Implications of smart spraying technology on the United States pesticide industry

by

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ABSTRACT

This thesis investigates the financial and environmental impact of introducing "smart spraying" technologies on various stakeholders within the row crop agriculture industry. Smart spraying incorporates cameras and artificial intelligence to sense weeds and only apply herbicides in those areas. The primary focus is to analyze the future implications of these technologies on the amount of active ingredient applied to common herbicides used in corn and soybean production. By examining these factors, the research aims to provide valuable insights that enable farmers, custom applicators, retailers, distributors, basic manufacturers, and policy makers to formulate mid- and long-term strategies. The study employs a comprehensive approach, incorporating quantitative data analysis and qualitative assessments to evaluate the potential economic benefits and challenges associated with smart spraying technologies. The findings highlight significant shifts in market dynamics, offering a consideration for stakeholders navigating the evolving landscape of agricultural weed control.

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CHAPTER I: INTRODUCTION

1.1 Purpose

Weed control is a cornerstone of modern agriculture, directly influencing crop yields. Previous research has shown weed control can increase grain yield of different arable crops by 19% to 372% (Das, et al., 2024). The primary strategy employed to control weeds is the use of herbicides. Currently, many different herbicide products are approved by the Environmental Protection Association (EPA) to use on corn (*Zea maize*) and soybean (*Glycine max*) crops in the United States, the focus of this study. Despite this, the emergence and intensification of weed resistance in recent years has required producers to alter their weed control strategies. One implication of weed resistance is the increased adoption of residual herbicides to prevent weed emergence. In addition, farmers have had to add additional compounds with different modes of action, as well as increase application rates for those compounds. Adding residual herbicides and tank-mixing 'foliar herbicides' with multiple modes of action into weed management plans has led to an increased cost for farmers to effectively control weed populations in their crop fields. As effective weed control has become more challenging in corn and soybean production, companies have devoted resources to develop solutions that can address challenges such as weed resistance and increasing weed management costs.

One such technology that has recently launched into the agricultural marketplace is a technology called smart spraying. Although multiple companies have commercialized 'smart spraying' technologies, the concept remains the same. Smart sprayers utilize boom-mounted cameras and artificial intelligence (AI) processors to detect then apply herbicides only if weeds are detected by the boom mounted cameras.

The companies coming to market with these technologies are promoting a reduction in herbicide usage of 60% up to 95% (Wilson, 2023).

Through a combination of literature review, data modeling, sensitivity analysis, and case studies, this thesis evaluates how smart spraying could reshape weed management practices. It explores implications for stakeholders, including farmers, pesticide manufacturers, distributors, custom applicators, retailers, and policymakers. Adoption barriers, such as upfront costs and technological limitations, are explored to understand their implications on adoption. Ultimately, the study aims to provide a comprehensive framework for understanding smart spraying's potential to balance agricultural productivity with economic and environmental sustainability while offering actionable insights for strategic decision-making for those involved in the United States pesticide industry.

The research begins by establishing the importance of weed control and the evolution of herbicide-tolerant cropping systems, setting the stage for smart spraying as a response to current challenges. Drawing on data from the United States Geological Survey (USGS) Pesticide National Synthesis Project (1992–2018), the study quantifies historical herbicide use and models future reductions based on a median herbicide savings rate of 45.4%, derived from field trials. A technology adoption curve is applied to forecast penetration across 177.6 million corn and soybean acres, projecting an 84% adoption rate by 2034. Financially, the analysis estimates a cumulative $2.9 billion reduction in herbicide market value, alongside per-acre savings for farmers and revenue opportunities for custom applicators. Environmentally, it assesses toxicity reductions using LD50-weighted risk quotients, revealing disproportionate benefits compared to volume decreases.

CHAPTER II: LITERATURE REVIEW

2.1 Importance of weed control

In the context of crop production, a weed has been colloquially defined as a plant out of place. (Steil 2024) Any vegetative growth other than the desired crop in the field is considered a weed. Examples of major weeds in corn and soybean production include waterhemp (amaranthus rudis), palmer amaranth (amranthus palmeri), giant ragweed (ambrosia trifida), or even volunteer corn (zea mays).

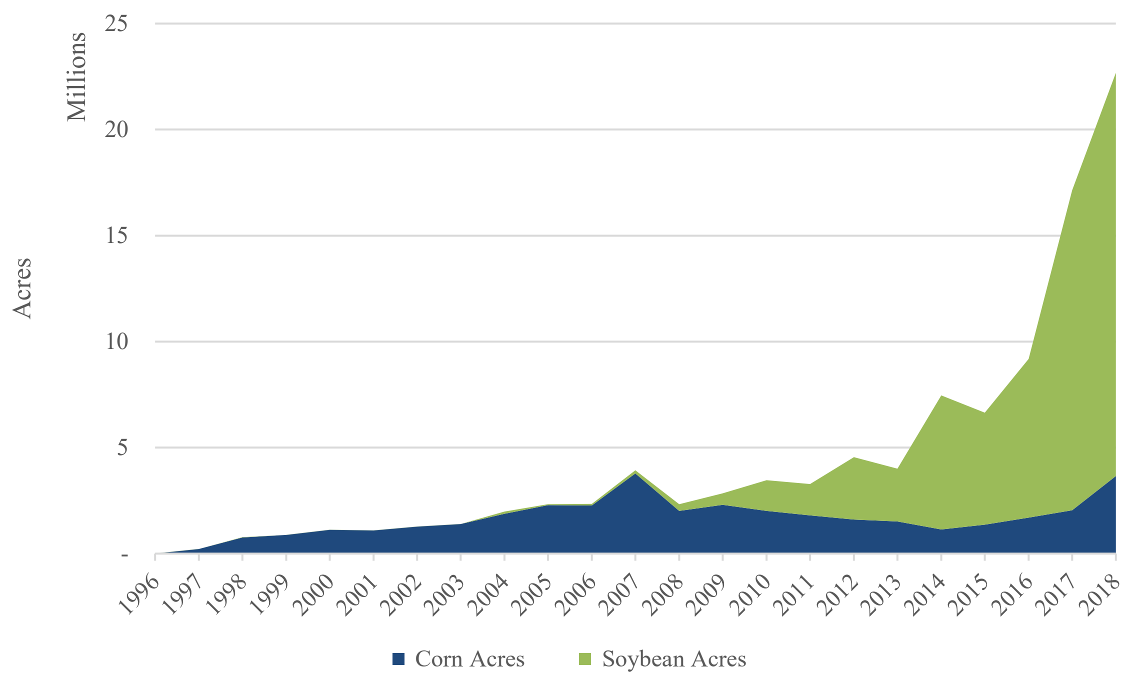
Weed control is crucial for maintaining crop yield and quality. Weeds compete with crops for essential resources such as light, water, and nutrients, so their presence can significantly reduce crop productivity (Lawrence & Beiermann, 2019). Competition from weeds is sensed by the crop through detection of light wavelengths that differ from the light wavelengths detected from bare soil. When a crop detects competition from a weed it will devote more resources to growing taller and spend less energy producing seed. Additionally, weeds can harbor pests and diseases that further threaten crop health. Effective weed management, including the use of pre-emergence and post-emergence herbicides, is essential to prevent yield loss and ensure the economic viability of crop production.

2.2 Herbicide Resistant Cropping Systems

Advancements in biotechnology in the 1990's changed the herbicide landscape. Herbicide tolerant cropping systems were launched in major crop markets (Reddy & Nandula, 2012). In 1996, glyphosate tolerant corn, soybeans, and cotton were commercialized allowing for over the top in-crop applications of glyphosate that would kill the growing crop without the technology. Glyphosate tolerant cropping systems were rapidly adopted and by 2001 over 68% of soybean acreage in the United States were glyphosate tolerant with adoption plateauing in 2014 at 94% (U.S. Department of Agriculture, 2024).

