Optimizing Herbicide Application In Corn Cultivation

Across Iowa, Illinois, and Nebraska

Group 6

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1 Introduction

The use of glyphosate, a widespread herbicide in America's farmlands, is currently under active discussion regarding its safety. Since 2015, the International Agency for Research on Cancer (IRAC) has categorized glyphosate as a probable carcinogen for humans. While the debate over the use of glyphosate has yet come to an end, the use of this herbicide has surged 15 times in the past two decades[1]. The reliance on glyphosate presents a key dilemma - how to balance agricultural productivity with environmental protection. In light of these concerns, our project stands at the forefront of this challenge, aiming to delicately balance the optimization of glyphosate usage, along with other herbicides, to safeguard environmental sustainability within key agricultural landscapes across the United States.

Our project narrows its focus to study the complex interactions between herbicide applications and crop yields in the states of Iowa, Illinois, and Nebraska, as they are reported to be the states that use the most herbicides in the US[15]. This localized research ensures an in-depth understanding of herbicide dynamics in these states, which is consistent with our goal of reducing the overuse of herbicides while maintaining yields of major crops.

At the heart of our work is a combination of mathematical modeling and optimization techniques, implemented through a data analysis approach, which goes beyond crunching numbers to consciously developing refined strategies that strike a delicate balance between reducing the use of harmful herbicides and ensuring continued yield increases in important crops like corn.

The significance of our pursuit transcends the boundaries of agricultural fields, promising profound benefits for three primary stakeholders:

1. **Consumers:** By mitigating risks associated with herbicide exposure in crops, consumers stand to enjoy safer and healthier produce, underscoring our commitment to their well-being.

2. **Agricultural Community:** Farmers, as stewards of the land, stand to gain significantly. Our strategies aim to alleviate risks linked to herbicide usage while preserving crop yields, fostering sustainable farming practices, and reducing financial burdens.

3. **Government and Regulatory Bodies:** Insights from our project hold immense promise for policymakers, offering empirical data to inform evidence-based regulations that strike a balance between agricultural demands and environmental conservation imperatives across diverse regions.

Through innovative optimization techniques and a nationwide focus, our mission is anchored in pioneering solutions that resonate with societal well-being, environmental stewardship, and the longevity of American agriculture.

2 Problem Description And Formulation

2.1 Problem Description

Our work aims to address the question of how to reduce the injurious nature of multiple herbicide compounds without compromising production for Illinois, Iowa and Nebraska. Corn, being an annual crop with a 16-week growth cycle from late Spring to Fall, requires herbicide treatment at three stages of planting. The soil treatment as a preparation step for the planting starts a few weeks before the actual planting, and needs to be re-treated after harvest. To simplify the complexity of the problem, in this model, we assume a period of four weeks for before planting, and eight weeks for after planting. These three stages compose the full herbicide treatment cycle of corn of 28 weeks.

Other constraints further complicates the analysis due to varying usage timing and quantity requirements specified on herbicide labels, which are non-negligible for ensure the safety, efficacy, and productivity of crop yield[13]. This herbicide usage optimization analysis aims to propose a method to minimize the impact of the herbicide treatment while maintaining the production yield, taking into account the intricate constraints posed by different application timings Appendix 6.2 - Corn Growth Cycle and Herbicide Treatment Timing.

2.2 Variable Definition

x_{ijk}**:** Quantity of herbicide i used for week j of corn plant growth, in kg/acre, for state k

z_{ijk}**:** Binary variable for indicating the presence of herbicide usage for herbicide i for week j in state k

where $i \in \{0, ..., 12\}$, $j \in \{0, ..., 27\}$, and $k \in \{0, 1, 2\}$

2.2.1 Objective Function

Minimize usage of glyphosate in 3 states (first priority):

$$min \sum_{k=0}^{2} \sum_{j=0}^{27} x_{9jk} \cdot z_{9jk}$$

Minimize usage of overall herbicide in 3 states (second priority):

$$min \sum_{k=0}^{2} \sum_{i=0}^{12} \sum_{j=0}^{27} x_{ijk} \cdot z_{ijk}$$

2.2.2 Constraints

There are 7 types of constraints added to our model. All the constraints are the same for each state; therefore, all the constraints are for $k \in \{0, 1, 2\}$

1. **Objective Function Constraints:** They aim to ensure uniform herbicide application across different types and growth stages within each state, guaranteeing consistent overall herbicide usage.

   Total Usage for State k: $\sum_{j=0}^{27}\sum_{k=0}^{12} x_{ijk} \cdot z_{ijk}$ Glyphosate Usage for State k: $\sum_{j=0}^{27} x_{8jk} \cdot z_{8jk}$

2. **Lower Bound Usage Constraints:** There are required minimum usage of herbicide to ensure production yield.

   $$Baseline_k + \sum_{i=0}^{12}(\sum_{j=0}^{27} x_{ijk} \cdot coef_{ik}) \geq Yield\_Min_k$$

   In this constraint, the $Baseline_k$, $coef_{ik}$ and $Yield\_Min_k$ are constants.

