvest. Weeds were not controlled prior to cover crop planting.

Dekalb corn hybrid (DK 63-55) was planted on 9 May 2018 and 7 May 2019. Nitrogen fertilizer was split in one application before planting, and a second side-dress application at V5. A total of 160 kg N ha^{-1} of UAN nitrogen were applied one day before planting. At V5, 56 kg N ha^{-1} of urea nitrogen was hand-broadcast on the soil surface. On the date of corn planting, a pre-emergence herbicide was applied in the subplots that receive this treatment (Figure 2.1). Around thirty days after planting, all subplots received a post-emergence herbicide application (Figure 2.1).

2.3. Field measurements.

2.3.1. Cover crop and weed biomass.

Cover crop and weed biomass were collected at two different times: i) in the fall, prior to oat winterkill (on 28 November 2017 and 12 December 2018), and ii) in the spring, prior to each cover crop termination (on 26 April 2018 and 15 April 2019 for early termination and 3 May 2018 and 30 April 2019 for the late termination). For biomass samplings in the fall, two biomass samples were collected from each main plot in subplot areas that did not received the fall herbicide application. For biomass sampling in the spring, two samples were collected from each subplot (Figure 2.1). Samples were collected by clipping all the aboveground biomass at the soil surface in an area of 0.25 m^2. Biomass was separated into cover crop and weed fractions. Each sample was dried at 60ºC until a constant weight was reached and then weighed.

2.3.2. Ground cover.

Digital images were taken during the cover crop growing season from each sub plot to quantify the percentage of ground cover. Two images were taken from two randomly assigned locations within each subplot. Images were taken weekly at a consistent height above the soil surface with a Nikon Coolpix camera (S6900, 16 megapixels Nikon, Tokyo, Japan) from 27 October 2017 and 14 November 2018 (after fall broadleaf herbicide application) until stem elongation began in the Spring.

After adjusting image quality from each individual photo to a standard pixel size (800 pixels by 600 pixels), photos were analyzed using Image J (Schneider et al., 2012) following procedures outlined in Purcell (2000) and Haramoto (2019). The range of hue, saturation and brightness was adjusted to best differentiate pixels containing green, living plants (cover crops + weeds) from those containing soil and/or previous crop residue. The range of hue values before the oat was winter-killed ranged from 31 to 117 to capture green, live canopy cover in the image. However, after the oat was winter-killed, these settings resulted in a mix of green and light brown pixels that captured living cereal rye but also dead oat residue. Hence, the lower hue threshold was adjusted to values ranging from 46 to 21 with a maximum threshold fixed in 117 to best capture green, living canopy on each set of pictures.

2.4. Data Analysis.

Analysis of cover crop and weed biomass in the fall was performed with a one-way ANOVA to test the effect of the rotation type (i.e., cover crop after different MG and fallow control). The rotation type was treated as a fixed factor, and block and its interaction with other factors as random effects. For the analysis of weed biomass in the spring, a three-way ANOVA was used with rotation type, cover crop termination, herbicide treatment, and their interactions included as fixed effects in the model, and block as a random effect. For cover crop biomass in the spring, the ANOVA analysis included rotation type, cover crop termination and their interactions as fixed effects in the model, and block and its interaction with other factors as random effects. Both tests were conducted with SAS (v. 9.4, SAS Institute, Cary, NC) using PROC MIXED. For all ANOVA, significant means comparisons were performed using slicing and Tukey HSD method. Effects were considered significant in this and subsequent analyses when p values were less than 0.05. Before conducting the ANOVA, the normality of residuals and homogeneity of variances was checked. Weed biomass data collected in the fall (2017 and 2018) and spring 2018 as well as cover crop biomass collected in spring 2018 were log transformed to meet assumptions of normality except for weed biomass in spring 2017 were square root transformed.

Ground cover were analyzed with an ANOVA using PROC MIXED in SAS (v. 9.4, SAS Institute, Cary, NC) and considering data collected over time as repeated measures. The rotation type (without the control fallow), herbicide treatment and time were considered as fixed factors, and block as random. The heterogeneous Toeplitz matrix was used as the variance / covariance structure as it resulted in the most parsimonious model fit (assessed by having the lowest AIC value). Additionally, we selected one key date, before the oat was winter-killed, to analyze the effect of cover crop planting date on percentage of ground cover with a PROC MIXED procedure and without considering the time factor. In addition, we analyzed percentage of ground cover for no cover crop treatments using repeated measurements to determine the evolution of weed ground cover. Herbicide treatment and time were considered as fixed factors, and block as random. Data were also analyzed with a PROC MIXED procedure with herbicide treatment as fixed factor, time as a random repeated measure, and block as the subject. The same variance/covariance structure described above was also used in this case since it resulted in the best model fit.

3. RESULTS

3.1. Cover crop and weed biomass in the fall.

The ANOVA for cover crop and weed biomass showed that there was a significant effect of the rotation type on cover crop biomass in both years (Table 2.2). Results show that oats represented between 88 to 65% of the total cover crop biomass in 2017 and between 95 to 44% in 2018 while cereal rye represented between 12 to 35% in 2017 and 5 to 56 in 2018 (Figure 2.2). Nonetheless, when cover crop planting date was delayed the difference between oat and cereal rye biomass decreased as a consequence of less optimal conditions for oat growth, except for cover crops planted after MG 2 and 3 which resulted in similar oat/cereal rye biomass.

In both years, cover crop biomass showed a clear trend, with treatments in rotation after MG 1 cultivars producing the most biomass, and cover crop biomass decreasing with later MG cultivars and planting dates (Figure 2.2). In 2017, cover crop biomass after full season MG 4 cultivars was lower compared to any other rotation type (Figure 2.2a). In 2018, cover crop biomass after a full season MG 4 cultivar was only statistically different compared to cover crops biomass produced after MG 1 soybeans (Figure 2.2b).

Interestingly, data collected on weed biomass in the fall showed a similar pattern to that of cover crop biomass (Figure 2.3). There was also a significant effect of the rotation type in weed biomass by this time (Table 2.2). Fall weed biomass in cover crop treatments after MG 1 soybeans was highest on average, and fall weed biomass decreased in cover crops planted after later MG soybeans. In 2017, weed biomass with cover crops planted after MG 1 soybeans was 410 kg ha^{-1} higher than after MG 4 soybeans (*p*=0.003), but did not differ from weed biomass after MG 2 (*p*=0.7837), MG 3 soybeans (*p*=0.0798) or after MG 4 soybeans with no cover (*p*=0.219) (Figure 2.3a). Plots had a high proportion of volunteer soybeans in 2017 that was included in the total weed biomass. In 2018 biomass from volunteer soybeans was separated and analyzed independently from the total weed biomass (Figure 2.3b). Net weed biomass analysis for 2018, was performed on a sampling on 8 November, over one month before oats were winter killed in mid December. In December, most plots had negligible weed biomass at this time and we were not able to adequately analyze these data. In plots with enough biomass to sample, more weed biomass was observed in the earlier plantings. Weed biomass in the control treatment averaged 83.4 kg ha^{-1}.

Results from 2018 obtained from the sampling on 8 November show that biomass from volunteer soybeans contributed to increase weed biomass in the fall after MG 1 and 2 soybeans. Weed biomass was greatest in cover crop treatments planted earlier in rotation after short- season soybeans (Figure 2.3). Weed biomass in cover crop treatments after MG 1 soybeans biomass was similar to MG 2, and greater than MG 3 (*p*=0.0278), MG 4 (*p*=0.0134), and no cover (*p*=0.0012) treatments.

3.2. Cover crop and weed biomass in the spring.

By the time of cover crop termination in the spring, cover crop aboveground biomass was comprised of a single species, cereal rye. Only the fall herbicide had been applied by the time of cover crop termination. Hence, factors included in the ANOVA of spring weed biomass included the rotation type, the herbicide treatment (fall herbicide or no fall herbicide), and termination time (Table 2.3). The cover crop biomass was only influenced by termination time ($p < 0.0001$) in both years, indicating that planting a cereal rye-oat mix earlier in the fall did not lead to an increased cereal rye biomass production in the spring (Table 2.2). There was a significant increase in cover crop biomass when delaying cover crop termination of 2331 and 2316 kg ha^{-1} in 2017 and 2018 respectively (Figure 2.4). These biomass differences can be associated to a longer cover crop growing season in the spring during a period of favorable environmental conditions (temperature, solar radiation) and with sufficient soil moisture, which favored fast cereal rye growth.

In 2018, the ANOVA of spring weed biomass showed significant main effects of rotation type, termination time, and herbicide treatment on weed biomass ($p<0.0001$), as well as a significant rotation type by herbicide treatment interaction ($p=0.0008$) (Table 2.3). However, in Spring 2019 weed biomass was affected only by the rotation type ($p<0.0001$) and the termination time ($p=0.0002$), but not by the herbicide treatment ($p=0.9264$). The main effect of termination time on weed biomass indicated that weed biomass was highest by the time of the late cover crop termination in both 2018 and 2019 (Figure 2.5). By the spring, in both growing seasons, results indicate that cover crops planted earlier in the fall after a short-season MG cultivar did not improve weed suppression the following spring (Figure 2.6 a,b). Relative to the no cover treatment, all cover crop treatments were able to reduce weed biomass in the spring by 60% or more in

2018, and by 80% or more in 2019. In addition, weed biomass in 2018 was reduced with the fall herbicide application across in rotation types, except for the MG 1 and 3 treatment (Figure 2.5a). This suggests that when there is a high pressure of winter annual weeds, the combination of cereal rye plus a fall broadleaf herbicide would be the most effective management strategy.

