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Farmer Attitudes Toward Cooperative Approaches to Herbicide Resistance Management: A Common Pool Ecosystem Service Challenge

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Analysis

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ABSTRACT

Dramatic growth in herbicide-resistant (HR) weeds in the United States threatens farm profitability and may undercut environmentally beneficial farming practices. When HR weeds move across farm boundaries due to ecological processes or human action, a common pool resource challenge emerges, requiring farmer cooperation to manage such weeds effectively. We investigate the scope for cooperative management using responses to a national survey on HR weed issues to test a recursive model of three preconditions for collective action: (1) concern about HR weeds migrating from nearby lands; (2) communication with neighbors about HR weeds; and (3) belief that cooperation is necessary for effective resistance management. Results suggest that farmers who relied more on Extension educators regarding weed management, were more likely to satisfy each precondition. Further, concern about weeds resistant to multiple herbicides as well as concern about HR weed mobility positively influence concern about migration and views toward cooperation. Farmer time constraints and "techno-optimism" (a belief that herbicide discoveries will solve resistance problems) detract from the perceived need for cooperative approaches. A different set of factors significantly affect each precondition, suggesting heterogeneity in the underlying casual mechanisms. The findings can help tailor collective action to different socio-ecological settings experiencing HR weed resistance issues.

1. Introduction

Sensitivity to herbicides among a weed population is an under-appreciated ecosystem service. Herbicides kill weeds by disrupting the balance of biochemical and physiological processes of plants, governed by the given gene pool. By conserving the susceptibility of weeds to herbicides through various management tactics, the effectiveness of such herbicide applications can be sustained. However, if the same herbicide is used repeatedly, selection pressure favors the survival of weeds resistant to said herbicide and other herbicides with similar mechanisms of action. Through evolution, this leads to a population of herbicide-resistant (HR) weeds. Early research noted that susceptibility of insects to insecticides was an exhaustible resource that could be depleted through repetitive use of specific insecticides (Hueth and Regev, 1974; Miranowski and Carlson, 1986). Such resource depletion now appears to be occurring with herbicides. A rise in HR weeds threatens the sustainability of genetically engineered HR crop systems, jeopardizes food security, and poses human health and environmental

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risks (NRC, 2010; 2016; Swinton and Van Deyenze, 2017).

Adding another layer to this problem is the mobility of certain HR weeds, which travel across farms and over landscapes. Early research on managing pest resistance concluded that mobility was a problem with insect pests, but not weeds (Clark and Carlson, 1990; Carlson and Wetzstein, 1993; Gould, 1995; Pannell and Zilberman, 2001; Llewellyn et al., 2001). Recent evidence, however, indicates HR weed mobility is more significant than previously thought, although the risk pattern varies by species (Beckie et al., 2015; Ervin and Frisvold, 2016; Shaner and Beckie, 2014). Mobility of weeds occurs through the following avenues: pollen movement; water conveyance of weed seeds; migratory bird flights; interstate livestock feed; and other processes, e.g., machinery transport (Diggle and Neve, 2001; Norsworthy et al., 2009; Dauer et al., 2006; Sosnoskie et al., 2012). If seed mobility is pervasive, maintaining herbicide efficacy becomes a common pool resource (CPR) challenge, thwarting decentralized market-based management, as negative externalities between farmers transpire. The unique characteristics of CPR systems make it costly to exclude individuals from benefiting from their use (Ostrom, 1990). Weed scientists have called for collective, regional responses among farmers, acknowledging common pool problems (Beckie et al., 2015; Shaner and Beckie, 2014).

Traditionally, the predominant approach to manage HR weeds has been through education and technical assistance (E&TA) programs, administered by both public and private entities, to influence individual farmer decisions (Shaw, 2016). In particular, E&TA programs attempt to influence farmers into voluntarily adopting best management practices (BMPs) (Norsworthy et al., 2012). Despite broad scientific consensus regarding BMPs and the considerable resources devoted to programs promoting their use, HR weeds continue to spread (Owen, 2016; Heap, 2018).

Two preliminary conclusions may be drawn regarding E&TA efforts. First, the adoption of a number of critical BMPs recommended in E&TA programs remains limited (Frisvold et al., 2009; Prince et al., 2012; Riar et al., 2013; Dong et al., 2016). Second, the number and spatial spread of resistant weeds species across North America has continued to increase (Heap, 2018). Proposals for improving the efficacy of E&TA programs have been advanced but are embryonic and their efficacy remain open to question (Asmus and Schroeder, 2016; Schroeder et al., 2018). One possible reason for the lack of success of E&TA programs is that benefits to farmers remain dependent on their neighbors' willingness to also engage in BMPs. Moreover, farmers tend to be less willing to adopt BMPs when presented with uncertain payoffs (Doohan et al., 2010).