3. **Upper Bound Usage Constraints for before/at/after planting:** Regulations dictate maximum allowable usage for all herbicides during distinct stages: pre-planting (weeks 1 to 4), planting (weeks 5 to 19), and post-planting (weeks 20 to 28).

   $$x_{ijk} \cdot z_{ijk} \cdot has\_ub_i \leq ub_i \quad for \quad j \in \{0, \ldots, 3\} \qquad x_{ijk} \cdot z_{ijk} \cdot has\_ub_i \leq ub_i \quad for \quad j \in \{4, \ldots, 18\}$$
   $$x_{ijk} \cdot z_{ijk} \cdot has\_ub_i \leq ub_i \quad for \quad j \in \{19, \ldots, 27\}$$

   In these constraints, the has_ub_i and ub_i are constants.

4. **Special Quantity Restriction Constraints:** Several herbicides are subject to limitations regarding the maximum usage on week j.

   - On week 1 - 18, the usage of 2,4-D cannot be more than 0.41 kg/acre: $\sum_{j=0}^{17} x_{0jk} \cdot z_{0jk} \leq 0.41$
   - On week 4 - 8, the usage of alachlor cannot be more than 2.05 kg/acre: $\sum_{j=3}^{7} x_{1jk} \cdot z_{1jk} \leq 2.05$
   - On week 1 - 3, the usage of atrazine cannot be more than 1.814368kg: $\sum_{j=0}^{2} x_{2jk} \cdot z_{2jk} \leq 1.814368$
   - On week 4 - 8, the usage of atrazine cannot be more than 1.91kg/acre: $\sum_{j=3}^{7} x_{2jk} \cdot z_{2jk} \leq 1.91$
   - On week 8 - 17, the usage of bromoxynil needs to be within 0.4 - 0.49 kg/acre:
     $\sum_{j=7}^{16} x_{3jk} \cdot z_{3jk} \geq 0.40$ $\sum_{j=7}^{16} x_{3jk} \cdot z_{3jk} \leq 0.49$
   - On week 4 - 6, the usage of dicamba cannot be more than 0.506kg/acre: $\sum_{j=3}^{5} x_{4jk} \cdot z_{4jk} \leq 0.506$

- Before week 2, the usage of diflufenzoapyr cannot be more than 0.17kg/acre: $\sum_{j=0}^{1} x_{5jk} \cdot z_{5jk} \leq 0.17$
- On week 4 - 7, the usage of diflufenzoapyr cannot be more than 0.23kg/acre: $\sum_{j=3}^{6} x_{5jk} \cdot z_{5jk} \leq 0.23$
- On week 8 - 12, the usage of diflufenzoapyr cannot be more than 0.11kg/acre: $\sum_{j=7}^{11} x_{5jk} \cdot z_{5jk} \leq 0.11$
- On week 1 - 3, the usage of EPTC cannot be more than 2.784kg/acre: $\sum_{j=0}^{2} x_{6jk} \cdot z_{6jk} \leq 2.784$
- On week 4 - 5, the usage of EPTC cannot be more than 1.804kg/acre: $\sum_{j=3}^{4} x_{6jk} \cdot z_{6jk} \leq 1.804$
- Before week 8, the usage of foramsulfuron cannot exceed 0.04082 kg/acre: $\sum_{j=0}^{6} x_{7jk} \cdot z_{7jk} \leq 0.04082$
- The usage of glyphosate cannot exceed 2.0581737kg/acre/year: $\sum_{j=0}^{27} x_{8jk} \cdot z_{8jk} \leq 2.0581737$
- The usage of halosulfron cannot exceed 0.07541 kg/acre/year: $\sum_{j=0}^{27} x_{9jk} \cdot z_{9jk} \leq 0.07541$
- The usage of nicosulfron cannot exceed 0.0709764kg/acre/year: $\sum_{j=0}^{27} x_{10jk} \cdot z_{10jk} \leq 0.0709764$

5. **Presence Restriction Constraints:** Several herbicides are subject to limitations regarding the maximum number of applications and/or the timing of their application.

   - 2,4-D can only have 1 treatment per year: $\sum_{j=0}^{27} z_{0jk} \leq 1$
   - Alachlor cannot be used after week 13: $\sum_{j=13}^{27} z_{1jk} = 0$
   - Dicamba cannot be used from week 16: $\sum_{j=15}^{27} z_{4jk} = 0$
   - Diflufenzoapyr cannot be used from week 16: $\sum_{j=15}^{27} z_{5jk} = 0$

   Due to the report page limit, we are putting the remaining presence restriction constraints in the Appendix 6.3.

6. **Mixing Restriction Constraints:** Several herbicides exhibit incompatibility with specific other herbicides.

