sustainability

MDPI

Article

Herbicide Resistance, Tillage, and Community Management in the Pacific Northwest

Katherine Dentzman * and Ian Cristofer Burke

Department of Crop and Soil Sciences, Washington State University, Pullman, WA 99164, USA; icburke@wsu.edu
* Correspondence: katie.dentzman@wsu.edu

Abstract: The use of glyphosate as a replacement for tillage has been credited with spurring the adoption of conservation tillage in the United States. With herbicide-resistant weeds becoming a significant agronomic problem, however, it is unclear whether conservation tillage gains are in danger of being reversed as farmers turn to tillage to manage weeds that herbicides can no longer kill. Using 2015 focus groups, a 2016 national survey, and an ongoing Community Herbicide Resistance Management Initiative in four communities of the Pacific Northwest we assess the following questions: (1) How do U.S. farmers view tillage as an option for controlling herbicide-resistant weeds, (2) Do attitudes towards and experience with herbicide-resistant increase farmers' usage of tillage, and (3) Can community management provide an avenue for maintaining conservation tillage while also increasing effective management of herbicide-resistant weeds? We find that many farmers consider tillage to be an emergency fail-safe in managing weeds, that there is a complex relationship between herbicide resistance awareness, concern, and tillage use that can be partly explained by experience and dedication to conservation tillage, and finally that community management has the potential to provide the support and resources necessary to prevent a large-scale increase in tillage related to herbicide resistance management.

Keywords: herbicide resistance; conservation tillage; community management

Citation: Dentzman, K.; Burke, I.C. Herbicide Resistance, Tillage, and Community Management in the Pacific Northwest. *Sustainability* **2021**, *13*, 1937. https://doi.org/su13041937

Academic Editors: David Ervin, Sonia Graham, David R. Shaw and and Marc A. Rosen

Received: 31 December 2020
Accepted: 8 February 2021
Published: 11 February 2021

1. Introduction

Herbicide-resistant weeds present an obvious threat to farming livelihoods in that they reduce crop yield and quality and require significant time and expenditure to manage [1,2]. Several studies have documented the financial burden herbicide resistance places on growers; for instance, in Georgia and Arkansas, the presence of glyphosate-resistant Palmer amaranth was found to increase management costs in cotton by $48/ha [2]. Economics are an important consideration in growers' choice of weed management strategies [1–3].

However, another important impact of herbicide-resistant weeds is environmental. In particular, the threat of a widespread return to tillage to control weeds is gaining traction as a topic of import [4–6]. Conservation tillage, defined as low- or no-tillage systems, have achieved substantial adoption with associated environmental benefits including reduced soil erosion and runoff [5]. A reduction or elimination of tillage has been especially impactful in farming systems with highly erodible land, such as dryland wheat farming systems in the Pacific Northwest (PNW) [7,8]. These systems, and their associated environmental gains, may come under threat due to the presence of herbicide-resistant weeds that can no longer be controlled chemically. In such cases, growers might choose to introduce some level of tillage back into their farming system in order to manage weeds through cultivation.

The reintroduction of tillage as a trend has been studied extensively in Southern and Western Australia. In a phone survey of growers, D'Emden and Llewellyn [4] found that herbicide resistance and associated weed control issues were the main reasons growers reduced their usage of no-till methods; this same relationship was also found by

Thomas et al. [9]. A later study by Llewellyn, D'Emden, and Kuehne [10] supported the persistence of this trend over time. Relatedly, the effectiveness and availability of pre-emergence herbicides were found to be a key factor in the adoption of no-till systems [11].

Studies in the United States have echoed the findings from Australia. Price et al. [5] credit the introduction of glyphosate-resistant crops with a drastic increase in the adoption of conservation tillage practices. Empirically, Roberts et al. [12] confirm that there is a statistically significant relationship between fields planted with herbicide-tolerant crops and the adoption of conservation tillage practices in Tennessee, while Frisvold, Boor, and Reeves [13] found that the diffusion of herbicide-resistant cotton was interdependent with the adoption of conservation tillage. However, conservation tillage has also been associated with the development of herbicide-resistant weeds such as glyphosate-resistant Palmer amaranth [5].

Because tillage can disrupt weed seed germination and seedling growth, it is sometimes recommended in some areas as an emergency stop-gap measure to deal with herbicide-resistant weed infestations [5]. Some reports suggest that there has been a 9.2 percent decrease in the use of no-till (averaged across the U.S.) as a direct result of herbicide-resistant weed problems [6]. As a consequence, there has been increased research into the possibility of strategic, single, or occasional tillage to control herbicide-resistant weed populations in conservation tillage systems without incurring serious negative impacts on soil properties and crop yields [6,14,15].