3.3. Cover crop and weed ground cover.

The repeated measures analysis of cover crop ground cover indicated that only rotation type and its interaction with date had a significant impact on the percentage of ground cover over time in both 2017/18 and 2018/19 growing seasons (Table 2.3). Thus, the percentage of ground cover over time is shown by cover crop rotation type treatment in Figure 2.7. Percentage of ground cover was different among rotation type treatment until 26 March (2018) and 28 January (2019), in where ground cover was similar across all cover crop treatments (Figure 2.7). Based on these results, we chose the date in were oat winterkilled to quantify differences in percentage of ground cover (indicated with the arrow in figure 2.7) across the different cover crop treatments. Results from the first growing season show that before the oat was winterkilled (28 Nov 2017), percentage of ground cover was different across rotation type treatments. Cover crops planted after MG 1 had 27% more ground cover than MG 2, 36% more than MG 3 and 75% more than MG 4 (p<0.0001). In 2018/19 growing season, the percentage of ground cover before oat winterkilled (11 Dec 2018) for MG 1 did not differ from MG 2 (p=0.2875). However, cover crops planted after MG 1 were able to have 24 % more of ground cover than MG 3 (p = 0.0004) and 39 % more than MG 4 (p < 0.0001).

The analysis of repeated measured from fallow treatments was used to test the effect of the different herbicide treatments on weed canopy cover (Table 2.4). Results indicated that herbicide and its interaction with date had an effect on percentage of ground cover during the 2017/18 growing season, but during 2018/19 only the interaction was significant (Table 2.4). In 2017/18, weed biomass was different across herbicide treatments from the 9 February until 26 March. In 2018/2019 herbicide and its interaction with time was significant. However, differences in herbicide treatments for a given date resulted in not being significant.

4. DISCUSSION

4.1. Evaluation of management strategies to increase cover crop biomass.

We observed differences in cover crop biomass produced during 2017/18 and 2018/19 that can be associated to differences in environmental conditions each year, such as temperature and water availability (Vernard and Roberts, 2017, 2018; Mirsky et al., 2011; Webster et al., 2016). When evaluating treatment effects on cover crop biomass, our results indicate that planting cover crops after MG 1 soybeans was effective to increase biomass from a mixed cover crop in the fall in comparison to planting cover crops after MG 4. However, cover crop biomass the following spring, composed only of cereal rye, was similar across all cover crop treatments regardless of the previous soybean MG cultivar in the rotation, and the cover crop planting date in the fall. Instead, it was the date of termination that influenced cereal rye biomass in the spring. Previous research has found that cover crop biomass increases when advancing cover crop planting date, as a consequence of a longer cover crop growing window (Prabhakara et al., 2015; Teasdale et al., 2004; Thapa et al., 2018). Data from our study would be consistent with these studies when total cover crop biomass is added up (spring + fall biomass), including senesced oat biomass. However, when evaluating only treatment effects on the cereal rye cover crop, differences across treatments and overall fall biomass were very small (< 200 kg ha^{-1}), likely due to competition from oats. This could partially explain the lack of differences in cereal rye biomass across rotation type treatments which survived the winter and regrowth the following spring. It would be interesting to evaluate in another study if a winter cereal rye without the oat competition would have greater differences in biomass in the fall, and if these differences would be sustained the following spring as Lawson et al (2015) did.

4.2. Cover crop management strategies for enhanced weed suppression.

An unexpected outcome from our study was that cover crops planted earlier in the fall after a short-season soybean did not improve weed suppression. Instead, total weed biomass increased when cover crops were planted after early MG soybeans, contrary to our initial hypothesis. These outcomes are likely because weed biomass is not solely influenced by cover crop biomass, but other environmental and physical factors might have contributed to differences in weed biomass across treatments. First, full-season soybean maturities have a longer growing season, increased vegetative biomass and crop residue at harvest compared to short-season soybeans (Edwards et al., 2005; Egli, 1993). Thus, these conditions would lead to less light reaching the soil surface, which is associated with enhanced inhibition of weed germination (Upadhyaya and Blackshaw, 2007). Second, environmental conditions for the time of soybean harvest were more favorable in short-season MG soybeans, than later on when full-season MG 4 cultivars were harvested. These improved environmental conditions and longer growing season for weed or cover crops after early MG soybeans did not only increase fall cover crop biomass production, but weed biomass growth during the same period. Daily average temperature and solar radiation during this critical fall period will decrease rapidly over time, resulting in less optimal environmental conditions at the start of the fallow/cover crop period after a late harvested cash crop. For instance, the historical monthly average temperature in Lexington, KY is 20.2°C in September, but decreases to 8°C in November (UK Ag Weather Center http://www.agwx.ca.uky.edu). Hence, environmental conditions for weed germination and growth would be less favorable after full-season MG cultivars, and could explain the results obtained in our study.

The amount of solar radiation reaching the soil surface has a large effect on weed emergence, and fast development of a canopy cover can be an effective weed control measure (Upadhyaya and Blackshaw, 2007). Our results showed that cover crops planted earlier after short season MG soybeans had a greater canopy cover in the fall in both years, and in early spring in one out of two years. Thus, cover crops planted earlier were able to achieve a full canopy earlier in the growing season, and would be more effective suppressing emergence of new weeds. However, the higher weed biomass observed in this study after short-season MG soybeans is not well explained by differences in cover crop canopy cover. Instead, our results suggests that weed biomass was affected to a larger extent by temperature conditions after soybean harvesting influencing early weed emergence, and that the increased cover crop canopy cover was not able to offset weed pressure from weeds that had already emerged.

4.3. Cover crop-herbicide integrated management recommendations.

The fall herbicide treatment was effective in reducing the weed biomass by the time of cover crop termination the following spring, depending on environmental conditions and weed pressure each year. For instance, the winter annual weed pressure in 2018 was relatively low and the fall herbicide application did not further reduce an already low weed biomass the following spring. Hence, this suggests that in fields in where there is a high pressure of winter annual weeds applying a fall herbicide will improve weed suppression with or without cover crops. Percentage of ground cover analysis for these plots also supports our previous conclusion because ground cover differences were only expressed in the field with high pressure of winter annual weeds and close to corn planting.

5. CONCLUSION

Our initial hypothesis stated that adapting a short-season soybean into crop rotations will allow to advance cover crop planting date increasing its biomass production and percentage of ground cover, resulting in better weed control. Our outcomes for 2017/2018 and 2018/2019 showed that planting a cover crop earlier in the fall increased cover crop biomass production and percentage of ground cover. This increase was between 27 and 97 % when comparing cover crop plantings after MG 1 and 4. However, cover crop planted after a MG 1 cultivar did not have an effect on weed suppression either in the fall nor in the spring. Nonetheless, cover crops were able to improve weed suppression in comparison with the no cover treatments and this suppression was higher when using a fall herbicide application and there was a high winter annual weed pressure in the field.

6. CHAPTER 2: TABLES AND FIGURES.

Table 2. 1. Subplot herbicide treatments.

Treatment	Description	Trade name	Active ingredient	Rate	Application time 2017 - 2018	Application time 2018 - 2019
				g ai or ae ha^{-1}*		
1	Fall burn-down + PRE and POST corn emergence	Clarity	dicamba	650 ae	11/08/2019	11/05/2019
		Acuron	Bicyclopyrone	21.9 ai	05/09/2019	05/07/2019
			Mesotrione	87 ai		
			S-Metolachlor	787 ai		
			Atrazine	368 ai		
		Roundup Powermax	Glyphosate	720 ae	06/15/2018	06/13/2019
2	PRE and POST corn emergence	Acuron	Bicyclopyrone	21.9 ai	05/09/2019	05/07/2019
			Mesotrione	87 ai		
			S-Metolachlor	787 ai		
			Atrazine	368 ai		
		Roundup Powermax	Glyphosate	720 ae	06/15/2018	06/13/2019
3	POST corn emergence	Roundup Powermax	Glyphosate	720 ae	06/15/2018	06/13/2019

* rates for dicamba and glyphosate are given in g a.e. (acid equivalent) ha^{-1} while rates for the remaining products are in g a.i. (active ingredient) ha^{-1}

Table 2. 2. Probability values from the ANOVA of cover crop and weed biomass in the fall of 2017 and 2018, and spring of 2018 and 2019. In the fall, rotation type (RT) and its interactions were considered as a fixed factor while in the spring rotation type, cover crop termination, herbicide treatment and their interaction were considered as fixed factors.

Effect	Cover Crop Biomass†				Weed Biomass			
	Fall 2017	Spring 2018	Fall 2018	Spring 2019	Fall 2017	Spring 2018	Fall 2018	Spring 2019
Rotation type (RT)	0.0023	NS	0.0123	NS	0.0045	<0.0001	0.0225	<0.0001
Termination	-	< 0.0001	-	< 0.0001	-	<0.0001	-	0.0002
RT* Termination	-	NS	-	NS	-	NS	-	NS
Herbicide	-	-	-	-	-	<0.0001	-	NS
RT*Herbicide	-	-	-	-	-	0.0008	-	NS
Herbicide * Termination	-	-	-	-	-	NS	-	NS
RT*Herbicide*Termination	-	-	-	-	-	NS	-	NS

† Cover crop biomass includes only data from rotations with winter cover crop.

Table 2. 3. ANOVA of the percentage of canopy cover in cover crop treatments during the 2017/19 and 2018/19 fall-spring period. Rotation type and herbicide treatment were considered as fixed effects, and date was included as a repeated measures covariable in the model.

	2017/18		2018/19	
Effect	DF	*p* value	DF	*p* value
Rotation type (RT)	3	<.0001	3	0.0059
Herbicide	1	0.4328	1	0.4126
RT*Herbicide	3	0.3900	3	0.2631
RT*Date	42	<.0001	24	<.0001
Herbicide*Date	14	0.8367	8	0.6084
RT*Herbicide*Date	42	0.7085	24	0.9876

Table 2. 4. ANOVA of the percentage of weed cover in herbicide treatments during the 2017/19 and 2018/19 fall-spring period. Rotation type and herbicide treatment were considered as fixed effects, and date was included as a repeated measures covariable in the model.

