Economic and Behavioral Drivers of Herbicide Resistance Management in the U.S.

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Abstract: Weeds invade farms, grow and reproduce aggressively. For more than half a century, the primary tool used by farmers to control weeds has been herbicides, but the effectiveness of herbicides is declining due to herbicide resistance. An option available for farmers to better balance weed control and herbicide resistance is to adopt resistance management practices that prevent or slow the evolution of resistance. However, the adoption of resistance management has been low. This study aims to explore the impact of economic and behavioral factors on a farmer's choice over chemical, cultural and mechanical methods of weed control. We use multivariate regression analysis and 2016 farm-level weed management data from farmers in 28 states across the U.S. to identify the farmer and farm operation characteristics that are most associated with farmers' weed management decisions. The analysis shows that the negative externality from a neighbor's perceived lack of adoption of herbicide resistance management practices leads to a farmer's more diligent weed and resistance management, while a low tolerance for risk and impatience discourage the adoption herbicide resistance management. The analysis also provides novel insights into how the economic and non-monetary motivations of farmers relate to their use of alternative weed management practices.

1. Introduction

Weeds are a major constraint for agricultural crop production. Management of weeds has been accomplished primarily with herbicides for more than half a century. Reliance on herbicides has resulted in the evolution of herbicide-resistant weeds and increased crop loss due to reduced herbicide efficacy. The effectiveness of pesticides is declining as weeds evolve resistance due to widespread and repeated exposure. This evolution occurs as weeds that are susceptible to the herbicide are killed by exposure to it and do not reproduce, while weeds that are resistant to the herbicide survive exposure and reproduce.

In the past, new herbicide-resistant weed species were managed through the development and release of new herbicide sites of action. However, two decades ago a different strategy emerged. Corn, cotton, soybean and other crops were genetically engineered with tolerance to herbicides such as glyphosate. This allowed farmers to use these herbicides selectively in crops that previously would have been damaged by them. It has been more than 30 years since the last new herbicide sites of action, HPPD inhibitors, were introduced in 1982 for weed control in row crops (Green 2014; Hurley and Frisvold 2016), in part because of the unprecedented adoption of glyphosate-tolerant crops and the use of glyphosate. Yet, with sixteen glyphosate-resistant weed species in the U.S. and at least one weed species resistant to 23 out of the 26 known herbicide sites of action, it has become clear that engineering herbicide-tolerant crops is at best, a temporary solution to the weed management problem.

Given that the research and commercial development of a new safe herbicide can take 11 years and cost manufacturers between $50 and 70 million in the United States (Ollinger and Fernandez-Cornejo 1995), weed scientists have encouraged farmers to use a more diverse set of weed management practices that include cultural (e.g., planting date and narrow rows) and mechanical (e.g., cultivation and tillage) in addition to chemical tactics in an effort to avoid the evolution of herbicide-resistant weeds. Adoption of diverse tactics by farmers has been low.

Explanations for low adoption are wide ranging. The possible motives are farmers' broad range of concerns about the complexity, lack of flexibility, inconvenience of adopting diverse management tactics. For example, Carpenter and Gianessi (1999) were among the first to report that simplicity and flexibility were the primary reasons farmers switched to herbicide-focused weed control programs. Bonny (2008) compared transgenic with conventional soybean, and found that the simplification of weed control and greater work flexibility were two principal advantages that helped explain the rapid diffusion of transgenic soybean.

There is increasing evidence that farmers have concerns about the weed management in addition to flexibility, convenience, and simplicity. Human and environmental health can be of concern. Some studies find that farmers apply slightly more herbicide on herbicide-tolerant crops than that used on convention crop varieties (Fernandez-Cornejo and Caswell 2006; NRC 2010). Therefore, farmers who are concerned about the toxicity risks may promote the application of diverse tactics. However, there is evidence that glyphosate, the primary herbicide used on most herbicide tolerant crops over the past two decades, is less toxic to humans and less likely to persist in the environment than other alternative herbicides (Fernandez-Cornejo and McBride 2002; Fernandez-Cornejo et al. 2012). Thus, the potential effect of farmer concerns about human and environmental health is not completely clear.

Farmers may choose not to use diverse tactics to reduce the risk of herbicide-resistant weeds because the benefits are delayed and uncertain, while the costs are immediate and certain.

Movement of weeds across farm boundaries can create an externality where farmers prefer to rely on their neighbors to manage herbicide resistance. Farmers can be overly optimistic about the prospects of new herbicides or herbicide-tolerant crop varieties, making them reluctant to adopt more diverse tactics. Additional costs and more time requirements of using more diversified tactics further discourage adoption. Unfortunately, there has been relatively little research that attempts to identify which explanations are likely the most important drivers of a farmer's weed management decisions.

The objective of this research is to identify what factors are most strongly associated with a farmer's use of a range of herbicide, mechanical and cultural weed management tactics. This objective was accomplished using 2016 farmer survey data collected by Michigan State University. The survey instrument elicited information on a farmer's 2015 weed management practices, weed management concerns, and the most important considerations to the farmer when choosing which weed management tactics to use. Multivariate regression analysis was used to evaluate how weed management decision varied by farmer and farm operation characteristics. The contribution of the research is the broader behavioral as well as economic perspective it takes to better understand farmers' weed management decisions when compared to previous literature. The benefits of taking this broader perspective are the opportunity to identify novel pathways for encouraging farmers to proactively manage herbicide resistance. Such pathways can serve as new targets for regulatory policy, farmer education, and private or public incentives to address the significant challenges posed by herbicide-resistant weeds to U.S. agriculture.

2. Data Description and Method

2.1. Data Description

This study is based on data from a U.S. farm-level weed management survey conducted by the office for Survey Research, Institute for Public Policy and Social Research, Michigan State University in the year 2016. Farmers from 28 predominately corn, cotton, soybean and wheat producing states were surveyed using a mixed mode (internet and mail) method. The professional research questionnaire was designed by economists, weed scientists and sociologists from Iowa State University, Michigan State University, University of Minnesota, North Carolina State University, University of Arkansas, University of Arizona and Portland State University. The sampling design didn't target for specific crops, but for general weed management practices instead. First, the survey screened participants to ensure that the respondents were involved in a farming operation at the time of the survey was conducted. Also, to qualify for the survey, they had to be involved in making weed management decisions for the farming operation.

The survey started by asking questions about weed management strategies and practices in 2015, including types of field crops planted, total cropped area, important non-monetary considerations for making weed management decisions, and weed management practices that were used by the respondent in 2014-15. Then, questions about herbicide resistant weed knowledge and management were asked, including concerns about possible herbicide resistant weeds encroaching from neighboring farms, sources of for herbicide resistant weed problem help. These two sections were followed by several questions about the 2015 growing season, including farm demographics (household income sources, self-evaluation of their willingness to take risks and be patient), and personal demographics (gender, years of farming experience, total household income before taxes in 2014).

A total of 530 observations from 27 states were obtained with complete information for analysis. The list of the states is presented in Table 1. Compared with the census of agriculture conducted by United States Department of Agriculture in 2012 (USDA NASS 2012), the proportion of acres for each state in the survey deviated, sometimes substantially, from the proportion of acres reported by survey respondents. This is particularly true of the southern states of Arizona, Arkansas, Louisiana, and Mississippi, which were over represented in our responses, and more northern state of Iowa, Missouri, and Ohio, which were under represented in our responses. Panel A in Table 2 displays the distribution of farm sizes in the survey sample, and compares the proportion to the census of agriculture data. More than 90% of the farms in the survey had more than 180 acres, whereas in the census, farms with 10 to 179 acres occupied the majority among all farms in the 27 states in 2012. Thus, the survey respondents over-represent farms with more than 500 acres, and under-represented farms that were under 180 acres.

Turning to Panel B in Table 2, over 99% of the respondents were male with an average of 35.7 farming years and a standard deviation of 12.5 years. More than 65% of respondents reported that the farming operation was the major source of their household income, and about half had total household income of more than $100,000 before taxes in 2014, which exceeds $22,840, average total household income from farm-related sources before taxes reported in 2012 census of agriculture (USDA NASS 2012). More than sixty percent of respondents reported a household income range of $50,000-$250,000, and only 3.01% of them claiming a household income of less than $25,000. Almost none of the farms covered in the survey used organic methods or had certified organic operations.

Farmers were also asked about the types of field crops planted on their farming operation in 2015. The vast majority of farms (94.55%) dealt with multiple types of crops from corn, cotton, soybean, sugar beet, rice, wheat and other crops, such as tobacco and alfalfa. Farmers dealing with 2 crops accounted for the highest proportion, 44.17%, followed by the proportion of farmers dealing with 3 crops, 33.65%. Across the states, corn, soybean and wheat were the three crops that were most broadly planted (Figure 1). Cotton was not reported as an important cultivated crop in most of the States, except some southern states, such as Texas (20 out of 33 farms) and Louisiana (6 out of 16 farms).

2.2. Variables for Analysis

2.2.1 Control Variables

The main variables we use to explain variation in weed management decisions fall into six categories. These categories include farmer demographic characteristics, operation characteristics, key weed management concerns, concern about resistant weeds encroaching from neighbors' field, pessimistic and optimistic attitudes about herbicide resistance, and risk and time preferences.

Demographic information included gender, number of years farming, household income, and farm size by acre. Women were under represented in the present study (less than 1% of respondents). For possible economic factors, we also include the importance of herbicide cost and commodity price into the analysis using a five-point scale: *not important at all* (1) to *very important* (5).

For the weed management concerns, respondents were asked: "How important are each of the following to you?" which was followed by a list of ten items that may influence their weed management decisions. The response options ranged from not important at all (1) to very important (5). The list of items, along with the descriptive summary of responses is presented in Table 3. By conducting factor analysis, we were able to reduce this list of ten items to three factor scores based on the correlation in farmers' responses (Table 3). The first of these three factor scores reflects the importance of flexibility and convenience to farmers, with standardized factor loadings ranging from 0.55 to 0.85. The second reflects the importance of the effectiveness of weed control, with standardized factor loadings ranging from 0.46 to 0.75. The last represents the importance of human and environmental health concerns with standardized factor loadings ranged from 0.60 to 0.84.