This paper assesses the CPR conundrum and farmers' potential receptivity to cooperative approaches to resistance management. There has been limited empirical work on grower decisions to collectively control insect pests or weeds (Rook and Carlson, 1985; Graham and Rogers, 2017; Stallman and James Jr, 2015). Using responses from a national HR weed management survey, we provide evidence at a broader scale. Our study focuses on three preconditions for implementing CPR management: (1) farmers' concern about HR weeds migrating from nearby farming operations; (2) farmers' communication with their neighbors about HR weeds; and (3) farmers' views that HR weeds cannot be managed effectively without cooperation among farmers in a community. We use insights from literature in CPR, exhaustible resource management, and pest management to build a model linking the preconditions with key farmer and farm characteristics. Binary response probit regression estimations identify the effects of such characteristics on each precondition. The findings have implications for instituting cooperative approaches to HR weed management.

2. Background Literature

2.1. When Are Cooperative Approaches to HR Weed Management Feasible?

A substantial body of literature has investigated approaches to effectively manage CPRs. In his seminal article, Garrett Hardin (1968) focuses primarily on the need for governmental regulation. However, Ostrom and collaborators assemble evidence from around the globe indicating voluntary, community-based approaches can be effective (Ostrom, 1990, 2009; Ostrom et al., 2012). Their work documents the requirements for privately-led, voluntary schemes to not only materialize, but also persist. Three preconditions implicit to launching such collective action are: (1) awareness of the effects that others' actions have on one's own welfare; (2) communication between resource users; and (3) recognition of the need for cooperation to prevent resource exhaustion (Ostrom et al., 2012).

To effectively manage the weed gene pool, the heterogeneous community of farmers must address their differences to achieve an optimal solution path. This process includes a series of adaptive management steps – facilitation, negotiation, and bargaining – requiring time and resources from farmers (Ervin and Jussaume, 2014). The transaction costs of iterating toward effective management regimes may be substantial, but lower for those with strong community involvement and, in particular, good working relationships with Extension educators. Such costs become more tolerable to the degree that farmers perceive increased vulnerability and economic liability from their neighbors' weed control actions. A principal objective of our empirical analysis is to identify which farmers are more (and less) likely to view cooperation favorably.

Conceptual analyses of CPR management schemes to control HR weeds highlight several requirements: (1) strong scientific basis; (2) effective communication of scientific principles; (3) active involvement of social scientists to understand farmer behavior; (4) strong leadership; (5) ongoing monitoring, reporting, and evaluation; and (6) clear geographic boundaries (Ervin and Frisvold, 2016; Miranowski, 2016). These conceptual analyses implicitly assume the three preconditions described above are satisfied. Our study takes a step back, examining the accuracy of this assumption.

2.2. What Factors Influence farmers' Perceptions of HR Weed Mobility, Communication with Neighbors, and Their Receptivity to Cooperative Behavior?

To date, few studies have analyzed neighbor interactions to achieve collective action of HR weeds. As an exception, Stallman and James (2015) analyze the willingness of Missouri farmers to cooperatively manage pests. They surveyed growers about their willingness to work with neighbors to control pests, to cooperatively scout for pests, and to participate in county-wide crop rotation programs. Interest by Missouri farmers in cooperative action is high, as 91% of respondents said they would be willing to participate in such efforts. Moreover, the authors contend that simple, local cooperative efforts may be more popular than formal, county-wide efforts. In particular, a farmer's willingness to cooperate is positively associated with five factors: (1) they expect to receive a net benefit from pest control cooperation; (2) they have farms similar to their neighbors; (3) they are an active member of a community organization; (4) they have positive contact with Extension educators; and (5) they are concerned about the effect pesticides have on the environment.

Farmers' willingness to cooperate in community-based pest control, as seen in Stallman and James (2015), is a close variant of our third precondition. Their findings inform our choice of variables for empirical analysis. Our conceptual framework, explained below, also includes farmers' perceptions concerning weed mobility, personal mobility (ability to successfully farm elsewhere), and "techno-optimism" defined as the expectation that a new herbicide will be discovered by the time a weed develops resistance to a specific herbicide (Bain et al., 2017; Dentzman, 2018; Dentzman et al., 2016). Lastly, by using farmer responses from a national survey, which includes five major crop production regions, we assess whether the findings from Stallman and James (2015) extend beyond Missouri.

Graham and Rogers (2017) conducted a qualitative analysis of three local landholder groups in Australia which collectively managed weeds. Their findings suggest collective weed control is primarily about supporting the individual (farmer), proactively engaging landholders with the worst weed infestations, and focusing the group's efforts on the common challenge weeds pose. In addition, they argue that the more successful groups organized community events designed to build social relationships among members. Similarly, Stallman and James (2015) find a positive relationship between a farmer's level of social capital and willingness to work with neighbors on pest control. Although scale was not analyzed explicitly, the success of the small landholder groups implies that local, cooperative efforts are likely to be more successful than larger scale efforts. The landholder groups thought the government could assist their efforts by providing funds, engaging landholders who were unwilling to cooperate directly with the group, and controlling weeds on public lands. Ostrom et al. (2012) includes this supportive, but not necessarily regulatory, role of government in privately-led CPR management. This line of argument highlights the importance of determining the appropriate scale for HR weed management (Cumming et al., 2006):

> "Scale mismatches occur when the scale of environmental variation and the scale of social organization in which the responsibility for management resides are aligned in such a way that one or more functions of the social-ecological system are disrupted, inefficiencies occur, and/or important components of the system are lost (Cumming et al., 2006, p.2)."