	2017/18		2018/19	
Effect	DF	*p* value	DF	*p* value
Herbicide	1	0.0126	1	0.1956
Herbicide*Date	28	<.0001	16	0.0016

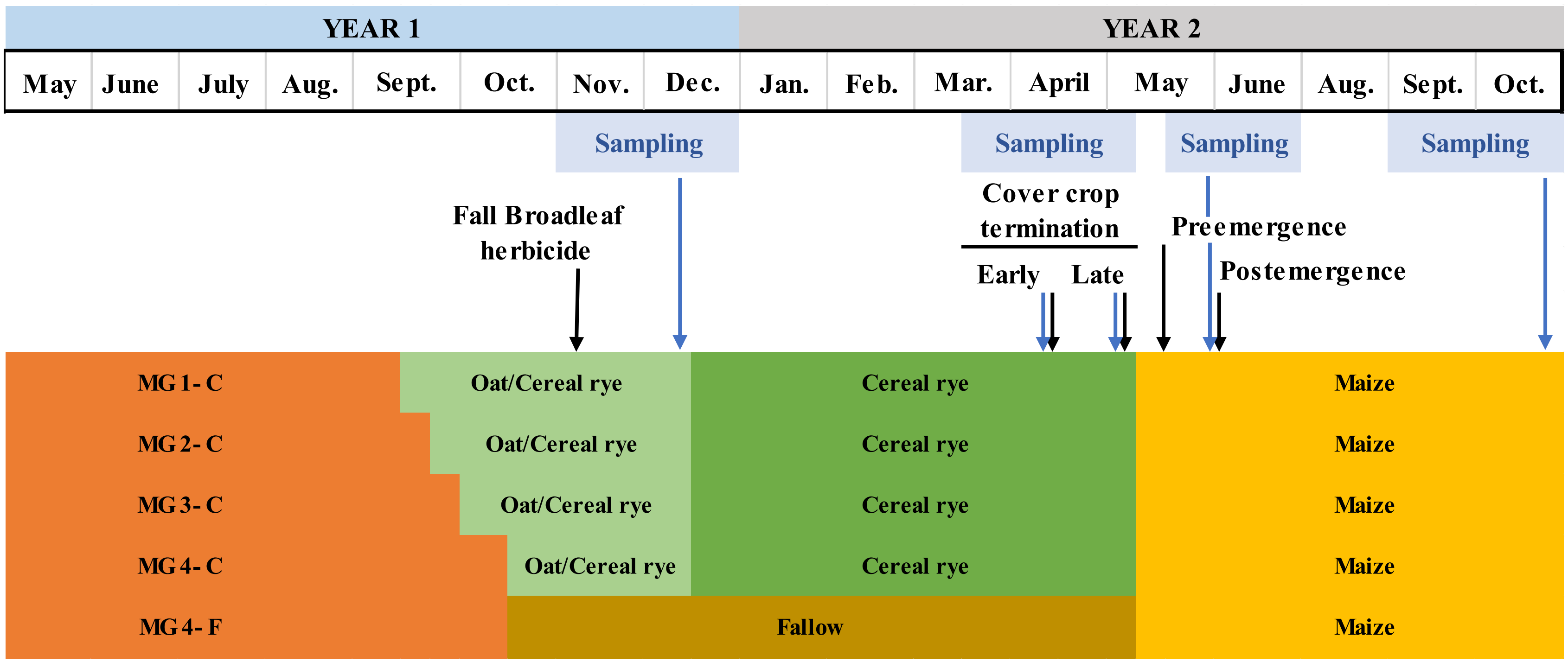

Figure 2. 1. Timeline for experiment 2 management for two consecutive years. Time line shows an estimate of the time in when activities were performed. Both November/December and March/April consisted on weed and cover crop biomass samplings. May/June and September/October consisted of weed biomass sampling only.

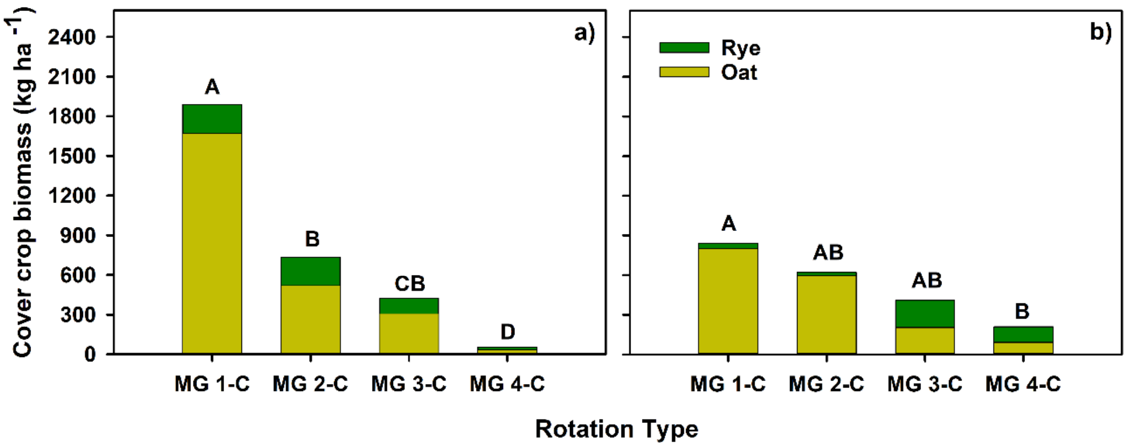

Figure 2. 2. Rye and Oat cover crop biomass by rotation type prior to oat winterkill (due to natural freezing temperatures) in 2017 (a) and in 2018 (b). Bars show standard error. Significant differences between a rotation type and within a growing season are denoted with different letters (significant at *p*<0.05).

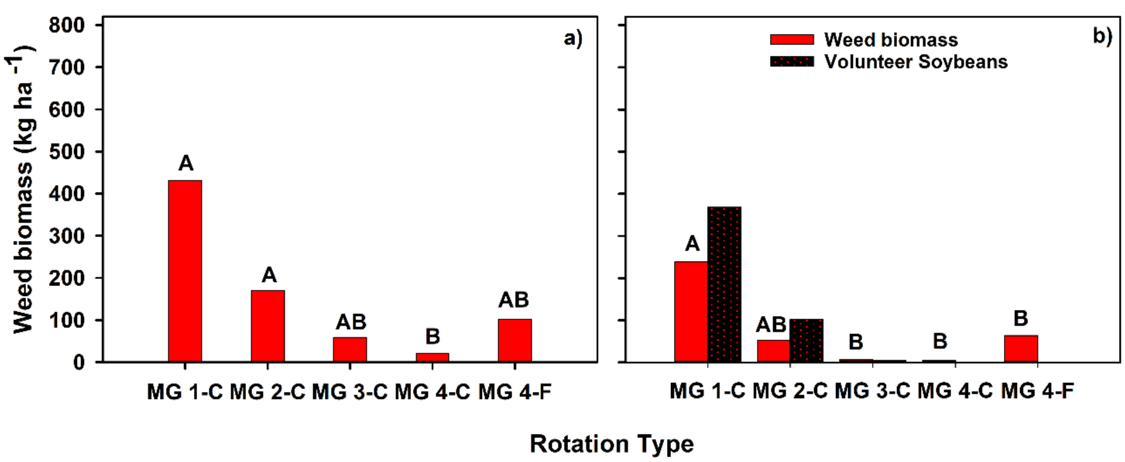

Figure 2. 3. Weed biomass in the fall for the different rotation treatments. In 2017 samples were collected on 28 Nov (a), while in 2018 samples were collected on 8 Nov (b). Data from volunteer biomass is also provided in 2018.

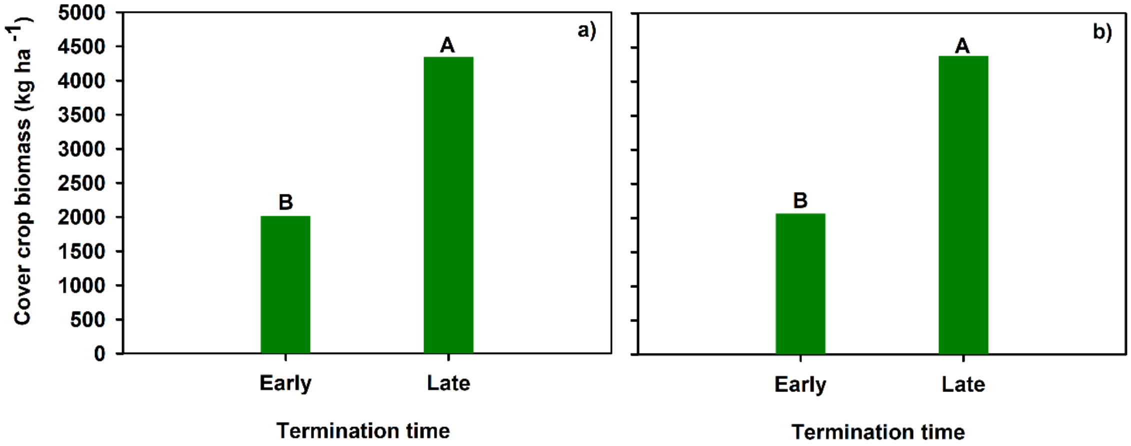

Figure 2. 4. Cover crop biomass produced by termination treatment in 2017 (a) and 2018 (b). Significant difference between cover crop biomass precede by termination time are denoted with letters (significant at $p<0.05$).