   - 2,4-D is not compatible with glyphosate: $z_{0jk} + z_{8jk} \leq 1 \quad j \in \{0, \ldots, 27\}$
   - Parquat is not compatible with glyphosate: $z_{11jk} + z_{8jk} \leq 1 \quad j \in \{0, \ldots, 27\}$

7. **Linking Decision Variables:**

   $x_{ijk} \leq z_{ijk} \cdot M \qquad\qquad x_{ijk} \geq z_{ijk} \cdot \epsilon$

   where M is a very large number and the ϵ is a very small number.

3 Numerical Implementation And Results

3.1 Data Description

To address the assumption that each type of herbicide used in the model contributes to the corn yield by a fixed quantity, we need to obtain the production increase per herbicide per unit used, as well as the production yield when no herbicide is used. Unfortunately, such data is not directly available. We can only find the estimated quantity used per type of herbicide per year and the total yield per acre.

For our analysis, we employed crop production data from 2014 to 2017 provided by the United States Department of Agriculture[14], coupled with the estimated annual agricultural pesticide usage for the same years from the U.S. Geological Survey[15]. We conducted three linear regression models for each state to predict production levels. The coefficients from these models were used to represent the impact of herbicides, while the intercept represented the baseline production in the absence of herbicide usage.

Furthermore, insights from the Herbicide Treatment Table by the University of California Integrated Pest Management Program[13] guided us in formulating specific guidelines for herbicide application. Following this table, we obtained the upper bound of the quantity of each herbicide for different stages of planting. We also referred to the herbicide labels to develop the herbicide treatment timing constraints and mixing constraints.

Finally, we collected the price of each herbicide from online retailers such as Solutions Pest & Lawn [5] for problem extension. We standardized the unit for the herbicide prices to USD/kg. This helps us to formulate the third objective of cost minimization.

Overall, combining information from these sources allowed us to better understand corn production dynamics and the impact of herbicides. This knowledge formed the basis for creating an effective strategy to support positive corn yields while promoting responsible herbicide use in the targeted states.

3.2 Model Selection

As mentioned earlier, glyphosate and other herbicides have exhibited adverse effects on human and environmental health. Our project aims to reduce the usage of glyphosate and other herbicides while sustaining corn production levels in our target states. This objective transforms the problem into a **Hierarchical Multi-objective Optimization** challenge.

Due to the complexity of our optimization task, **Mixed Integer Programming (MIP)** stands out as a suitable method. Specifically, this is evident in constraints related to herbicide application where binary indicators are essential to represent usage.

3.3 Implementation Details

3.3.1 Auxiliary Variables

In order to solve the optimization problem using Python Gurobi, we introduced several auxiliary variables.

$BromoxynilTreat1_k \quad \& \quad BromoxynilTreat2_k$: Week of the first/second treatment of bromoxynil for state k.

$BromoxynilTreat\_Aux_{kj}$**:** Auxiliary binary variable for bromoxynil treatment in state k on week j.

$StateUsage_k$**:** Quantity of herbicide used for State k.

$GlyphosateUsage_k$**:** Quantity of glyphosate used for State k.

For Bromoxynil, the product label specified that there should be a minimum 3-week gap between the two treatments, we then introduced these constraints:

$$BromoxynilTreat\_Aux_{kj} = z_{3kj} \cdot (j+1) \qquad for \quad j \in \{0, \ldots, 27\} \qquad k \in \{0,1,2\}$$

$$BromoxynilTreat2_j = \max BromoxynilTreat\_Aux_{kj} \qquad for \quad j \in \{0, \ldots, 27\} \qquad k \in \{0,1,2\}$$

$$BromoxynilTreat1_k \leq 3 + BromoxynilTreat2_k \qquad for \quad k \in \{0,1,2\}$$

$$\sum_{j=0}^{27} z_{3jk} \leq 2 \qquad for \quad k \in \{0,1,2\}$$

In Gurobi, a multi-objective model must be linear. We used two sets of auxiliary variables to address this problem.

$$StateUsage_k = \sum_{j=0}^{27} \sum_{k=0}^{12} x_{ijk} \cdot z_{ijk} \qquad GlyphosateUsage_k = \sum_{j=0}^{27} x_{8jk} \cdot z_{8jk}$$

We then minimize the auxiliary variables in the objective function. In this way, we ensure that the problem remains linear and can be solved by Gurobi.

3.3.2 Multiple Objective

In our hierarchical multi-objective optimization model, we implemented the $SetObjectiveN()$ function in Gurobi. Given our primary focus on glyphosate usage, we assigned priority 1 to the total quantity of glyphosate and priority 0 to the overall quantity of all herbicides.

3.4 Base Model Results

Upon optimization, we achieved significant outcomes across the three states: Illinois, Iowa, and Nebraska.

In Illinois, we maintained corn production at a stable 201 tons. Before optimization, the major herbicides used were atrazine and glyphosate, resulting in a total herbicide usage of 0.88 kg/acre, with glyphosate accounting for 0.42 kg/acre. Post-optimization, the major herbicides changed to atrazine, bromoxynil, and dicamba, significantly increasing the total herbicide usage to 3.55 kg/acre, while completely eliminating glyphosate usage.