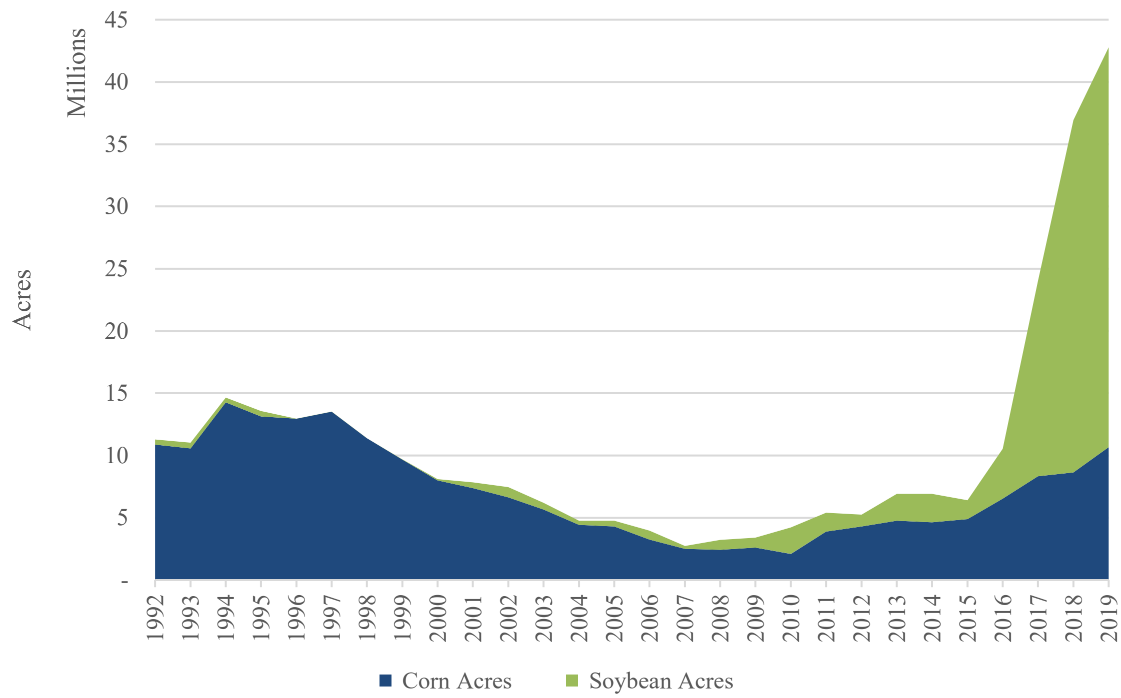
Following the widespread adoption of glyphosate tolerant soybeans, herbicide resistance to glyphosate developed which led to decreased efficacy. By 2014, 15 weed species in the United States had developed resistance to glyphosate (Ganie & Jhala, 2021). To address resistance issues, residual herbicide usage increased, glyphosate rates were increased, and alternative herbicide options were applied to effectively control resistant weed species. In 2009, glufosinate tolerant soybeans were made available. Glufosinate tolerance which was already bred into many corn hybrids as a marker gene gave growers an alternative broad-spectrum herbicide to address glyphosate resistance issues. Figure 2.1 shows the adoption of glufosinate in soybeans which increased from 531,373 acres in 2009 to 19,018,100 acres in 2018.

Figure 2.1 Glufosinate Acres Applied in United States



The year 2016 brought the next major development to herbicide tolerant cropping systems as soybeans tolerant to both glyphosate and dicamba were launched into the marketplace. Figure 2.2 shows the steep increase in dicamba applications in soybeans following the introduction of this new technology.

Figure 2.2 Dicamba Acres Applied in United States



The trend of biotechnology companies launching herbicide tolerant traits into the soybean marketplace continued with the introduction of three-way tolerance to glyphosate, 2,4-D, and glufosinate in soybeans and cotton branded as Enlist E3. A similar technology launched in 2021, branded as Xtendflex, which included a different three-way tolerance in soybeans to glyphosate, dicamba, and glufosinate. A summary of commercially available herbicide tolerant traits is detailed in Figure 2.3 (University of Tennessee, 2021).

Figure 2.3 Commercially Available Herbicide Tolerant Soybean Traits

Trait Name	Abbr.	Company	Sulf.	Gluf.	Glyp.	Dica.	2,4-D	Isox.
Sulfonylurea Tolerant[z]	STS, SR	Off patent	x					
Roundup Ready	RR, RR1	Off patent			x			
Roundup Ready 2 Yield	RR2, RR2Y	Bayer			x			
Roundup Ready 2 Xtend	RR2X	Bayer			x	x		
XtendFlex	XF	Bayer		x	x	x		
LibertyLink	LL	BASF		x				
GT27[y]	GT27	BASF			x			x
Enlist E3	E3	Corteva		x	x		x	

[z] Available stand-alone or as a stack with other traits

[y] Available stand-alone or as a stack with the LL trait

Source: University of Tennesse (2021)

Continued introductions of herbicide tolerant cropping systems in future years have been announced for broad acre crops such as corn, soybeans, and cotton. One such announcement came from Bayer in March 2025 as they introduced the launch of Vyconic herbicide tolerant soybeans to be commercialized in 2027. Vyconic soybeans will be tolerant to five herbicides including glyphosate, glufosinate, dicamba, 2,4-D, and mesotrione (Dinterman & Held, 2025).

2.3 Residual vs Foliar Herbicides

The distinction between different herbicides available in the market is important to understand the future implications of smart spraying technology. Broadly defined, herbicides fall into two different categories: residual and foliar. A foliar herbicide is applied to the foliar parts of the weeds above the soil and then absorbed by the exposed tissue of the weeds (The Editors of Encyclopedia Britannica 2025). A residual or soil applied herbicide is absorbed by the roots or shoots of weed seedlings preventing the weeds from ever growing in the crop field. Simply put, foliar herbicides kill weeds that have already emerged and are growing in the crop field at the time of application. Residual herbicides, on the other hand, will not control weeds that have already emerged in the field but will prevent weeds from emerging once the herbicide is active in the soil solution through rainfall, irrigation, or mechanical incorporation. Many herbicide strategies include residual herbicides applied pre-emerge followed by tank-mixing foliar herbicides with multiple modes of action to gain effective control on resistant weed species. The mode of action of a herbicide classifies the biological process or enzyme in the plant that the herbicide interrupts (Armstrong 2017). Over reliance on a single herbicide mode of action places heavy selection pressure on a weed population and can lead to resistant weed species. This paper focuses on glyphosate, glufosinate, 2,4-D, dicamba, and paraquat which are classified for the sake of this paper as 'foliar applied herbicides.' These herbicides were evaluated due to their common usage of controlling emerged weeds in corn and soybean production and are most likely to be affected by the adoption of smart spraying technologies.

2.4 Smart Spraying Technology

Historically, crop fields have been sprayed for weeds by ground-rig sprayers that apply a uniform rate of a herbicide tank-mix across the entire field. There are many different brands and types of sprayers from self-propelled to pull-behind, but what they all share in common is that they apply herbicides across the entire field regardless of weed pressure.

One technology that was introduced to become more efficient and is currently heavily adopted into the agricultural spraying market is automatic boom section control (McFadden, 2023). Section control technology reduces over-application of crop inputs such as herbicides by automatically turning off boom sections on the sprayer as it passes over previously treated areas of the field. Boom section control technology reduced spraying of the treated field area by 2.3% to 14.5% depending on the number of sections controls as reported by the University of Kentucky study (Luck, Stombach, & Shearer, 2024).

Building on automatic boom section control the next generation of spraying technology that aims to make herbicide applications more efficient is the introduction of 'Smart Spraying Technology.' Smart spraying technologies include any technologies available that utilize cameras, artificial intelligence, and sensors to gauge if there is weed pressure in that specific part of the field and only spray if there is. The goal of this technology is to drive the sprayer through the entire field and use the technology to sense weeds and only apply herbicides when weeds are detected. The companies that have developed and promoted these technologies are stating a reduction in herbicide usage of 60% up to 95% (Wilson, 2023)

John Deere, a market leader in sprayers, has brought John Deere See & Spray technology to the market available in three different packages. See & Spray Select, the base model, Seed & Spray Premium, the mid-tier model, and See & Spray Ultimate, the premium model. The features vary between the three different models, but this paper focuses on the See & Spray Ultimate model which allows users to utilize the technology for both pre-emerge and post-emerge applications. See & Spray Ultimate also comes with a dual tank system allowing users to utilize the smart spraying technology while simultaneously applying a residual product across the entire field.

Another large agricultural sprayer manufacture, AGCO, has entered a partnership with One Smart Spray to bring weed sensing camera technology to their sprayers. One Smart Spray option is offered through AGCO and Case sprayers and has comparable features and benefits to the John Deere See & Spray Ultimate system (Wilson, 2023).

