Identifying research priorities through decision analyses: a case study for cover crops

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Abstract

In Midwestern maize (Zea-mays L.)-based systems, planting an over-wintering cover crop such as rye (Secale cereale L.) following fall harvests of summer crops maintains continuous soil cover, offering numerous environmental advantages. However, while adoption of cover crops has increased over the past decade, on a landscape-scale it remains low. Identifying where agronomic research could be most impactful in increasing adoption is therefore a useful exercise. Decision analysis (DA) is a tool for clarifying decision trade-offs, quantifying risk, and identifying optimal decisions. Several fields regularly utilize DA frameworks including the military, industrial engineering, business strategy, and economics, but it is not yet widely applied in agriculture. Here we apply DA to a maize-soybean [Glycine max (L.) Merr.] rotation using publicly available weather, management, and economic data from central Iowa. In this region, planting a cover crop following maize (preceding soybean) poses less risk to the producer compared to planting following soybean, meaning it may be a more palatable entry point for producers. Furthermore, the risk of reduced maize yields when planting less than 10 days following rye termination substantially contributes to the overall risk cover crops pose to producers, but also has significant potential to be addressed through agronomic research. In addition to identifying research priorities, DA provided clarity to a complex problem, was performed using publicly available data, and by incorporating risk it better estimated true costs to the producer compared to using input costs alone. We believe DA is a valuable and underutilized tool in agronomy and could aid in increasing adoption of cover crops in the Midwest.

# Introduction

Many cropping systems in the United States (US) have undergone simplifications, now being composed of only a few, often annual, crops (Aguilar et al. 2015; Hijmans et al. 2016; Crossley et al. 2021). These systems often leave the soil fallow for some period of time, presenting notable environmental challenges including but not limited to increased risk of soil erosion and an increased potential for nutrient loss (Mitsch et al., 2001; Hatfield et al., 2009, Syswerda et al., 2012). The notion of ‘continuous living cover’ has been used to encourage creative solutions to these issues by focusing cropping system re-design on eliminating these environmentally-challenging fallow periods. Planting cover crops to reduce fallow periods is one such tactic that could at least partially address many of the environmental problems presented by annual cropping systems.

The US produces approximately one-third of the word’s maize (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] (FAO, 2022), with five states in the Midwestern region contributing over half of that production (USDA-NASS, 2022). It follows that large amounts of agricultural land in the Midwestern US are dedicated to cropping systems that grow only maize and soybean (Boryan et al., 2011; USDA-NASS Cropland Data Layer, 2021). Utilizing over-wintering cover crops in these systems has been shown to reduce soil erosion and nitrate leaching (Kaspar et al., 2007; Kaspar et al. 2012), reduce crop insurance losses (Aglasan and Rejesus, 2021), and possibly offer numerous other context-specific benefits (Basche et al. 2017; Nichols et al., 2022; Krupek et al. 2022). However, the Midwestern maize-soybean systems present challenges to cover crop adoption. In some regions of the US, cover crop adoption on annual cropland is above 25% and growing (Hamilton et al., 2017). Meanwhile, states comprising the Midwestern US exhibit some of the smallest adoption rates, with most states well below 10% adoption (Hamilton et al., 2017; Rundquist and Carlson, 2017; Seifert et al., 2018).