We want to know about how farmers' attitudes may affect their weed management decisions. There are in total three types of attitudes investigated in this study: concerns about herbicide resistant weeds encroaching from neighbors' fields, and pessimism and optimism about the prospects of future weed management. For the first of these attitudes, a 4-item scale measuring the concerns about getting herbicide resistant weeds encroaching from neighbors was offered. This set of items asked "To which extent you agree or disagree with the following" and was followed by a list of statements about herbicide resistant weeds encroaching from neighbors' fields (Table 4). A five-point response scale was given ranging from *strongly disagree* (1) to *strongly agree* (5). Similarly, respondents were also asked to evaluate a set of items related to their attitudes toward herbicide resistance (Table 4). We factor analyzed farmer responses to these items and constructed the pessimistic attitude scale using 2 items, and the optimistic attitude scale using 3 items.

Additionally, a respondent's tolerance for risk is calculated from a self-reported value describing the extent to which the farmer is *fully prepared to take risks* (score 10) or *not likely to take risks* (score 1). A respondent's time preference is calculated from a self-reported value with a 10-point response scale ranging from *very impatient* (1) to *very patient* (10). Farmer responses were normalized to a zero-one scale by dividing by ten. These risk and time preference variables were used alone and interacted. The measures have been validated and successfully used in previous research (e.g., Dohmen et al. 2011; Becker et al. 2012; Roe 2015).

In summary (Table 5), the control variables included in the analyses are farm size, gender, farming years, household income, herbicide costs, commodity price, risk and time preference, other non-monetary concerns, together with the state fixed effect to control the spatial and geopolitical difference in responses. Risk and patience preferences include three variables: risk tolerance, time preference, and their interaction. For the variables in the other non-monetary concerns, 19 survey questions are factored into 6 variables: safety and environment concern, flexibility, effectiveness of weed control, concern about resistant weeds from neighbors' fields, pessimistic attitudes about herbicide resistance, and optimistic attitudes about herbicide resistance.

2.2.2 Response Variables

The goal of the study is to explore the impact of the behavioral and economic factors on a farmer's choice over cultural, mechanical and chemical methods of weed control. The cultural methods include crop rotation, high seeding rates, choice of planting date to reduce weed competition, planting in narrow rows, and use of weed maps. Mechanical methods include inter-row cultivation, tillage, hand weeding, and use of mulches. The chemical methods include pre-emergent, post-emergent and post-harvest herbicide applications. Herbicide use was further explored in terms of the use of herbicide mixes, multiple herbicides (unmixed), full labeled herbicide application rates, and herbicide site of action rotation.

Of the three types of methods, chemical control practices make weed management easier and have been more widely used in the U.S. Moreover, many U.S. farmers rely on a single herbicide as the only chemical control, which increases the chances for herbicide resistant weeds. This resistance can result in significant crop loss and rising weed control cost. All the items included in the three types of methods were in the list for the question “Over the past two years, on what percentage of your fields on your entire farming operation did you use each of the methods to control weeds?” Responses were on a six-point scale ranging from *did not use* (1) to *80%-100%* (6). The methods are not mutually exclusive, so multiple methods within and across groups can be applied simultaneously on the same cropped fields. Table 6 shows the distribution of responses for all weed control techniques.

From Table 6 and it visualization in Figure 2, two results are clear. First, the patterns of the reported control practice application rate are different cross the three practice groups. Chemical Methods were most broadly applied to control weeds in the surveyed farms. Second, the patterns of the reported control practice application rate are different cross practices within each group. In the mechanical control practice group, tillage was widely used, while most respondents didn’t use inter-row cultivation at all. Similar contrasts can be found in the chemical and cultural control practice groups, between post-emergent and post-harvest herbicide in the chemical control practice group, and between crop rotation and weed maps in cultural control practice group. Methods included in the herbicide application method group share the highest degree of similarity in use rates in the sample. Since most farms in the sample planted a combination of the major crops, such as corn, soybean and wheat, setting constraints to restrict the types of crops would make little changes to the patterns of practice adoption shown in Figure 2. Also, research shows that farmers’ weed management decisions have many commonalities across crops when analyzing the most-important motivators of behavior (Hurley et al. 2009; Hurley and Mitchell 2014). Thus, we pool the data together, ignoring the types of crops in our analysis.

2.3. Analysis Method

Reduced form regression equations were jointly estimated using the user written cmp (conditional mixed process model) command in STATA (Roodman 2011). This command performs an analysis that is analogous to a seemingly unrelated regression for limited dependent variables and produces an estimate of the correlation in the unexplained errors. This correlation structure was further analyzed in an effort to identify complementary or substitutable combinations of management tactics. Multiple model specifications (Tobit, Interval regression and continuous regression) with and without state level fixed effects were estimated to explore the robustness of the results.

3. Results and Discussion

We evaluate the effects on a farmer's choice over chemical, cultural and mechanical methods of weed control, and on a farmer's choice over chemical methods and application methods. Table 7 and Table 10 report the corresponding estimation results by using interval regression, while Table 8 and Table 11 show the results by using Tobit regression, and Table 9 and Table 12 continuous regression. Here, we will discuss the results from four aspects: the impacts associated with concerns about resistant weeds from neighbors' field, the impacts of risk tolerance and patience, the impacts from optimistic and pessimistic attitudes toward herbicide resistance, and policy implications from other characteristics.

3.1. Impacts of Farmers' Concerns about the Resistance from the Neighbors' Fields

There are two ways to interpret the results based on the two possible directions of causality. First, as described by the survey questions in the construct of the variable, there are several possible ways for weed-seed to disperse between fields and be transformed from the "neighbor".

Therefore, the farmer's gain from managing resistance will be lower if the neighbor ignores resistance in his field. This suggests that weed susceptibility to herbicide is a common-pool-resource, and we may expect a "tragedy of the commons" result. The "tragedy of the commons" predicts that, since farmers expect it to be costly, or even impossible, to exclude other farmers from obtaining benefits from the susceptibility pool, the returns to farmers from the managing resistance will be reduced (Livingston et al. 2015; Ostrom et al. 1999). Without effective rules providing incentives to invest in rather than exploit the resource, farmers tend to reap the greatest benefit from this resource and reduce management costs by devoting less effort to resistance management. The effect of the internalization of negative externalities is a hastening of herbicide resistance. This should be especially the case when farmers believe resistant weeds are likely to spread to their fields from neighbors' fields.

Our findings appear to contradict this prediction. From the results tables, we observe that being more concerned about herbicide resistance encroaching from neighbors' fields leads to be more diligent weed and resistance management. Farmers that are more concerned that herbicide-resistant weeds can spread from neighbors' fields appear to use a greater diversity of management tactics, such as tillage, hand weeding, change of planting date, adjusted plant densities, and weed maps that help them avoid the development of resistance. They are also more likely to apply herbicide mixtures and use multiple (unmixed) herbicides. These two application practices can effectively delay resistance to the herbicide as different herbicides affect susceptible weeds differently, and it is difficult for weeds to develop resistance to multiple herbicides within a short time.

This result is contrary to the hypothesis set by the "tragedy of the commons". Farmers evaluate the marginal benefit and marginal cost before taking actions to manage the resistant weeds. However, to what extent the negative externality of a neighbor's free riding will influence farmers' management decision is yet to be determined. Some recent survey data suggest that, the proportion of neighbors free riding is not too high to preclude cooperation, which has already occurred in Arkansas (Smith 2012) and North Carolina (Everman 2014). With these consistent research results with ours, it is of interest that farmers may be able to pursue a long run economic goal resulting in higher returns over time without explicit rules limiting neighbors' free riding on resistant weed management.

The other direction of causality goes from resistant weed management adoption to the concerns over neighbors. From our results, for a farmer who devotes more time, money and energy in controlling resistant weed problems can be more worried about the neighbor's behavior, especially if the neighbor chooses to ignore resistant weeds. Neighbors free riding will reduce the expected return from the farmer's investment in weed management, because of all the possible ways for weed-seed to disperse between fields and be transformed from the neighbor. Though this direction of causality is less discussed in literature, we fail to eliminate the reasoning based on our reduced form estimations.

3.2. Impacts of Uncertainty

Another finding, which is consistent with the previous literature, is that a low tolerance for risk and impatience discourages resistance management. This is expected to occur because either adding other herbicides, using multiple herbicides or changing the herbicides with different sites of action can increase weed management costs. However, the benefits in terms of resistance management are uncertain, both because of the not-precisely-known efficacy of resistance management, and the common-pool-resource nature of weed susceptibility. As a result, the costs of resistance management are certain and immediate, whereas the benefits are uncertain and come later (if at all).

As one would expect from economic theory, our results show that farmers' risk tolerance and time preference are consistently found to be significantly associated with a farmer's decision to use alternative weed management tactics and application practices. Farmers who find themselves more prepared to take risks, or show greater patience, are more likely to adopt the diverse tactics, as well as the practices helping to avoid herbicide resistance.

Interestingly, we also find a consistent attenuating interaction between risk and time preferences in relation to weed management decisions. To fully understand the role of risk tolerance and time preferences, we assess the marginal effect of risk tolerance (time preference) on weed management practices at different values of a conditioning time preference (risk tolerance). In the context of continuous regression, we estimate a model with risk tolerance and time preference variables alone and interacted with each other, then plot the estimated

$$\frac{\partial\ weed\ management\ practice\ application}{\partial\ RiskTolerance\ (TimePreference)} = \beta_{risk(time)} + \beta_{interaction} * TimePreference\ (RiskTolerance)$$

from this model for different values of patience (risk) along with 95% confidence intervals. As recommended by Brambor, Clark and Golder (2006), if the CIs exclude zero at any time preference (risk tolerance) level, we conclude that the evidence rejects the null hypothesis that

$$\frac{\partial\ weed\ management\ practice\ application}{\partial\ RiskTolerance\ (TimePreference)} = 0$$

for this value of time preference (risk tolerance) level.

Figure 3-10 depict sample plots to test the interaction term, where Figure 3-6 illustrate the estimated marginal effect of risk tolerance at different time preference levels with 95 percent confidence intervals on adoption of weed management practices; and Figure 7-10 show the estimated marginal effect of time preference at different risk tolerance levels with 95 percent confidence intervals on adoption of weed management practices. We divide risk tolerance and time preferences into three groups based on the self-reported survey results: values smaller than one standard deviation below the mean ($0 \leq x \leq mean - sd$), within one standard deviation of the mean ($mean - sd < x \leq mean + sd$), and bigger than one standard deviation above the mean ($mean + sd < x \leq 1$). These groups are denoted as low risk-aversion, medium risk-aversion and high risk-aversion for risk tolerance; and low patience, medium patience and high patience for time preference, respectively.