Finally, there are several companies such as Greeneye Technology and Trimble, offering retrofit kits that allow users to upgrade their current sprayer system to a smart spraying capable unit. This research does not distinguish between smart spraying systems available in the marketplace as they all offer the same benefit of only applying herbicides where the technology senses weeds. However, the analysis below does assume the adoption of dual tank smart spraying systems. Dual tank systems allow users to realize the benefits of smart spraying technology without sacrificing the ability to apply residual herbicides across the entire field. Sarah Lancaster, Extension Weed Science Specialist at Kansas State University, was quoted saying, "These herbicides (residual herbicides) can control weeds for several weeks, which prevents yield loss due to early season weed competition and can greatly improve the effectiveness of a post-emergence application and give more flexibility for post-application timing." (Lancaster, 2021) Even with the introduction of smart spaying technology, it will be important to continue utilizing residual herbicides as part of a complete weed management program.

CHAPTER III: DATA AND MODELS

3.1 USGS Pesticide Data

To understand implications of the adoption of smart spraying technology, data was collected from the USGS Pesticide National Synthesis Project (USGS 2019) on pesticide usage across the United States from 1992 – 2018. For certain key results, the analysis focuses on five key herbicides that are categorized as 'foliar herbicides.' These include glyphosate, glufosinate, dicamba, 2,4-D, and paraquat. These five herbicides are commonly used in corn and soybean production to control emerged weeds. Depending on the cropping system, these herbicides can be applied at multiple timings which include either pre-plant (prior to planting the crop) or post-emerge (after the crop has emerged). Reported data does not classify the application timing of the herbicide (pre-emerge or post-emerge). The USGS reports data as kilograms (kg) of active ingredient applied each year by crop. Data was then converted from kg of active ingredient into pounds (lbs) of active ingredient by multiplying kg by ~ 2.2046 to align with EPA approved herbicide labels. Common use rates per acre of each of the five herbicides were pulled from their respective labels and stated as pounds of active ingredient applied per acre. Use rates are as follows: glyphosate (1.0 lbs active/acre), glufosinate (0.7 lbs active/acre), dicamba (0.5 lbs active/acre), 2,4-D (1.0 lbs active/acre), and paraquat (0.75 lbs active/acre).

An example of the formula for glyphosate use in soybeans in 2005:

1. $(35{,}032{,}026\ kg\ of\ glyphosate\ x\ 2.20462262) =$

   $77{,}232{,}396\ lbs\ of\ glyphosate$ active ingredient applied in US soybeans in 2005

2. $\frac{77{,}232{,}396\ lbs\ of glyphosate}{1.0\ \#\ glyphosate\ applied\ per\ acre} =$

   $77{,}232{,}396\ acres\ of\ glyphosate\ applied\ in\ soybeans\ in\ 2005$

An example of the formula for glufosinate use in soybeans in 2018:

1. $(6{,}038{,}494\ kg\ of\ glufosinate\ x\ 2.20462262) =$

   $13{,}312{,}600\ lbs\ of\ glufosinate$ active ingredient applied in US soybeans in 2018

2. $\frac{13{,}312{,}600\ lbs\ of glufosinate}{0.7\ \#\ glufosinate\ applied\ per\ acre} =$

   $19{,}018{,}000\ acres\ of\ glufosinate\ applied\ in\ soybeans\ in\ 2018$

3.2 'Smart Sprayer' Reduction Data & Adoption

This section derives estimates of herbicide reduction from smart spraying based on hypothetical adoption levels. Smart sprayer herbicide reduction data is quite variable based upon many different factors. Some of these factors include historical weed pressure, geographical location, precipitation, crop, tillage practices, use of residual herbicides, and timing of application. Herbicide reduction data was interpreted from a two-year multisite trial conducted by several University Weed Scientists (Avent, et al., 2024). They concluded that on average targeted sprays from the John Deere Smart Sprayer generated product savings of 28.4% to 62.4% on postemergence herbicides. Savings varied based upon timing and usage of residual herbicides. Due to the variance in reported herbicide reduction percentages, this research used the median of 28.4% to 62.4% which equals 45.4%.

Understanding what level of herbicide reductions are possible from smart spraying technologies is important in assessing the adoption of this technology. Whenever a new technology is launched into the marketplace assumptions about adoption over a time horizon must be made to analyze the future impact of the technology. In this case, the research utilized the commonly accepted technology adoption curve methodology over a ten-year time horizon (Batti, 2023). In this framework, technology adopters, farmers and custom applicators, are divided into five groups. Innovators, which account for 2.5% of the target audience, adopt the new technology instantly in year one. Early adopters, which account for 13.5% of the target audience, adopt the new technology in years two through five. Early majority, which account for 34% of the target audience, adopt the new technology in years six through eight. Late majority, which account for 34% of the target audience, adopt the new technology in years eight through ten. Finally, laggards, which account for 16% of the target audience, either do not adopt the new technology or adopt it after the ten-year launch horizon. Note also that this adoption pattern can be alternatively generated by a logistic curve or s-curve applied over a ten-year time horizon. Table 3.1 below shows how smart spraying technology could be adopted over a ten-year horizon and how that adoption would translate into the amount of corn and soybean acres that utilize the technology.

Table 3.1 Projected Annual Adopted 'Smart Sprayer' Acres (2024 to 2034)

Year	Percent Adoption	Corn/Soy Acres Planted (Millions)	Acres Adopted (Millions)
2024	2.5%	177.6	4.44
2025	5.9%	177.6	10.34
2026	9.3%	177.6	16.42
2027	12.6%	177.6	22.42
2028	16.0%	177.6	28.41
2029	27.3%	177.6	48.54
2030	38.7%	177.6	68.67
2031	50.0%	177.6	88.80
2032	61.3%	177.6	108.92
2033	72.7%	177.6	129.05
2034	84.0%	177.6	149.18

3.3 Data Models

To extrapolate potential reductions in the five herbicides analyzed, data was pulled from 2018 which was the most recently reported USGS pesticide data available for all five herbicide active ingredients. From there, the data was overlaid with corn and soybean planted acreage to produce an application intensity percentage by herbicide which is displayed in Table 3.2.

Table 3.2 Herbicide Application Intensity

Herbicide	Soybean Acres Applied	Corn Acres Applied
Glyphosate	118.96%	98.73%
2,4-D	11.18%	8.59%
Dicamba	31.44%	9.61%
Glufosinate	21.13%	4.07%
Paraquat	4.62%	8.67%

Table 3.2 can be interpreted as glyphosate was applied 1.18 times on every soybean acre planted in the United States. It is feasible that the percentage is higher than 100% or applied more than one time on each acre because herbicides can be applied multiple times on the same acre. Excluding glyphosate, the other four herbicides were applied on 4.62% to 31.44% of the total corn or soybean acres. By examining this preliminary herbicide usage data, it can be hypothesized that smart spraying technology will have the greatest impact on glyphosate volumes due to the heavy application intensity when compared to the other herbicide active ingredients. The following formula was utilized to predict the number of smart sprayer adopted acres at the end of the ten-year time horizon:

$$2024\ USDA\ corn\ and\ soybean\ planted\ acreage$$

$$x\ 84\%\ technology\ adoption\ rate$$

$$x\ applied\ acres\ of\ each\ herbicide\ in\ 2018$$

It was concluded that smart spraying technology adopted at 84% of planted acres by year ten would lead to a decrease in applied acres listed in Table 3.3 based on 76% or 45.4 % reduction in sprayed acres.

Table 3.3 Projected 'Smart Sprayer' Acres by Year 10

Herbicide	Acres Adopted (84%)	Acre Reduction (76%)	Acre Reduction (45.4%)
glyphosate	164,578,040	125,079,310	74,718,430
2,4-D	14,942,955	11,356,646	6,784,102
dicamba	31,029,979	23,582,784	14,087,611
glufosinate	19,051,989	14,479,512	8,649,603
paraquat	10,046,000	7,634,960	4,560,884
Total	**239,648,964**	**182,133,212**	**108,800,629**

All together 'smart spraying' technology has the potential to decrease applied acres of the five studied herbicides by 108,800,629 acres annually at the 45.4% reduction rate.