Low adoption rates within the Midwest have been the subject of numerous studies, and it is clearly a complex issue involving economics, climate constraints, field operations, management, equipment, culture, and technical knowledge (Lee et al., 2018, Church et al., 2020, Nichols et al., 2020a, Thompson et al., 2021; Yoder et al., 2021). One barrier we believe merits more attention is that of risk. Risk is defined as the probability of an undesirable event combined with the severity of the consequences should that event occur (CITE). Managerially, maize and soybean are both are planted in the late spring (April, May) and both are harvested in the fall (September, October, November). Producers typically fit over-wintering cover crops into these systems by planting a cover crop in the fall after the cash crop harvest, and terminating the cover crop it in the spring before the next cash crop is planted (CITE). Therefore, management of an over-wintering cover crop such as rye (*Secale cereale* L.) can conflict with cash crop management. As such, using a cover crop requires complex decision-making that balances risk and rewards in uncertain conditions. While perceived risks associated with cover cropping are often cited as barriers to adoption (Arbuckle and Roesch-McNally, 2015), to our knowledge that risk has not been well-quantified or explicitly included in economic analyses (e.g., Bergtold et al., 2019; Plastina et al., 2020). Furthermore, while lists of cover crop research priorities have been proposed (e.g., Carlson and Stockwell, 2013; Basche and Roesch-McNally, 2017), a tool for ranking priorities would be useful. By quantifying the risk associated with each decision point for producers, research priorities can be set to address and reduce the areas posing the highest risk. The use of risk as a ranking tool would also help researchers and funding organizations assess how resources can be used most impactfully. Furthermore, understanding how uncertainties around weather conditions elevate risks of profit loss is important for understanding both the mechanisms for delivering incentives, and the amount producers may need to be compensated for planting cover crops.

Decision analysis (DA) is an interdisciplinary tool that can be applied to analyze decision-making under uncertain conditions (XX). It can leverage both quantitative information and expert knowledge, incorporate different degrees of risk aversion, and through sensitivity analyses can allow exploration of the decision space (Muenning2017; Shackelford et al. 2019). It is a recognized tool for coping with risk in agriculture (Hardaker et al. 2015), and has been applied to understand agroforestry adoption risks, nitrate pollution loading, and explore optimal cropping system choices (Almasri et al. 2005; Gandorfer et al. 2011; Do et al. 2020). However, to our knowledge single attribute decision frameworks have not been applied to gain insight into management decisions related to cover crops in the maize/soybean systems of the Midwestern US. Therefore, the objectives of this study were two-fold:

1) Provide a case study using publicly available data to demonstrate the process and utility of applying decision analysis to cover crop systems

2) Use a basic analysis to suggest research priorities for cover crops in Central Iowa

We chose to use Central Iowa as a case study because Iowa has a large percentage of cropped land in maize-soybean systems that could benefit from the addition of cover crops (USDA NASS CDL, 2021). Central Iowa currently demonstrates a moderate amount of cover crop adoption compared to the rest of the state (Rundquist and Carlson, 2017), suggesting there is interest, but also barriers to adoption. Furthermore, Iowa’s land grant institution, Iowa State University, as well as the United States Department of Agriculture (USDA) National Laboratory for Agriculture and the Environment (NLAE) are located in Central Iowa and support a strong infrastructure for publicly funded agronomic research trials in this region.

# Methods and Materials

## Scenario set-up

We used cereal rye (*Secale cereale* L.) as our ‘model’ over-wintering cover crop because it is the most used cover crop in Iowa and is one of the most widely used cover crop species in the Midwest (Singer 2008). In a maize-soybean rotation, a cereal rye cover crop may be planted following either the soybean phase, or following the maize phase, each with scenario-specific benefits and challenges (**Figure 1**).

Soybeans are harvested earlier compared to maize (USDA NASS 2022), and earlier fall planting increases the probability of successful rye establishment and meaningful biomass production (Chatterjee et al. 2020). A rye cover crop will also offer larger reductions in soil erosion when planted following a soybean crop due to the low amounts of residue remaining in the field following soybean harvest (Kaspar et al. 2001). Both soybeans and maize crops can leave large reserves of nitrate in the soil in the fall that are susceptible to spring leaching (Martinez-Feria et al. 2019), which can be mitigated by overwintering cover crops (Kaspar et al. 2007; Kaspar et al. 2012). On-farm research has shown cover crop residue in soybean fields may allow producers to eliminate an herbicide pass (Nelson and Bennett 2018). Maize exhibits lower yields if planted less than 10 days following rye termination, while soybean yields are unaffected by the termination-to-planting timing (Johnson et al. 1998, Archarya et al. 2017; Acharya et al. 2020). In Iowa, maize yields benefit from earlier planting (Baum et al. 2019) while soybeans are less sensitive (Kessler et al. 2020), meaning delayed planting due to cover crop complications are more of a concern when the cover crop is followed by maize. Identification of the benefits and challenges of each scenario highlights the need to optimize decisions and provides an opportunity to identify where value could be realized in a decision.