The 95% confidence interval excludes zero in almost all cases, except for the marginal effect of risk tolerance at patient group on the use rate of inter-row cultivation and choosing planting date, and the marginal effect of time preference at risk-neutral group on the practice of high planting densities. This can be interpreted as evidence of a statistical relationship between risk tolerance and management practice adoption, and between time preference and management practice adoption. Moreover, though in terms of management practice adoption rate, the magnitudes of marginal effects are typically small as depicted in Figure 3-10. The values of marginal effects do vary cross groups for each management tactic and application practice, and a few marginal effects even have the sign changed: from positive, encouraging effects to negative, discouraging effects. Therefore, it is reasonable for us to include the interaction term, and the marginal effects of risk tolerance and time preference would have been overestimated if we omitted the interaction term, when its coefficient is negative.

Risk tolerances are not time preferences, but risk and time are intertwined. By including the interaction term, our analysis manages to make valid inferences about the marginal effects of risk tolerance and time preference on the adoption of weed management practices.

3.3. Impacts of Attitudes about Resistance Management

Farmers who are optimistic that new herbicides will soon be available are significantly less likely to use multiple herbicides or rotate herbicide sites of action, both of which reduce the risk of resistant weeds emerging. Farmers who are pessimistic about the development of herbicide resistance, on the other hand, will reduce the use of post-emergent herbicide, decrease the planting date change and the use of weed maps. Thus, farmers who are either over- or under-confident about the availability of the new chemistries will be less inclined to adopt herbicide resistance management.

Given the fact that it has been more than three decades since the last new site of action was introduced for weed control in row crops, it is difficult for farmers to predict either how fast herbicide resistance will emerge or when the next new herbicide will be discovered (Llewellyn et al. 2002; Hurley and Frisvold 2016), let alone the uncertain length of the commercialization process. Therefore, these results have strong policy implications that additional farmer education about the commercial development of an herbicide and the time it takes, which may help create incentives to promote resistance management.

3.4.Impacts from Economic and Other Non-Monetary Factors

From our results, we can conclude that farm operations with greater household income are associated with significantly higher pre- and post-emergence herbicide use. Herbicide costs appeared to be an important consideration that discourages farmer use of post-harvest herbicide applications. A closer attention to commodity price drives farmers to choose high planting densities, proper planting date and use full label herbicide rate to reduce weed competition. Economic factors are always considered as the major concern for farmers' weed management decision making (Weirich et al. 2011; Hurley and Frisvold 2016). The results from our analysis are generally consistent with that literature.

Farmers who report that human and environmental health concerns are important to their weed management decisions are significantly less likely to use the full labeled herbicide application rate. It is reasonable that human and environmental health concerns do not factor much into the weed management, since any human and environmental health costs are external to the farm, and do not directly affect profitability. However, using application rates that are below what is recommended on the label is bad for resistance management, and herbicide should be used in "precise proportion to the rate" to reach its most effectiveness (Laxminarayan and Brown 2000). Literature shows that, glyphosate is considered safer for human and environmental health than many alternative herbicides (Fernandez-Cornejo et al. 2012; Hurley and Frisvold 2016), and the use of glyphosate-tolerant crops decreases the number of applications per hectare, compared to conventional crops with the same tillage practices, at least for soybean (Nelson and Bullock 2003; Gardner and Nelson 2008). Thus, in weed-management systems with a heavy reliance on glyphosate-tolerant crops, using the full labeled herbicide application rate should not be a large human and environmental health concern for farmers. Our results suggest the contrary is true for some farmers, who use less than the labeled rate due to human and environmental health concerns.

Farmers who reported that convenience, flexibility and saving time were important considerations for their weed management decisions were significantly less likely to use multiple herbicides, full labeled herbicide application rates, herbicide site of action rotations, and crop rotations; all of which reduce the risk of herbicide-resistant weeds—a result that suggests these non-monetary factors are likely one of the more important drivers of herbicide-resistant weeds. This is more likely to be true for farms with larger sizes than average, such as those covered in this survey. Timely management is critical for success because of the number of acres that must be managed, all the regular operations needed to be performed, and the possible lack of labor or trained employees (Hurley and Frisvold 2016). Our analysis also finds that, farmers working on a larger farm will opt for applying pre-emergent herbicide and post-harvest herbicide, which help to make sense of results obtained regarding flexibility and convenience.

Farming experience is another factor that we examine. For farmers with more farming years, our results don't show strong evidence that experience will encourage diverse weed management practice adoption, but they are less likely to perform hand weeding, choose high plant densities, apply post-emergent herbicide, and multiple herbicides. They are more likely to use narrow rows and weed maps.

Male farmers are more likely to apply chemical methods, as well as crop rotation to control herbicide resistance which doesn't require frequent applications compared to other mechanical and cultural methods. Also, male farmers are less likely to use weed maps to grasp the big picture of resistance on their farm. However, since the sample of female farmers in our data was small, female farmers are under-represented in this analysis, giving us less confidence in the power of this result.

4. Conclusion

This study analyzes both economic and behavioral factors that are strongly associated with a farmer's use of a range of herbicide, mechanical and cultural weed management tactics, as well as the choice over herbicide application practices. Many previous studies have investigated only one or some of the factors included in this study, and fail to consider the impact of the farmers' attitudes (including the risk tolerance, patience, and pessimism and optimistism about the herbicide resistance). This contribution of the study allows a much broader behavioral perspective in the analysis.

Our results raise some doubt about the significance of the common-pool-resource management problem. Principal-agent theory suggests individual farmers are more likely to pursue a short-run economic goal by ignoring resistance, while it is the goal of the larger community to pursue a long-run economic goal and higher returns over time (Hurley and Frisvold 2016). We find evidence that suggests farmers can be more self-disciplined and exhibit greater foresight than we might otherwise expect. Indeed, if a farmer expects weeds are encroaching from neighbors' fields, redoubling his own weed management efforts might be a rational response even in the short-run. However, it is still too soon to claim there is not a negative externality problem based on our results, and we also need to test and confirm the direction of causality in future work.

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Table 1. Geographic characteristics

	Survey						USDA Census of Agriculture, 2012		
							% of Total Acres of Cropland used for Crops*		
State	No. of farm	%		Acre	%		Surveyed States		United States
Arkansas	37	6.98%		58962	8.21%		0.79%		0.65%
Alabama	4	0.75%		3130	0.44%		0.33%		0.27%
Arizona	3	0.57%		7440	1.04%		2.66%		2.18%
Delaware	2	0.38%		4150	0.58%		0.15%		0.12%
Georgia	3	0.57%		2430	0.34%		1.32%		1.09%
Illinois	36	6.79%		35709	4.97%		8.09%		6.64%
Indiana	12	2.26%		16710	2.33%		4.36%		3.58%
Iowa	38	7.17%		33392	4.65%		8.78%		7.21%
Kansas	33	6.23%		57199	7.96%		8.99%		7.39%
Kentucky	14	2.64%		20044	2.79%		1.95%		1.60%
Louisiana	22	4.15%		41745	5.81%		1.29%		1.06%
Maryland	7	1.32%		14551	2.03%		0.46%		0.38%
Michigan	16	3.02%		24748	3.45%		2.56%		2.11%
Minnesota	34	6.42%		27358	3.81%		7.13%		5.86%
Mississippi	27	5.09%		53497	7.45%		1.56%		1.28%
Missouri	10	1.89%		15110	2.10%		4.73%		3.88%
Nebraska	46	8.68%		50070	6.97%		7.23%		5.94%
North Carolina	24	4.53%		16586	2.31%		1.59%		1.31%
North Dakota	19	3.58%		39542	5.51%		8.64%		7.10%
Ohio	24	4.53%		14517	2.02%		3.64%		2.99%
Oklahoma	11	2.08%		16940	2.36%		3.27%		2.68%
South Carolina	9	1.70%		6835	0.95%		0.61%		0.50%
South Dakota	22	4.15%		38330	5.34%		6.23%		5.12%
Tennessee	15	2.83%		25315	3.53%		1.64%		1.35%
Texas	33	6.23%		69184	9.63%		7.73%		6.35%
Virginia	10	1.89%		8304	1.16%		0.95%		0.78%
Wisconsin	19	3.58%		16333	2.27%		3.30%		2.71%
Total	530			718131			100%		82.14%

* Cropland used for crops includes cropland harvested, crop failure, and summer fallow.

Table 2. Data Description

Panel A. Farms by size

Farms by size (%)	Survey	Surveyed States; USDA Census of Agriculture, 2012	
		Total Farm Acres[1]	Total Harvested Cropland Acres[2]
1 to 9 acres	0.19	7.13	13.95
10 to 49 acres	0.94	26.75	35.11
50 to 179 acres	8.11	32.32	31.79
180 to 499 acres	20.38	18.20	21.64
500 to 999 acres	24.34	7.43	6.91
1,000 acres or more	46.04	8.17	7.30

[1]Total land is the sum of cropland, pasture/range, forest-use land, special uses, urban area and other land.
[2]Cropland harvested is one of the three components of cropland used for crops.