3. Conceptual Model Development

Our study analyzes factors influencing the preconditions for collective action, that is, a farmer's concern about HR weeds migrating from nearby farming operations, discussing HR weeds with neighboring farmers, and belief that cooperation among farmers is needed to effectively manage HR weeds. Responses to the following survey questions were used to construct dependent variables that reflect a respondent's agreement with each precondition.

A. I am concerned about herbicide-resistant weeds spreading to my farming operation from nearby farming operations.
B. Have you ever discussed with the owner/manager of a field abutting or near one of yours whether herbicide-resistant weeds are becoming a problem in your region?
C. Weed resistance can be managed effectively <u>without</u> cooperation among farmers in a community.

Binary variables are constructed for each question, permitting the use of a probit model. Such variable construction is described in more detail later in the analysis.

3.1. Literature Identifying Potential Explanatory Factors

Previous studies help identify the factors that can affect collective weed management. Hurley and Frisvold (2016), surveying several studies, found multiple factors affecting weed management in general and herbicide resistance management (HRM) in particular. These included simplicity, convenience, flexibility, consistent crop protection, yield loss, and land stewardship. Hurley and Mitchell (2014) conducted a detailed factor analysis that identifies time management as well as human and environmental health concerns as key motivators of herbicide (and insecticide) management decisions. In an applicable study of cooperative insect pest management, Ayer (1997) highlighted the roles of expected profit, communication and information, and group size, heterogeneity, and transaction costs. These findings suggest a wide range of factors can influence herbicide resistance management. Therefore, potential explanatory variables include both pecuniary and non-pecuniary factors.

Factors that foster or hinder collective action efforts on resource management have received extensive study (e.g., Kahan, 2003; Ostrom, 1990; Ostrom, 2009). For example, collective action theory suggests individuals will be willing to cooperate with others in solving a problem to the degree they derive positive net benefits in doing so. People are less likely to cooperate if they perceive high costs of participating with an unfamiliar group, especially when large transaction costs prevail. If farmers have a strong set of social relationships with their neighbors, reflecting high social capital, they will more likely be able to detect HR weed movements and entertain possible cooperative approaches (Pretty, 2003).

3.2. Hypotheses

Using insights from the literature, we propose the following hypotheses:

Hypothesis 1. <u>Extension influence</u> – We posit the influence of Extension educators in providing information to farmers regarding HRM has a positive effect on each dependent variable. Extension education can augment both the human and social capital of farmers to the degree farmers access the information (Prokopy et al., 2008). Therefore, farmers who assess more importance to Extension education are expected to be more aware of and concerned about HR weed migration, more inclined to communicate with their neighbors about HR weeds, and more likely to view cooperative approaches as necessary for effective management.

Hypothesis 2. <u>Inadequate time</u> – Diversifying weed management practices to control resistance involves added management and labor time, which pose a significant opportunity cost for the operator (Gunsolus and Buhler, 1999; Owen, 2016). Hurley and Mitchell (2014) and Hurley and Frisvold (2016) discuss time concerns as a significant factor in HRM. Fernandez-Cornejo et al. (2005), Riar et al. (2013), and Smith (2002) have documented time requirements as a significant constraint in weed management.

Hypothesis 3. <u>Multiple resistant (MR) weed concern</u> – A farmer's degree of concern about the presence of weeds resistant to multiple herbicides is taken as an indicator of the perceived benefits of managing HR weeds. Recent studies demonstrate that, if a farmer and neighbor both manage glyphosate resistance to horseweed in soybean production, long-run farm net returns will increase over uncoordinated actions (Livingston et al., 2016). Stallman and James Jr (2015) found that Missouri farmers' perceived benefit of cooperation on pest control significantly increases their willingness to participate in such efforts.

Hypothesis 4. <u>Weed mobility</u> – Growing evidence documents HR weed movement between neighboring farms of sometimes great distances (Ervin and Frisvold, 2016). The recognition of this negative externality can prompt farmers to consider ways to avert damages to their operations. Therefore, we expect this variable, measuring the operator's concern about HR weed mobility, will have a positive effect on each dependent variable. One might surmise this variable to be highly related to the dependent variable that measures the level of concern about HR weed migration from nearby lands. However, our empirical results suggest the two variables capture distinct effects.

Hypothesis 5. <u>Techno-optimism</u> – The extent to which farmers expect the development and commercialization of a new herbicide chemistry that will effectively and economically control HR weeds affects their willingness to manage resistance (Dentzman et al., 2016). A higher level of techno-optimism translates to less concern about the migration of such weeds and less willingness to participate in cooperative HR weed management. Dentzman (2018) finds the level of techno-optimism is lower for farmers who report HR weeds on their operations. This may explain why farmers are more likely to use integrated weed management practices if they have serious HR weed

Table 1
Variable descriptions and summary statistics for regression sample (N = 565).