## Decision structure

The two cover crop scenarios were translated into a decision model with known states, uncertainties, and values. The two scenarios were treated as separate decision sets, but the sets were composed of the same decision structure (**Figure 2**). Each component of the decision model is described in more detail below.

### Fall uncertainties

Cover crops are most often planted following cash crop harvests (SARE 2020). Soybean crops in Central Iowa are harvested in September or October, and maize in October or November (USDA NASS 2022). Planting cover crops into standing crops before harvest can increase the probability of establishment (Wilson et al. 2014) but requires specialized equipment that is not yet widely used. We therefore assume cover crop planting occurs after cash crop harvest.

Rye cover crop seeds requires sufficient precipitation to germinate, and sufficient heat units to establish such that the plants survive the winter. Failure to germinate or failed establishment results in wasted seed, wasted fuel, and possible weed problems the following spring. To estimate the probability of successful rye establishment, we used historical from 1988-2019 at the AMES-8-WSW station from the Iowa Environmental Mesonet (IEM 2022). We chose this dataset because it had previously undergone an extensive quality check (Archontoulis et al. 2020). While the amount of precipitation needed for rye to germinate depends on soil moisture conditions at planting, crop advisors and producers often assume 1.27 cm (0.5 inches) is needed (Sarrantonio1994), which is consistent with field studies (Fisher et al., 2011; Wilson et al. 2013) and simulation model assumptions (Feyereisen et al. 2006; Marcillo et al. 2019). While we assumed 1.27 cm was needed for our baseline analysis, this assumption was tested through a sensitivity analysis (see Sensitivity Analysis section).

Growing degree days (GDDs) represent an estimation of the number of heat units accumulated above a threshold temperature specific to a crop. For rye the threshold is 0 or 1 deg Celsius (Feyereisen2006). We are unaware of studies demonstrating the required amount of fall GDDs accumulated for successful rye over-wintering, and acknowledge it will depend on several additional factors including soil texture and snow cover. We estimated rye requires 200 GDDs to successfully establish before winter, but tested the sensitivity of this assumption (see Sensitivity Analyses section).

Using 30 years of weather data, we calculated (i) the probability the site received 1.27 cm of rainfall during an allotted timeframe, and (ii) the probability of achieving 200 GDDs in the allotted timeframe (**Table 1**). The timeframes differed by scenario (rye following soybean, rye following maize; **Figure 1**) to account for the generally earlier harvest dates for soybean compared to maize (USDA NASS 2022). We chose to calculate the precipitation and GDD probabilities separately rather than as a joint probability to aid in assessing how breeding efforts could increase changes of establishment. We recognize this model for establishment is a simplification of the complex interactions between weather, soil, and management considerations. While more sophisticated modelling approaches have been utilized for predicting cover crop establishment (Baker et al. 2009, Marcillo et al. 2019; Nichols et al. 2020b), they require specialized skillsets and a significant time commitment. Our goal in this exercise is to demonstrate how insights can be obtained using publicly available data and approachable methodologies. Models using GDDs are popular in agronomy extension, and are commonly used in making crop production decisions.

### Spring uncertainties

To comply with governmental crop insurance cost-share policies, cover crops must be terminated before the cash crop is planted (Bergtold et al. 2019; USDA RMA 2019). Iowa has a humid continental climate wherein a significant amount of precipitation occurs during the spring months. In addition to the direct constraints precipitation exerts, performing field operations in wet soils can result in undesirable outcomes including long-term soil compaction issues and equipment malfunctions. The USDA National Agricultural Statistics Service (NASS) surveys farmers to determine the number of days suitable for fieldwork (workable-field day; WFD) for each week throughout the year (USDA NASS 2018). A ‘suitable’ day is defined as one in which weather and field conditions allow producers to work in fields the majority of a given day. Determining whether a day is a ‘suitable’ is subjective, but provides valuable information about the state of progress and constraints of agricultural production on a landscape level.