3.4 Financial Impacts

With such drastic potential decreases in herbicide usage due to the adoption of smart spraying technology, many firms involved in the pesticide industry need to understand this information to make more informed decisions as they set mid- and long-term business strategies. The clientele beyond farmers who will be most impacted include businesses in three different categories: retailer/custom applicator, chemical distributor, and basic pesticide manufacturer. These parties need to be separated because the implementation of these technologies across the industry could have different effects on each client. The retailer/custom applicator either purchases chemical inputs such as herbicides and applies them with their own equipment or sells directly to growers who apply the products themselves. A few examples of retailers are Nutrien Ag Solutions, local cooperatives, or an independently run input business. The chemical distributor aggregates products from various manufactures across the industry and sells them directly to the retailer. Examples in the industry include Nutrien Ag Solutions (wholesale), Winfield United, and Rosen's Inc. Finally, the basic manufacturer researches and physically formulates pesticides to sell on the market. Some companies classified as a basic manufacturer include Corteva, Bayer, and

Albaugh. They all need to understand how decreased sales volumes of herbicides could affect profitability, logistics, product mix, and capital expenditures. Once these clients have a stronger understanding of potential implications, they can formulate new approaches or go-to-market strategies to address these changes.

To quantify the acre reduction of smart spraying technology at the end of the ten-year time horizon into an economic dollar value the following conversions were made. Acres reduced of each herbicide studied were converted back into total pounds of active ingredient by dividing the total acre reduction by the pounds of active ingredient applied per acre.

For example, 8,649,603 acres of glufosinate can be converted back to pounds of active ingredient as follows:

$$8{,}649{,}603\ acres\ x\ 0.7\#\ glufosinate/ac = 6{,}054{,}722\ lbs\ of\ active\ reduced$$

Next, pounds of active ingredient were converted into gallons of commercially available herbicide products. Liberty 280 SL (or generic alternatives), which contains 2.8 pounds of active ingredient per gallon, is a branded formulation of glufosinate commonly sold in the United States:

$$\frac{6{,}054{,}722\ lbs\ of\ active\ ingredient}{2.8\ lbs\ of\ active\ ingredient\ per\ gallon} = 2{,}162{,}400 \text{ gallons of Liberty 280 SL/Generic}$$

In summary, at the end of the ten-year adoption horizon, ‘Smart Spraying’ technology has the potential to reduce Liberty 280 SL and generic alternatives by 2.16 million gallons annually. A complete list of these reductions for the branded and generic versions of the five studied herbicides is in Table 3.4.

Table 3.4 Product Gallons Reduced by Year (2024 to 2034)

Product	2024	2026	2028	2030	2032	2034
Roundup Powermax 3	277,970	1,028,490	1,779,010	4,299,275	6,819,539	9,339,804
Generic 5.4# Glyphosate	222,376	822,792	1,423,208	3,439,420	5,455,631	7,471,843
Enlist One	30,286	112,059	193,831	468,426	743,021	1,017,615
Generic 6# 2,4-D	13,461	49,804	86,147	208,189	330,231	452,273
Engenia	25,156	93,079	161,001	389,086	617,172	845,257
Generic 4# Dicamba	20,964	77,566	134,168	324,239	514,310	704,381
Liberty 280 SL	38,614	142,873	247,132	597,235	947,337	1,297,440
Generic 2.8# Glufosinate	25,743	95,249	164,754	398,156	631,558	864,960
Gramaxone 3.0 SL	20,361	75,336	130,311	314,918	499,525	684,133
Generic 3# Paraquat	13,574	50,224	86,874	209,945	333,017	456,088

To further refine these predictions, details about manufacturer market share and specific products sold were analyzed from the Agropages 2024 Market Insight Magazine (Longjian 2024). This report states that sales of first-tier agrochemical giants (Syngenta, Bayer CropScience, BASF, and Corteva) accounted for 59.5% of the total sales of the top 20 companies. These four listed basic manufacture companies are sellers of ‘branded products’ in the marketplace. Their major products include Roundup PowerMax 3 (glyphosate) from Bayer CropScience, Liberty 280SL (glufosinate) from BASF, Engenia (dicamba) from BASF, Gramoxone SL 3.0 (paraquat) from Syngenta, and Enlist One (2,4-D) from Corteva. Given that these companies account for approximately 60% share of the crop protection marketplace, it is assumed their branded product offerings have a 60% market share position for each of the herbicides studied.

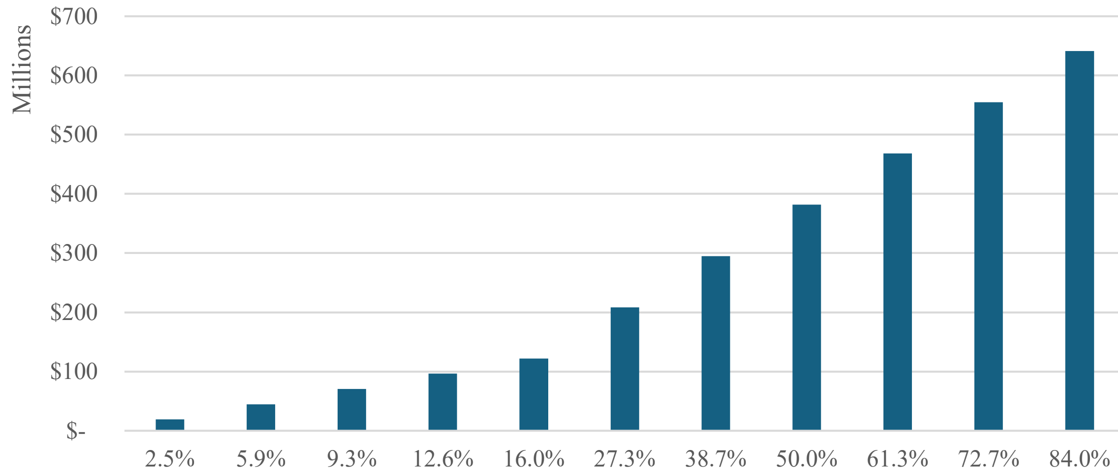
All five herbicides studied in this research are considered post-patent with readily available generic offerings in the marketplace. However, due to herbicide resistant cropping systems, there are regulations on when a branded product must be used instead of a generic alternative. For example, when making in-crop applications of dicamba to XtendFlex traited soybeans (tolerant to glyphosate, glufosinate, and dicamba) only EPA registered dicamba formulations (Engenia and Xtendimax) are allowed to be applied over the top as ‘foliar’ applications. Generic versions of glyphosate and glufosinate are legally allowed to be applied to Xtendflex traited soybeans. Similar to Xtendflex soybeans, when utilizing 2,4-D in Enlist E3 cropping systems, users must apply the EPA approved over the top product, Enlist One (2,4-D) or Enlist Duo (2,4-D and glyphosate premixed). It is important to note that when this research was conducted there were not approved over the top formulations of dicamba (Engenia and Xtendimax) for use in the 2025 growing season by the EPA. Dicamba was still included in this research because the registrants (BASF and Bayer) of approved over the top dicamba formulations had applied for new labels with the EPA following the 2024 court ruling that vacated those herbicide labels. In addition to new labels being applied for, Bayer announced the launch of Vyconic herbicide tolerant soybeans to be commercialized in 2027, which includes herbicide tolerance to glyphosate, glufosinate, dicamba, 2,4-D, and mesotrione. Going forward it is likely dicamba will continue to be used as a 'foliar' product in herbicide tolerant soybeans, preplant burndown applications, and in corn. Dicamba based corn herbicides and generic formulations of dicamba are EPA approved for the 2025 growing season and beyond.

Given the foregoing, to compute the financial implications, market share was established at 60% for branded products and 40% for generic products. Next, the reduced gallons of each herbicide were multiplied by the average price paid by United States growers in 2024 based on the '2025 USA Ag Chem Pricing Transparency Report' published by FBN (Farmers Business Network, 2025). For example, in the case of glufosinate products, the revenue reductions are given by:

= 1,297,440 gallons Liberty 280 SL x $44.62/gal average farmer price paid = $57,891,772

= 864,960 gallons generic Glufosinate 280 SL x $23.42/gal average farmer price paid = $20,257,370. In total branded Liberty and generic versions will have an economic value reduction of $78 million dollars annually at the end of the ten-year adoption horizon. The economic dollar value reductions by adoption rate from the introduction of smart spraying technology is listed in Figure 3.1.