Variables	Survey question/description	Mean	S.D.
Dependent			
Concern about HR weeds spreading from nearby operations	I am concerned about herbicide-resistant weeds spreading to my farming operation from nearby farming operations: Binary variable = 1 for somewhat agree or strongly agree, = 0 for strongly disagree, somewhat disagree, or neither agree nor disagree.	0.71	0.45
Discuss HR weed problems with neighbors	Have you ever discussed with the owner/manager of a field abutting or near one of yours whether herbicide-resistant weeds are becoming a problem in your region? Binary variable = 1 for yes, = 0 for no.	0.56	0.50
Disagree that HR weeds can be managed w/o cooperation	Weed resistance can be managed effectively without cooperation among farmers in a community. Binary variable = 1 for somewhat disagree or strongly disagree, = 0 for strongly agree, somewhat agree, or neither agree nor disagree.	0.611	0.488
Hypothesized			
Extension influence	Importance of extension educators for developing weed management approaches. 5-point Likert scale: 1 = not at all/not applicable, 2 = somewhat unimportant, 3 = neither important nor unimportant, 4 = somewhat important, 5 = very important.	3.61	1.12
Inadequate time	I do not have adequate time for managing weeds on my farm. 5-point Likert scale: 1 = strongly disagree, 2 = somewhat disagree; 3 = neither agree not disagree, 4 = somewhat agree, 5 = strongly agree.	1.97	1.14
Multiple resistant weed concern	How concerned are you about the presence of weeds resistant to multiple herbicides on your farming operation? 4-point Likert scale: 1 = not concerned at all, 2 = not very concerned, 3 = somewhat concerned, 4 = very concerned.	3.46	0.74
Weed mobility perceived	Even if I keep my fields clean, I could get herbicide-resistant weeds from neighboring farms. 5-point Likert scale: 1 = strongly disagree, 2 = somewhat disagree, 3 = neither agree nor disagree, 4 = somewhat agree, 5 = strongly agree.	4.20	0.84
Techno-optimism	By the time a weed develops resistance to an herbicide, at least one new herbicide will have been found to replace it. 5-point Likert scale: 1 = strongly disagree, 2 = somewhat disagree, 3 = neither agree nor disagree, 4 = somewhat agree, 5 = strongly agree.	2.39	1.02
Other grower influence	Importance of other growers for developing weed management approaches. 5-point Likert scale: 1 = not at all/not applicable, 2 = somewhat important, 3 = neither important nor unimportant, 4 = somewhat important, 5 = very important.	3.90	0.97
Community ties	I have strong ties to other farmers in my community. 5-point Likert scale: 1 = strongly disagree, 2 = somewhat disagree, 3 = neither agree nor disagree, 4 = somewhat agree, 5 = strongly agree.	4.08	0.89
Personal mobility	I could farm in any location successfully without having to learn new skills. 5-point Likert scale: 1 = strongly disagree, 2 = somewhat disagree, 3 = neither agree nor disagree, 4 = somewhat agree, 5 = strongly agree.	2.51	1.16
Controls			
Operator age	Respondent's age in years.	57.5	11.8
Risk tolerance	How do you see yourself? Are you generally a person who is fully prepared to take risks or do you try to avoid taking risks? 10-point scale: 1 = don't like to take risks and 10 = fully prepared to take risks (for analysis purposes, this variable was scaled between zero and one by dividing by ten)	0.704	0.191
Cropland acres	Owned and rented acres operated by the respondent in thousands.	1.42	1.52
Owned acres	Percent of cropland acres owned by the respondent.	48.6	34.2
State average acres	Average number of cropland acres operated by farmers in the respondent's state of operation in thousands of acres[a].	0.301	0.234
Rotating herbicides	Over the past two years, on what percentage of your fields on your entire farming operation did you use each of the following methods to control weeds? Rotating herbicide modes of action annually. 6-point scale: 1 = did not use, 2 = less than 20%, 3 = 20–39%, 4 = 40–59%, 5 = 60–79%, 6 = 80–100%	4.29	1.71

[a] This secondary data is from the 2012 USDA NASS agricultural census.

infestation problems on their own farm (Bonny, 2016; Livingston et al., 2016).

Hypothesis 6. Other grower influence – We query respondents about the importance of social networks for obtaining information about weed management approaches. Consistent with the findings of Dentzman and Jussaume (2017), we expect farmers who assign higher importance to the information they obtain from other farmers to be more aware of HR weed migration, communicate more with neighbors about HR weed issues, and better understand the advantages of cooperative approaches.

Hypothesis 7. Community ties – The degree to which a farmer interacts with their community likely reflects the level of social connectedness in the area. Assuming higher levels translate to lower organizational costs, it should positively affect a farmer's receptivity to cooperative approaches. In addition, it is possible that higher levels of connectedness promote the sharing of HR weed information. We expect that a respondent's degree of community involvement to have a positive effect on farmers' willingness to cooperate with neighbors in HR weed management, similar to Stallman and James (2015).