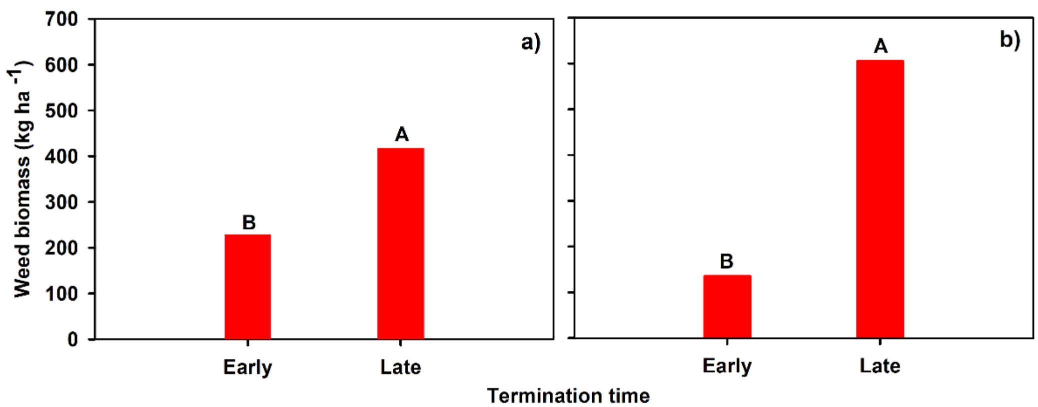

Figure 2. 5. Weed biomass production in the spring by the time of early and late cover crop termination in 2017 (a) and 2018 (b). Significant differences within the same growing season are labeled with different letters (significant at $p<0.05$).

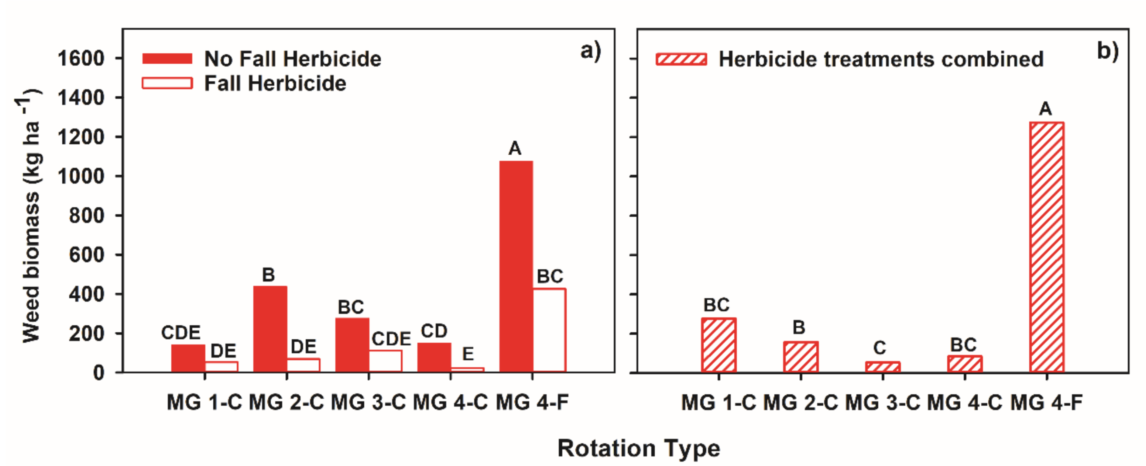

Figure 2. 6. Weed biomass at cover crop termination by herbicide treatment and/or rotation type in 2017 (a) and 2018 (b). In 2018, there was only a significant effect of rotation type, and results area averaged across herbicide treatments.

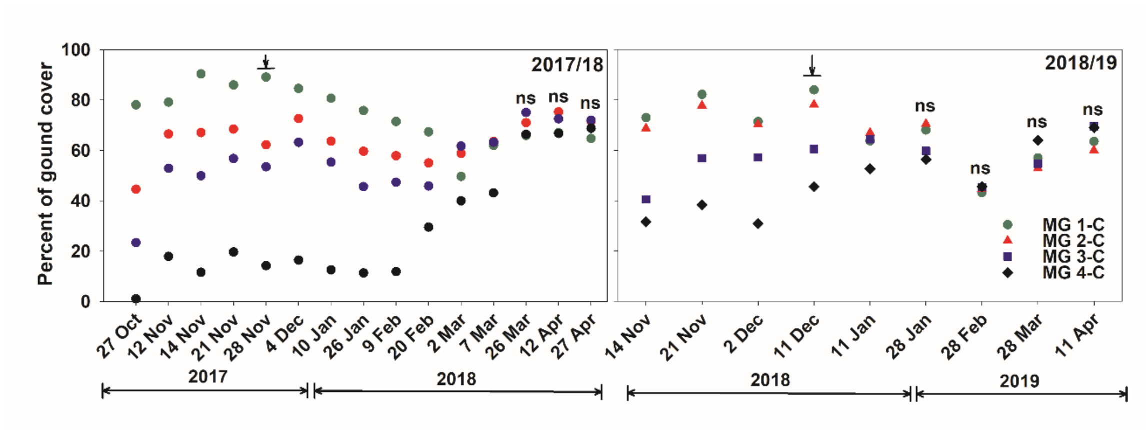

Figure 2. 7. Effect of the rotation treatment on percentage of cover crop ground cover during the 2017/18 and 2018/19 fall-spring period. Only treatments with a winter cover crop are included in this graph. Arrow represent the key date selected to evaluate the effect of MG and ns indicate when percentage of ground cover was not significant across treatments.

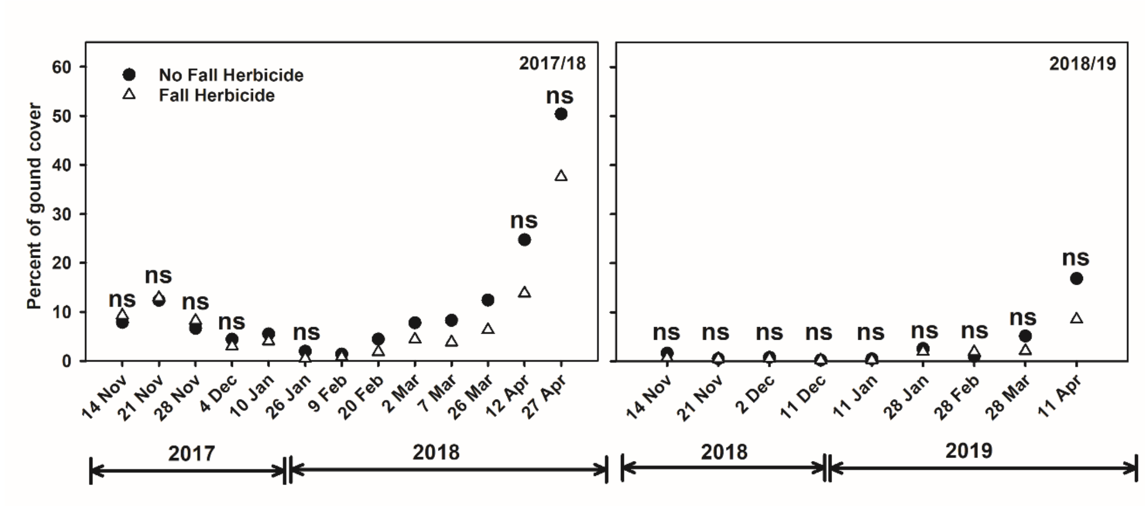

Figure 2. 8. Percent of weed ground cover from control plots without a cover crop (MG4 - F) by herbicide treatment during the 2017/18 and 2018/19 fall/spring.

Chapter 3: Sensitivity analysis on the impact of cover crops on nitrogen and water availability in corn.

ABSTRACT

In the last years, the use of cover crops has raised interest into agricultural research because of the many benefits associated to this practice, such as reduced runoff and nitrogen losses through leaching. However, cover crops can reduce water and nitrogen availability for the next cash crop compared to a winter fallow depending on the environmental conditions and cover crop management. The objective of this study was to quantify cover crops impact on nitrogen and water dynamics under different cover crop management options in a soybean-cover crop or fallow-corn rotation and for 30-yr of weather data in Lexington, KY, using a crop simulation model. On a future step, after corn and cover crop calibration, we will also conduct a sensitivity analysis for the aforementioned responses across different soil properties, and changes in precipitation, to increase the applicability of our results to other locations. We performed crop rotation simulations using DSSAT v 4.7.5.0 software and the SEQUENCE option to simulate a 2-yr soybean-cover crop or fallow – corn rotation. Treatments included soybean MG cultivars from 2 to 4 that allowed an earlier planting of cover crops, a fallow control treatment, and two cover crop termination times (26 April and 8 May). Simulations were conducted on a silty clay loam soil. Overall, results show a large variability across the 30-yr period. Cover crops planted after different soybean MG cultivars had similar biomass and N uptake before termination, which was associated with N availability and not cover crop planting date. Cover crops terminated early, reduced soil-available water at corn planting by only 1 to 3 mm in comparison to fallow, while delaying cover crop

termination reduced soil available water at corn planting by 11 to 15 mm. Cover crops reduced runoff on average by 1 to 7 mm. Corn transpiration was between 6 to 9 mm lower when corn followed cover crops. Planting cover crops reduced soil nitrogen content at corn plating by 21 to 30 kg ha^{-1} in comparison to fallow and delaying cover crop termination added an additional nitrogen reduction of 4 to 5 kg ha^{-1}. As a result, cover crops reduced cumulative nitrogen uptake by 7 to 19.2 kg ha^{-1} compared to a fallow treatment, and when delaying cover crop termination this reduction was greater (8.2 to 11 kg N ha^{-1}).

1. INTRODUCTION

Winter cover crops are grown between two summer cash crops with the goal of producing ground cover during the winter months. In the last years, the use of cover crops has raised interest in agricultural research because of the many benefits associated to this practice. Some of these benefits include a reduction in soil erosion (Dabney, 1998; Langdale et al., 1991; Mutchler and McDowell, 1990), an increase in the natural abundance of beneficial insects (Letourneau et al., 2011; Sunderland and Samu, 2000; Tilman et al., 2002), and a greater herbicide resistant weed control (Sarrantonio and Gallandt, 2003; Wiggins et al., 2015, 2016).