Iowa also maintained stable corn production at 202 tons. Initially, atrazine and glyphosate were the primary herbicides, resulting in a total herbicide usage of 0.75 kg/acre, with glyphosate usage at 0.38 kg/acre. After optimization, the major herbicides shifted to bromoxynil and dicamba, slightly increasing the total herbicide usage to 1.23 kg/acre while eliminating glyphosate usage entirely.

Nebraska's results were notable, maintaining its corn production at 181.2 tons—a slight 0.14% increase from the initial 181 tons. Initially utilizing atrazine and glyphosate, the total herbicide usage stood at 1.05 kg/acre, with glyphosate usage at 0.54 kg/acre. Post-optimization, the major herbicides transitioned to bromoxynil and dicamba, significantly reducing the total herbicide usage to 0.91 kg/acre, completely eliminating glyphosate usage.

Overall, our model successfully minimized glyphosate usage and optimized overall herbicide usage while maintaining or slightly enhancing corn production across the three states.

Figure 1 prominently displays the effective elimination of glyphosate usage achieved by our model in all three states. However, this elimination of glyphosate led to a consequential rise in the usage of alternative herbicides. This trade-off accentuates the complete cessation of glyphosate usage, highlighting its inverse correlation with the increased usage of other herbicides.

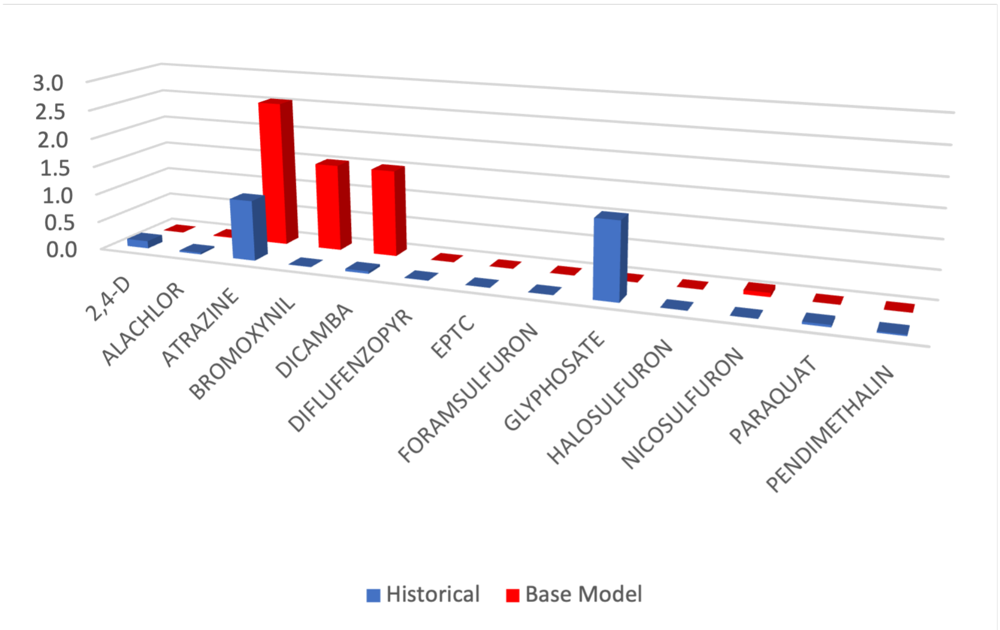

Figure 1: Herbicide Usage (Historical vs. Base Model)

Figure 2 indicates a clear trade-off between eliminating glyphosate and decreasing usage of total herbicides. The model increased dicamba and bromoxynil to compensate for the yield contributed by glyphosate.

Figure 3 displays the herbicide mix change after optimization by state. atrazine has significantly increased in Illinois but decreased in other states. This could possibly caused by the relatively higher coefficient of atrazine in Illinois compared to the rest of the two states.

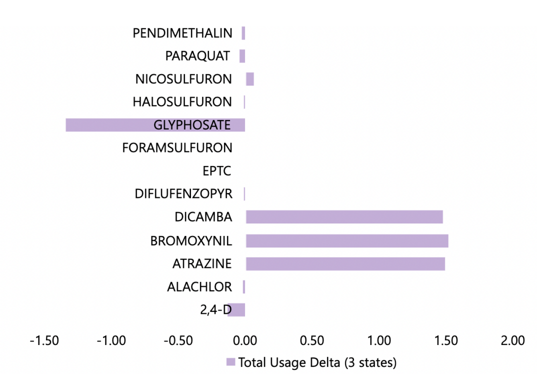

Figure 2: Change In Herbicide Usage (From Historical to Base Model)