Hypothesis 8. Personal mobility – Respondents were asked whether they "could farm in any location successfully without having to learn new skills." We hypothesize that each precondition is negatively affected if a farmer considered it to be relatively easy to move to another location. The ability to move away from weed problems may substitute for addressing them on a current operation.

In addition, we control for farmer and farm operation characteristics that have been used in other studies of pest control adoption (e.g., Fernandez-Cornejo et al., 2005; Frisvold et al., 2009; Dong et al., 2016). Such characteristics may be correlated with some of our hypothesized variables and dependent variables of interest and serve to reduce potential omitted variable bias. For example, consider operator age. We expect older farmers have shorter planning horizons and/or higher discount rates, leading to reduced willingness for HR weed management. Other characteristics, such as risk tolerance, are also included (Dohmen et al., 2011). Farm size and percent of land owned are included to estimate possible farm structure influences. We also include average state farm size to detect possible influence from surrounding farm configurations. On a regional scale, larger average farm size may dampen the externality, as there are fewer interactions between farmers, ultimately, reducing the interaction costs of communication. Depending upon the geometric pattern, farm boundaries typically increase with farm size. In this case, larger average farm size may increase a farmer's concern about HR weed migration, and in turn, their

Table 2
Probit regression results for concern about migration of herbicide-resistant weeds from nearby farming operations.

Variable	Coefficient	*t*-Statistic	Marginal change in probability for a decrease/increase in the explanatory variable[a]	
			Decrease	Increase
Extension influence	0.112*	1.94	−0.033	0.031
Inadequate time	−0.117**	−2.14	−0.035	–
Multiple resistant weed concern	0.295***	3.42	−0.094	0.074
Weed mobility perceived	0.552***	7.35	−0.189	0.122
Techno-optimism	−0.066	−1.03	0.018	−0.019
Other grower influence	−0.056	−0.82	0.016	−0.016
Community ties	0.079	1.10	−0.023	0.022
Personal mobility	0.085	1.53	−0.025	0.023
Age	−0.017***	−3.03	0.027	−0.029
Risk tolerance	−0.075	−0.22	0.002	−0.002
Cropland acres	−0.005	−0.12	0.000	0.000
Owned acres	0.000	0.03	0.000	0.000
State average acres	−0.229	−0.88	0.002	−0.002
Rotating herbicides	−0.010	−0.27	0.003	–
Constant	−1.854***	−2.75	–	–

Observations = 565; Maximized Log-likelihood = −277.01; Likelihood Ratio Test = 123.07*** with 14 degrees of freedom; Pseudo R^2 = 0.182; Significance levels: * = 10%, ** = 5%, and *** = 1%.

[a] All changes are evaluated at the mode of categorical variables and mean of continuous variables. Marginal probability changes for categorical variables are evaluated for a one-unit change from the mode when feasible (e.g., the mode is not the maximum or minimum category). Marginal probability changes for continuous variable are evaluated for a 10% change in the mean.

Table 3
Probit regression results for discussion of herbicide-resistant weeds issues with neighbors.

Variable	Coefficient	*t*-statistic	Marginal change in probability for a decrease/increase in the explanatory variable[a]	
			Decrease	Increase
Concern about HR weeds spreading from nearby operations	0.342**	2.49	−0.180	–
Extension influence	0.136***	2.59	−0.048	0.045
Inadequate time	−0.061	−1.20	−0.021	–
Multiple resistant weed concern	0.071	0.86	−0.025	0.024
Weed mobility perceived	0.038	0.51	−0.013	0.013
Techno-optimism	0.037	0.64	−0.013	0.013
Other grower influence	0.178***	2.88	−0.064	0.058
Community ties	0.148**	2.26	−0.053	0.048
Personal mobility	−0.048	−0.96	0.016	−0.017
Age	−0.004	−0.75	0.007	−0.008
Risk tolerance	0.246	0.83	−0.008	0.008
Cropland acres	0.051	1.28	−0.002	0.002
Owned acres	−0.002	−1.29	0.004	−0.004
State average acres	−0.841***	−3.30	0.009	−0.009
Rotating herbicides	0.068**	1.99	−0.024	–
Constant	−2.08***	−3.27	–	–

Observations = 565; Maximized Log-likelihood = −342.21; Likelihood Ratio Test = 91.34*** with 15 degrees of freedom; Pseudo R^2 = 0.118; Significance levels: * = 10%, ** = 5%, and *** = 1%.

[a] All changes are evaluated at the mode of categorical variables and mean of continuous variables. Marginal probability changes for categorical variables are evaluated for a one-unit change from the mode when feasible (e.g., the mode is not the maximum or minimum category). Marginal probability changes for continuous variable are evaluated for a 10% change in the mean.

perceived need for cooperation. In addition, we include a measure of the respondent's reported annual rotation of herbicide modes of action (MOA). Regular MOA rotation is a BMP to reduce selection pressure for HR weeds (Owen, 2016). However, there is a caveat, as farmers generally do not adopt integrated weed management practices until HR weeds move within their farm boundary (Bonny, 2016; Livingston et al., 2016; Llewellyn et al., 2004).