Panel B. Distribution by socio-economic variables

	Sample
Gender (%)	
Men	99.06
Women	0.94
Farming year (%)	
3-25 years	20.45
26-35 years	27.2
36-45 years	35.28
46-55 years	13.32
55-65 years	3
66-86 years	0.75
Household income (%)	
Less than $15k	0.38
$15k to $25k	2.63
$25k to $50k	10.32
$50k to $100k	33.02
$100k to $250k	33.21
$250k to $500k	12.76
$500k or more	7.69
Major source of household income (%)	
farming operation	65.98
off-farm sources	18.61
equal between above options	15.41
Farming operation certified organic (%)	
Entire	0
Part, but not all	0.94
Use organic methods, but not certified organic	1.5
None	96.8

Table 3. Average scores* for various concerns of farmers' adoption

	Code	Average	SD
Flexibility & convenience	f1		
Flexibility & convenience		4.28	0.73
Simplicity		4.08	0.84
Convenience		4.03	0.87
Concerns about safety and environment	f2		
Worker safety		4.36	0.93
Protecting wildlife		4.17	0.93
Protecting water quality		4.48	0.84
Controlling soil erosion		4.42	0.90
Effective weed control	f3		
Protecting yield		4.86	0.48
Having long lasting weed control		4.70	0.58
Having residual control		4.53	0.69

* Scale 1 (not important at all) to scale 5 (very important)

Table 4. Average scores* for various attitudes of farmers' adoption

	Code	Average	SD
Concerns about herbicide resistant weeds from neighborhood	ff1		
I am concerned about herbicide resistant weeds spreading to my farming operation from nearby farming operations.		3.90	1.02
I am concerned about herbicide resistant weeds spreading to my county from nearby counties.		3.90	0.96
I am concerned about herbicide resistant weeds spreading to my region of the U.S. from other regions.		3.83	1.02
Even if I keep my fields clean, I could get herbicide resistant weeds from neighboring farms.		4.18	0.86
Pessimistic attitude to herbicide resistance	ff2		
When new weed management technologies are introduced, it is only a matter of time before pests evolve resistance.		4.03	0.78
Modern agricultural practices contribute to the conditions that spur evolution of herbicide resistant weeds.		3.74	1.03
Any new chemical mode of action that is developed to control weeds will be overused.		3.57	0.98
Optimistic attitude to herbicide resistance	ff3		
Weed resistance can be managed effectively without cooperation amongst farmers in a community.		2.38	1.13
By the time a weed develops resistance to an herbicide, at least one new herbicide will have been found to replace it.		2.40	1.01

*scale 1 (strongly disagree) to 5 (strongly agree)

Table 5. Control variable descriptive statistics

Variable	Mean	Standard Deviation	Minimum	Maximum
Gender	0.99	0.10	0.00	1.00
Farming Years	35.70	12.52	3.00	86.00
Household Income	4.66	1.15	1.00	7.00
Total Farm Acres	1354.96	1416.27	3.00	9000.00
Herbicide Cost	4.41	0.75	1.00	5.00
Commodity Price	4.86	0.48	1.00	5.00
Flexibility & Convenience	-0.003	0.93	-4.52	0.84
About Human & Environment Health Concerns	-0.015	0.91	-3.97	1.22
Effectiveness of Weed Control Concerns	-0.02	0.90	-7.08	0.83
Risk Tolerance	0.70	0.19	0.10	1.00
Patience	0.61	0.22	0.10	1.00
Risk Tolerance × Patience	0.44	0.20	0.02	1.00
Herbicide Resistant Weeds from Neighborhood	0.003	0.95	-3.20	1.42
Pessimistic Attitude to Herbicide Resistance	-0.0005	0.77	-2.64	1.80
Optimistic Attitude to Herbicide Resistance	-0.0007	0.68	-1.63	2.21
Observations	530			

Figure 6. Distribution of Control Techniques Responses

		0%	>20%	20-39%	40-59%	60-79%	80-100%	No Response
Cultural Methods	Crop Rotation	4.69%	2.25%	5.25%	14.63%	15.57%	54.78%	2.81%
	High Seeding Rates/Plant Densities	43.90%	10.32%	10.88%	11.63%	9.01%	9.38%	4.88%
	Choice Planting Date to Reduce Weed Competition	58.35%	11.07%	6.57%	10.32%	5.44%	7.13%	1.13%
	Narrow Rows	37.71%	2.25%	5.44%	14.07%	12.57%	27.20%	0.75%
	Weed Maps	81.24%	5.25%	3.38%	2.81%	2.25%	3.75%	1.31%
Mechanical Methods	Inter Row Cultivation	75.23%	7.88%	3.38%	3.94%	2.63%	3.38%	3.56%
	Tillage	23.08%	10.69%	10.13%	14.07%	12.95%	26.27%	2.81%
	Hand Weeding	39.02%	36.96%	8.63%	6.19%	2.63%	5.07%	1.50%
	Planted Cover Crop/ Used Mulches	59.29%	15.01%	6.94%	7.50%	3.38%	5.63%	2.25%
Chemical Methods	Pre-Emergent Herbicide	7.32%	3.56%	4.50%	13.13%	13.13%	56.66%	1.69%
	Post-Emergent Herbicide	2.25%	1.31%	2.81%	10.13%	14.63%	67.17%	1.69%
	Post-Harvest Herbicide	50.09%	11.26%	6.75%	10.88%	5.44%	8.63%	6.94%
Herbicide Use	Herbicide Mixes	4.13%	1.69%	5.07%	11.07%	25.70%	50.47%	1.88%
	Multiple Herbicides	3.00%	2.63%	3.38%	12.95%	22.89%	52.53%	2.63%
	Use Full Label Herbicide Rate	2.06%	2.44%	4.69%	10.88%	20.26%	57.41%	2.25%
	Rotating Herbicide Modes of Action Annually	13.32%	5.44%	6.94%	20.26%	19.51%	32.65%	1.88%

Table 7. Weed Control Methods - Interval Regression Results. [a.b.]

	Mechanical Method				Chemical Method			Cultural Method				
Interval regression	Inter-row Cultivation	Tillage	Hand weeding	Mulches	Pre - emergent Herbicide	Post - emergent Herbicide	Post - harvest Herbicide	Crop Rotation	Plant Densities	Planting Date	Narrow Rows	Weed Maps
acre	+	+	+	+*	+***	+	+***	+	+	+	+	+
gender	-	+	+	-*	+**	+***	-	+**	+	-	+	-***
farming years	-	-	-***	-	-	-**	+	-	-**	+	+***	+***
household income	-	-	+	+	+**	+**	+	+**	-	-	-	+
risk tolerance	-	+**	+	+***	+**	+**	+	+**	+	-	+	-
time preference	+	+***	+	+*	+***	+**	+	+	+	-	+	+
interaction term	-	-**	-	-**	-**	-**	-	-*	-	+	-	+
safety and environment concern	+	+	+	+**	-	-	-	+	+	+	+	-
flexibility	+	+	-	-	-	-	+	-*	+	+	+*	+
pest evolution concern	-	-**	+	-	+	+	-	+	+	-	+	-
herbicide costs	+	+	+	-	-	+*	-*	+	-*	+	+	-
commodity price	+	+	+	-	+	+	+	+	+***	+*	-	+
neighboring	+*	+**	+*	+	+	+*	+*	+*	+**	+***	-	+*
pessimistic	+	-	+	-	-	-***	-	+	-*	-**	+	-**
optimistic	+	+**	-	+	-	-	-	+	+	+	+	+

[a.] Statistical significance is noted by * at the 10% level, ** at the 5% level, *** at the 1% level.
[b.] Results for the state dummies are included in the regression but omitted here to save space.

Table 8. Weed Control Methods - Tobit Regression Result. [a.b.]

	Mechanical Method				Chemical Method			Cultural Method				
Tobit	Inter-row Cultivation	Tillage	Hand weeding	Mulches	Pre - emergent Herbicide	Post - emergent Herbicide	Post - harvest Herbicide	Crop Rotation	Plant Densities	Planting Date	Narrow Rows	Weed Maps
acre	+	+	+	+	+***	+	+***	+	-	-	+	+
gender	-	-	+	-**	+*	+**	-	+*	+	-	+	-***
farming years	-	-	-***	-	-*	-***	-	-	-**	+	+***	+***
household income	-	-	+	-	+*	+**	+	+	-	-	-	+
risk tolerance	-	+*	-	+***	+	+	+	+	+	-	+	-
time preference	-	+**	+	+*	+*	+	+	+	+	-	+	+
interaction term	+	-*	+	-**	-	-	-	-	-	+	-	+
safety and environment concern	-	+	+	+**	-	-	-	+	+	+	+	-
flexibility	+	+	-	-	-	-	+	-*	+	+	+	+
pest evolution concern	-	-**	+*	-	+	+	-	+	+	-	+	-
herbicide costs	+	+	+	-	-	+	-**	+	-**	-	+	-
commodity price	+*	+	+	-	+	+	+	-	+***	+*	-	+
neighboring	+	+*	+*	+	-	+	+*	+	+**	+**	-	+*
pessimistic	+	-	+	-	+	-***	+	+	-	-*	+	-**
optimistic	+	+	-*	+	-	+	-	+	+	+	+	+

[a.] Statistical significance is noted by * at the 10% level, ** at the 5% level, *** at the 1% level.
[b.] Results for the state dummies are included in the regression but omitted here to save space.

Table 9. Weed Control Methods - Continuous Regression Result. [a.b.]

	Mechanical Method				Chemical Method			Cultural Method				
Continuous regression	Inter-row Cultivation	Tillage	Hand weeding	Mulches	Pre - emergent Herbicide	Post - emergent Herbicide	Post - harvest Herbicide	Crop Rotation	Plant Densities	Planting Date	Narrow Rows	Weed Maps
acre	+	+	+	+	+***	+	+***	+	-	-*	+	+
gender	+	+	+**	-	+**	+***	+	+***	+	+	+	-***
farming years	+	-	-***	+	-	-**	+	-	-*	+	+***	+***
household income	-	-	+	+	+**	+**	+	+**	-	-	-	+
risk tolerance	+	+**	+	+***	+***	+***	+	+**	+	+	+*	+
time preference	+	+**	+	+***	+***	+***	+	+	+	+	+	+*
interaction term	-	-**	-	-***	-***	-***	-	-**	-	-	-*	-
safety and environment concern	+	+	+	+**	-	-	-	+	+	+	+	-
flexibility	+	+	-	-	-	-	+	-*	+	+	+*	+
pest evolution concern	-	-**	+	-	+	-	-	+	-	-	+	-
herbicide costs	+	+	+	+	-	+**	-*	+	-	+	+	+
commodity price	+	+	+	-	+	+	+	+	+**	+	-	+
neighboring	+*	+**	+*	+	+	+*	+**	+*	+*	+**	-	+*
pessimistic	+	-	+	-	+	-***	-	+	-	-**	+	-**
optimistic	+	+**	-	+	-	-	+	+	+	+	+	+

[a.] Statistical significance is noted by * at the 10% level, ** at the 5% level, *** at the 1% level.