Figure 3.1 Economic Herbicide Value Reduction by Adoption



In total 'smart spraying' technology adopted at 84% in year ten would have an annual decrease in economic value of the five herbicides studied of $641,092,115. Based on reporting from Mordor Intelligence, the US herbicide market in 2025 is estimated at $11.45 billion dollars (Mordor Intelligence, 2025). This reduction would equate to a 5.6% decrease in the United States herbicide market, and this only accounts for the use of the five studied herbicides in corn and soybean production.

When looking at specific product implications (branded and generic) of the five herbicides studied, Table 3.5 outlines the cumulative economic dollar value reduction over the ten years studied.

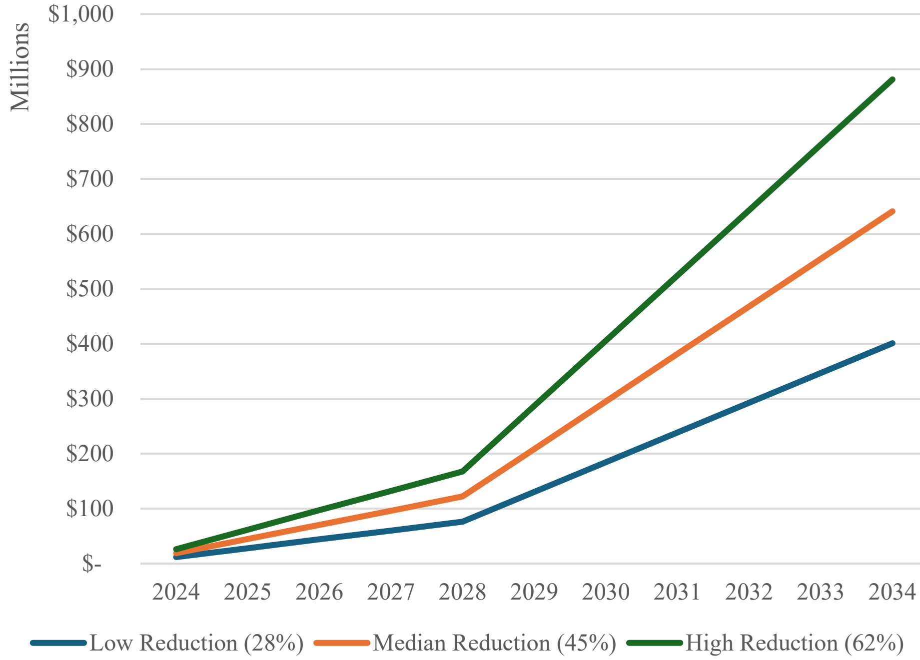
Table 3.5 Cumulative Economic Dollar Value Reduced (2024 to 2034)

Product	Avg Price	Total
Roundup Powermax 3	$ 22.70	$ 959,739,910
Generic 5.4# Glyphosate	$ 16.52	$ 558,763,116
Enlist One	$ 55.27	$ 254,602,761
Generic 6# 2,4-D	$ 27.97	$ 57,264,267
Engenia	$ 125.58	$ 480,506,336
Generic 4# Dicamba	$ 34.18	$ 108,985,689
Liberty 280 SL	$ 44.62	$ 262,063,789
Generic 2.8# Glufosinate	$ 23.42	$ 91,700,799
Gramaxone 3.0 SL	$ 28.24	$ 87,457,095
Generic 3# Paraquat	$ 19.86	$ 41,003,262
Total		**$ 2,902,086,626**

3.5 Sensitivity Analysis

Previous research published on John Deere's smart spraying technology saw a variance in herbicide reduction from 28% to 62% (Avent, et al., 2024). The prior model focuses on the median reduction of 45.4%, but it is important to understand the high and low reduction estimates. Variability in herbicide reduction could be attributed to several different factors including geographic differences in weed pressure, residual herbicide usage, and crop rotation. The low estimate (28%) could represent a field or farm that has high weed pressure and low adoption of residual herbicides leading to a smaller reduction. The high reduction estimate (62%) would likely be in an area with lower weed pressure, effective residual herbicide usage, and timely applications. Figure 3.2 shows the variance in economic reductions based on the low, median, and high reduction estimates.

Figure 3.2 Sensitivity Analysis (Low to High Reduction Estimates)



3.6 Upfront Technology Investment

To assess whether smart sprayer adoption could reach 84% by year ten, an economic payback analysis was conducted for farmers and custom applicators. Upfront investment costs vary depending on the smart sprayer model purchased, leading to different payback outcomes. Upgrading a new John Deere sprayer to the See & Spray Ultimate model costs the buyer an additional $139,000 when purchased new from the factory. For retrofitting, the See & Spray Premium model can be added to model year 2018 and newer sprayers for a one-time cost of $25,000 (Seymour 2024). Both models incur a subscription fee of $5.00 per acre, calculated based on unsprayed (weed-free) acres. When amortizing the upfront cost over 5 years at an 8% interest rate, the annualized upgrade cost for an Ultimate model is $34,148 and $6,262 for the Premium model. Unlike the Ultimate model, the See & Spray Premium lacks dual-tank capabilities, affecting residual herbicide application efficiency. For instance, a grower aiming to apply a targeted foliar herbicide and a uniform pre-emerge residual herbicide must make two passes with the Premium model: one for smart spraying emerged weeds and another for uniform residual application to prevent weed emergence. If the grower does not make two passes and incur additional cost, the residual herbicide will only be applied where the smart sprayer identified growing weeds. .

A 2024 Beck's study compared herbicide savings across smart sprayer models and compared them to a traditional broadcast application in Table 3.6 (Beck's Practical Farm Research 2024).

Table 3.6 Smart Sprayer Herbicide Savings

Treatment	Herbicide Cost/Ac	See & Spray Savings	Yield (Bu/Ac)
Standard Broadcast	$42.64	-	72.9
See & Spray Premium (1 pass)	$17.80	$24.84	76.2
See & Spray Premium (2 pass)	$29.79	$12.85	77.1
See & Spray Ultimate	$29.84	$12.80	77.1

All treatments received a pre-emerge broadcast residual application, excluded from the herbicide costs above. Post-emerge, all treatments included a residual herbicide, with the Standard Broadcast and Ultimate models applying it uniformly. The See & Spray Premium (2 pass) involved two post-emerge foliar applications, while others had one post-emerge foliar application. Beck's research suggests that savings from the two John Deere models are similar when integrated into a weed management plan with residual herbicides. Spraying in-crop residuals as a targeted application could lead to more savings as evidenced in the See & Spray Premium (1 pass) example but could reduce yield due to increased weed pressure as shown in Table 3.6.

To understand the capabilities of smart sprayers from a productivity standpoint, the following equation was used to determine how many acres a smart sprayer can cover in an hour.

$$Acres\ sprayed\ per\ hour = \frac{MPH\ x\ swath\ width\ x\ field\ efficiency}{8.25}$$

Given this, a John Deere See & Spray Ultimate machine with 120-foot booms driving 10 MPH at 80% field efficiency could cover 116 acres per hour or 1,160 acres per 10 hour working day. Based on reported NASS data, the average number of days suitable for field work during the primary spraying season (April through July) ranges from 3.1 to 5.9 days per week. Taking the average number of days suitable for field work (4.5 days per week) one smart sprayer could apply 5,220 acres per week. When applied over the 12-week spraying season, the John Deere See & Spray Ultimate machine can cover 62,640 acres in a growing season. There are many variables such as field typography, road time between fields, breakdowns, and water tendering capabilities that could alter actual sprayed acres per year, but 62,000 acres provides a hypothetical maximum of the capabilities of the sprayer.

3.7 Breakeven Cost

Beyond the additional upfront expenditure to purchase a smart sprayer, recurring costs such as subscription fee and herbicide cost were analyzed to understand a herbicide breakeven cost for adoption of this technology. Breakeven herbicide cost is defined as the cost per acre where net benefit of smart sprayers is zero, balancing annualized upfront investment and subscription cost with herbicide savings.

$$Breakeven\ herbicide\ cost = \\ = \frac{Subscription\ fee\ per\ acre + (\frac{annualized\ upfront\ cost}{acres\ per\ year})}{Herbicide\ reduction\ percentage}$$

At the 45.4% herbicide reduction level, breakeven herbicide cost by acres sprayed for the two smart sprayer models are listed in Table 3.7.