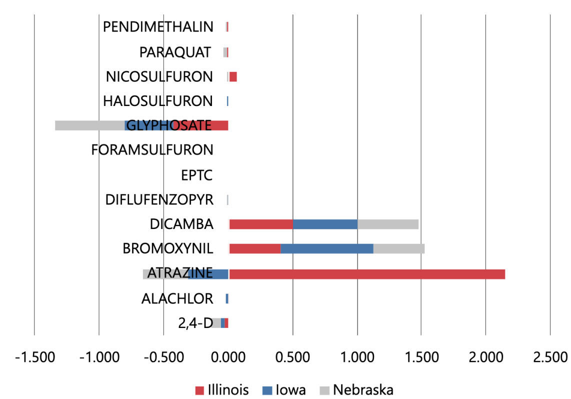

Figure 3: Change In Herbicide Usage By State (From Historical to Base Model)

4 Problem Extensions

4.1 Additional Objective

The previous optimization results underscore a noticeable trade-off between glyphosate usage and other herbicides. It also raises an intriguing question about potential dependencies on pricing in herbicide selection. In this section, our primary focus shifts towards addressing the concerns of one of our main stakeholders – the Agricultural Community, particularly the farmers within the states of Iowa, Illinois, and Nebraska. Cost becomes a pivotal consideration for these stakeholders, especially when implementing changes in their practices. Our key objective now entails minimizing costs associated with herbicide usage. To achieve this, we've incorporated the market prices of the 13 herbicides, sourced from websites such as [5].

Here are our new Objective Functions:

Minimize the cost of herbicide in 3 states (first priority):

$$min \sum_{i=0}^{12} (\sum_{k=0}^{2} \sum_{j=0}^{27} x_{ijk}) \cdot Price_i$$

Minimize usage of glyphosate in 3 states (second priority):

$$min \sum_{k=0}^{2} \sum_{j=0}^{27} x_{9jk} \cdot z_{9jk}$$

Minimize usage of overall herbicide in 3 states (third priority):

$$min \sum_{k=0}^{2} \sum_{i=0}^{12} \sum_{j=0}^{27} x_{ijk} \cdot z_{ijk}$$

4.2 Extended Model Result

The outcomes from the extended model align with the expected relationship between cost and herbicide usage in agricultural practices. As anticipated, the lower cost associated with certain herbicides resulted in higher usage. Specifically, prioritizing cost-effectiveness led to a notable 47.8% reduction in total herbicide expenditure, emphasizing the impact of cost-centric decision-making. Meanwhile, the model demonstrated a corresponding 10.9% increase in total herbicide usage. This emphasizes how reduced costs incentivize farmers to employ more cost-efficient herbicides to maintain weed control and optimize crop yields.

Through comparing the results from the historical data, the base model, and the extended model, we noticed substantial shifts in crucial aspects. While corn production remained relatively stable across scenarios, the shift in major herbicides used stands out prominently. The extension model prioritized the usage of bromoxynil and dicamba owing to their cost-effectiveness, diverging from the base model's reliance on atrazine, primarily due to the latter's higher unit cost.

Additionally, the extension model has a significant surge in total herbicide usage compared to historical and base model scenarios. The extension model's increase from 2.68 kg/acre historically to 6.31 kg/acre marks a notable 134.7% rise. This surge highlights the model's cost-centric approach, favoring alternative herbicides offering a better balance between efficacy and cost. Despite a high reduction in herbicide costs compared to the base model, this cost reduction did not correspond with decreased herbicide volumes. This reflects the significant relationship between cost-effectiveness and herbicide application.

Despite the rise in overall herbicide usage seen in both models, Figure 4 clearly shows a major success: our model nearly eliminated the use of glyphosate, which was our main goal. This decrease in glyphosate use is an important achievement, showing our dedication to using fewer harmful chemicals while still controlling weeds on farms. This shift away from glyphosate also demonstrates our commitment to finding better and more eco-friendly herbicides for sustainable farming. The extension model prioritized the usage of bromoxynil and dicamba owing to their cost-effectiveness, diverging from the base model's reliance on atrazine, primarily due to the latter's higher unit cost.

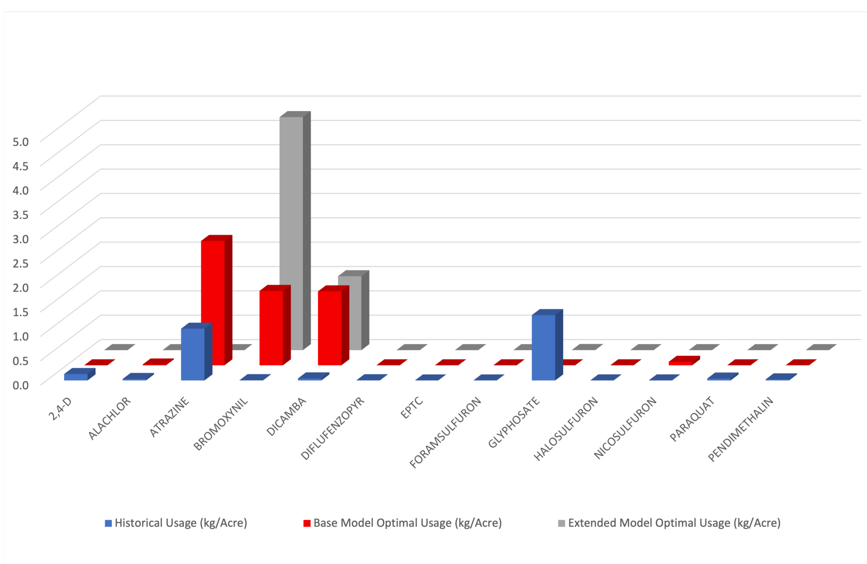

Figure 4: Herbicide Usage (Historical vs. Base Model vs. Extended Model)