[b.] Results for the state dummies are included in the regression but omitted here to save space.

Table 10. Herbicide Application Methods - Interval Regression Results. [a.b.]

	Chemical Method			Application Method			
Interval regression	Pre- emergent Herbicide	Post - emergent Herbicide	Post- harvest Herbicide	Herbicide Mix	Multiple Herbicide	Full label Herbicide rate	Change MOA
acre	+*	+	+***	+	+*	+	+**
gender	+***	+***	-	+	+*	+	+**
farming years	-	-**	+	-	-*	+	+
household income	+*	+**	+	+**	+	+	+
risk tolerance	+***	+**	+	+***	+***	+***	+
time preference	+***	+**	+	+***	+***	+***	+
interaction term	-***	-**	-	-***	-***	-***	-
safety and environment concern	-*	-	-	+	-	-*	+
flexibility	-	-	+	-	-**	-**	-**
pest evolution concern	+**	+	-	+	+	+	+*
herbicide costs	+	+*	-*	-	+	+	-
commodity price	+*	+	+	+	+	+**	+
neighboring	-	+*	+	+***	+***	+	+
pessimistic	+	-***	-	-	+	+	-
optimistic	-	-	-	-	-***	-	-**

[a.] Statistical significance is noted by * at the 10% level, ** at the 5% level, *** at the 1% level.

[b.] Results for the state dummies are included in the regression but omitted here to save space.

Table 11. Herbicide Application Methods - Tobit Regression Results. [a.b.]

	Chemical Method			Application Method			
Tobit	Pre -emergent Herbicide	Post -emergent Herbicide	Post -harvest Herbicide	Herbicide Mix	Multiple Herbicide	Full label Herbicide rate	Change MOA
acre	+***	+	+***	+	+*	+	+
gender	+*	+**	+	+	+	+	+**
farming years	-*	-***	+	-*	-***	+	+
household income	+*	+***	+	+**	+	+	+
risk tolerance	+**	+	+	+***	+***	+	+**
time preference	+**	+	+	+***	+***	+	+
interaction term	-**	-	-	-***	-***	-	-**
safety and environment concern	-	-	-	+	-	-**	+
flexibility	-	-	+	-	-**	-**	-*
pest evolution concern	+*	+	+	+	+	+**	+*
herbicide costs	-	+	-*	+	+	+	-
commodity price	+	+	+	-	-	+**	+
neighboring	-	+	+**	+**	+*	+	+
pessimistic	+	-***	-	+	+	+**	+
optimistic	-	-	+	-	-***	-**	-***

[a.] Statistical significance is noted by * at the 10% level, ** at the 5% level, *** at the 1% level.

[b.] Results for the state dummies are included in the regression but omitted here to save space.

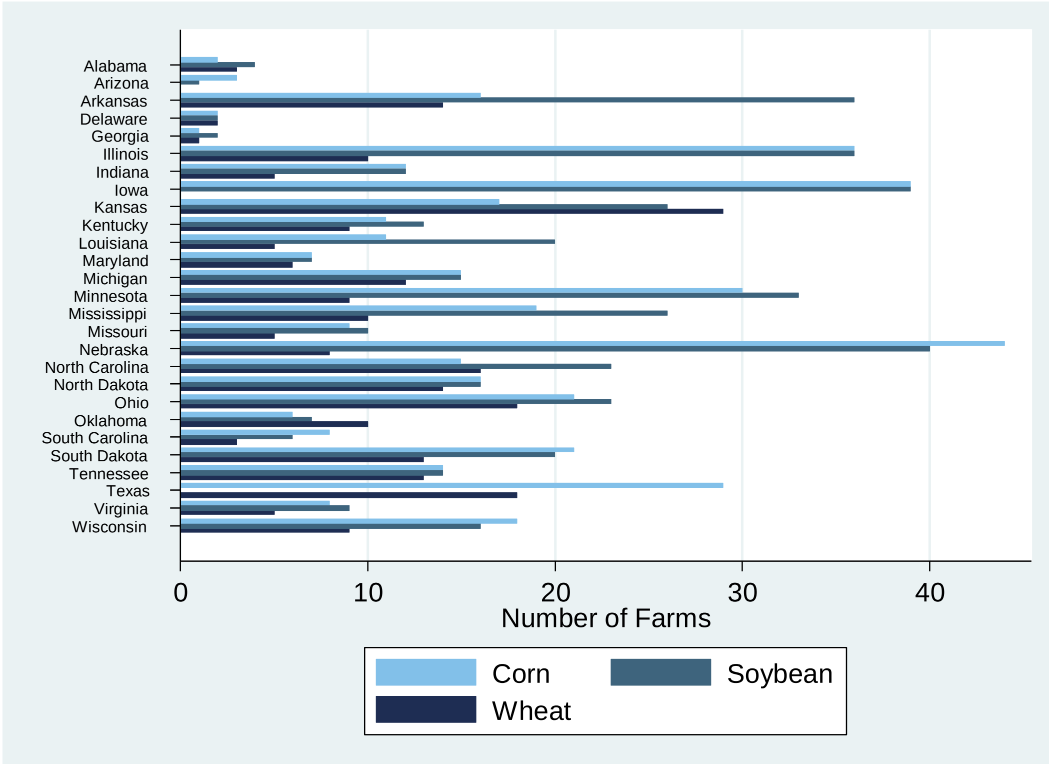
Table 12. Herbicide Application Methods - Continuous Regression Results. [a.b.]

	Chemical Method			Application Method			
Continuous regression	Pre -emergent Herbicide	Post -emergent Herbicide	Post -harvest Herbicide	Herbicide Mix	Multiple Herbicide	Full label Herbicide rate	Change MOA
acre	+***	+	+***	+	+	+	+*
gender	+**	+***	+	+**	+**	+**	+***
farming years	-	-**	+	-	-*	+	+
household income	+**	+**	+	+**	+	+	+
risk tolerance	+***	+***	+	+***	+***	+***	+**
time preference	+***	+***	+	+***	+***	+***	+
interaction term	-***	-***	-	-***	-***	-***	-**
safety and environment concern	-	-	-	+	-	-***	+
flexibility	-	-	+	-	-**	-**	-**
pest evolution concern	+	-	-	+	+	+	+*
herbicide costs	-	+**	-*	+	+	+	-
commodity price	+	+	+	+	+	+***	+
neighboring	+	+*	+**	+***	+***	+	+
pessimistic	+	-***	-	-	+	+	+
optimistic	-	-	+	-	-**	-	-***

[a.] Statistical significance is noted by * at the 10% level, ** at the 5% level, *** at the 1% level.

[b.] Results for the state dummies are included in the regression but omitted here to save space.