Table 3.7 Herbicide Breakeven Cost by Acres Sprayed

Acres Sprayed	See & Spray Ultimate	See & Spray Premium
1,000	$80.55	$18.85
3,000	$30.18	$9.62
5,000	$20.11	$7.77
7,000	$15.79	$6.98
10,000	$12.55	$6.39

Table 3.7 states that a John Deere See & Spray Ultimate machine spraying 5,000 annual acres must have a per-acre herbicide cost greater than $20.11/ac to have a positive net benefit when adopting the technology. Referencing the broadcast herbicide cost per acre of $42 from the Beck's study, all scenarios listed in Table 3.7, except for See & Spray Ultimate used on 1,000 acres, would provide a justifiable break-even to use the smart spraying technology.

3.8 Farmer Adoption Model

For a farmer end-user to adopt smart spraying technology the upfront and recurring costs are analyzed to understand the financial implications of adoption. In 2024, Iowa State University tested John Deere's See & Spray Ultimate sprayer on 415 acres which led to a 76% herbicide savings ($15.70/ac) and economic savings of $6,500 (Houser, Darr, & Huffman, 2024). Based on previously stated information about the cost to purchase and run a John Deere smart sprayer, there is an additional upfront cost versus traditional sprayers and a per acre subscription fee. The net benefit of the fields studied by Iowa State in 2024 are presented in Table 3.8.

When adding in the per acre fee of $5 for unsprayed acres, there is a strong return for the farmer due to herbicide savings outweighing the per acre fee of unsprayed acres. Based on the per acre net benefit of $8.14/acre from the Iowa State study, it would take a grower approximately 3,075 acres to payback the additional $25,000 for a See & Spray

Table 3.8 See & Spray Farmer Savings by Field

Location	Field Size (acres)	Product Applied (acres)	Herbicide Savings %	Herbicide Savings $	Subscription Fees	Net Benefit	Net Benefit Per Acre
Field 1	110.7	14.2	87%	$1,515.05	$482.50	$1,032.55	$9.33
Field 2	71.9	40.3	44%	$496.12	$158.00	$338.12	$4.70
Field 3	104.7	30.2	71%	$1,169.65	$372.50	$797.15	$7.61
Field 4	37.1	3.5	91%	$527.52	$168.00	$359.52	$9.69
Field 5	90.1	11.2	88%	$1,238.73	$394.50	$844.23	$9.37
	414.5	**99.4**	**76%**	**$4,947.07**	**$1,575.50**	**$3,371.57**	**$8.14**

Premium model and 17,097 acres to payback the additional $139,000 for the See & Spray Ultimate model. In addition, this suggests that if custom applicators could pass some of the savings to the farmer, farmers relying on custom application services would still be able to save money with an applicator using a targeted smart sprayer.

To examine a real-world scenario, we consider a Southeast Kansas farmer who has 1,500 acres of corn and 1,500 acres of soybeans. The farmer will make two applications per year of herbicide for each crop with a John Deere See & Spray Ultimate machine. Based on the Southeast Kansas farmers' acreage (6,000 acres sprayed annually), they could payback the initial $139,000 investment in three years based on the per-acre net benefit of $8.14/ac. When adjusting the model to look at the John Deere See & Spray Premium sprayer and incorporating a higher per-acre herbicide savings ($24.84/ac), as reported in the Beck's research, investment payback occurs at 1,000 acres sprayed. Totaling the average per acre savings across the other 5,000 acres they spray annually leads to additional savings of $124,200 in year one.

For farmers, large and small, there are opportunities to adopt smart spraying technologies, but they need to consider annual acres applied and current herbicide costs to make informed decisions on investing in this technology.

3.9 Custom Applicator Adoption Model

Custom applicators are hired by farmers to apply crop protection pesticides such as herbicides to their fields. The historical business model followed by custom applicators is to charge a per acre fee on the acres sprayed as well as making a margin on the products being applied. The 2025 Iowa Farm Custom Rate Survey reported that the average per acre charge for custom spray applications was $7.55/ac (Johanns & Hart, 2025). On average, custom applicators mark up their herbicides and other products applied by approximately

25%. Table 3.9 shows per acre profitability of the four application methods published by Beck's.

Table 3.9 Custom Application Revenue

Treatment	Product Margin	App Fee	Revenue/Ac
Standard Broadcast	$10.66	$7.55	$18.21
See & Spray Premium (1 pass)	$4.45	$7.55	$12.00
See & Spray Premium (2 pass)	$7.45	$7.55	$15.00
See & Spray Ultimate	$7.46	$7.55	$15.01

Based on the results, applicators are at risk of losing ~ $3.00 to $6.00 per acre in revenue by adopting smart spraying technology. To recoup reduced product margin revenue, custom applicators will have to adjust their pricing model to make smart spraying adoption feasible for their business. This could be done through increasing their product margin higher than 25%, increasing their per acre custom application fee, marking up the $5/ac subscription fee charged by John Deere, or negotiating with the farmer to split/share the savings. If a new pricing tactic is deployed by a custom applicator, they must generate more revenue per acre than a traditional broadcast application to recoup the upfront initial investment.

As an example of how this could be done consider the same fields from the Iowa State study and suppose a custom applicator charges a 100% markup on the $5/ac subscription fee. That is, for each acre not treated, they charge $10 per acre to the farmer. Table 3.10 summarizes applicator revenues and farmer net benefits under this pricing model.

Table 3.10 Customer Applicator Revenue Model – Low Herbicide Cost

Location	Field Size (acres)	Standard Broadcast (Rev/Ac)	See & Spray Ultimate (Rev/Ac)	Farmer Net Benefits (Rev/Ac)
Field 1	110.7	$10.69	$12.31	$4.97
Field 2	71.9	$10.69	$11.51	$2.51
Field 3	104.7	$10.69	$12.01	$4.06
Field 4	37.1	$10.69	$12.37	$5.16
Field 5	90.1	$10.69	$12.32	$4.99
-	**414.5**	**$10.69**	**$12.10**	**$4.33**

By replacing lost product margin with a markup on the subscription fee, custom applicators would generate an additional $1.41/ac in revenue when compared to broadcast applications. In addition, the grower paying for these services would see a net benefit of $4.33/ac compared to standard broadcast. In this example, the grower's net benefit is cut in half, but it allows the custom applicator to generate more revenue than a traditional broadcast application leading to a win for the grower and custom applicator.

In the previous example shown in Table 3.10, herbicide cost was relatively low at $15.70/ac. The next example shows a scenario where the cost of the herbicide doubles to $31.40/ac and the markup on the subscription fee doubles to charge the grower $15/ac on unsprayed acres. Results are displayed in Table 3.11.

Table 3.11 Customer Applicator Revenue Model – High Herbicide Cost

Location	Field Size (acres)	Standard Broadcast (Rev/Ac)	See & Spray Ultimate (Rev/Ac)	Farmer Net Benefits (Rev/Ac)
Field 1	110.7	$13.83	$17.07	$14.30
Field 2	71.9	$13.83	$15.46	$7.21
Field 3	104.7	$13.83	$16.48	$11.67
Field 4	37.1	$13.83	$17.20	$14.85
Field 5	90.1	$13.83	$17.09	$14.36
	414.5	**$13.83**	**$16.66**	**$12.47**

In both scenarios, low and high herbicide cost, there is net benefit for both the grower and custom applicator. By adopting updated pricing models, custom applicators will have the ability to adopt smart spraying technology while generating additional revenue to recoup the additional upfront cost of the technology. For the farmer, they will see a net benefit of hiring a custom applicator who utilizes smart spraying technology in the range of $4.33/ac up to $12.47/ac based on the scenarios listed in Table 3.10 and Table 3.11.

Finally, for custom applicators, scale and efficiency will be a key determinant of profitable success with adoption of smart spraying systems. However, with the hypothetical capabilities of a See & Spray Ultimate machine spraying approximately 62,000 acres per year, custom applicators using an updated pricing model will be able to scale smart spraying profitably.

3.10 Toxicity Analysis

Assessing how the adoption of smart spraying impacts total applied herbicide does not account for the fact that herbicides are highly heterogeneous in their level of toxicity. Therefore, this section re-weights herbicides by their toxicity level, which allows for a more accurate assessment of the potential environment benefits from smart spraying.

Toxicity of pesticides is analyzed by the EPA prior to an approved label and commercial launch of newly registered pesticides products. One common form of toxicity screening is lethal dose 50 (LD50), which measures the acute toxicity of an active ingredient required to kill fifty percent of the tested population (Hock 2022). The five herbicides analyzed in this research have the following LD50 levels with respect to rats, which serve as a proxy for potential toxicity to humans.