Historical data shows that in Iowa, the number of WFDs during the spring can severely restrict field activities (Urban et al 2015; Edwards 2020). In the spring, the presence of a living cover crop that must be terminated before the cash crop can be planted can potentially add to the spring workload for a farmer. Cover crop termination may require an extra field pass in addition to cash crop planting. While this depends on whether producers typically do a pre-plant herbicide pass, the operation is much less crucial when the goal is simply to eliminate weeds before planting compared to killing a live cover crop. As such, for this exercise we assumed cover crop termination requires an additional set of field working-days, but did not assume extra herbicide or fuel costs associated with terminating the cover crop. meaning farmers who use a rye cover crop may require more spring WFDs than those who do not. This fact introduces an important component of risk that is often not accounted for explicitly in economic analyses. Societal-level benefits such as reduced nitrate leaching, as well as farm-level benefits such as the potential to off-set weed control costs, increase as spring cover crop termination dates are delayed and cover crop biomass increases (Finney et al. 2016; Thapa et al. 2018; Nichols et al. 2020b). However, if WFDs occur early in April, the producer must choose whether to utilize them to terminate the cover crop, or wait in order to accrue more benefits from prolonged cover crop growth while simultaneously running the risk of not having sufficient WDs in late April, resulting in delayed cash crop planting. Furthermore, if the cover crop is terminated too close to maize planting (<10 day gap), the cover crop may further reduce maize yields (Johnson et al. 1998; Acharya et al. 2017; Quinn et al. 2021). This termination-planting gap is less crucial for soybean crops planted after rye cover crops, but if the cover crop is not terminated before cash crop planting, producers may be violating crop insurance requirements and render the cash crop ineligible for coverage. Therefore, understanding the uncertainty around WFDs in the spring is an important component for cover crop decision analyses.

In years with very low spring precipitation, delaying cover crop termination can also result in decreased cash crop yields due to the cover crop’s use of stored soil water needed for cash crop production. While this risk is possible, due to climatic patterns it is not common in Central Iowa (Daigh et al. 2014; Martinez-Feria et al. 2016). Therefore, the risk of cover crops inducing drought-related yield reductions in the following cash crop is not considered in this exercise.

Cover crops can be terminated using mechanical (tilling, roller-crimping, mowing) or chemical (herbicide) means. All termination methods have conditions under which they are most effective, but a fair assumption is that each method works best with two sequential WFDs. Likewise, while planting activities may be carried out with only one WFD, we assume two WFDs are necessary to accommodate the large range of cover crop termination and pre-plant activities a producer might be engaged in. When applying this analysis to a specific system, these assumptions can be adjusted to reflect a producer’s particular operations.

Workable field days are estimated by surveying farmers about how many days in the previous week were field-workable. The data is therefore reported as a number of days within a seven-day calendar period, with this period being inconsistent between years. For the purposes of this exercise, we chose to take the total WFDs over the seven-day reporting period and divide the total by seven to assign a number of WFDs to each calendar day the reporting week included. We then created five spring categories (early April, late April, early May, late May, June). Workable field day values were then summed within these spring calendar categories. More details, including R code, concerning this procedure can be found in supplemental material. The probability of two and four WFDs being reported in a given spring category was then calculated using data from 1988-2019.

### Value

Partial budgets were used to estimate costs and values of each decision. Extension publications, farming group publications, and peer-reviewed literature were used to guide each estimation. Sensitivity analyses were performed on most values, and instances where conclusions were overly sensitive to assumed values are noted in the results section.

To estimate the direct costs associated with planting and terminating a cover crop we used Iowa State University’s ‘Economics of Cover Crops’ decision tool (Iowa State University Extension, 2018). While these prices will fluctuate depending on the price of fuel and labor, we feel they are sufficiently representative for this exercise (**Table 2**).