4. Methods

4.1. Survey and Data

From 2014 to 2016, an interdisciplinary research team implemented a survey to gain a better understanding of weed management practices among farmers across the United States. The sample included

Table 4
Probit regression results for disagreement that herbicide-resistant weeds can be managed effectively without community cooperation.

Variable	Coefficient	*t*-Statistic	Marginal change in probability for a decrease/increase in the explanatory variable[a]	
			Decrease	Increase
Discuss HR weed problems with neighbors	0.072	0.59	0.023	–
Concern about HR weeds spreading from nearby operations	0.253*	1.84	−0.132	–
Extension influence	0.157***	2.94	−0.047	0.041
Inadequate time	−0.130***	−2.58	−0.038	–
Multiple resistant weed concern	0.214***	2.61	−0.065	0.054
Weed mobility perceived	0.162**	2.21	−0.048	0.042
Techno-optimism	−0.225***	−3.82	0.056	−0.068
Other grower influence	0.109*	1.75	−0.032	0.029
Community ties	−0.034	−0.51	0.009	−0.010
Personal mobility	−0.100**	−2.01	0.027	−0.029
Age	0.005	0.99	−0.008	0.008
Risk tolerance	0.265	0.87	−0.007	0.007
Cropland acres	0.002	0.06	0.000	0.000
Owned acres	0.003	1.44	−0.004	0.004
State average acres	0.206	0.82	−0.002	0.002
Rotating herbicides	−0.007	−0.20	0.002	–
Constant	−1.78***	−2.80	–	–

Observations = 565; Maximized Log-likelihood = −334.53; Likelihood Ratio Test = 86.31*** with 16 degrees of freedom; Pseudo R^2 = 0.114; Significance levels: * = 10%, ** = 5%, and *** = 1%.

[a] All changes are evaluated at the mode of categorical variables and mean of continuous variables. Marginal probability changes for categorical variables are evaluated for a one-unit change from the mode when feasible (e.g., the mode is not the maximum or minimum category). Marginal probability changes for continuous variable are evaluated for a 10% change in the mean.

approximately 9000 farmers from 28 states, comprising five major row crop production regions (Dentzman, 2017). The full mixed-mode survey conducted via electronic and regular mail is available from the authors. The response rate was approximately 10%. We compared demographic characteristics of respondents with Census and USDA information bases. Statistical *t*-tests suggest that, within these regions, respondents are skewed toward older, white individuals who operated slightly larger farms. Even so, our survey includes more small-scale farms than previous grower surveys regarding weed management. Such surveys are limited in scope, as they only include farms with at least 250 acres of corn, soybeans, or cotton (Marra et al., 2004; Foresman and Glasgow, 2008; Johnson et al., 2009; Givens et al., 2011; Frisvold et al., 2009; Hurley et al., 2009).

4.2. Modeling Analysis

We consider a recursive model to capture the relationships between the three preconditions. Define the three dependent variables as:

$$C1 = \begin{cases} 1 & \text{If strongly agree or somewhat agree to"I am concerned about HR weeds spreading to my farming operation from nearby farming operations"} \\ 0 & \text{Otherwise} \end{cases}$$

$$C2 = \begin{cases} 1 & \text{If discussed with the owner/manager of a field abutting or near one of theirs about whether HR weeds are becoming a problem in their region} \\ 0 & \text{Otherwise} \end{cases}$$

$$C3 = \begin{cases} 1 & \text{If strongly disagree or somewhat disagree to"Weed resitance can be managed effectively without cooperation amongst farmers in a community"} \\ 0 & \text{Otherwise} \end{cases}$$

Three equations specify the general recursive model structure to be estimated:

$$C_1 = \beta_1 X + \varepsilon_1 \tag{1}$$

$$C_2 = \beta_2 X + \gamma_{21} C_1 + \varepsilon_2 \tag{2}$$

$$C_3 = \beta_3 X + \gamma_{31} C_1 + \gamma_{32} C_2 + \varepsilon_3 \tag{3}$$

where β_1, β_2, and β_3 are coefficients for the vector of explanatory and control variables, X. γ_{21}, γ_{31}, and γ_{32} are coefficients for the dependent variables in Eqs. (2) and (3). And, ε_1, ε_2, and ε_3 are error terms. We specify the common set of explanatory variables, X, for each regression equation.

