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

Gina A. Nichols[1,2*], Cameron MacKenzie[3]

[1]Field to Market: The Alliance for Sustainable Agriculture, Washington DC, USA

[2]Department of Agronomy, Iowa State University, Ames, IA, USA

[3]Department of Industrial and Manufacturing Systems Engineering, Iowa State University, Ames, IA, USA

*** Correspondence:**
Corresponding author
virginia.nichols@gmail.com

Keywords: decision analysis, cover crop, Iowa, maize, soybean, risk

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.

1 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 incorporates two components, uncertainty and negative consequences, and is frequently measured with probabilities describing the potential severity of consequences (Kapland and Garrick, 1981; Bedford and Cooke, 2001; Hubbard 2020). 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 (SARE 2020). 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 is an interdisciplinary tool that can be applied to analyze decision-making under uncertain conditions (Howard, 1988; Howard and Abbas, 2010; Clemen and Reilly, 2013). 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 (Cegan et al., 2017; 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, explore optimal cropping system choices, and to promote sustainable agricultural practices (Almasri et al., 2005; Gandorfer et al., 2011; Talukder et al., 2017; Do et al., 2020). However, to our knowledge decision analysis 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.

2 Methods and Materials

2.1 Decision set

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 producer has six main decision alternatives that make up the decision set:

1) Do not plant a cover crop following soybeans
2) Plant a cover crop following soybeans, plan to terminate early April
3) Plant a cover crop following soybeans, plan to terminate late April
4) Do not plant a cover crop following maize
5) Plant a cover crop following maize, plan to terminate early April
6) Plant a cover crop following maize, plan to terminate late April

Each alternative has unique benefits and challenges (**Figure 1**). Planting a cover crop following soybeans (decision alternatives 1-3) offers several advantages, but also carries challenges. Soybeans are harvested earlier compared to maize (USDA NASS 2022), allowing for earlier fall cover crop planting which 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). Soybeans 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). Delaying cover crop termination can enhance these benefits (decision alternative 3), but carries the risk of delaying maize planting, which often results in lower maize yields (Baum et al., 2019). Regardless of the decision whether to terminate the cover crop early, maize may have lower yields if planted less than 10 days following rye termination (Johnson et al. 1998, Archarya et al. 2017; Acharya et al. 2020), meaning decision alternatives 2-3 carry an inherent risk of reduced maize yields.

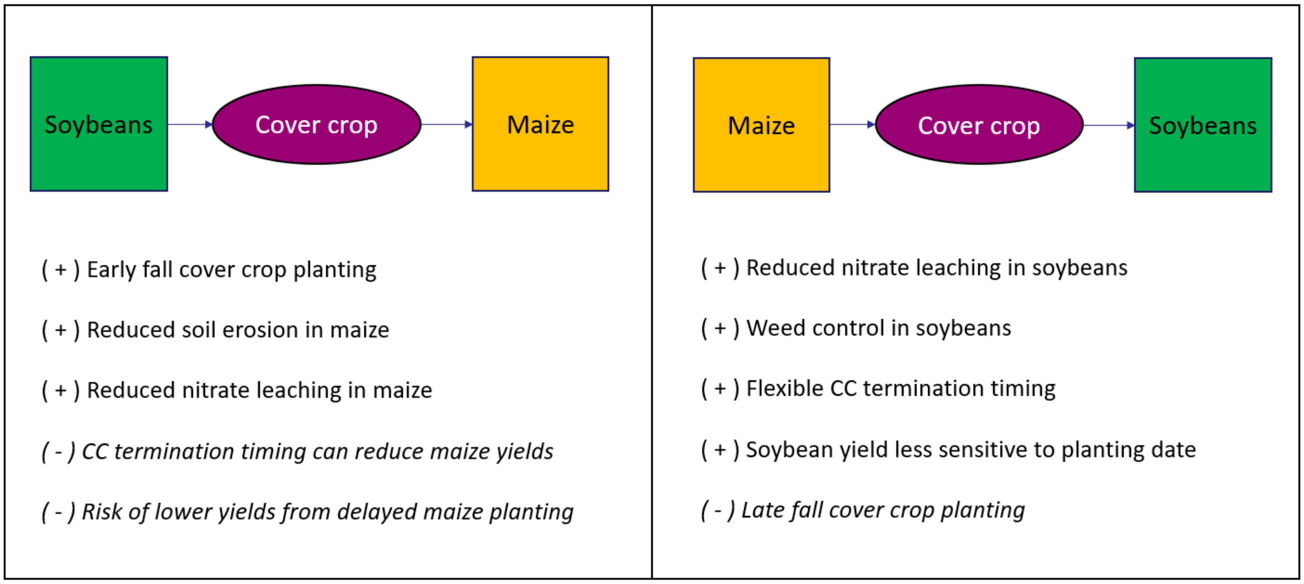

Figure 1 Winter cover crops can be planted following soybean harvest (*left*) or following maize harvest (*right*); each decision alternative presents unique benefits (+) and challenges (-)

Planting a cover crop following maize (decision alternatives 4-6) likewise carry both advantages and challenges. Like soybean, maize may leave large reserves of soil nitrate after harvest, and an over-wintering cover crop can help prevent it from leaching into water bodies in the spring (Kaspar et al. 2007; Kaspar et al. 2012; Martinez-Feria et al., 2019). Additionally, unlike maize, soybeans are generally unaffected by the cover crop termination timing (Johnson et al. 1998, Archarya et al. 2017; Acharya et al. 2020), and soybeans yields are less sensitive to planting dates than maize (Kessler et al. 2020). Furthermore, on-farm research has shown cover crop residue in soybean fields may allow producers to eliminate an herbicide pass (Nelson and Bennett 2018), an effect that can be enhanced by delayed cover crop termination (decision alternative 6). However, maize is generally harvested later than soybeans in the fall (USDA NASS 2022), resulting in later cover crop planting and therefore a lower probability of successful establishment. Identification of the benefits and challenges of each decision alternative highlights the need to use a quantitative approach to decision optimization, which can be achieved using decision analysis frameworks.

2.2 Decision structure

The decision set was translated into a decision model with known states, uncertainties, and values, each described below.

2.2.1 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 available. 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 of a cover crop to germinate or establish results in wasted seed, wasted fuel, and possible weed problems the following spring. 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 Section 2.3.2).

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 (Feyereisen et al. 2006). We are unaware of studies estimating the cumulative fall GDDs required 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 Section 2.3.2).