In the US Mid-South and Upper-Midwest region, small grain cover crops such as cereal rye and wheat are well adapted in rotation with grain cash crops because of winter hardiness, high aboveground biomass production, and winter weed suppression (Haramoto, 2019). However, early cover crop seeding dates are critical for a good cover crop establishment and biomass production in the fall (Bich et al., 2014; Hively and Cox, 2001; Johnson et al., 1998; Sarrantonio and Gallandt, 2003). Greater cover crop biomass production has been associated with increased weed control benefits (Haramoto, 2019; Sarrantonio and Gallandt, 2003; Teasdale and Mohler, 2000), and increased soil aggregation (Fageria et al., 2005; McVay et al., 1989). A recent simulation study in KY, OH, and NE, showed that adapting to short-season soybean maturities would advance harvest by 6.6 to 11 days per unit decrease in cultivar maturity when soybean was planted on May 15 (Sciarresi et al., under review). This study showed that it was possible to adapt to MG 0 to 3 cultivars depending on the location without yield penalty, and these would provide an average cover crop growing window of 34 to 51 days or 257 to 270 growing degree days (GDD; base 4.4 ºC) after a soybean crop planted on May 15 (Sciarresi et al, under review). One aspect not yet studied from this management adaptation is the impact on soil water and nitrogen dynamics, and the carry over effects on the following crop.

Several studies have focused on cover crops impact on nitrogen and/or water dynamics (Kuo and Jellum, 2002; Feyereisen et al., 2006; Salado-Navarro and Sinclair, 2009; Krueger et al., 2011; Gabriel et al., 2012; Ward et al., 2012; Salmerón et al., 2014). Potential benefits from cover crops include a reduction in nutrient loses (Jackson, 2000; Di and Cameron, 2002; Salazar et al., 2019), in particular N loses through leaching in maize cropping systems (McCracken et al., 1994; Salmerón et al., 2010), and an increase in soil water infiltration (Dapaah and Vyn, 1998; Fageria et al., 2005; Hargrove, 1986; McVay et al., 1989; Meisinger et al., 1991). Nitrogen contained in cover crop biomass, that would have been otherwise lost through leaching during winter, can be mineralized and be available for the next crop, improving the overall system’s N balance (Jackson, 2000; Salmerón et al., 2014). However, there are also potential negative effects when cover crops reduce nitrogen and water availability for the next crop. Previous studies in other regions have shown that non-legume cover crops can negatively influence corn yields due to nitrogen limitation (Miguez and Bollero, 2006; Salmerón et al., 2010), and reduce water availability for the next crop (Qi et al., 2011). This could limit yields of corn grown commonly in rotation after soybean in US Mid-South and Upper-Midwest region, when the winter cover crop growing window and biomass produced is increased.

Another management factor that will influence cover crop biomass production and aboveground N content is the date of cover crop termination in the spring (Lawson et al., 2015; Liebl et al., 1992; Sainju and Singh, 2001) because a greater cover crop biomass accumulation will imply grater C:N ratio. Adapting soybean maturity to increase the cover crop growing cycle, or delaying termination dates could increase the ecosystem services provided by cover crops. However, it is critical to evaluate water and N dynamics under these management adaptations. Although several studies have explored the effect of these management adaptations on cover crop biomass production, these studies are limited to a number of years, locations, and/or soil types (Lawson et al., 2015; Liebl et al., 1992; Sainju and Singh, 2001). Hence, there is still uncertainty on how these variables will influence water and nitrogen availability for the next crop.

Calibrated dynamic process-based crop models can be used to explore numerous scenarios and treatment combinations, and predict water and Nitrogen cycling to identify best management recommendations. These tools have been successfully used to study crop rotations in Argentina (Salado-Navarro and Sinclair, 2009), United States (Feyereisen et al., 2006), Africa (Musinguzi et al., 2014; Soler et al., 2011), and Spain (Salmerón et al., 2014). The Decision Support System for Agrotechnology Transfer

(DSSAT) (Hoogenboom et al., 2015; Jones et al., 2003) is a software comprising many crop models with the ability to simulate crop rotations and carry-over effects on soil water and nitrogen. This software has been previously evaluated against field data to simulate water and nitrogen dynamics with different crop rotations (Kelly et al., 1997; Kovács et al., 1995; Porter et al., 2010; Salmerón et al., 2014).

The objective of this study was to conduct a preliminary evaluation of the impact of different cover crop management adaptations (cover crops planted after soybean MG 2 to 4 cultivars, and two cover crop termination times) on nitrogen and water dynamics using 30-yr of weather variability in Lexington, KY. On a subsequent step, the model will be parametrized with field data from different locations in KY to further identify management adaptations that optimize water and N cycling and availability for corn grown after cover crops.

2. MATERIALS AND METHODS

2.1. Simulation scenarios.

Crop rotation simulations were performed with the DSSAT v 4.7.5.0 software and the SEQUENCE option to simulate crops in rotation and carry-over of water and soil nitrogen. A rotation of soybean – cover crop or fallow – corn (2-yr) with soybean planted on 1 May and corn planted on 10 May was used as the baseline to analyze the effect of different winter cover crop managements adaptations. Simulations were conducted for 30-yr of weather data in Lexington, KY, with re-initialization of water and N at the start of each 2-yr rotation. The management adaptation factors that were evaluated are: (1) cover crops (or fallow) following soybean MG cultivars 2 to 4 allowing an earlier (MG 2) or later (MG 4) cover crop planting time, and (2) cover crops terminated on 25 April or two weeks later. To account for year-to-year variability, simulations were carried out using historical 30-yr (1987-2017) weather data from.

The soybean part of the rotation was simulated using CROPGRO-Soybean, the winter wheat cover crop was simulated using CROPSIM - CERES, and CERES-Maize was used to simulate corn. Reference evapotranspiration was calculated based on Priestley and Taylor (1972). The CENTURY soil organic matter module (Parton et al., 1994) in DSSAT was used to simulate organic carbon and nitrogen decomposition. This module has been previously used to simulate organic carbon and nitrogen in long-term studies (Kelly et al., 1997; Smith et al., 1997), in low-input systems (Soler et al., 2011), and short term effects of cover crops on corn aboveground N (Salmerón et al., 2014). To allow cover crop planting as close as possible to soybean harvest maturity, cover crops were planted based on the latest predicted soybean harvest across the 30-yr period.

2.2. Experimental data and model parametrization.

Soybean crop growth coefficients for DSSAT-CROPGRO for MG 0 to 4 already calibrated under our conditions were used (Sciarresi et al., under review). Sciarresi et al. (under review) found that MG 2 to 4 cultivars had similar yields in Lexington, KY depending on the year and soil conditions, and would provide a range in harvest and cover crop sowing dates to test our hypothesis.

A preliminary calibration of corn growth coefficients for DSSAT-CERES was conducted with data from an irrigated trials during 2017 and 2018 in Lexington, KY (Di Salvo et al., unpublished data). Plots were arranged in a split plot design with irrigation management (irrigation vs. rainfed) as the split-plot factor with four replications. The corn hybrid P2089 was planted on May 3 in 2017 and May 9 in 2018 on a Bluegrass-Maury silt loam (fine, mixed, active, mesic, Typic Paleudalfs) with a planting density of 7.8 plants m^{-2}. Plots were 9 m length and 4 row wide with a row spacing of 0.76 m. Irrigation was applied with a drip tape when cumulative water deficit reached 40 mm based on a daily water balance of precipitation and crop evapotranspiration demand calculated based on Allen et al., 1998. Both years plots were fertilized with ammonium nitrate at a rate of 320 kg of N ha^{-1} divided into three application of 106 kg N ha^{-1} each at planting, V6 and V14 (Ritchie and Hanway, 1989). Pests were chemically and/or manually controlled during the season when required.

The CERES – Maize model requires calibration of six growth coefficients: thermal time from emergence to end of juvenile phase (P1), photoperiod sensitivity (P2), thermal time from flowering to physiological maturity (P5), maximum kernel number per plant (G2), kernel growth rate during linear phase and under optimal conditions (3), and phyllochron interval (PHINT). Coefficient P2 was fixed to 0.300 days and the other coefficients were calibrated in consecutive steps to minimize the RMSE in the prediction of anthesis, harvest maturity, number of kernels per ear, kernel weight, and grain yield. Thereafter, the rainfed treatments will be used to evaluate the model under conditions of water stress after parametrization of soil properties. A second set of experiments will be used to calibrate the different organic C and N pools in CENTRUY and evaluate CERES-Maize model performance predicting yield, and grain/aboveground N in corn grown after a cover crop and with different nitrogen fertilizer rates (Quinn et al., unpublished data). This study consisted of a three way factorial study with a main rotation factor including cover and no cover crop treatment, two nitrogen application times and six nitrogen fertilizer rates for Lexington, KY in 2018 and Lexington, Glendale, and Princeton, KY in 2019. At each site, in season data collection included cover crop biomass production, total carbon and nitrogen content, inorganic soil nitrogen content at the time of cover crop termination, corn developmental stages, total nitrogen content in corn ear leaf tissue at R1, total corn biomass, grain weight and nitrogen content, and corn stalk nitrate concentration at R6. End of season data collection will include grain test weight, yield and yield components.

For the purpose of this thesis chapter, simulations were run with a generic silty clay loam soil described in Table 3.1. After further model parametrization and evaluation for prediction of grain yield and aboveground N content with observed data, final simulation results will be generated for a research publication.