Figure 1. Types of field crops planted on the farming operation in 2015



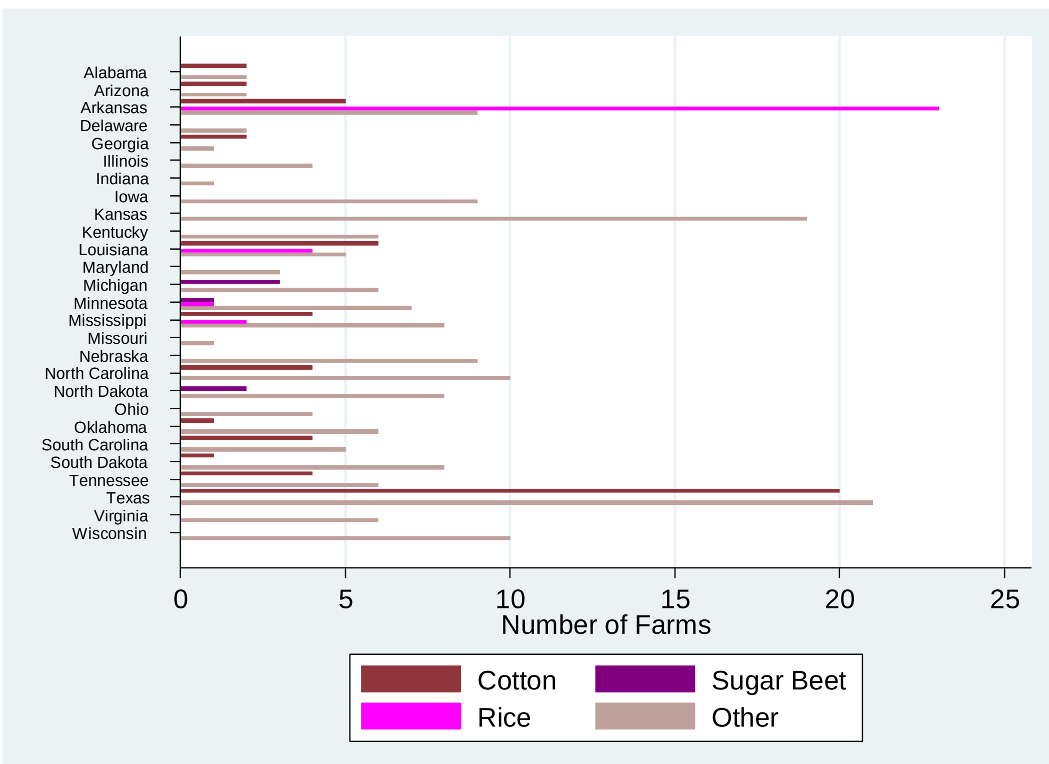


Figure 2. Distribution of Control Techniques Responses

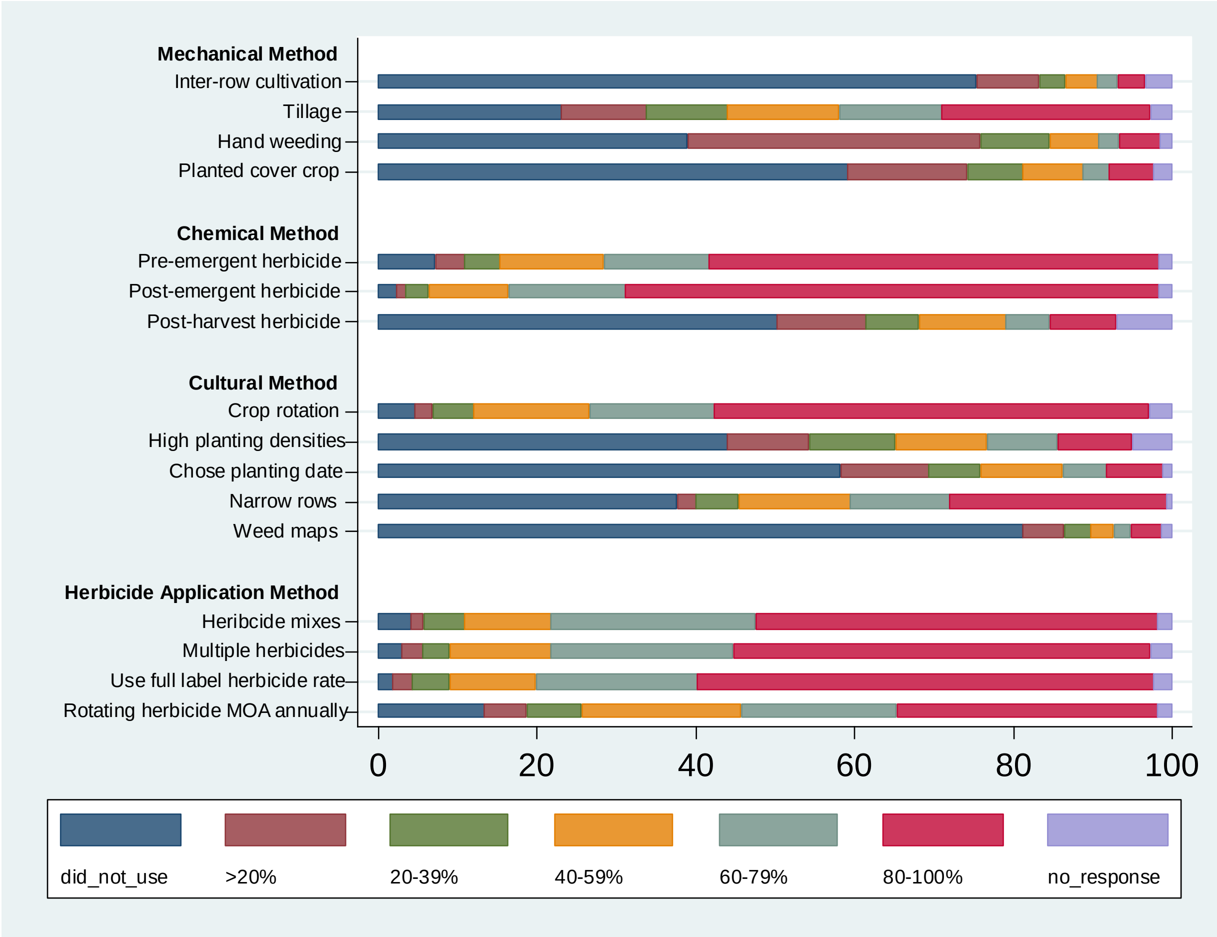


Figure 3. Estimated Marginal Effect of Risk Tolerance at Different Time Preference Level with 95 percent confidence intervals on adoption of weed management practice

---- Mechanical Method

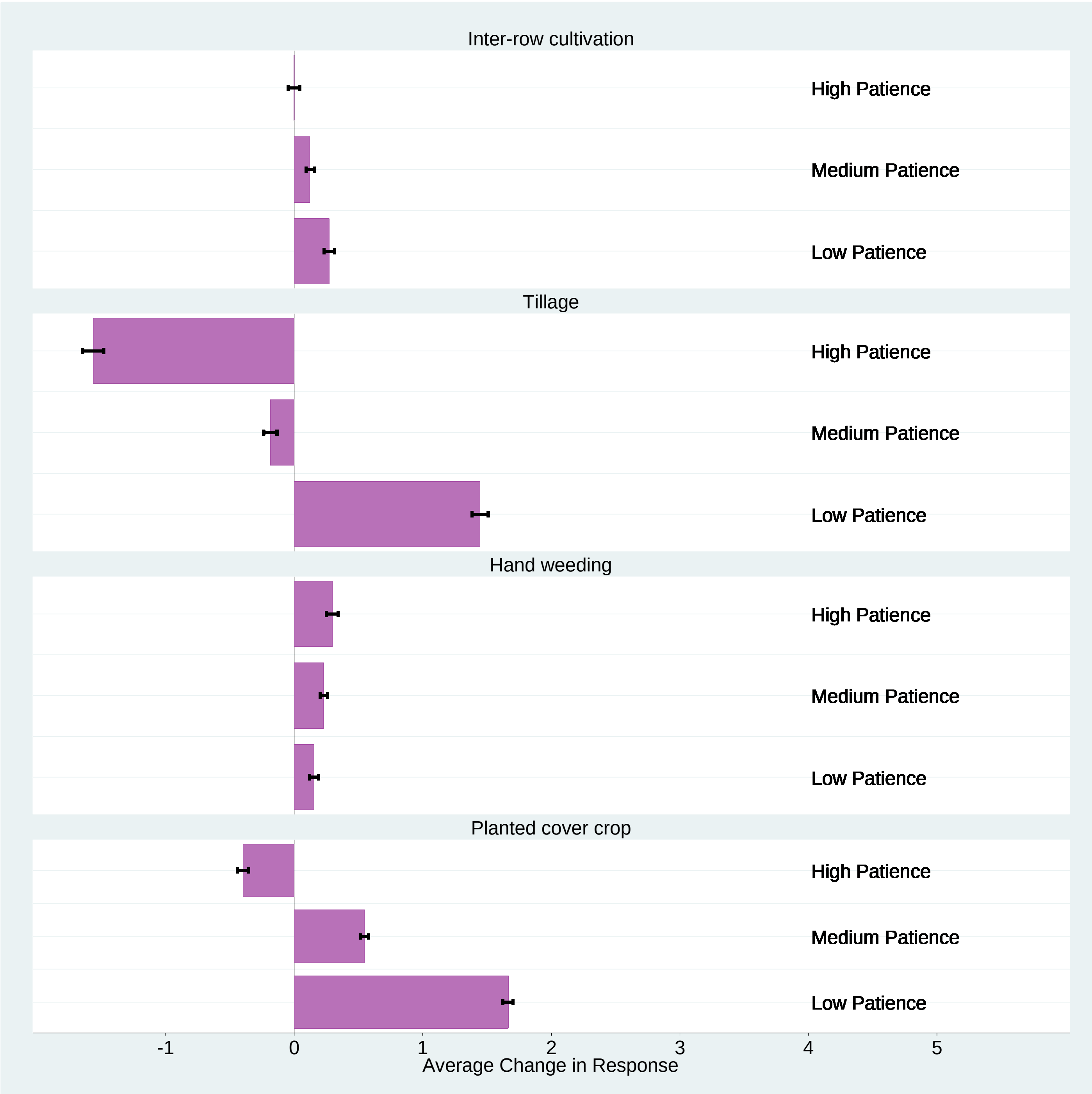


Figure 4. Estimated Marginal Effect of Risk Tolerance at Different Time Preference Level with 95 percent confidence intervals on adoption of weed management practice

---- Chemical Method

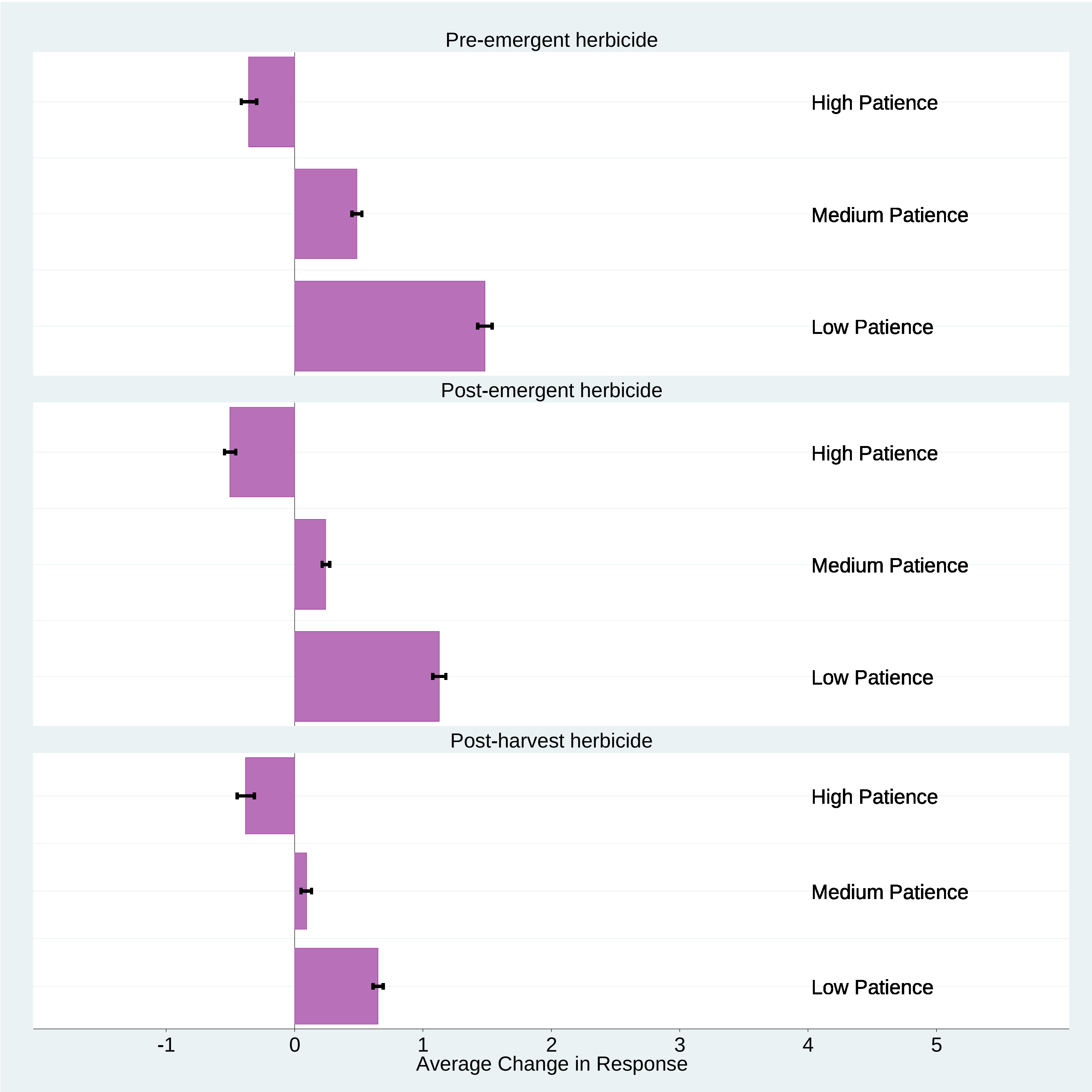


Figure 5. Estimated Marginal Effect of Risk Tolerance at Different Time Preference Level with 95 percent confidence intervals on adoption of weed management practice