To estimate the probability of successful rye establishment, we used 30 years of historical weather data (1988-2019) collected 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). 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 decision alternative 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.

2.2.2 Spring uncertainties

Iowa has a humid continental climate wherein a significant amount of precipitation occurs during the spring months. In addition to the direct constraints on management that 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). 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). Therefore, 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 producer. Additionally, the decision to plant a cover crop may result in an extra spring field pass requirement. While this depends on whether producers typically have 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. In short, we assumed producers who plant 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.

The decision of cover crop termination timing will also affect WFDs, and therefore may indirectly affect cash crop yields. If a producer has WFDs in early 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. 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, the by choosing not to utilize early April WFDs, the producer risks not having sufficient WFDs in late April to terminate the cover crop, resulting in delayed cash crop planting and a possible concomitantly reduction in yields. Therefore, understanding the uncertainty around WFDs in the spring is an important component in assessing optimal decision alternatives.

In this analysis we only include the uncertainties associated with WFDs. 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 30 years of historical data (1988-2019).

2.2.3 Value

The main contributions of decision values were estimated using partial budgets and included the costs from planting a cover crop, the savings from planting a cover crop, and the income from the subsequent cash crop. Extension publications, farming group publications, and peer-reviewed literature were used to guide each estimation. Sensitivity analyses were performed on assumed values (Section 2.3.2), and instances where conclusions were overly sensitive to assumptions were noted.

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**).

When the cover crop was followed by a maize crop (decision alternatives 1-3), we assumed herbicide costs were equal in the cover crop and no-cover alternatives (\$205 ha^{-1}). When the cover crop was followed by a soybean crop (decision alternatives 4-6), we utilized information from on-farm experiments showing producers reduced herbicide costs due to the mulch provided by a late-terminated cover crop. Therefore, in the decision alternative where the cover crop was terminated in late April or later followed by soybean planting (decision alternative 6), 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 in decision alternatives 3 and 6 was included in sensitivity analyses.

2.3 Decision analysis

2.3.1 Building decision trees

Decisions can be visualized and modelled using decision tree notation (Howard and Abbas, 2010; Clemen and Reilly, 2013). 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. We assume a risk-neutral decision maker which means that the decision maker should choose the alternative that maximizes his or her expected profit. A square in the decision tree represents a choice between two or more alternatives, and a circle represents an uncertainty where each branch stemming from the uncertainty is assigned a probability. The first decision for the producer is whether or not to plant a cover crop in the fall (**Figure 2**). If the producers chooses to plant a cover crop, there is an uncertainty about whether or not sufficient precipitation occurs followed by a second uncertainty about whether or not sufficient GDDs are accumulated. If sufficient precipitation and sufficient GDDs occur, the producer makes a second decision about whether or not to terminate in early April. This decision is followed by uncertainties in the number of WFDs available in a given time frame (Figure S1). The decision tree is solved using a “rollback” procedure starting from the right-hand side of the tree. If a decision (square) node is encountered, the alternative with the largest expected monetary value is selected. If an uncertainty (circle) node is encountered, the expected monetary value is calculated using the probabilities on the branches. Iteratively following this procedure results in determining the alternative for the first decision (whether or not to plant a cover crop in the fall) that maximizes the producer's expected monetary value.

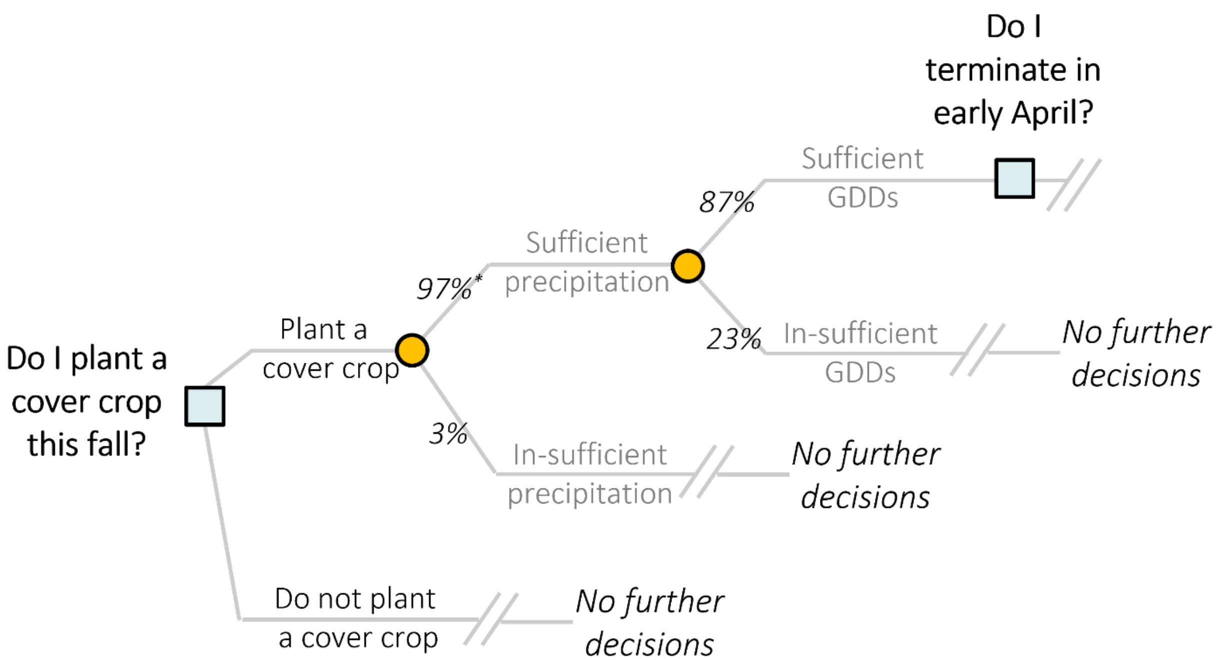

Figure 2 Decision tree visualization for planting a cover crop following a soybean crop. The first decision (light blue square) is whether or not to plant a cover crop. If the producer chooses to plant a cover crop, there is uncertainty about precipitation and growing degree days (GDDs); if the cover 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.

2.3.2 Sensitivity analyses

Sensitivity analysis on the assumptions about the uncertainties and parameters can provide insight into the criticality and importance of an assumption or variable on the decision. 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 (see supplemental files and Gupta 2022 for details).