In order to account for the effect of cover cropping on income from crop yields, we needed to estimate the net revenue a producer expects per unit crop yield. The net revenue from a crop will depend on producer costs of production as well as market prices, both of which vary significantly across years. To overcome this variability, we looked at production costs (Iowa State University Extension, 2022) and market prices (USDA NASS 2022) from 2013-2021, calculated the net revenue per unit crop yield for each year, then took the year with the maximum net revenue for each crop (**Table S1**). By calculating the net revenue in this manner, when a rye cover crop negatively impacted cash crop yields our analyses represented the highest potential costs of those effects. All prices and calculations are available in supplemental material.

Maize was assumed to have a maximum yield of 10.7 dry Mg ha-1 (200 bu ac-1) and soybean a yield of 1.4 dry Mg ha-1 (60 bu ac-1), which are representative of the state average yields in Iowa (USDA NASS 2022). Maize yield is sensitive to planting date, with later planting dates being associated with lower yields (Kucharik et al. 2008; Baum et al. 2019). We therefore assume a graduated yield penalty increasing from 5-20% as maize planting occurs past April (**Table S2**). On average, winter cover crops such as rye have been shown to have a neutral effect on subsequent maize and soybean yields (Marcillo and Miguez, 2017), but numerous studies have suggested planting maize less than 10-14 days following cover crop termination can result in lower maize yields (Johnson et al. 1998, Acharya et al. 2017, Quinn et al. 2022). We therefore assumed a 10% decrease in maize yield reduction if maize planting occurred less than 14 days after cover crop termination (**Table S2**).

For maize following a cover crop, we assume herbicide costs are equal in the cover crop and no-cover system ($205 ha-1). For soybean following a cover crop, several on-farm experiments have shown producers can reduce herbicide costs due to the mulch provided by a late-terminated cover crop. Therefore, in cases when the cover crop is terminated in late April or later, a $37 ha-1 savings in herbicides was applied (Nelson and Bennett, 2018).

There are currently no payments available to farmers in Iowa for the societal benefits reaped from delaying cover crop termination. However, other areas in the US have implemented payment structures that reward late termination due to the societal benefits gained from late termination (Maryland Department of Agriculture, 2022), so the potential for this payment was included in sensitivity analyses.

## Decision analysis

### Building decision trees

Decisions can be visualized and modelled using decision tree notation (CITE). The full decision model is available in supplemental files and consists of building out a branch for each unique decision node and uncertainty outcome with probabilities, then assigning a value to each branch. When modelling risk-neutral decision-makers, the dollar value of the branch is equal to the expected utility, and all calculations can be done with the raw dollar values. Each decision node’s branch is assigned a value based on the values of that branch weighted by the probability of that branch occurring. The optimal decision is the one with the maximum value (NEEDS WORK AND A CITATION). A shortened visualization of the decision tree is with uncertainties is presented below as an example, with uncertainties calculated as described in the Methods and Materials section (**Figure 3**).

### Sensitivity analyses

Sensitivity of decision values to assumptions was assessed using the Data Table functionality in Excel (Gupta2022). Not sure how in-depth to go with this. The sensitivity of outcomes was assessed for the precipitation required for rye germination, the number of GDDs needed for rye to over-winter, the relative reduction in maize yields when maize was planted less than 10 days following rye termination, the incentive payments offered to plant rye, and the incentive payments offered to delay termination of rye. Additionally, sensitivity analyses were performed on the assumed revenues and costs associated with each scenario to ensure conclusions were not overly sensitive to these assumptions.

# Results and Discussion

## Weather uncertainties

On average, Central Iowa received 7.4 and 4.2 cm of rain from 15-Oct and 1-Nov through 30-Nov, respectively. This equated to a high probability (>80%) of the rye cover crop receiving sufficient precipitation for germination (>1.27 cm) in both planting scenarios (**Table 3**). This result was robust against uncertainty in our assumptions; even if rye required almost double the assumed precipitation, the probability of receiving that amount of rainfall did not drop below 80% for either planting scenario (**Figure S1**). While the probability of accumulating sufficient GDDs (200) was high when the rye was planted following soybeans (15-Oct planting date), it dropped quickly to only 23% chance of success when planted following maize (1-Nov planting date; **Table 3**).