---- Cultural Method

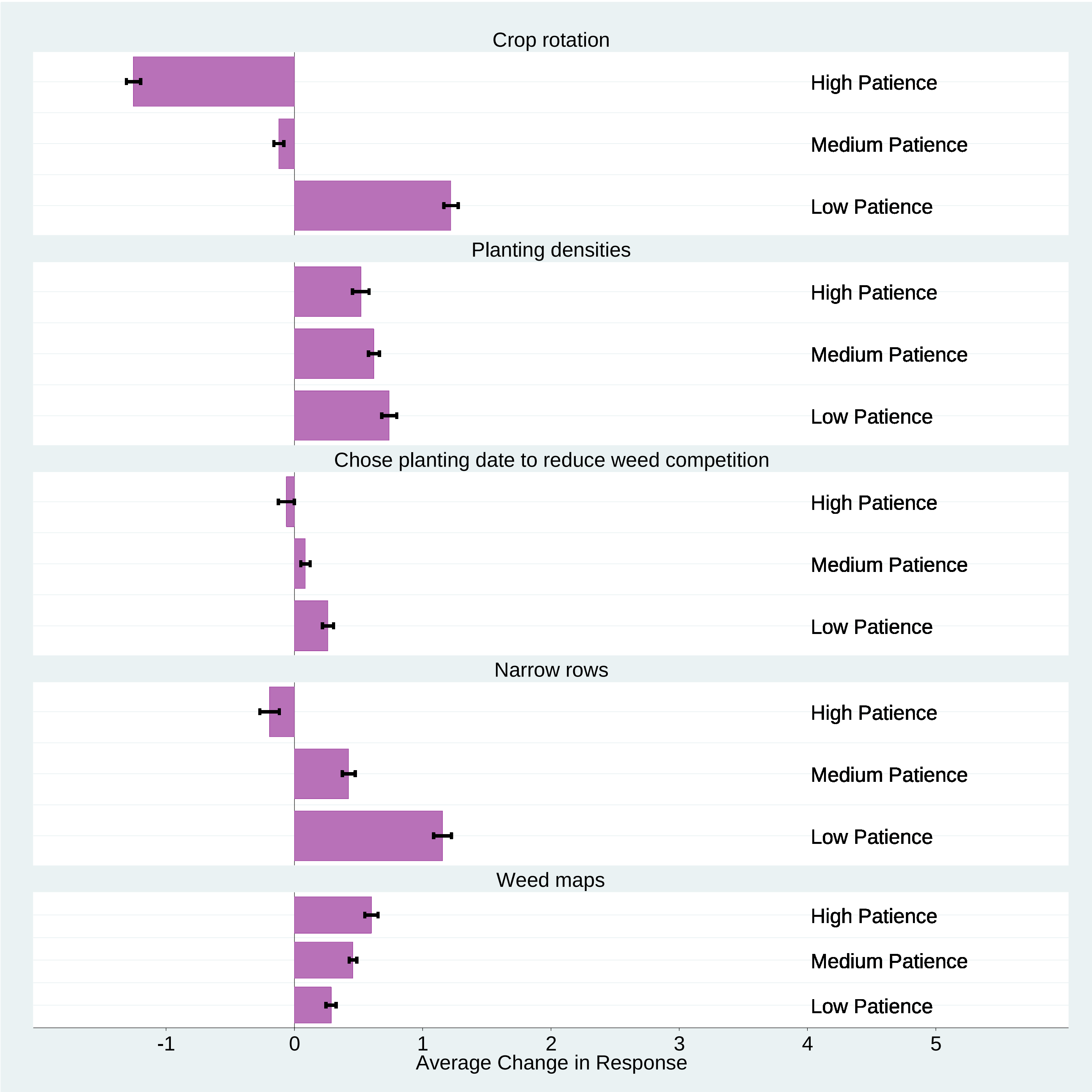


Figure 6. Estimated Marginal Effect of Risk Tolerance at Different Time Preference Level with 95 percent confidence intervals on adoption of weed management practice

---- Herbicide Application Method

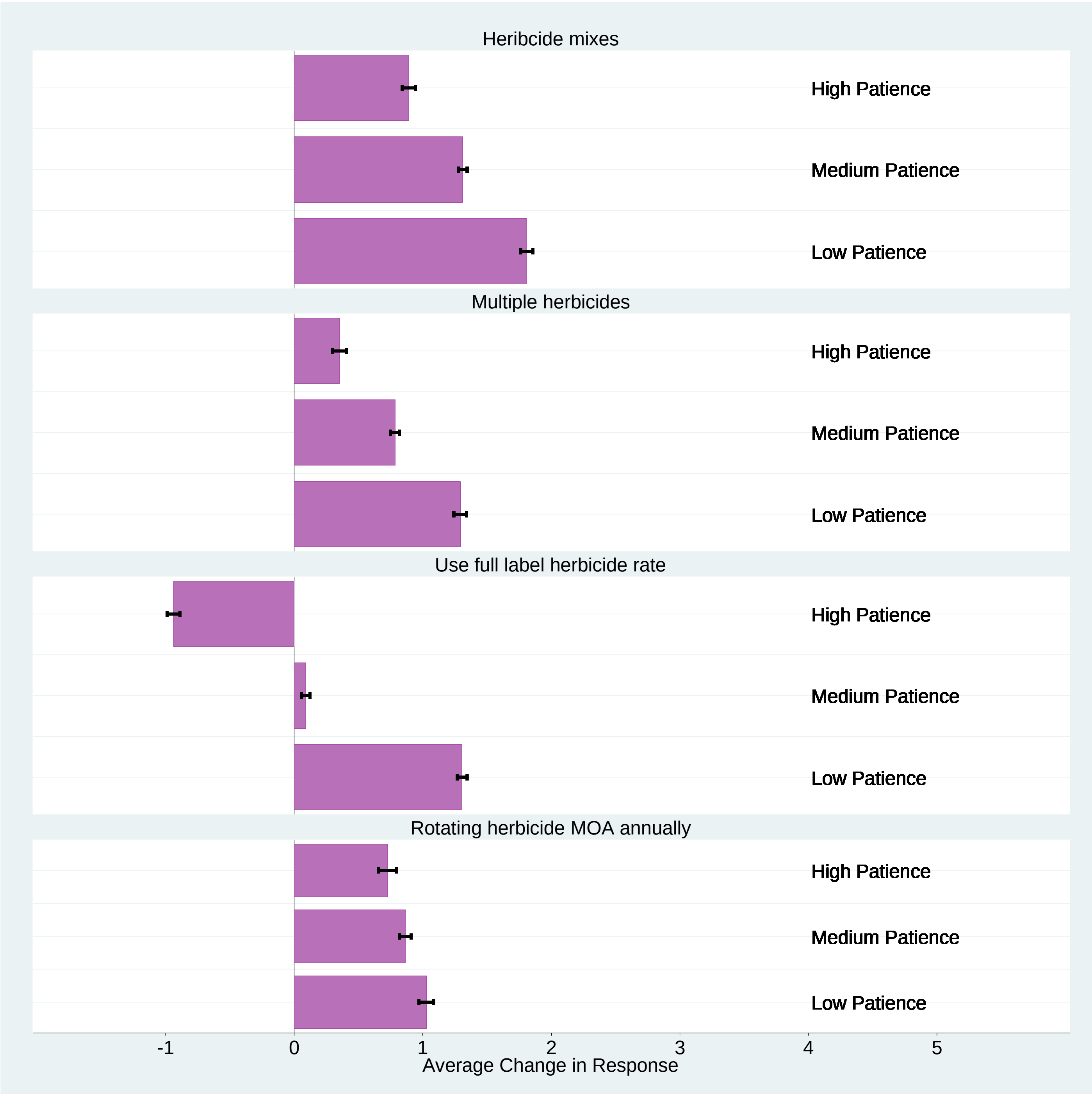


Figure 7. Estimated Marginal Effect of Time Preference at Different Risk Tolerance Level with 95 percent confidence intervals on adoption of weed management practice