3 Results and Discussion

3.1 Optimal decisions

Assuming a modest \$12 ha^{-1} incentive for planting a cover crop, the overall expected the overall expected monetary value of not planting any cover crop is greater than the expected monetary value of planting a cover crop, regardless of the sequencing scenario (**Figure 3**). Within the decision sets that include the alternative of planting a cover crop, the value of the decision is maximized if the alternative to terminate the cover crop in early April.

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, our analyses show the optimal decision is to terminate the cover crop as soon as possible (**Figure 3**). This results from the risks posed by delaying cover crop termination outweighing the monetary benefits. Interestingly, the termination decision differential is highest when the cover crop precedes maize, which is the sequencing in which society may benefit the most (higher mitigation of erosion and nitrate leaching). Therefore while society would stand to benefit the most from subsidizing this sequencing, this sequencing would require the highest incentives to render late April termination the optimal decision. 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.

Interestingly, our analyses also expose a moral hazard. If a producer chooses to plant a cover crop preceding a maize crop and receives a cost-share or incentive for doing so, the scenario where the cover crop fails to establish produces that highest decision value within that decision set (**Figure 3**). This is due to the risk of reduced maize yields from spring management of the cover crop. Therefore, under a system of flat payments for planting a cover crop, in this sequence producers have a financial incentive to manage the cover crop in the fall such that it fails to over winter. It is important to provide support for producers as they learn to manage cover crops, and often cover crop establishment is out of a producer’s control. However, our analyses demonstrate the complexity in determining the best payment structures.

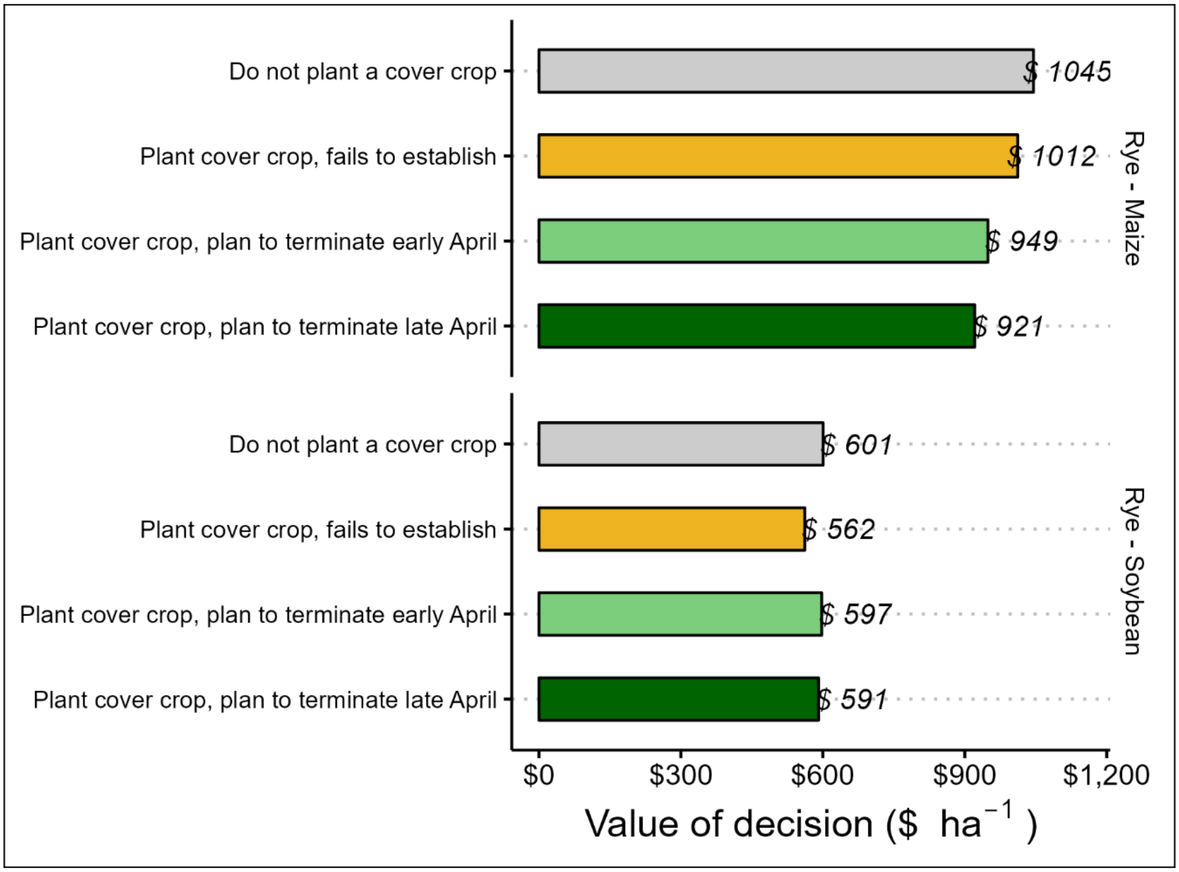

Figure 3. Value of each decision alternative assuming a $12 ha^{-1} incentive payment for planting a cover crop.

3.2 Sensitivity to cost-share/incentives

If there are no cost-shares or incentive programs, the overall expected monetary value of not planting any cover crop is greater than the expected value of planting a cover crop, regardless of the sequencing scenario (in **Figure 4**, this is seen from the ‘do not plant rye’ alternative having a greater value when the cost share or incentive is $0 on the horizontal axis). However, current incentive programs may be enough to make planting a cover crop preceding a soybean cash crop (‘Rye-Soybean’) the optimal decision. If the incentive is greater than $45 ha^{-1}, the expected monetary value of planting rye prior to soybeans is greater than not planting rye.