Table 3.12 Rat LD50 by Herbicide

Active ingredient	Acute LD50 (mg/kg)
2,4-D	699
Dicamba	1,707
Glufosinate	1,910
Glyphosate	5,600
Paraquat	112

The table can be interpreted as it took 699 mg/kg for 2,4-D to kill 50% of the rat population. From there, a risk quotient (quantity divided by LD50) can be calculated to compute the LD50-weighted quantity. The risk quotient for a compound, denoted by i, is defined as:

$$RQ_i = \frac{Q_i}{LD50_i}$$

Where Q_i is the quantity applied. In effect, the risk quotient re-weights chemicals by how toxic they are. For example, glyphosate has an LD50 of 5,600, which is 50 times larger than the LD50 for paraquat. This means that, by this measure, one kilogram of paraquat is equivalent to 50 kilograms of glyphosate. The total applied toxicity associated with all herbicides in a given year can be expressed as:

$$TRQ = \sum_i RQ_i$$

Applying the adoption (84%) and herbicide reduction (45.4%) variables allows for analysis of reduced toxicity versus reduced kilograms (or pounds on the ground). Corn and soybean data was separated to understand differences in toxicity among herbicides used by crop. Soybean data showed a reduction in applied kg per year of 25.33% with a reduction in the TRQ of 28.96%. Corn data showed a reduction in kg per year of 14.98% with a reduction in the TRQ of 19.00%. For both crops, the total applied toxicity decreased more significantly than the total kg of herbicide applied. Comparing the differences in TRQ reductions can be explained by the following graphs showing total kg of herbicide applied versus toxicity (RQ). Soybeans saw a large increase in TRQ from 2008 to 2018 while corn had a steady TRQ from 2000 to 2018.

Figure 3.3 Soybean Toxicity

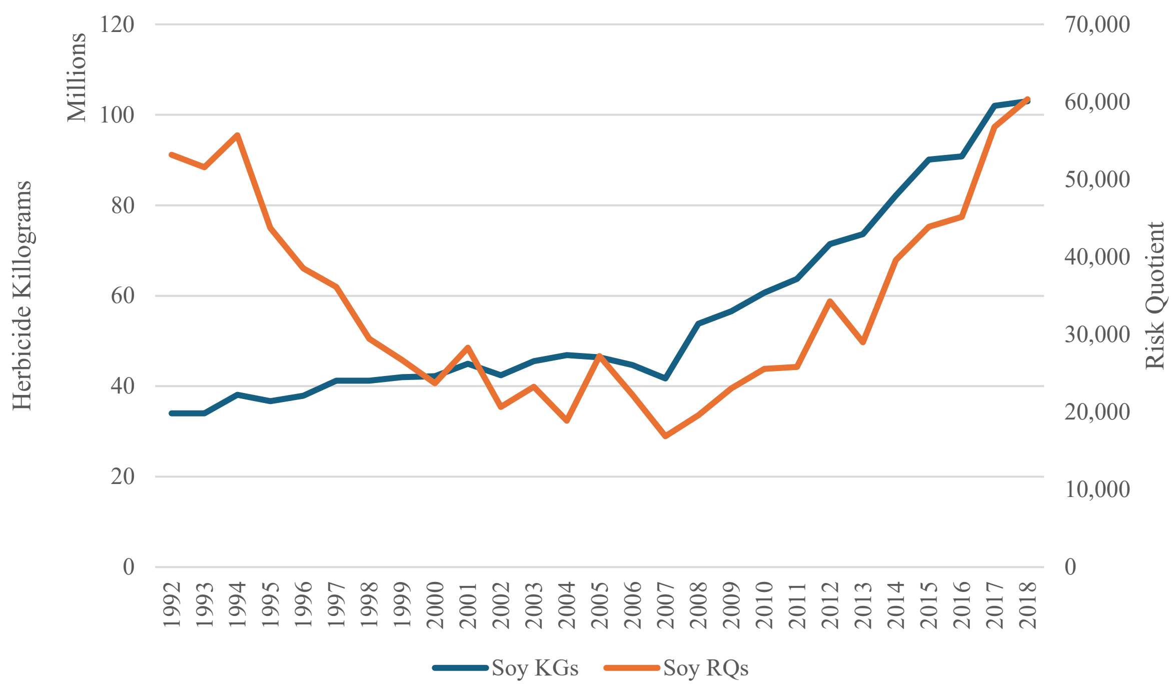
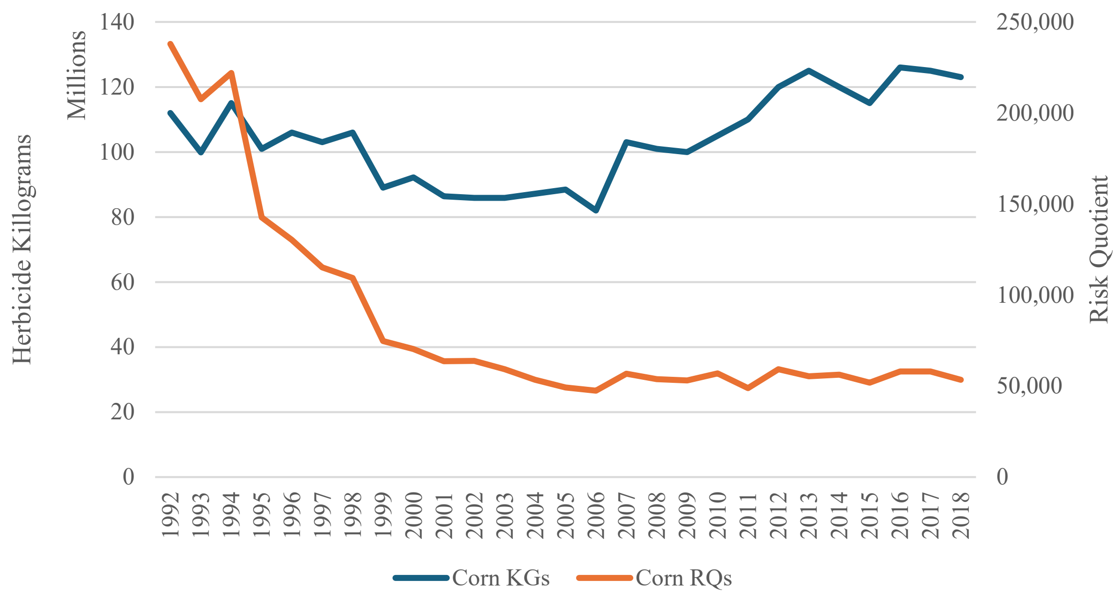


Figure 3.4 Corn Toxicity



3.11 Limitations of Analysis

Due to the availability of reported pesticide data from the USGS, this research used herbicide volumes from 2018. Because the data is six years out of date, there have been shifts or changes in the five herbicides studied. For example, 2,4-D and glufosinate usage is likely understated due to the launch of Enlist E3 and XtendFlex cropping systems. Dicamba usage is likely overstated with label and usage restriction changes since 2019.

Limitations of the capabilities of actual smart spraying technologies in the marketplace were not discussed in this research but could provide a barrier to adoption. For example, how accurate are the systems at identifying the weeds and accurately deciding when to spray. Even with a margin of error around 5%, weed control would not be deemed acceptable by the end user. If a smart sprayer system misses 5% of the weeds in the field, it will lead to having to respray the field which increases cost and decreases efficiency.

Based on available information, there are limitations of the John Deere See & Spray system. These limitations relate to planting width, crop height, and other environmental factors. As of the writing of this research, the John Deere technology cannot operate in soybeans planted in 15-inch rows. This will significantly limit the acreage the technology can be used on unless there are upgrades to the technology within the ten-year adoption horizon.

Analysis within this research assumed adoption of dual-tank smart spraying systems allowing users to selectively apply their foliar herbicide where weeds are present while simultaneously applying a residual herbicide across the entire field. Several of the systems available in the marketplace do not have these capabilities. Therefore, the data could be overstating the reduction in foliar applied herbicides if there are significant usage decreases of residual herbicides.

CHAPTER IV: SUMMARY AND CONCLUSIONS

This research explored the transformative potential of smart spraying technologies within the pesticide industry, with a specific focus on their financial and environmental impacts on herbicide use in corn and soybean production. By integrating quantitative data from the USGS Pesticide National Synthesis Project, a technology adoption curve, and detailed models, this research offers a comprehensive analysis of how these innovative systems could reshape weed management practices and influence stakeholders across the supply chain.