5 Conclusions And Recommendations

5.1 Conclusions

As we successfully minimized glyphosate to zero usage, it triggered an increase in the utilization of other herbicides. This underscores a fundamental trade-off between glyphosate and alternative herbicide usage. Moreover, our findings strongly suggest that farmers tend to incline towards more cost-efficient herbicides.

Therefore, we have two pieces of advice for our stakeholders. For farmers, we recommend building an eco-friendly and consumer-centric image by replacing the current herbicide mix with the optimized more eco-friendly mix solution. For the governmental bodies and herbicide suppliers, we recommend considering reimbursing the cost of eco-friendly herbicides.

5.2 Opportunities For Model Improvement

Although the optimization model offers an approach to investigate the issue of herbicide over-usage in the US, the solution result does not fully capture the complexity of the problem of real-world scenarios. The project was limited by several factors, primarily related to data availability. The absence of standardized regulations on the herbicide usage quantity makes it extremely difficult to obtain precise information on the amount of herbicide applied in crop production, and there is no universal measurement of how different herbicide products exert negative impact on the environment. The model treats all herbicides to have the same level of impact except glyphosate. The model also assumes a uniform price for each type of chemical, whereas, in reality, each chemical product company offers herbicides with different ratios of active ingredients, with extensive usage instructions, each at a different price.

Moreover, the coefficient of each herbicide that reflects its contribution to the production of crops is generated from historical estimates of herbicide usage and quantity of crop production. By doing so, we are assuming that the herbicide usage follows the same distribution and there is no overuse of herbicide in current daily practices. Also, though we aimed to minimize the overall herbicide usage, it is not necessarily the most optimal solution for the farmers, consumers, and the environment.

In summary, as more data becomes available in these fields, our model will not only yield more significant results but also have the potential to be expanded. This expansion would allow it to tackle more intricate issues, including the impact of various other pesticides.