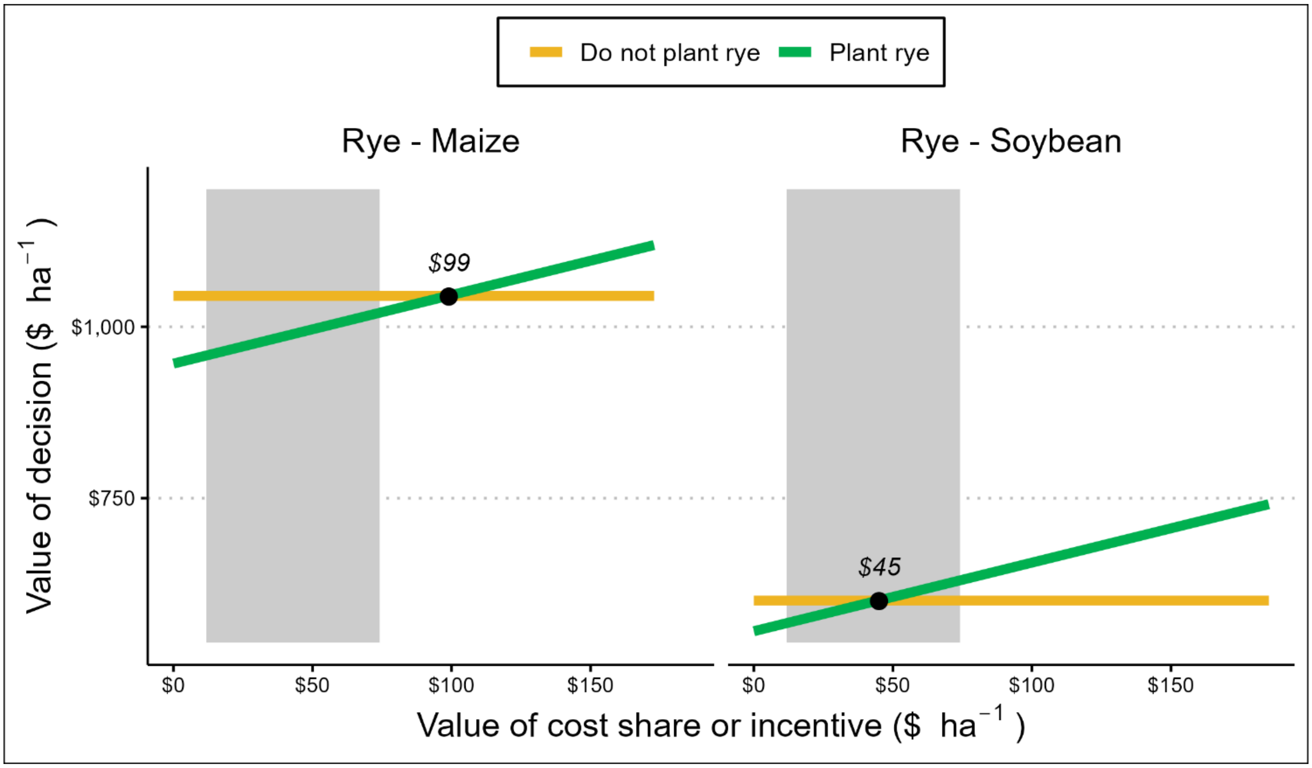

Figure 4. Planting a rye cover crop (green line) required \$99 ha^{-1} and \$45 cost shares/incentives, respectively for a soybean-rye-maize and maize-rye-soybean scenario to make decision values equal to not planting a cover crop (gold line); gray box represents range of current incentive values.

When a cover crop precedes a maize crop ('Rye-Maize' in **Figure 4**), within the current range of incentives the optimal decision is to not plant a cover crop. However, this recommendation is 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 ha^{-1}). The exact causes of the reduced yield in maize are not yet clear and likely 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 planting a rye cover crop in these systems.

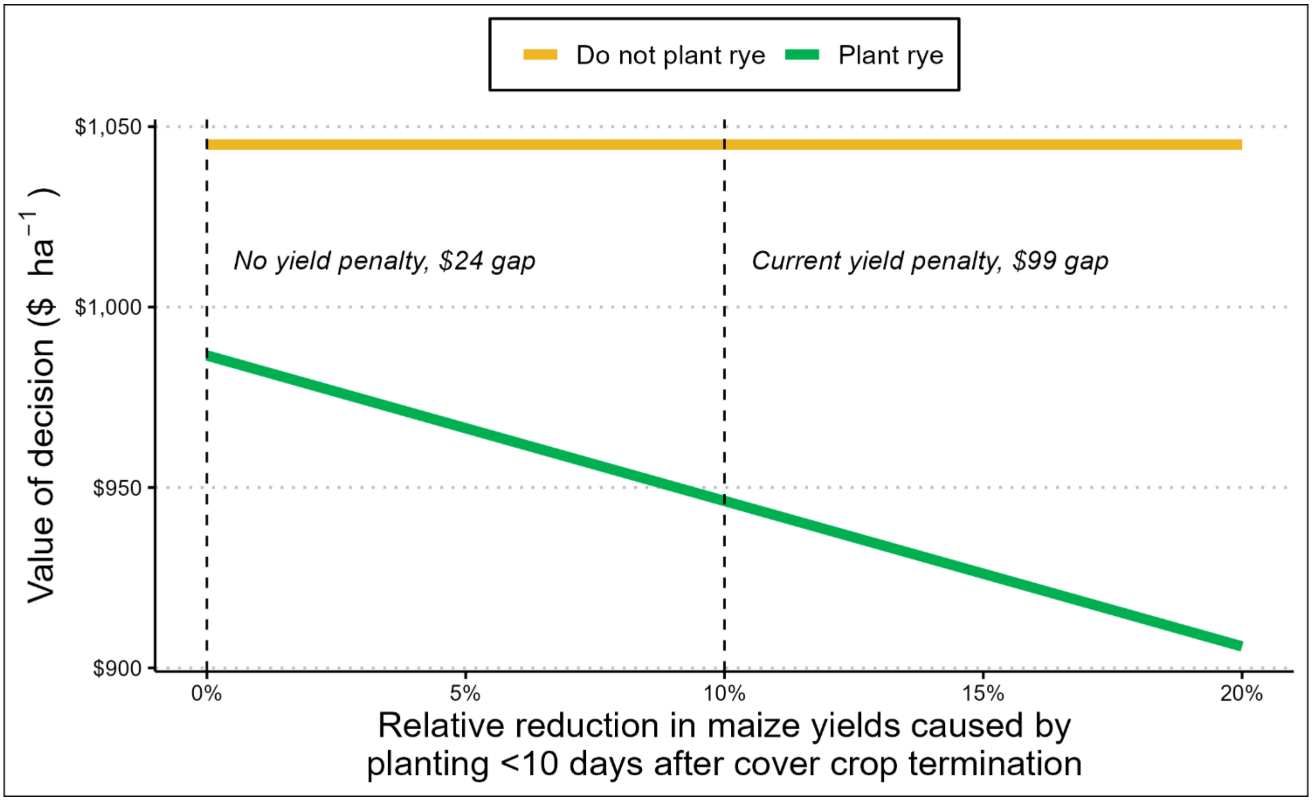

Figure 5 Current estimates show maize yields are reduced by approximately 10% when maize is planted <10days after terminating a cover crop; if agronomic research efforts were able to eliminate this yield reduction the difference in decision values would be within the range of current incentive programs.