2.3. Data analysis

Model performance during calibration and evaluation will be assessed using the root mean square error between observed and simulated data (Equation 1). Model outputs that will be evaluated against observed data are date of anthesis and physiological maturity in corn, kernel number, individual kernel number, corn yield and aboveground N content, as well as cover crop biomass and aboveground nitrogen content.

$$\text{RMSE} = [N^{-1}\Sigma_{i=1}^{n}(P_i - O_i)^2]^{0.5} \quad (1)$$

In addition, the model efficiency (ME) will be computed as:

$$\text{ME} = 1 - \frac{\sum_{c=1}^{N}(S_c - O_c)^2}{\sum_{c=1}^{N}(O_c - O_{av})^2} \quad (2)$$

where O_c is the observed value for flowering and physiological maturity date, kernel number, individual kernel number and yield for a given hybrid, S_c is the simulated value, O_{av} is the mean of the environment, and N is the number of observations for each cultivar. The ME ranges from -∞ to 1, with 1 being the optimal value. ME values between 0 and 1 are general viewed as acceptable level of model performance while values <0 indicate that the observed value is a better predictor than the simulated.

Simulation scenarios under different cover crop management adaptations will evaluate model outputs on total soil inorganic N (N-NO_3 and N-NH_4^+) and crop soil available water at corn planting, corn total transpiration and N uptake, total N-NO_3- leached, as well and net N mineralized during the corn growing season. Results will be analyzed calculating the average and standard error based on 30-yr simulations, and with cumulative probability graphs.

3. RESULTS

3.1. *Cover crop biomass production and nitrogen uptake*

The average harvest maturity date of soybean based on the 30-yr simulation was Sep 8 (MG 2), Sep 17 (MG 3), and Oct 8 (MG 4) with a range of +/- 10 days from year to year (data not shown). To simplify cover crop model settings, the latest soybean harvest date for each treatment was used to define a fixed cover crop planting date for each of the 30-yr simulations. Thus, simulations were conducted with cover crops planted on 16 Sep, 25 Sep, and 8 Oct after MG 2, 3, and 4 soybeans, respectively.

There was large variability in predicted cover crop biomass and total nitrogen uptake across the 30 years indicated by the large standard errors (Figure 3.1). On average, cover crop biomass ranged from 3.6 Mg ha^{-1} after MG 2 soybeans to 4.2 Mg ha^{-1} after MG 4 soybeans (Figure 3.1a). Cover crops terminated late accumulated 0.72 to 1 Mg ha^{-1} more than when cover crops were terminated early. On average, cover crop nitrogen uptake ranged from 56.5 kg N ha^{-1} after MG 2 soybeans to 50.3 kg N ha^{-1} after MG 4 soybeans (Figure 3.1b). Delaying termination increased cover crops N uptake by only 3.7 to 4.9 kg N ha^{-1} (Figure 3.1b).

Overall, planting cover crops earlier after short-season MG cultivars had a minimal effect on cover crop biomass and N uptake. However, there was high year-to-year variability in cover crop biomass produced and N uptake across the 30-yr, that was larger for cover crop planted soybean MG 4.

3.2. *Water dynamics during the corn growing season*

Total crop available water at corn planting, cumulative runoff and total seasonal transpiration showed a large variability from year-to-year, represented by the standard error in Figure 3.2. When cover crops were terminated early, differences on crop soil available water at corn planting were negligible, only 1 to 3 mm higher after the cover crop than after a winter fallow. In contrast, delaying cover crop termination by 2 weeks reduced total crop available water by 15 mm (MG 2), 16 mm (MG 3) and 11 mm (MG 4) on average across the 30-yr (Figure 3.2a).

Similarly, the effect of the treatments on cumulative runoff during the corn growing season were small. Cumulative runoff was on average 7 and 4 mm lower when cover crops were planted after MG 2 and 3 soybeans, respectively, and 1 mm higher when cover crops followed soybean MG 4 relative to the fallow (Figure 3.2b). Delaying cover crop termination had a negligible effect on water runoff during the corn growing season (< 1mm) (Figure 3.2b).

The final water availability for corn was evaluated by comparing total seasonal corn transpiration across treatments. Cover crops planted after a full season MG 4 soybean reduced corn transpiration by 6 mm. When cover crops were planted earlier after MG 2 soybeans, corn transpiration was reduced by an additional 9 mm compared to cover crops planted after MG 4 soybeans. Delaying cover crop termination reduced corn transpiration further, on average by 6 to 7 mm (Figure 3.2c). Overall, cover crops had a relatively small but negative effect on water availability for corn. The cumulative probability graphs for corn transpiration indicate that when planting cover crops after MG 2 soybeans, corn transpiration would be reduced in 32 % of the years (Figure 3.4 a). When cover crops were planted after soybean MG 3 and 4 this probability increased to 38 % and 40% respectively (Figure 3.4 b,c).

3.3. *Nitrogen dynamics during the corn growing season*

Not surprisingly, initial inorganic N content at maize planting was lower when cover crops were introduced in the crop rotation (Figure 3.3 a). The reduction in soil inorganic N was greater when cover crops were planted earlier. There were 30, 28, and 21 kg ha^{-1} less soil inorganic N at corn planting after cover crops following MG 2, 3, and 4 soybeans, respectively (Figure 3.3a). When cover crops termination was delayed, soil inorganic N was reduced by only 4 – 5 kg N ha^{-1} more on average on the day of corn planting. There was a large standard error in soil inorganic N for all treatments that was greatest after MG 4 soybeans, caused by high year-to-year variability (Figure 3.3a).

Cover crops reduced N leaching during the intercrop period between soybean and corn by 32%. N leaching during the corn growing season was very low in corn after the fallow treatment with only 4-6 kg N ha^{-1} on average. The residual effect of cover crops reduced further this amount by only 1-2 kg N ha^{-1} (Figure 3.3b). Delaying cover crop termination reduced N leaching but the effect was minimal under these conditions of limited N leaching (< 1 kg N ha^{-1}) (Figure 3.3b).

Cumulative net N mineralization during the corn growing season was also highly variable from year-to-year, indicated by the error bars (Figure 3.3c). Net N mineralization was greatest in rotations with MG 4 soybeans, and under fallow treatments. When cover crops termination was delayed, net N mineralization during the corn growing season was reduced by 4 - 5 kg N ha^{-1} (Figure 3.3c).

There overall effect of the different treatments on corn N availability was evaluated by quantifying treatment effects on corn N uptake. Similar to other variables evaluated, corn N uptake showed a high standard error across the years simulated (Figure 3.3 d). On average, when comparing cover versus fallow treatments, cover crops reduced cumulative nitrogen uptake by 19.2 kg ha^{-1} (MG 2), 17.1 kg ha^{-1} (MG 3), and 7 kg ha^{-1} (MG 4) compared to a fallow treatment. When cover crops were terminated late, corn N uptake was reduced to a greater extent, on average by 30 kg ha^{-1} (MG 2), 28.1 kg ha^{-1} (MG 3) and 15.2 kg ha^{-1} (MG 4) (Figure 3.3 d). Overall, delaying cover crop termination reduced corn N uptake by 8.2 and 11 kg N ha^{-1} (Figure 3.3 d).

Results from the cumulative probability graphs indicate that corn N uptake was the lowest when following cover crops terminated late across all rotation treatments. When cover crop or fallow followed soybean MG 2 and 3, for a given nitrogen uptake value

(~300 Kg ha^{-1} or greater) probabilities were the highest for corn after fallow (84%), followed by corn after early cover crop termination (74%) and corn after late cover crop termination (63%) (Figure 3.4 a,b). However, when cover crop or fallow followed soybean MG 4 the probabilities of corn having ~300 Kg ha^{-1} of nitrogen uptake or greater became similar across rotation treatments with 82% chances for corn followed fallow, and 77% chances when corn follow early or late termination.

4. DISCUSSION

Our objectives were to quantify the impact of cover crops on nitrogen and water dynamics, and in particular on nitrogen and water availability for a corn grown after a soybean – cover crop/fallow rotation. Our preliminary results from 30-yr simulations showed a 0.62 Mg ha^{-1} decrease in cover crop biomass when planting cover crops after MG 2 soybeans compared to full-season MG 4 soybeans. This small treatment effect on cover crop biomass was unexpected but is consistent with the cover crop biomass analysis in Chapter 2, that showed no differences in spring biomass for cover crops planted after MG 1 to 4 soybeans. A delay in cover crop termination of 13 days increased biomass by only 0.86 Mg ha^{-1} on average based on the 30-yr simulations, compared to 2.3 Mg ha^{-1} observed in Chapter 2. Interestingly, our simulations showed that cover crop N uptake was 6.2 kg N ha^{-1} higher on average after MG 2 soybeans compared to MG 4. These results and the overall low cover crop N uptake indicate that the low biomass production was partially associated to a very low N availability during the cover crop growing season. Results obtained under a soil with more residual inorganic N and/or higher organic matter may increase crop biomass and N uptake for cover crops planted earlier. This hypothesis is also supported by preliminary simulations that allowed carry-over of C, water and N for 30-yr and accumulation of soil organic matter over time, increasing N availability during the cover crop growing season (data not shown). Thus, model simulations after complete model calibration and parametrization of soil properties will be essential for providing robust predictions of cover crop biomass and N uptake for the treatments evaluated. Overall, there was a high year-to-year variability on both cover crop biomass and N uptake, that was greater than the effect of the treatments evaluated. However, simulation results showed that cover crops planted after MG 2 would reduce the 30-yr based standard error in biomass and N uptake by 44 and 12%, respectively compared to cover crops planted after MG 4 cultivars. Therefore, planting cover crops earlier after short-season MG cultivars may provide higher stability in cover crop biomass to ensure a minimal growth that enhanced ecosystem services (i.e. weed management, reduced soil erosion).