6 Appendix

6.1 Glyphosate Historical Usage Trend

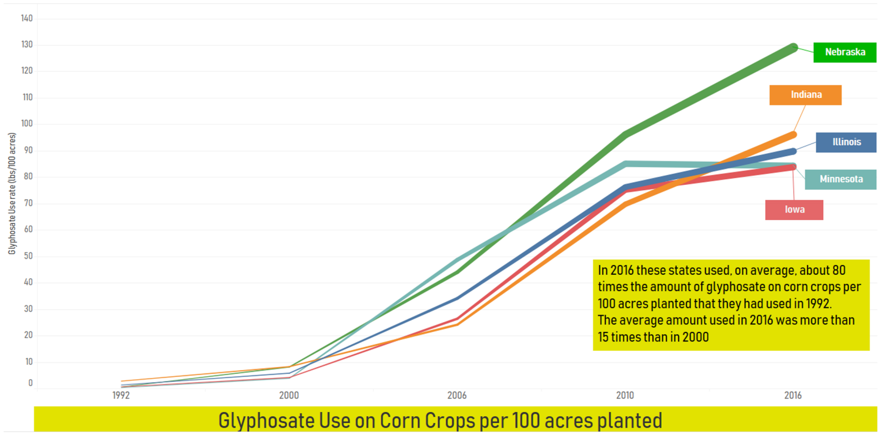

Figure 5: Glyphosate increase over the years

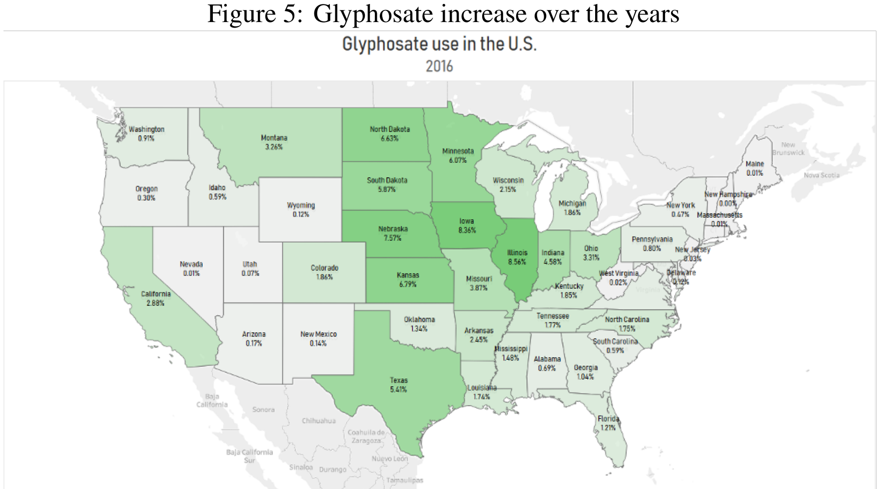

Figure 6: Glyphosate usage in the United States

6.2 Corn Growth Cycle and Herbicide Treatment Timing

Figure 7: Corn Growth Cycle and Herbicide Treatment Timing

6.3 Constraints - Presence Restriction Constraints Cont.

- Halosulfuron can only have 2 treatments per year: $$\sum_{j=0}^{27} z_{9jk} \leq 2$$
- Paraquat can only have 3 treatments per year: $$\sum_{j=0}^{27} z_{11jk} \leq 3$$
- Paraquat cannot be used between week 4 and week 8: $$\sum_{j=3}^{7} z_{11jk} = 0$$
- Pendimethalin can only have 1 treatment per year: $$\sum_{j=0}^{27} z_{12jk} \leq 1$$
- Glyphosate cannot be used from week 19: $$\sum_{j=18}^{27} z_{8jk} = 0$$
- Foramsulfuron cannot be used from week 9: $$\sum_{j=8}^{27} z_{7jk} = 0$$