The findings indicate that smart spraying technologies, which leverage cameras and artificial intelligence to target herbicide applications only where weeds are detected, could substantially reduce herbicide use. Based on a median reduction estimate of 45.4%, derived from field trials ranging from 28% to 62%, the adoption of this technology over a ten-year period could decrease the application of five key foliar herbicides (glyphosate, glufosinate, 2,4-D, dicamba, and paraquat) by over 108 million acres annually by year ten, assuming an 84% adoption rate across U.S. corn and soybean acres. Glyphosate, due to its high application intensity, is projected to experience the most significant reduction, highlighting the technology's potential to address the challenges posed by widespread herbicide use and resistance.

Financially, this shift translates into a notable economic impact on the pesticide industry. By year ten, the annual economic value of these five herbicides could decrease by approximately $641 million, with a cumulative reduction exceeding $2.9 billion over the decade. This decline poses challenges for stakeholders, including manufacturers, distributors, and retailers, who will need to adapt their product portfolios, pricing strategies, and market approaches to remain competitive. For farmers and custom applicators, the upfront and recurring costs of smart spraying systems must be balanced against potential savings from reduced herbicide use, with case studies suggesting net economic benefits under certain conditions.

Environmentally, the adoption of smart spraying technologies offers promising benefits. The toxicity analysis, utilizing LD50 values, reveals that the reduction in herbicide use could decrease total applied toxicity more significantly than the reduction in volume alone, by 28.96% in soybeans and 19% in corn, compared to volume reductions of 25.33% and 14.98%, respectively. This disproportionate decrease in toxicity highlights the potential for smart spraying to enhance the sustainability of agricultural practices by mitigating the environmental footprint of herbicide applications. For example, the government (or EPA) may want to incentivize smart spraying adoption to reduce off-target movement (drift and volatility) for certain herbicides like dicamba. Incentivization could allow a smart sprayer user to have less label restrictions when applying herbicides like dicamba.

For stakeholders, the implications are multifaceted. Manufacturers may need to pivot toward innovation in precision agriculture technologies or alternative weed control solutions, while distributors and retailers could explore new service models or product offerings to offset declining herbicide sales. Farmers stand to gain from reduced input costs and improved environmental compliance, though adoption decisions will hinge on economic viability and regional weed pressures. Policymakers, meanwhile, should consider incentives or regulations to accelerate the uptake of such technologies, aligning agricultural productivity with sustainability objectives.

In conclusion, smart spraying technologies represent a pivotal advancement in the pesticide industry, poised to drive significant reductions in herbicide use, reshape market dynamics, and enhance environmental outcomes. As technology matures, stakeholders must proactively adapt to this evolving landscape, leveraging the insights from this research to inform mid- and long-term strategies. Looking ahead, future studies could refine these projections by examining real-world adoption rates, regional variations in herbicide reduction, and the technology's integration with other precision agriculture tools. Additionally, investigating its long-term effects on weed resistance, crop yields, and farm-level economics will further illuminate the full scope of this transformative innovation. Through such efforts, the agricultural sector can harness smart spraying technologies to achieve a more sustainable and economically resilient future.

WORKS CITED

Armstrong, J. (2017). *Herbicide How-to: Understanding Herbicide Mode of Action.* Stillwater, OK: Oklahoma State University.

Avent, T., Norsworthy, J., Patzold, W., Schwartz-Lazaro, L., Houston, M., Butts, T., & Vasquez, A. (2024, August 30). Comparing herbicide application methods with.

Batti, K. (2023, March 16). *What Fix*. Retrieved March 6, 2025, from https://whatfix.com/blog/technology-adoption-curve/

Beck's Practical Farm Research. (2024). *Sprayer Application Study.* Beck's Hybrids.

Brown, B. (2009). The History of Economics. *Economics Journal of History*, 4-12.

Das, T. K., Behera, B., Nath, P. C., Ghosh, S., Sen, S., Raj, R., . . . Singh, R. G. (2024). Herbicides use in crop production: An analysis of cost-benefit, non-target toxicities and environmental risks,. *Crop Protection, Volume 181*.

Dinterman, C., & Held, A. (2025, March 3). *Successful Farming*. Retrieved March 6, 2025, from https://www.agriculture.com/bayer-introduces-next-gen-solution-for-flexible-weed-management-11689392

Doe, J. B. (2009). Financial Impact of US Economic Crisis. *Agribusiness Worldwide, June/July*(1), 4-12.

Farmers Business Network. (2025). *USA Ag Chem Price Transparencey Report 2025.* FBN.

Ganie, Z., & Jhala, A. (2021, April 5). *UNL Cropwatch*. Retrieved March 6, 2025, from https://cropwatch.unl.edu/multiple-herbicide-resistant-weeds-and-challenges-ahead/

Hock, W. (2022, June 30). *Extension PSU*. Retrieved March 6, 2025, from https://extension.psu.edu/toxicity-of-pesticides

Houser, D., Darr, M., & Huffman, R. (2024, August 22). *Iowa State University Extension*. Retrieved March 6, 2025, from https://crops.extension.iastate.edu/cropnews/2024/08/precision-spraying-technology

Johanns, A., & Hart, C. (2025). *2025 Iowa Farm Custom Rate Survey.* Iowa State Extension.

Lancaster, S. (2021, March 18). *EUpdate Agronomy*. Retrieved March 6, 2025, from https://eupdate.agronomy.ksu.edu/article_new/residual-herbicides-for-corn-432-1

Lawrence, N., & Beiermann, C. (2019, January 9). *Cropwatch.UNL*. Retrieved February 6, 2025, from https://cropwatch.unl.edu/2019/importance-early-season-weed-control/

Longjian, H. (2024, October 14). *Agropages*. Retrieved March 6, 2025, from https://news.agropages.com/News/NewsDetail---51737.htm

Luck, J., Stombach, T. S., & Shearer, S. A. (2024, April). *Basic of Automatic Section Control for Agricultural Sprayers.* Retrieved March 6, 2025, from UKY: https://publications.ca.uky.edu/sites/publications.ca.uky.edu/files/aen102.pdf

McFadden, N. G. (2023). *Precision Agriculture in the Digital Era: Recent Adoption on U.S. Farms.* USDA.

Mordor. (2023). *Mordor Intelligence.* Retrieved from https://www.mordorintelligence.com/industry-reports/us-herbicide-market

Mordor Intelligence. (2025, April 2). *www.mordorintelligence.com/industry-reports*. Retrieved from www.mordorintelligence.com: https://www.mordorintelligence.com/industry-reports/us-herbicide-market

Reddy, K., & Nandula, N. (2012, March). Indian Journal of Agronomy. *Herbicide resistant crops: History, development and current technologies*, pp. 2-6.

Seymour, C. (2024, February 26). *Successful Farming*. Retrieved March 6, 2025, from https://www.agriculture.com/sprayer-upgrade-kits-technology-options-and-pricing-8599615

Steil, A. (2024, March 19). *Yard and Garden.Extension.IAState*. Retrieved February 6, 2025, from https://yardandgarden.extension.iastate.edu/faq/how-do-i-know-if-plant-weed

The Editors of Encyclopedia Britannica. (2025, March 5). *Britannica.com/science/herbicide*. Retrieved March 6, 2025, from Britannica.com: https://www.britannica.com/science/herbicide

U.S. Department of Agriculture. (2024, July). *Adoption of Genetically Engineered Crops in the United States*. Retrieved March 6, 2025, from https://www.ers.usda.gov/data-products/adoption-of-genetically-engineered-crops-in-the-united-states/documentation

University of Tennesse. (2021, January 12). *UT Crops.* Retrieved March 6, 2025, from New.UTCrops: https://news.utcrops.com/wp-content/uploads/2021/01/Soybean-Herbicide-Tolerance-Trait-Summary.jpg

USDA. (2010). Retrieved April 10, 2011, from http://www.ers.usda.gov/StateFacts/

USDA. (2020). *Precision agriculture technology adoption in US farming: 2010-2020.* USDA.

USGS. (2019). National Pesticide Synethesis Project.

Wilson, M. (2023, July 5). *Will a Smart Srpayer Pay Off on Your Farm*. Retrieved February 5, 2025, from https://www.farmprogress.com/technology/will-a-smart-sprayer-pay-off-on-your-farm-