Results showed that incorporating cover crops into soybean-corn rotations would reduce corn transpiration by just 12 mm on average. This reduction was due to a lower soil moisture content at corn planting, that was more accentuated when cover crops were terminated late. Similar studies have reported a lower water content in the soil profile when non-legume cover crop were terminated later as well (Liebl et al., 1992; Moschler et al., 1967; Munawar et al., 1990). Interestingly, the reduction in soil moisture after a cover crop was partially offset by increased infiltration and less runoff during the corn growing season as also showed by Kleinman et al. (2005) and Espejo-Pérez et al. (2013). Based on the low absolute effect of cover crops on corn transpiration, it is not likely that cover crops will limit corn water availability in Lexington, for a soil of similar physical properties. In fact, results from probability graphs only showed reductions in corn seasonal transpiration in less than 30% of the years, and these were always under 50 mm. In soils of limited water holding capacity or in locations with relatively less precipitation, our simulations indicate that an early cover crop termination would be an effective management adaptation to reduce water limitation for the next crop. Further analysis of the soil water dynamics after complete model parametrization is essential to better identify management factors that will minimize water runoff and not compromise available water for the next crop in our conditions.

Our results indicate that the soil inorganic N at corn planting was significantly reduced after cover crops (31% less on average). This is consistent with other studies that evaluated the effect of cover crops on soil inorganic N in semi-arid environments with low winter precipitation and N leaching (Salmerón et al., 2014, 2011, 2010). Our simulations indicate that in our environment of high winter precipitation, soil inorganic N differences across treatments were still evident the following spring. However, it is critical to further evaluate these results after complete model parametrization.

Previous studies have reported a reduction in nitrogen leaching with cover crops grown during winter, but residual effects of cover crop on N leaching during the next cash crop growing season are less frequently reported (Brandi-Dohrn et al., 1997; McCracken et al., 1994; Salmerón et al., 2010; Tonitto et al., 2006). Our simulations indicate a small reduction on N leaching in corn grown after cover crops compared to a fallow, that could be enhanced after model parametrization with a soil of increased organic matter.

Net N mineralization during the corn growing season included net N mineralization from soil organic N, and from any decaying previous crop residue and cover crop biomass on the soil surface. Our results showed similar net N mineralization in fallow treatments and in corn after a cover crop terminated early. However, when delaying cover crop termination, there was a 17% reduction in net nitrogen mineralization as a consequence of a larger biomass accumulated by the crop and higher C:N ratio. Corn N uptake was 16% lower when corn followed cover crops implying that to maintain similar rates of nitrogen uptake across rotation treatments, a greater N fertilization rate would be required in corn following a cover crop in our conditions. Results from probability graphs showed that corn nitrogen uptake was similar for corn following either fallow or cover crops early terminated in 100% of the years. Hence, terminating cover crops early would be a management strategy for incorporating cover crops into crop rotations without nitrogen limitation. Simulations conducted after complete model parametrization may provide recommended cover crop termination dates that minimize risk of N limitation for our conditions, and for soils of different organic matter.

Given the large standard error in the components of the nitrogen and water balance evaluated across the 30 years, it was evident that environmental and climatic effect explained a large part of the variability in the results obtained. It is likely that simulations after complete model parametrization and with increased inorganic soil N will enhance these year-to-year differences. Finally, given the high sensitivity of the model to soil parametrization, performing a sensitivity analysis for different soil properties outside of the observed conditions will allow to better explore the magnitude of environmental and climatic factors affecting cover crop biomass, nitrogen and water availability and uptake to identify best management strategies that optimize cover crops ecosystem services and cash crop production.

5. CONCLUSION

Overall our results, although preliminary, show that there is a potential to incorporate cover crops into crop rotations without compromising cash crop production. The management practice that was able to allow cover crops to grow without reducing available water for the next cash crop was cover crops terminated earlier following any of the soybean MG. However, introducing non-legume cover crops into crop rotations had a negative impact on initial nitrogen content for corn growing season even though cover crops were able to reduce inorganic nitrogen losses through leaching. Despite this nitrogen limitation, cover crops that followed soybean MG 4 and were terminated earlier were the best management strategy to allow cover crop introduction while maintaining corn nitrogen uptake similar to corn following fallow period.

Water and nitrogen dynamics had a large variability across the 30 years. Hence, further work should focus on exploring the factors that have the largest effect on nitrogen and water availability to help improve management recommendations that will minimize the effect of that variability across the 30 years. In particular, for this study, further steps will emphasize on the improvement of model calibration especially to accurately simulate nitrogen and water dynamics across the crop rotation as well as perform a sensitivity analysis accounting for different soil properties, and changes on precipitation, to rise the applicability of our results to other locations.

6. TABLES AND FIGURES.

Table 3. 1. Soil characteristics for crop simulations including textural and hydrological parameters. Soil hydrological parameters include the volumetric water content at permanent wilting point or soil lower limit (LL), the volumetric water content at field capacity or soil drainage upper limit (DUL), and at saturation (SAT), saturated hydraulic conductivity (Ks), and bulk density (BD).

Soil type	Depth	Clay	Silt	Organic C	Total N	LL	DUL	SAT	K_s	BD
Silty clay loam	0 - 30	30.0	60.0	1.14	0.11	0.21	0.41	0.49	0.15	1.27
	30 - 90	30.0	60.0	0.97	0.1	0.20	0.40	0.48	0.15	1.29
	90 - 150	30.0	60.0	0.45	0.04	0.19	0.37	0.46	0.15	1.35

† Soil parameters within each profiles were averaged across different horizons to present data in a summarized way.

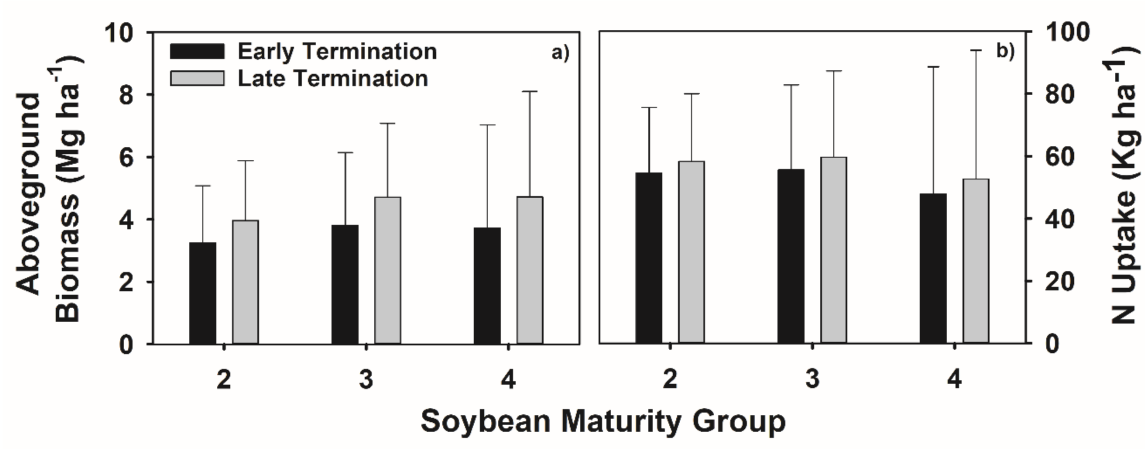

Figure 3. 1. Simulated cover crop aboveground biomass (a) and total nitrogen uptake (b) by soybean MG and cover crop termination time in the spring. Values are averages across 30-yrs. Error bars represent standard error.

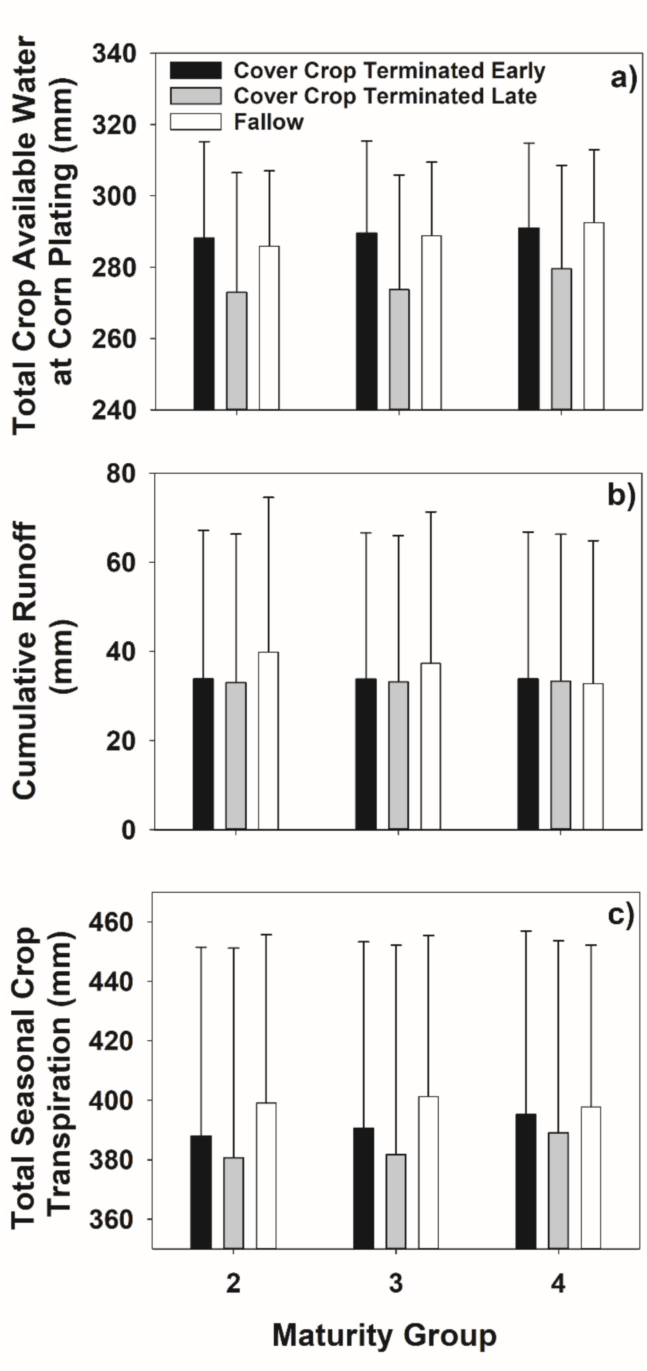

Figure 3. 2. Simulated total crop available water (0 to x cm soil profile) at corn planting (a), and cumulative runoff (b), and total seasonal crop transpiration (c) during the corn growing season by rotation and cover crop termination treatment. Values are averages across 30-yrs. Error bars show standard error.