Given the system of equations, there is the possibility that the introduction of outcome variables in regression Eqs. (2) and (3) will lead to endogeneity bias (i.e. C_1 may be correlated with ε_2 in Eq. (2) and/or C_1 or C_2 may be correlated with ε_3 in Eq. (3)). To account for this issue, we can estimate the fully observed recursive probit model developed in Roodman (2011). When we perform this estimation, we cannot reject the null hypothesis of exogeneity. Since Roodman's model assumes normality, we repeat the exercise with the linear probability model and seemingly unrelated regression. Again, we are unable to reject exogeneity.[1] Since we do not find evidence of endogeneity, we report results from estimating independent probit models for each equation.[2]

5. Results

Table 1 presents descriptions and summary statistics of the dependent and explanatory, both hypothesized and control, variables and sample used in the analysis.[3] Most farmers (71%) express concern about HR weeds migrating from their neighbors' operations. The magnitude of this percentage proves consistent with recent science documenting HR weed migration (e.g., Beckie et al., 2015). Despite a clear majority expressing concern about HR weed migration, only a slight majority (56%) report discussing HR weeds with a neighbor who operated nearby fields. Finally, a sizeable majority of respondents (61%) agree that community-wide cooperation is necessary to effectively manage HR weeds. In short, most respondents satisfy the three preconditions.

[1] The results of this analysis are detailed in the Supplementary online material, Appendix B.

[2] Independent linear probability models are also estimated to explore the robustness of the results to the probit's normality assumption. These results are reported in the Supplementary online material, Appendix C. These robustness tests include estimates without the control variables in order to expand the usable sample.

[3] Descriptive statistics for the full survey sample are in the supplementary online material, Appendix A.

5.1. Multivariate Probit Analyses

Tables 2–4 present the results of the probit estimations of Eqs. (1)–(3). As mentioned in the previous section, each model includes the same hypothesized and control variables, while also accounting for the recursive nature of the equations. Tables 3 and 4 indicate partial support for the recursive model structure. Concern about HR weed migration from neighbors is positively associated with discussion of HR weeds in Eq. (2) and belief in the need for cooperative weed management in Eq. (3). While the coefficient for discussion of HR weeds is positively associated with the belief in the need of cooperation in Eq. (3), it is not statistically significant.

5.1.1. Concern over HR Weeds Spreading from Nearby Farming Operations

The first regression yields several significant effects influencing migration concern, each of which remains consistent with its hypothesized sign (Table 2). Significant positive effects are estimated for HR weed mobility, concern about MR weeds, and Extension influence. Whereas, inadequate time for operators exerts a significant negative effect. Operator age, a control variable, also shows a significant negative effect, albeit small.

5.1.2. Communication with Neighbors About HR Weeds

Table 3 presents the results for whether a farmer has discussed HR weed issues with their neighbors. Previous research has consistently found face-to-face communication to be an important precursor to collection action of CPR problems (see Ostrom, 1998). Concern about HR weeds migrating from nearby farming operations (C1), the recursive model linkage, Extension influence, other grower influence, and community ties all exhibit significant positive effects as hypothesized. Of the control variables, average state farm size has a significant negative effect; whereas, the rotation of MOAs, a BMP, has a significant positive effect.

5.1.3. Need for Cooperation

Eq. (3) examines the factors associated with respondents' views toward the need for collective action to effectively manage HR weeds. This precondition is theorized to be the product of concern about HR weed migration from nearby farming operations (C_1), communication with neighbors about HR weed issues (C_2), and other explanatory variables. Table 4 indicates that multiple factors are significant, each consistent with our hypotheses. As previously mentioned, (C1) has a significant positive effect, supporting the recursive model. However, (C2) is not significant, weakening a link in the recursive chain. Extension influence, MR weed concern, weed mobility concern, and other grower influence all have significant positive effects.

Following CPR theory, farmers who find weeds to be especially mobile are more likely to perceive collective action as a necessary management approach. Both techno-optimism and personal mobility have significant negative effects, with the magnitude of the effect larger for techno-optimism. The strong effect of techno-optimism is on farmer attitudes about weed management are consistent with other analyses (Dentzman, 2018; Dentzman et al., 2016). Borrowing from economic theory, we argue that, when there are more substitutes (or there are believed to be more substitutes) for herbicides that are no longer effective, because of resistance, farmers will be less likely to engage in collective action. And, in terms of personal mobility, operators who can easily farm elsewhere may not see the benefit of engaging in collective action in an area with a large HR weed infestation, as doing so would increase transaction costs.

6. Conclusions and Implications

A growing body of agronomic and ecological research suggests that some HR weed species can be quite mobile, making susceptibility to herbicides a common property resource. As such, traditional education and technical assistance (E&TA) programs aimed at influencing individual farmers may be less than fully effective. Our survey results suggest most growers view susceptibility under a CPR framework: 87% of respondents agreed or strongly agreed with the statement, “Even if I keep my fields clean, I could get herbicide-resistant weeds from neighboring farms.” This is consistent with other studies that find mitigation is beyond the control of a single farmer, instead depending on their neighbors' behaviors and other factors (Llewellyn and Allen, 2006; Wilson et al., 2008).