6.4 Base Model Results

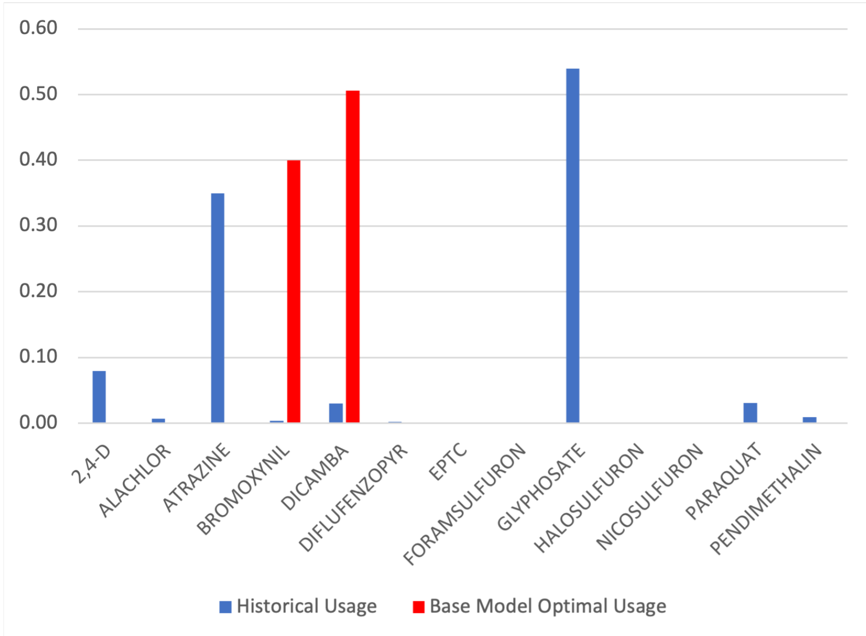

Figure 8: Herbicide Usage In Nebraska

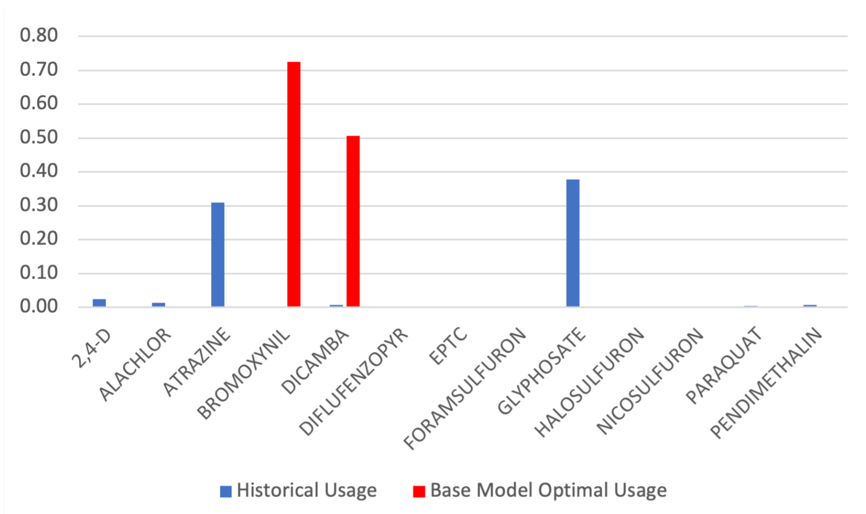

Figure 9: Herbicide Usage In Iowa

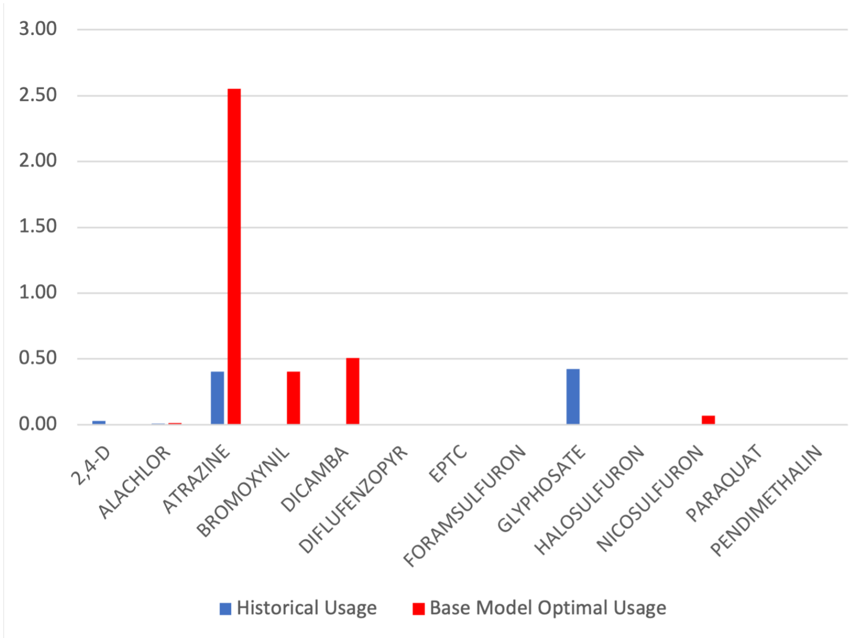

Figure 10: Herbicide Usage In Illinois

6.5 Extended Model Result

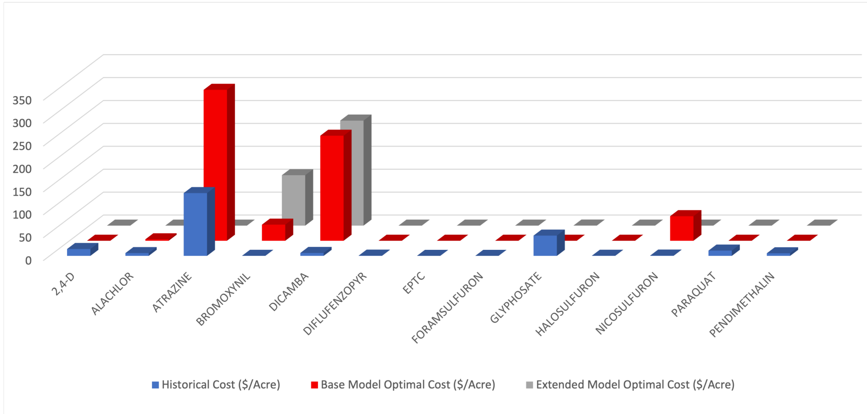

Figure 11: Herbicide Cost (Historical vs. Base Model vs. Extended Model)

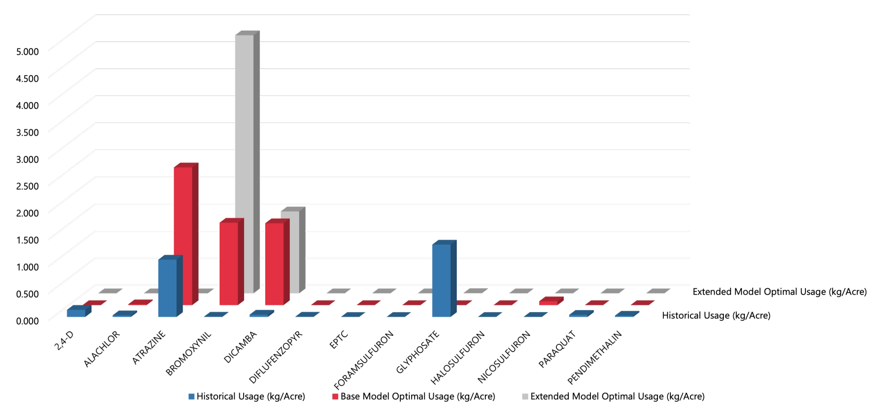

Figure 12: Herbicide Usage (Historical vs. Base Model vs. Extended Model)

	Historical	**Base Model Optimal**	**Extension Model Optimal**
Corn Production	584 tons	584.2 tons	584.2 tons
Major Herbicide Used	Atrazine, Glyphosate	Atrazine, Bromoxynil, Dicamba	Bromoxynil, Dicamba, Paraquat
Total Herbicide Usage	2.68 kg/acre	5.69 kg/acre	6.31 kg/acre ⬆
Glyphosate Usage	1.34 kg/acre	0 kg/acre	0 kg/acre
Herbicide Cost	227 US$/acre	650 US$/acre	339 US$/acre ⬇
Major Cost Driver	2,4-D, Glyphosate, Diflufenzopyr	Atrazine, Bromoxynil, Dicamba	Bromoxynil, Dicamba, Paraquat

Figure 13: Herbicide Usage and Cost Table (Historical vs. Base Model vs. Extended Model)

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