3.3 Sensitivity to weather

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 sequences (**Figure 6, Table S3**). 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 6**). 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 S3**). The probability of establishment was very sensitive to the assumed number of GDDs needed for establishment, as well as the sequencing (rye following soybeans or rye following maize).

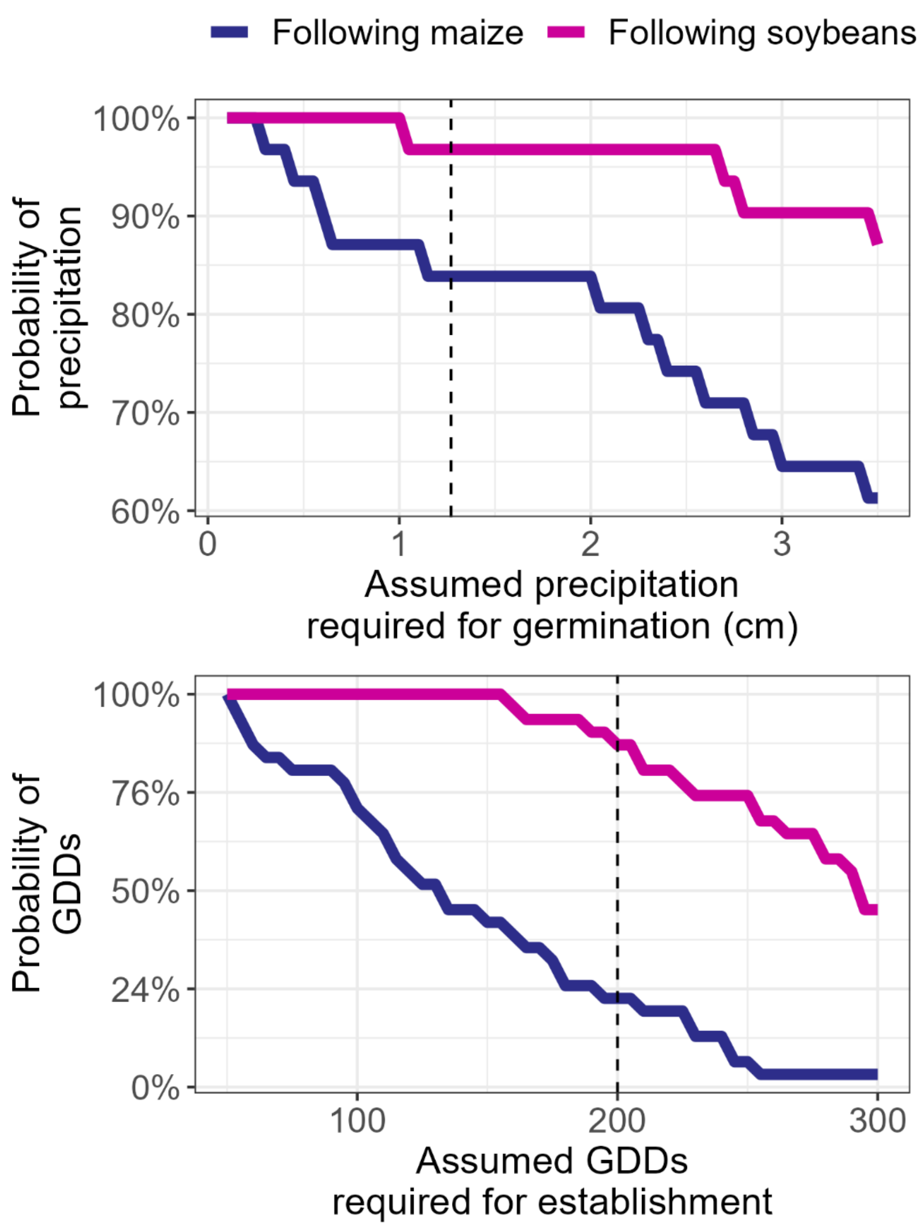

Figure 6 Sensitivity of outcomes to assumption of fall weather for rye planted following maize (dark blue; 1-Nov planting date), and following soybeans (pink; 15-Oct planting date). (*Top*) The probability of receiving sufficient precipitation is not sensitive to sequencing nor the assumed amount required for germination. (*Bottom*) The probability of accumulating sufficient GDDs for rye establishment is very sensitive to both the sequencing and the number of GDDs required

These results can be used to guide cover crop breeding efforts. Our analysis demonstrates in most cases, precipitation is not the limiting factor for cover crop establishment in Central Iowa, and rye planted in the fall has a high probability of receiving enough precipitation to germinate. 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), and our analyses indicate the benefits gained from breeding for smaller seeds would not be substantial. 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 suggest fall GDDs are the most limiting factor in Central Iowa. We assumed a base temperature of 0 degrees Celsius, and breeding for a base temperature below freezing would likely be difficult. Our results indicate both the need to better quantify fall GDD requirements for rye cover crop establishment, and that 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 producers 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. Our analyses indicate these types of activities are well-suited to reducing the risk associated with planting a cover crop in Central Iowa.

In the spring, the number of WFDs presented a great deal of uncertainty (**Table 3**). 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 producers 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 in helping producers manage this risk.

4 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.

5 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.

6 Author Contributions

GN conceived of and designed the analyses, collected the data, performed the analyses, and wrote the first draft of the manuscript. CM designed the analyses, and edited the manuscript.

7 Funding

This material is based upon work supported in part by the National Science Foundation (Grant no. DGE-1828942).

8 Acknowledgments

We acknowledge Dr. Sarah Ryan for organizing a workshop for the NSF DataFEWSion program that sparked this collaboration.

9 References

Aglasan, S., and Rejesus, R. M. (2021). An Analysis of Crop Insurance Losses, Cover Crops, and Weather in US Crop Production. e 2021 Agricultural & Applied Economics Association Annual Meeting, Austin, TX, August 1 – August 3

Aguilar, J., Gramig, G. G., Hendrickson, J. R., Archer, D. W., Forcella, F. et al. (2015). Crop Species Diversity Changes in the United States: 1978–2012. PLOS ONE 10(8): e0136580. doi: 10.1371/JOURNAL.PONE.0136580.