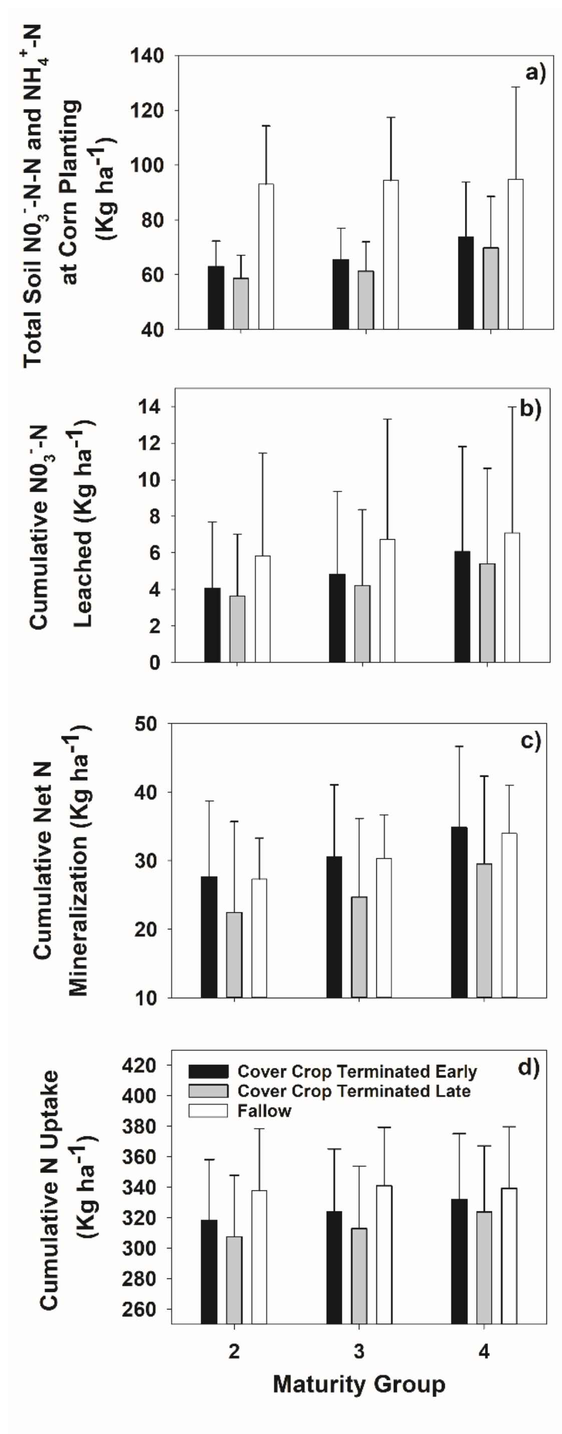

Figure 3. 3. Simulated total soil inorganic nitrogen (NO_3^--N + and NH_4^+-N) at corn planting (a), and cumulative NO_3^--N leached (b), cumulative net N mineralization (c), and cumulative nitrogen uptake (d) during the corn growing season by rotation type and cover crop termination time. Values are averages across 30-yrs. Error bars show standard error.

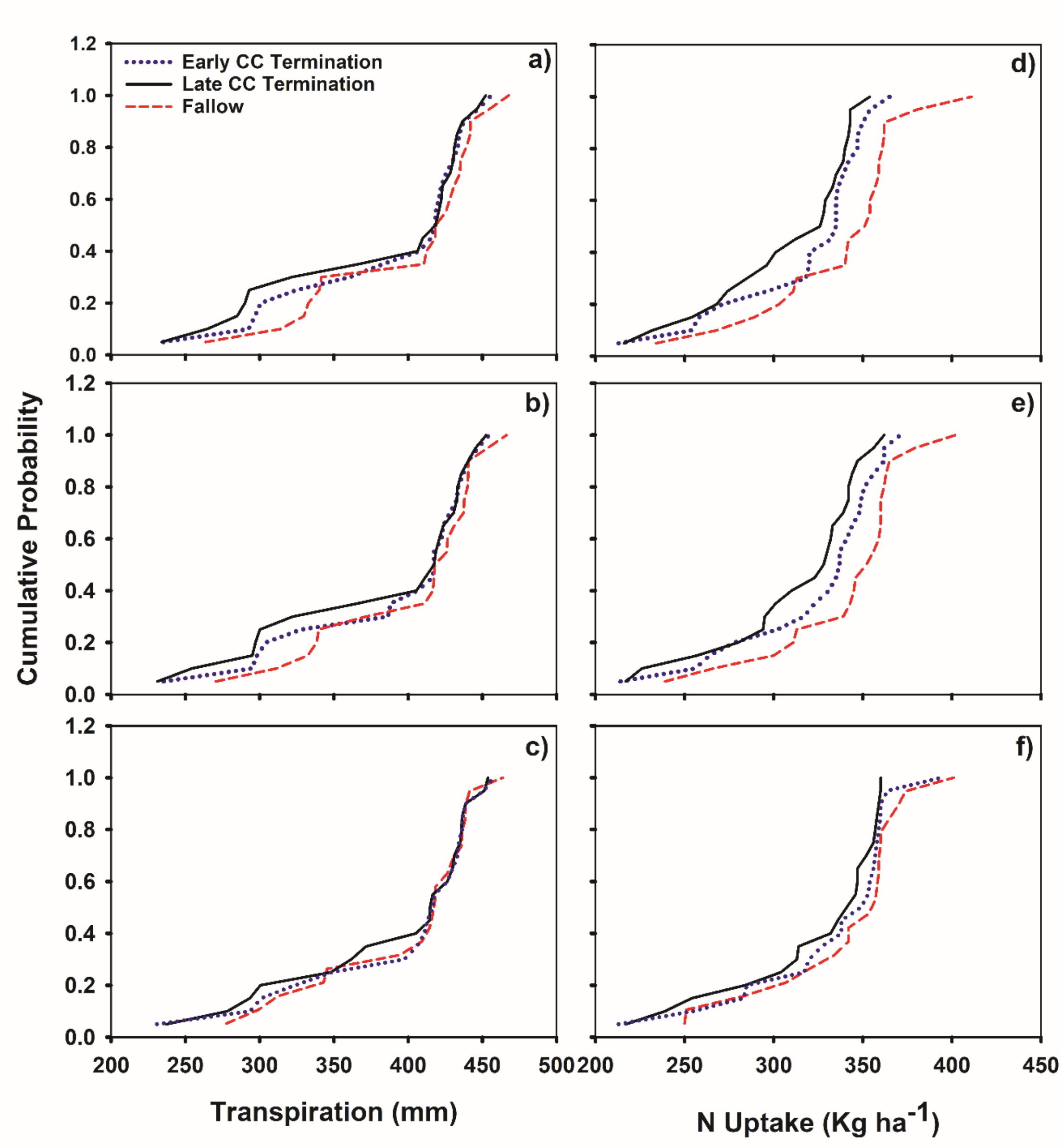

Figure 3. 4. Cumulative probability of simulated corn seasonal transpiration (a,b,c) and simulated nitrogen uptake (d,e,f) for corn planted on Sep 16 after fallow or cover crops following MG 2 soybeans, (a, d) planted on Sep 25 following MG 3 soybeans (b, e), and planted on Oct 8 following MG 4 soybeans.

CONCLUSIONS

In chapter 1, the DSSAT-CROPGRO model was able to accurately predict date of soybean harvest maturity and yield for soybean MG 0 to 4 cultivars using model crop growth coefficients derived from rMG. Our multi-factor sensitivity analysis showed that under both rainfed and irrigated conditions, MG selection explained a low percentage of yield variability. Soil type and precipitation patters explained most of the yield variability under rainfed conditions, and planting date in irrigated conditions. MG 0 to 3 cultivars were able to advance soybean harvest date by 6.6 to 11 days when soybeans were planted in May and between 1 to 7.3 days when soybeans were planted in July, without yield penalty. Winter-killed cover crops planted after soybean MG 0 to 3 were able to accumulate 186 to 670 GDD when soybean was planted on May 15 and 45 to 167 GDD while winter-hardy cover crop would increase the fall growing window to 432 to 819 GDD following soybean planted in May, and to 238 to 353 GDD after soybean planted in July.

In Chapter 2, planting cover crops resulted in an efficient management strategy to reduce weed biomass in the fall an in the spring. Planting cover crops earlier in the fall resulted in a greater biomass accumulation and percentage of ground cover early in the fall but did not have an effect at termination time. Planting cover crops earlier, did not improved weed suppression in neither the fall nor the spring. A fall herbicide application improved weed control when there was a high pressure of winter annual weeds. Delaying cover crop termination increased cover crop biomass production but did not reduce weed biomass in the spring.

In Chapter 3, preliminary results from our simulations showed that it is possible to introduce cover crops into crop rotations without reducing water availability for the next cash crop. However, cover crop management strategies were not able to incorporate cover crops without reducing nitrogen availability. Planting cover crops after soybean MG 4 with an early termination resulted in 7 kg ha^{-1} less of nitrogen uptake with no reduction in soil available water. Simulations over 30 years showed a large variability in the results. Therefore, quantifying the factors that have the largest effect on nitrogen and water availability will certainly improve the understanding of the system to choose the best management recommendations.

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