These results can be used to guide cover crop breeding efforts. Breeding varieties that require less precipitation for establishment would likely involve breeding for smaller seeds, which carries inherent tradeoffs (e.g., Carleton and Cooper 1972, Mohler et al. 2009). Our analysis demonstrates in most cases, precipitation is not the limiting factor for cover crop establishment in Central Iowa. Conversely, a study done in Minnesota showed precipitation accounts for the highest amount of variation in rye establishment, followed by temperature (Wilson et al. 2013), demonstrating the value of evaluating weather-related risks locally. While our results do not account for how the precipitation is distributed across time and how that may impact germination, our results suggest this area of Iowa can support larger precipitation requirements for cover crops without experiencing a significant reduction in the probability of cover crop germination. Our results also indicate GDDs are the most limiting factor in this area. We assumed a base temperature of 0 degrees Celsius, and breeding for a base temperature below freezing would likely be difficult. Our results indicate research focused on identifying management tactics that allow for earlier cover crop planting may be most effective in increasing the probability of successful cover crop establishment in Central Iowa. For example, some farmers report switching to earlier maturing soybean and maize varieties when adopting cover crops in order to plant the cover crop earlier (Plastina et al., 2020). Some areas have organized blocks of producers who share in aerial seeding costs, and custom seeding equipment/services that allows for seeding into a standing crop is becoming more common.

In the spring, the number of WFDs presented a great deal of uncertainty (**Table 4**). Over the entire spring period (1-Apr through 31-May), on average there was a 79% probability of two or more WFDs in a given two-week period, and only a 46% probability of four or more WFDs. We assumed two or more WFDs were needed to successfully complete a cover crop termination activity, and two additional WFDs were needed to complete cash crop planting activities. Therefore, producers wishing to terminate and plant within a two-week period may not have sufficient WFDs to do so. The probability of two or more WFDs was higher in May compared to April, indicating paying producers to delay cover crop termination may also increase the chances the producer can terminate in the planned timeframe.

Our analyses indicate there is generally more risk in the spring compared to the fall when using a cover crop. A Midwestern focus group found some farmers had been switching to winterkill cover crop varieties because of the difficulties associated with killing the cover crop and planting a cash crop in a timely manner in the spring (Plastina et al., 2020). For this analysis we assumed the rye cover crop could be terminated at any point, but the stage of rye growth will affect how easy it is to terminate, particularly when using mechanical termination (Creamer et al., 2002; Mirsky et al., 2009). Decision support tools that help producers decide if early termination is the best choice could be beneficial.

## Optimal decisions

Assuming no cost-shares or incentive payments, the decision value of not planting a cover crop is higher than for planting a cover crop, regardless of the sequencing scenario (**Figure 4**). This analysis indicates current incentive programs are enough to make planting a cover crop preceding a soybean cash crop the optimal decision. When a cover crop precedes a maize crop, incentives needed to make planting a cover crop the optimal decision are very sensitive to the reduction in maize yield due to planting less than 10 days following cover crop termination (**Figure 5**). If the reduction in yield were eliminated, the difference between the value of not planting a cover crop and planting a cover crop could be reduced from $99 ha-1 to $24 ha-1, bringing the difference into the range of current incentive programs in this area ($12-74). The exact causes of the reduced yield in maize are not yet clear and may vary by context (Patel et al. 2019; Quinn et al. 2021). Our analyses demonstrate that this phenomenon poses a significant risk to producers, and a better understanding of the drivers and identification of ways to predict when yield declines are likely would greatly reduce the financial risk associated with a rye cover crop in these systems.