Almasri, M. N., and Kaluarachchi, J. J. (2005). Multi-criteria decision analysis for the optimal management of nitrate contamination of aquifers. Journal of Environmental management. 74(4):365-381.

Acharya, J., Bakker, M. G., Moorman, T. B., Kaspar, T. C., Lenssen, A. W., & Robertson, A. E. (2017). Time interval between cover crop termination and planting influences corn seedling disease, plant growth, and yield. Plant disease, 101(4), 591-600.

Acharya, J., Moorman, T. B., Kaspar, T. C., Lenssen, A. W., and Robertson, A. E. (2020). Cover crop rotation effects on growth and development, seedling disease, and yield of corn and soybean. Plant disease, 104(3), 677-687.

Arbuckle, J. G., & Roesch-McNally, G. (2015). Cover crop adoption in Iowa: The role of perceived practice characteristics. Journal of Soil and Water Conservation, 70(6), 418-429.

Archontoulis, S.V., Castellano, M.J., Licht, M.A., Nichols, V., Baum, M., Huber, I., Martinez-Feria, R., Puntel, L., Ordóñez, R.A., Iqbal, J. and Wright, E.E. (2020). Predicting crop yields and soil-plant nitrogen dynamics in the US Corn Belt. Crop Science, 60(2), pp.721-738.

Baker, J.M. and Griffis, T.J. (2009). Evaluating the potential use of winter cover crops in corn–soybean systems for sustainable co-production of food and fuel. Agricultural and forest meteorology, 149(12), pp.2120-2132.

Basche, A., & DeLonge, M. (2017). The impact of continuous living cover on soil hydrologic properties: A meta-analysis. Soil Science Society of America Journal, 81(5), 1179-1190.

Basche, A. D., & Roesch-McNally, G. E. (2017). Research topics to scale up cover crop use: Reflections from innovative Iowa farmers. Journal of Soil and Water Conservation, 72(3), 59A-63A.

Baum, M. E., S. V. Archontoulis, and M. A. Licht. (2019). Planting date, hybrid maturity, and weather effects on maize yield and crop stage. Agronomy Journal 111(1):303-313.

Bedford, T., and Cooke, R. (2001). Probabilistic risk analysis: foundations and methods. Cambridge University Press.

Bergtold, J. S., Ramsey S., Maddy, L., and Williams, J. R. (2019). A review of economic considerations for cover crops as a conservation practice." Renewable Agriculture and Food Systems 34(1): 62-76.

Boryan, C., Yang, Z., Mueller, R. and Craig, M. (2011). Monitoring US agriculture: the US Department of Agriculture, National Agricultural Statistics Service, Cropland Data Layer Program. http://dx.doi.org/10.1080/10106049.2011.562309 26(5): 341–358. doi: 10.1080/10106049.2011.562309.

Carlson, S., & Stockwell, R. (2013). Research priorities for advancing adoption of cover crops in agriculture-intensive regions. Journal of Agriculture, Food Systems, and Community Development, 3(4), 125-129.

Carleton, A. E., and Cooper, C. S. (1972). Seed size effects upon seedling vigor of three forage legumes 1." Crop Science 12(2): 183-186. https://doi.org/10.1002/aepp.13248

Cegan, J. C., Filion, A. M., Keisler, J. M., and Linkov, I. (2017). Trends and applications of multi-criteria decision analysis in environmental sciences: literature review. Environment Systems and Decisions, 37(2), 123-133.

Chatterjee, N., Archontoulis, S. V., Bastidas, A., Proctor, C. A., Elmore, R. W., and Basche, A. D. (2020). Simulating winter rye cover crop production under alternative management in a corn-soybean rotation. Agronomy Journal, 112(6), 4648-4665.

Church, S. P., Lu, J., Ranjan, P., Reimer, A. P., & Prokopy, L. S. (2020). The role of systems thinking in cover crop adoption: Implications for conservation communication. Land use policy, 94, 104508.

Clemen, R. T., and Reilly, T. (2013). Making hard decisions with DecisionTools. Cengage Learning.

Creamer, N. G., & Dabney, S. M. (2002). Killing cover crops mechanically: Review of recent literature and assessment of new research results. American Journal of Alternative Agriculture, 17(1), 32-40.

Crossley, M.S., Burke, K. D., Schoville, S. D. and Radeloff, V. C. (2021). Recent collapse of crop belts and declining diversity of US agriculture since 1840. Global Change Biology 27(1): 151–164. doi: 10.1111/GCB.15396.

Daigh, A. L., Helmers, M. J., Kladivko, E., Zhou, X., Goeken, R., Cavdini, J., ... and Sawyer, J. (2014). Soil water during the drought of 2012 as affected by rye cover crops in fields in Iowa and Indiana. Journal of Soil and Water Conservation, 69(6), 564-573.

Da Silva, G. A., Han, G., Kandel, Y. R., Mueller, D. S., Helmers, M., Kaspar, T. C., & Leandro, L. F. (2021). Field Studies on the Effect of Rye Cover Crop on Soybean Root Disease and Productivity. PhytoFrontiers, (ja).

Do, H., Luedeling, E., & Whitney, C. (2020). Decision analysis of agroforestry options reveals adoption risks for resource-poor farmers. Agronomy for Sustainable Development, 40(3), 1-12.

Edwards, W. (2020). The number of days suitable for fieldwork in Iowa is shrinking. Iowa Staet University Extension and Outreach. https://www.extension.iastate.edu/agdm/articles/edwards/EdwMar20.html [Accessed September 2, 2022]

Feyereisen, G. W., Wilson, B. N., Sands, G. R., Strock, J. S., & Porter, P. M. (2006). Potential for a rye cover crop to reduce nitrate loss in southwestern Minnesota. Agronomy Journal, 98(6), 1416-1426.

Finney, D. M., White, C. M., & Kaye, J. P. (2016). Biomass production and carbon/nitrogen ratio influence ecosystem services from cover crop mixtures. Agronomy Journal, 108(1), 39-52.

Fisher, K. A., Momen, B., & Kratochvil, R. J. (2011). Is broadcasting seed an effective winter cover crop planting method?. Agronomy Journal, 103(2), 472-478.

Food and Agriculture Organization (FAO). (2020). FAOSTAT Crops and livestock products. https://www.fao.org/faostat/en/#data/QCL [Accessed September 1, 2022]

Gandorfer, M., Pannell, D., and Meyer-Aurich, A. (2011). Analyzing the effects of risk and uncertainty on optimal tillage and nitrogen fertilizer intensity for field crops in Germany. Agricultural Systems 104(8): 615-622.