A second major finding is concern about the migration of HR weeds from nearby farming operations (C1) significantly influences the likelihood of farmers communicating with neighbors about HR weed issues (C2) and their perceived need for collective action (C3). While this lends support to the recursive model, C2 does not significantly influence C3. That is, having such a discussion with neighbors does not perfectly translate into positive views toward cooperation. Although C1 is estimated to positively influence C2 and C3, the distribution of farmers responses to these questions are very different. Our study finds that 71% of respondents express concern about HR weed migration. However, only 56% discuss HR weed issues with their neighbors and 61% believe that cooperation is necessary for effective resistance management. Focus group research has revealed the extreme reticence some growers have about discussing weed management problems with neighbors (Dentzman and Jussaume, 2017).

Why then is concern about weed mobility *not* perfectly translating into communication with neighbors and perceived need for collective action? Our results indicate that the set of significant variables are not uniform across each stage of the recursive model. While the signs of such variables are as hypothesized, only Extension influence significantly affects all three stages. Two factors, MR weed concern and perceived weed mobility, significantly influence the first and third stages. This result suggests heterogeneity exists in the mechanisms supporting collective action. As such, the development of HR weed management should be approached with careful nuance. Diversity in such conditions characterizes HR weed management as a wicked problem (Jussaume and Ervin, 2016).

We single out concern about MR weeds because of its key role in CPR theory as a potential benefit of collective action. The latest evidence indicates that the overall rate of newly confirmed herbicide-resistant weed species to any herbicide mode of action has slowed since 2005 in the United States (Kniss, 2018). However, the number of MR weed species/state pairs – which captures both the number and geographic spread of MR weeds – continues to increase at an increasing rate (Heap, 2018). MR weeds are especially challenging to manage, and our findings show that the concern of such weeds increases the concern about HR weeds migrating from nearby farming operations and increases the perceived need for cooperation.

Studies frequently cite farmer time constraints as a possible barrier to the adoption of more proactive HR weed management practices (Beckie, 2006; Hurley and Frisvold, 2016; Owen, 2016; Norsworthy et al., 2012). Yet, with the notable exception of Riar et al. (2013), such studies do not attempt to statistically examine the role of time constraints. Our results show strong statistical support for the hypothesis that time constraints serve as a barrier to our preconditions, in particular, concern about HR weed migration and beliefs toward cooperative management.

On a positive note, farmers who place greater importance on Extension educators regarding weed management are more likely to perceive a need for collective action. This finding is consistent with Ervin and Frisvold (2016) and Stallman and James (2015). The experience of the Zero Tolerance Program to control HR Palmer amaranth in Clay County, Arkansas is another example of the crucial role of Extension professionals in overcoming barriers to collective action (Barber et al., 2016).

Finally, techno-optimism has a significant, negative effect on the belief of the need for cooperative HR weed management. Dentzman

(2018) suggests some farmers are already skeptical of the future of herbicide chemistries, but express faith in them to cope with their own perceived dependency on herbicidal weed control. No new commercial herbicide MOAs have been commercialized in the past 30 years. Industry has introduced new herbicide tolerant crops to more existing MOAs. Yet, many weed species are already resistant to these herbicides (Davis and Frisvold, 2017). As such, the agricultural chemical industry is providing growers with mixed messages about the availability of new herbicides that will solve current resistance problems. While some industry representatives assign a very low probability of new herbicide chemistries in the foreseeable future (Stübler et al., 2016), others predict that in the future, "your odds of weed-resistance development pretty much drop to zero," and the herbicide resistance issue will be eliminated by 2050 (Pates, 2016).

Using a similar measure of techno-optimism, Sun et al. (2017) find that farmers with higher levels of techno-optimism are less likely to engage in the rotation of herbicide MOAs and/or use multiple herbicides. In a study of Australian farmers, Llewellyn et al. (2007) find those who believe new herbicides would be available soon are less likely to adopt weed resistance management practices, compared to farmers more uncertain about the availability of new compounds. Consequently, we argue one option to encourage the uptake of HR weed management, both privately and collectively, is to more effectively counter excessively optimistic messaging about the availability of new compounds.

In closing, reversing the dramatic increase in herbicide resistance, especially MR weeds, will require new strategies, departing from past E&TA approaches targeting individual growers. A key component must be community cooperation in the affected landscape, negating the disincentives embedded in CPR situations. Stallman (2011) identifies pest control as an ecosystem service (ES) well suited for collective management at the landscape level. Landscape level management is critical for the management of ecosystem services from agriculture (Goldman et al., 2007; Swinton et al., 2007). Cumming et al. (2013) argue that establishing resilient landscapes requires the creation of relevant institutions acting at appropriate scales to modify and moderate the demand for ecosystem services. Consistent with wicked problems (Shaw, 2016), the biophysical, economic, and social conditions framing HR weed management vary across landscapes (Jussaume and Ervin, 2016). Therefore, determining the appropriate scale and relevant institutions will likely be an exercise in experimentation, learning, and adaptive management. The significant factors of each precondition for cooperative action found in this study can inform the search for efficacious strategies.

Declaration of Interest

None.

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Appendix A. Supplementary Data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolecon.2018.11.023.

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