## Timing of cover crop termination

Many of the benefits reaped from planting cover crops (e.g., reduced soil erosion, reduced nitrate leaching, non-chemical weed control) are directly related to the amount of biomass the cover crop produces (Finney et al. 2016; Thapa et al. 2018; Nichols et al. 2020b). However, in areas that lack incentives for delaying cover crop termination to allow the cover crop to grow, the optimal spring decision is to terminate the cover crop as soon as possible (**Fig. 6**). Delaying cover crop termination will likely delay cash crop planting. While society arguable benefits the most from producers planting cover crops preceding corn (erosion and nitrate leaching mitigation), the producer benefits the least and is exposed to additional weather risks. Understanding the risks and benefits through this lens allows incentives to be targeted to achieve the most benefit. The state of Maryland has created a tiered incentive system wherein producers are compensated more for early planting and late termination of cover crops (Maryland Department of Agriculture, 2022). Our analysis indicates having compensation rates differ by cropping sequence may also be an approach worth considering.

## Moral hazards

Our analyses showed that if a producer plants a cover crop preceding a maize crop and receives a cost-share or incentive for doing so, the best outcome occurs if the cover crop does not successfully over winter (**Figure S2**). This is due to the risk of reduced yields from spring management of the cover crop. Therefore, under a system of flat payments for planting, producers have a financial incentive to manage the cover crop in the fall such that it fails to over winter.

# Conclusions

Using publicly available data and reasonable assumptions, we were able to gain significant insight into localized priorities for cover crop research. Using historical weather data, NASS surveys on workable field days, extension publications, and a partial budget for cover crop economics we were able to build a single-attribute decision model, and model decision values assuming a risk-neutral producer. We found including only the costs of seed and fuel in cover crop economics underestimates the additional financial risk producers assume due to the extra spring work cover crops might entail in areas with limited numbers of workable field days during that time. We found there is minimal information on the number of growing degree days required for a rye cover crop to successfully overwinter, and that this may have a large impact on risks associated with planting cover crops in Central Iowa. In Central Iowa, identifying ways to ensure early cover crop planting and managements that render maize yields less sensitive to rye cover crop termination timing could significantly help reduce the financial risk of planting cover crops. Furthermore, flat payments for planting cover crops may result in a moral hazard, wherein the decision value for planting a cover crop preceding a maize crop is maximized when the cover crop fails to establish in the fall. Policies that promote alternative or tiered payment structures could rectify this while still providing support for producers as they learn to manage cover crops.

# Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

# Author Contributions

The Author Contributions section is mandatory for all articles, including articles by sole authors. If an appropriate statement is not provided on submission, a standard one will be inserted during the production process. The Author Contributions statement must describe the contributions of individual authors referred to by their initials and, in doing so, all authors agree to be accountable for the content of the work. Please see [here](http://home.frontiersin.org/about/author-guidelines#AuthorandContributors) for full authorship criteria.

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# Data Availability Statement

The datasets [GENERATED/ANALYZED] for this study can be found in the [NAME OF REPOSITORY] [LINK]. Please see the [Data Availability section of the Author guidelines](https://www.frontiersin.org/about/author-guidelines#AvailabilityofData) for more details.

# Figure legends and tables

**Figure 1** Winter cover crops can be planted following soybean harvest (*left*) or following maize harvest (*right*); each scenario presents unique benefits (+) and challenges (-)

**Figure 2**. Decision diagram for planting a cover crop, with a decision (light blue squares) of whether to plant in the fall, and a decision of whether to wait until late April to kill the cover crop in the spring. Weather conditions present uncertainties (yellow ovals), with the cover crop status in the spring being known with certainty (yellow donut). Value (dark blue hexagons) is derived from producer’s net profit and societal benefits. Solid arrows indicate probabilistic dependence, dashed arrows indicate a context-specific dependence.

**Figure 3** Decision tree visualization for planting a cover crop following a soybean crop. The first decision (light blue square) is whether or not to plant a cover crop. If the producer chooses to plant a cover crop, there is uncertainty about precipitation and growing degree days (GDDs); if the cover crop is successfully established the producer will have to decide whether to terminate the cover crop in early April, or to wait until late-April.

**Figure 4.** Planting a rye cover crop (green line) required $99 ha-1 and $45 cost shares/incentives, respectively for a soybean-rye-maize and maize-rye-soybean scenario to make decision values equal to not planting a cover crop (gold line); gray box represents range of current incentive values.