Guputa, S. (2022). Sensitivity Analysis in Excel | One & Two Variable Data Table. https://www.wallstreetmojo.com/sensitivity-analysis-in-excel/ [Accessed September 1, 2022]

Hamilton, A. V., Mortensen, D. A., & Allen, M. K. (2017). The state of the cover crop nation and how to set realistic future goals for the popular conservation practice. Journal of Soil and Water Conservation, 72(5), 111A-115A.

Hardaker, J. B., Lien, G., Anderson, J. R., & Huirne, R. B. (2015). Coping with risk in agriculture: Applied decision analysis. Cabi.

Hatfield, J. L., McMullen, L. D., & Jones, C. S. (2009). Nitrate-nitrogen patterns in the Raccoon River Basin related to agricultural practices. Journal of soil and water conservation, 64(3), 190-199.

Hijmans, R.J., Choe, H., and Perlman, J. (2016). Spatiotemporal Patterns of Field Crop Diversity in the United States, 1870–2012. Agricultural & Environmental Letters 1(1): 160022. doi: 10.2134/AEL2016.05.0022.

Howard, R. A. (1988). Decision analysis: Practice and promise. Management science, 34(6), 679-695.

Howard, R., and Abbas, A. E. (2010). Foundations of Decision Analysis‖(manuscript).

Hubbard, D. W. (2020). The failure of risk management: Why it's broken and how to fix it. John Wiley & Sons.

Iowa Environmental Mesonet (IEM). (2022). https://mesonet.agron.iastate.edu [Accessed September 1, 2022]

Iowa State University Extension. (2018). Economics of Cover Crops worksheets. https://www.extension.iastate.edu/agdm/crops/html/a1-91.html [Accessed September 1, 2022]

Iowa State University Extension. (2022). Esimated Costs of Crop Production. https://www.extension.iastate.edu/agdm/crops/html/a1-20.html [Accessed September 1, 2022]

Johnson, T. J., Kaspar, T. C., Kohler, K. A., Corak, S. J., and Logsdon, S. D. (1998). Oat and rye overseeded into soybean as fall cover crops in the upper Midwest. Journal of Soil and Water Conservation, 53(3), 276-279.

Kaplan, S., and Garrick, B. J. (1981). On the quantitative definition of risk. Risk analysis, 1(1), 11-27.

Kaspar, T. C., Radke, J. K., & Laflen, J. M. (2001). Small grain cover crops and wheel traffic effects on infiltration, runoff, and erosion. Journal of Soil and Water Conservation, 56(2), 160-164.

Kaspar, T.C., Jaynes, D.B., Parkin, T.B. and Moorman, T.B., (2007). Rye cover crop and gamagrass strip effects on NO3 concentration and load in tile drainage. Journal of environmental quality, 36(5), pp.1503-1511.

Kaspar, T. C., Jaynes, D. B., Parkin, T. B., Moorman, T. B., and Singer, J. W. (2012). Effectiveness of oat and rye cover crops in reducing nitrate losses in drainage water. Agricultural Water Management, 110, 25-33.

Kessler, A., Archontoulis, S. V., & Licht, M. A. (2020). Soybean yield and crop stage response to planting date and cultivar maturity in Iowa, USA. Agronomy Journal, 112(1), 382-394.

Krupek, F. S., Mizero, S. M., Redfearn, D., and Basche, A. (2022). Assessing how cover crops close the soil health gap in on-farm experiments. Agricultural & Environmental Letters, 7(2), e20088.

Kucharik, C. J. (2008). Contribution of planting date trends to increased maize yields in the central United States. Agronomy Journal, 100(2), 328-336.

Lee, D., Arbuckle, J. G., Zhu, Z., & Nowatzke, L. (2018). Conditional causal mediation analysis of factors associated with cover crop adoption in Iowa, USA. Water Resources Research, 54(11), 9566-9584.

Marcillo, G. S., & Miguez, F. E. (2017). Corn yield response to winter cover crops: An updated meta-analysis. Journal of Soil and Water Conservation, 72(3), 226-239.

Marcillo, G. S., Carlson, S., Filbert, M., Kaspar, T., Plastina, A., & Miguez, F. E. (2019). Maize system impacts of cover crop management decisions: A simulation analysis of rye biomass response to planting populations in Iowa, USA. Agricultural Systems, 176, 102651.

Martinez-Feria, R. A., Dietzel, R., Liebman, M., Helmers, M. J., & Archontoulis, S. V. (2016). Rye cover crop effects on maize: A system-level analysis. Field Crops Research, 196, 145-159.

Martinez-Feria, R., Nichols, V., Basso, B., & Archontoulis, S. (2019). Can multi-strategy management stabilize nitrate leaching under increasing rainfall?. Environmental Research Letters, 14(12), 124079.

Maryland Department of Agriculture (2022). Maryland's 2022-2023 Cover Crop Program. https://mda.maryland.gov/resource_conservation/Pages/cover_crop.aspx [Accessed September 1, 2022]

Mirsky, S. B., Curran, W. S., Mortensen, D. A., Ryan, M. R., & Shumway, D. L. (2009). Control of cereal rye with a roller/crimper as influenced by cover crop phenology. Agronomy Journal, 101(6), 1589-1596.

Mitsch, W. J., Day, J. W., Gilliam, J. W., Groffman, P. M., Hey, D. L., Randall, G. W., & Wang, N. (2001). Reducing Nitrogen Loading to the Gulf of Mexico from the Mississippi River Basin: Strategies to Counter a Persistent Ecological Problem: Ecotechnology—the use of natural ecosystems to solve environmental problems—should be a part of efforts to shrink the zone of hypoxia in the Gulf of Mexico. BioScience, 51(5), 373-388.

Mohler, C. L., Liebman, M. and Staver, C. P. (2009). Weed life history: identifying vulnerabilities.Ecological management of agricultural weeds: 40-98. Cambridge University Press. https://doi.org/10.1017/CBO9780511541810

Nelson, H. and S. Bennett. (2018). Cereal Rye Cover Crop for Reducing Herbicides in Soybeans. Practical Farmers of Iowa Cooperators' Program. https://practicalfarmers.org/research/cereal-rye-cover-crop-for-reducing-herbicides-in-soybeans/ [Accessed February 2022]

Nichols, V., English, L., Carlson, S., Gailans, S., and Liebman, M. (2020a). Effects of long-term cover cropping on weed seedbanks. Frontiers in Agronomy, 2, 591091.