---- Mechanical Method

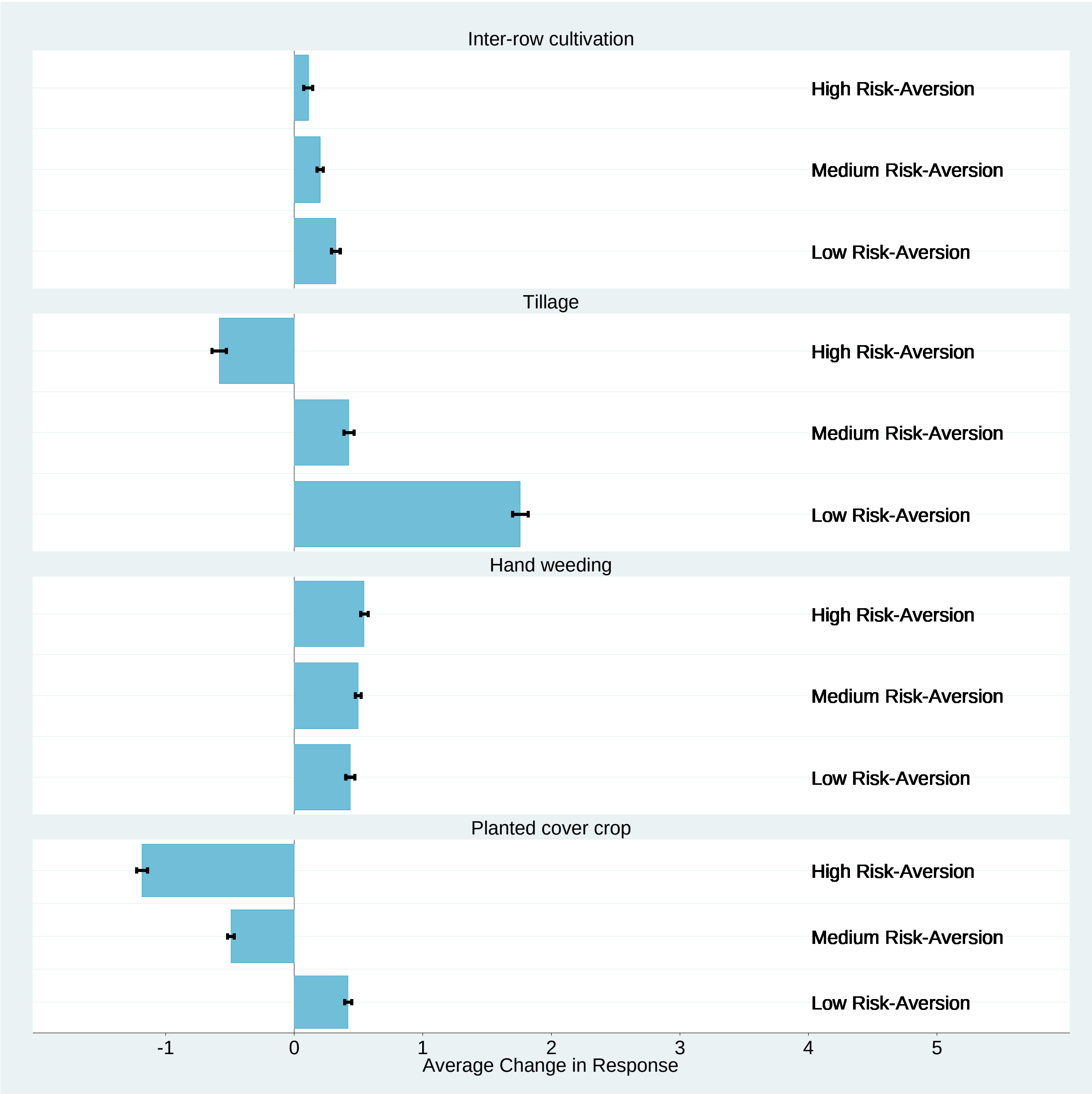


Figure 8. Estimated Marginal Effect of Time Preference at Different Risk Tolerance Level with 95 percent confidence intervals on adoption of weed management practice

---- Chemical Method

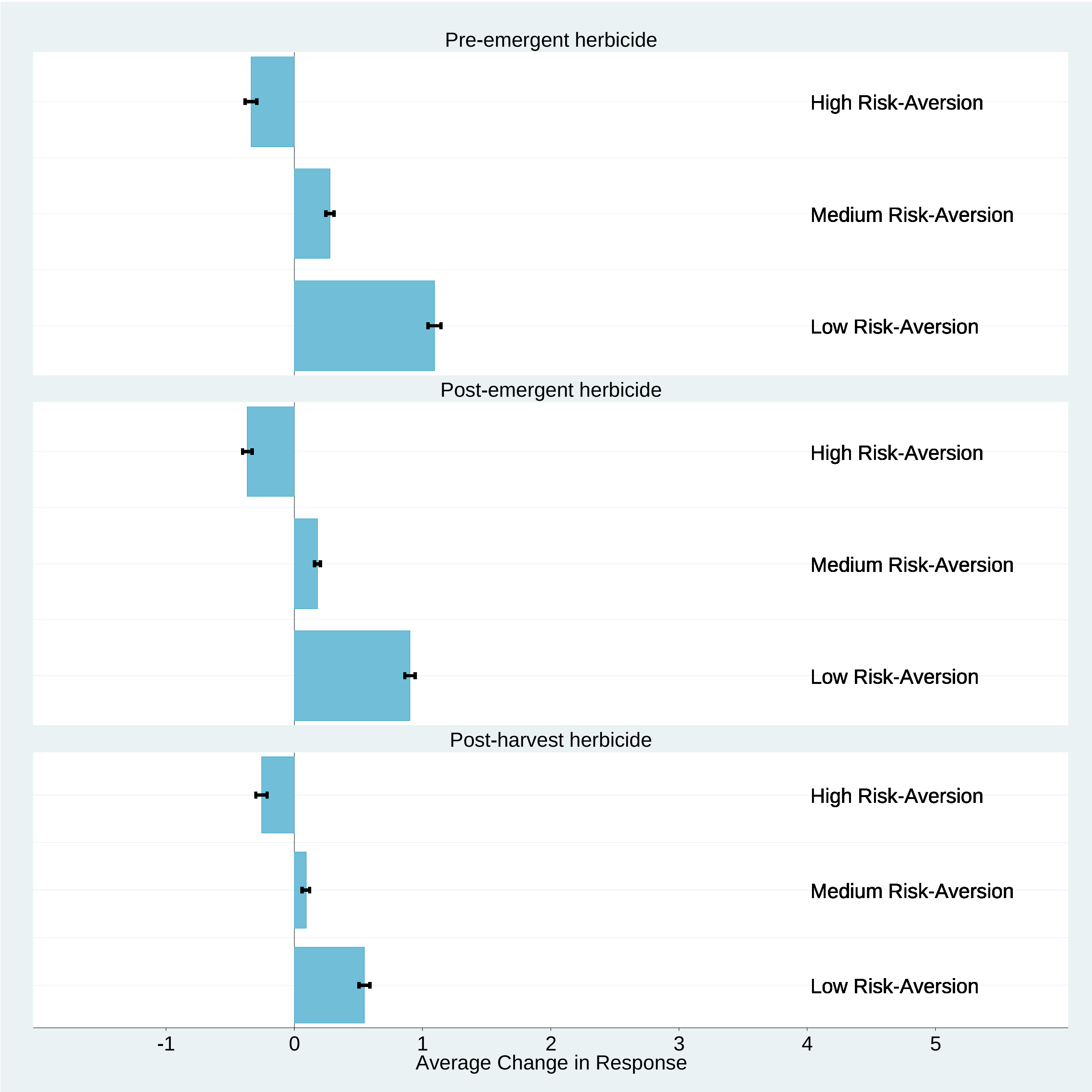


Figure 9. Estimated Marginal Effect of Time Preference at Different Risk Tolerance Level with 95 percent confidence intervals on adoption of weed management practice

---- Cultural Method

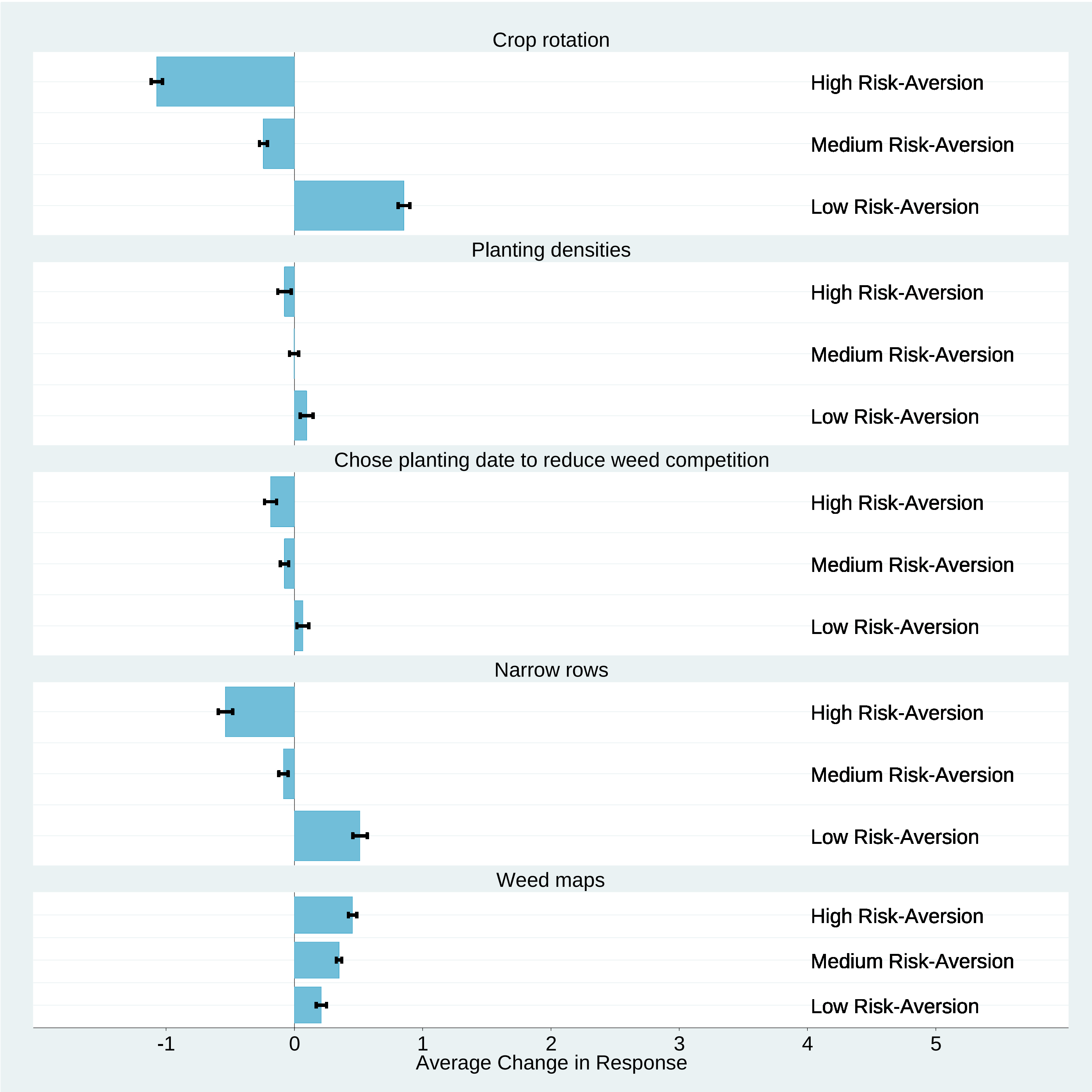


Figure 10. Estimated Marginal Effect of Time Preference at Different Risk Tolerance Level with 95 percent confidence intervals on adoption of weed management practice

---- Herbicide Application Method