**Figure 5** Current estimates show maize yields are reduced by approximately 10% when maize is planted <10days after terminating a cover crop; if agronomic research efforts were able to eliminate this yield reduction the difference in decision values would be within the range of current incentive programs.

**Figure 6** If a cover crop is planted and successfully overwinters, the optimal decision is to terminate the cover crop as early as possible, being worth $27 and $6 ha-1 more when preceding maize and soybean, respectively.

**Table 1** Timeframes assumed for estimating fall weather uncertainties

|  |  |  |
| --- | --- | --- |
| **Scenario** | **Assumed fall precipitation time frame** | **Assumed fall GDD accumulation time frame** |
| Soybean – *Rye* – Maize | 15-Oct through 30-Nov | 15-Oct through 1-Dec |
| Maize – *Rye* - Soybean | 1-Nov through 30-Nov | 1-Nov through 1-Dec |

**Table 2.** Summary of economic assumptions for each scenario, including whether there is less than 10 days between cover crop termination and planting of the cash crop

|  |  |  |  |
| --- | --- | --- | --- |
|  | **No cover crop system** | **Cover crop system** | |
|  |  | **<10 day gap** | **>10 day gap** |
| ***Cover crop*** |  |  |  |
| *Cover crop seed* | - | $20 ha-1 | $20 ha-1 |
| *Cover crop planting* | - | $32 ha-1 | $32 ha-1 |
| *Cost-shares/insurance discounts with cover crop planting* | - | $12-74 ha-1 | $12-74 ha-1 |
| ***Cover crop preceding maize*** | |  |  |
| *Herbicide costs* | $205 ha-1 | $205 ha-1 | $205 ha-1 |
| *Maize income (assumed $2.14 net income per bushel)* | | |  |
| Planted early April | $1057 ha-1 | - | $951 ha-1 (90%) |
| Planted late April | $1057 ha-1 | $1057 ha-1 | $951 ha-1 (90%) |
| Planted early May | $1004 ha-1 (95%) | $1004 ha-1 (95%) | $889 ha-1 (85%) |
| Planted late May | $951 ha-1 (90%) | $951 ha-1 (90%) | $846 ha-1 (80%) |
| Planted June | $846 ha-1 (80%) | $846 ha-1 (80%) | $740 ha-1 (70%) |
| ***Cover crop preceding soybean*** | |  |  |
| *Herbicide costs* | $205 ha-1 | $168 ha-1 | $168 ha-1 |
| *Soybean income (assumed $4.06 net income per bushel)* | | | |
| Planted early April |  |  |  |
| Planted late April | $601 ha-1 | $601 ha-1 | $601 ha-1 |
| Planted early May | $601 ha-1 | $601 ha-1 | $601 ha-1 |
| Planted late May | $571 ha-1 (95%) | $571 ha-1 (95%) | $571 ha-1 (95%) |
| Planted June | $541 ha-1 (90%) | $541 ha-1 (90%) | $541 ha-1 (90%) |

**Table 3**. Summary of fall weather uncertainties in Central Iowa estimated using 30 years of historical weather data

|  |  |  |
| --- | --- | --- |
| *Scenario* | *Probability of receiving 1.27 cm of precipitation before 30-Nov* | *Probability of accumulating 200 growing degree days (GDDs)* |
| Soybean-Rye  (15-Oct planting) | 97% | 87% |
| Maize-Rye  (1-Nov planting) | 84% | 23% |

**Table 4.** Summary of probabilities of workable field days (WFDs) in a given timeframe based on 30 years of NASS survey data (NASS)

|  |  |  |
| --- | --- | --- |
| *Management Window* | *Probability of two or more workable field days (WFDs)* | *Probability of four or more WFDs* |
| 1-Apr through 15-Apr | 69% | 48% |
| 16-Apr through 30-Apr | 71% | 37% |
| 1-May through 15-May | 89% | 45% |
| 16-May through 31-May | 87% | 55% |
|  | | |