Nichols, V., Martinez-Feria, R., Weisberger, D., Carlson, S., Basso, B., & Basche, A. (2020b). Cover crops and weed suppression in the US Midwest: A meta-analysis and modeling study. Agricultural & Environmental Letters, 5(1), e20022.

Nichols, V. A., Moore, E. B., Gailans, S., Kaspar, T. C., and Liebman, M. (2022). Site-specific effects of winter cover crops on soil water storage. Agrosystems, Geosciences & Environment, 5(1), e20238.

Pantoja, J. L., Woli, K. P., Sawyer, J. E., & Barker, D. W. (2015). Corn nitrogen fertilization requirement and corn–soybean productivity with a rye cover crop. Soil Science Society of America Journal, 79(5), 1482-1495.

Park, B., Rejesus, R. M., Aglasan, S., Che, Y., Hagen, S. C., & Salas, W. (2022). Payments from agricultural conservation programs and cover crop adoption. Applied Economic Perspectives and Policy.

Patel, S., Sawyer, J. E., & Lundvall, J. P. (2019). Can management practices enhance corn productivity in a rye cover crop system?. Agronomy Journal, 111(6), 3161-3171.

Plastina, A., Liu, F., Miguez, F., & Carlson, S. (2020). Cover crops use in Midwestern US agriculture: perceived benefits and net returns. Renewable Agriculture and Food Systems, 35(1), 38-48.

Quinn, D. J., Poffenbarger, H. J., Leuthold, S. J., & Lee, C. D. (2021). Corn response to in-furrow fertilizer and fungicide across rye cover crop termination timings. Agronomy Journal, 113(4), 3384-3398.

Roesch-McNally, G. E., Basche, A. D., Arbuckle, J. G., Tyndall, J. C., Miguez, F. E., Bowman, T., & Clay, R. (2018). The trouble with cover crops: Farmers' experiences with overcoming barriers to adoption. Renewable Agriculture and Food Systems, 33(4), 322-333.

Rundquist, S. and Carlson, S. (2017). Mapping cover crops on corn and soybeans in Illinois, Indiana and Iowa, 2015-2016. Environmental Working Group. https://www.ewg.org/research/mapping-cover-crops-corn-and-soybeans-illinois-indiana-and-iowa-2015-2016 [Accessed September 1, 2022]

Sustainable Agriculture Research and Education (SARE). (2020). National Cover Crop Surveys. https://www.sare.org/publications/cover-crops/national-cover-crop-surveys/ [Accessed September 2, 2022]

Sarrantonio, M. (1994). Northeast Cover Crop Handbook. Soil Health Series. Rodale Institute, Kutztown, PA

Seifert, C. A., Azzari, G., and Lobell, D. B. (2018). Satellite detection of cover crops and their effects on crop yield in the Midwestern United States. Environmental Research Letters, 13(6), 064033.

Shackelford, G. E., Kelsey, R., Sutherland, W. J., Kennedy, C. M., Wood, S. A., Gennet, S., ... & Dicks, L. V. (2019). Evidence synthesis as the basis for decision analysis: a method of selecting the best agricultural practices for multiple ecosystem services. Frontiers in sustainable food systems, 83.

Singer, J. W. (2008). Corn belt assessment of cover crop management and preferences. Agronomy Journal, 100(6), 1670-1672.

Syswerda, S. P., Basso, B., Hamilton, S. K., Tausig, J. B., and Robertson, G. P. (2012). Long-term nitrate loss along an agricultural intensity gradient in the Upper Midwest USA. Agriculture, Ecosystems & Environment, 149, 10-19.

Thompson, N. M., Reeling, C. J., Fleckenstein, M. R., Prokopy, L. S., and Armstrong, S. D. (2021). Examining intensity of conservation practice adoption: Evidence from cover crop use on US Midwest farms. Food Policy, 101, 102054.

Talukder, B., Blay-Palmer, A., Hipel, K. W., and vanLoon, G. W. (2017). Elimination method of multi-criteria decision analysis (MCDA): A simple methodological approach for assessing agricultural sustainability. Sustainability 9:287. doi:10.3390/su9020287

Urban, D. W., Roberts, M. J., Schlenker, W., and Lobell, D. B. (2015). The effects of extremely wet planting conditions on maize and soybean yields. Climatic Change 130(2):247-260.

USDA National Agricultural Statistics Service (USDA NASS). (2018). National Crop Progress – Terms and Definitions.

https://www.nass.usda.gov/Publications/National_Crop_Progress/Terms_and_Definitions/index.php [Accessed September 1, 2022]

USDA National Agricultural Statistics Service (USDA NASS). (2022). Quick Stats. https://quickstats.nass.usda.gov [Accessed September 1, 2022]

USDA National Agricultural Statistics Service Cropland Data Layer (USDA NASS CDL). (2021). Published corn data layer [Online]. USDA-NASS, Washington, DC. https://nassgeodata.gmu.edu/CropScape/ [Accessed August 10, 2021]

USDA Risk Management Agency (USDA RMA). (2019). 2020 Cover Crops Insurance and NRCS Cover Crop Termination Guidelines. https://www.rma.usda.gov/en/News-Room/Frequently-Asked-Questions/2020-Cover-Crops-Insurance-and-NRCS-Cover-Crop-Termination-Guidelines [Accessed September 1, 2022]

Wilson, M. L., Baker, J. M., and Allan, D. L. (2013). Factors affecting successful establishment of aerially seeded winter rye. Agronomy Journal, 105(6), 1868-1877.

Wilson, M. L., Allan, D. L. and Baker, J. M. (2014). Aerially seeding cover crops in the northern US Corn Belt: Limitations, future research needs, and alternative practices.Journal of Soil and Water Conservation 69(3): 67A-72A.

Yoder, L., Houser, M., Bruce, A., Sullivan, A., and Farmer, J. (2021). Are climate risks encouraging cover crop adoption among farmers in the southern Wabash River Basin?. Land Use Policy, 102, 105268.

1 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 for more details.

2 Figure legends and tables

Table 1 Timeframes assumed for estimating fall weather uncertainties related to precipitation and growing degree days (GDDs)

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	-	\$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 probabilities of workable field days (WFDs) in a given timeframe based on 30 years of NASS survey data (USDA NASS 2022)

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