Despite the decrease in conservation tillage as a result of herbicide resistance, in some areas, vibrant communities of growers dedicated to conservation tillage have arisen—particularly in the PNW as a result of the Solutions to Environmental and Economic Problems (STEEP) program [7]. STEEP was, first and foremost, a multidisciplinary research program that incorporated agronomic and soil scientists with economists and sociologists, teamed with growers, to address the incredible erosion rates in the PNW. Community building resonates with sociological research that found growers who are more engaged in their local communities are less likely to rely on herbicide-central weed control methods and more likely to practice integrated weed management [16]. Therefore, it seems possible that community engagement, and especially community building on the part of growers practicing conservation tillage, may be able to ameliorate some of the herbicide-resistance-induced return to conventional tillage.

Our research addresses this potential relationship through the following research questions:

1 How do growers in the U.S. view tillage as an option for controlling herbicide-resistant weeds?

2 How do attitudes and experiences with herbicide-resistant weeds impact…
   a. the likelihood of growers using tillage to control weeds?
   b. the proportion of farmland a grower tills?

3 Can community management provide an avenue for maintaining–or even promoting–conservation tillage systems while simultaneously dealing with the threat of herbicide-resistant weeds?

We address the above questions using a mixed-methods social science approach. Our quantitative data consist of a national survey conducted in 2016; our qualitative data consist of focus groups conducted in 2016 in the Midwest and Southern U.S., along with listening sessions, interviews, and community meetings in the PNW from 2019 to 2020.

2. Methods

2.1. Background

Our methodological approach is the result of a mixed-methods triangulation in which quantitative data and qualitative data were separately collected and analyzed. We employ a convergence model [17] in which each phase of data collection was independent of the other, with results compared and contrasted in order to guide iterative interpretation with qualitative results informing quantitative interpretations as well as the reverse. This approach allows us to provide a more complete picture of the relationship between herbicide resistance and tillage by producing generalizations through survey data alongside in-depth situated knowledge from focus groups and community initiative participants [17].

2.2. Research Question One

We address our first research question—how growers view tillage as an option for controlling herbicide-resistant weeds—using data collected from ten focus groups with 64 corn and soybean growers conducted from February to May of 2015. Two focus groups were conducted in Arkansas, four in Iowa, two in Minnesota, and two in North Carolina. These locations were chosen due to the prevalence of herbicide resistance and connections the research team had with local universities. Organization and facilitation of the focus groups were carried out in accordance with best practices outlined by Morgan [18].

Six to ten participants were recruited for each focus group by university extension educators in each state. The groups took place at extension buildings, community centers, and restaurants and lasted about one and a half hours each. The primary researcher facilitated discussions and audio recording, while a second researcher took notes on general themes discussed. Most of the 64 total participants were white men (60 were white, 62 were male). The median age of participants was 52, with ages ranging from 24 to 79. Seventy percent of participants reported farming with a partner, most often their father or spouse. Operated acreage ranged from zero (retired) to 9200 acres with a median of 1300. Corn, soybeans, and wheat were the most common crops grown, although some respondents also grew other grain crops, vegetables, and fruits. Compared with USDA Census of Agriculture Data from 2012, our data were slightly skewed towards older white men who operated larger-than-average farms. Our results are therefore less likely to represent the views of young, non-white, and women farmers operating smaller farms.

Three lines of questioning, with prompts, were employed: (1) how should/would a grower react to herbicide-resistant weeds on their own farm, (2) how should/would a grower react to herbicide-resistant weeds on their neighbor's farm, and (3) will herbicide resistance be a short- or long-term problem? Discussions were facilitated by the moderator with probes, requests for additional detail, and guidance to keep the discussion on topic. Discussion of tillage was not explicitly requested—respondents raised this topic naturally when responding to the above questions.

All focus groups were transcribed using a professional service and coded by three coders. We employed a summarizing approach using inductive category formation [19] to identify consistent major themes within and across all 10 focus groups. During coding, tillage emerged as a sub-theme related to herbicide-resistant weed management but was not specifically targeted for analysis at that time. Subsequently, the primary researcher went back to the transcripts and identified each instance in which tillage or cultivation was discussed. Truncated quotations of each instance were organized into an Excel spreadsheet and an inductive approach was used to group quotations into thematic categories. Categories were assessed and condensed to the highest level of abstraction, and representative quotations for each category were identified.

2.3. Research Question Two

For our second research question, related to how growers' attitudes and experiences of herbicide resistance impact their use of tillage, we used data from a national survey of growers conducted in the winter of 2015 and spring of 2016. Questions were related to growers' perspectives on and management of herbicide resistance (see Table 1 for wording and coding of the questions used in this analysis). The survey was sent to approximately 9000 corn and soybean growers in 28 states comprising five major row crop production regions. A total of 839 useable surveys were returned for a response rate of 9.3 percent. Of the respondents, 98.2 percent were male, with an average age of 57.5 years. Farm size ranged from 0 (retired) to 20,000 with an average of 1381 acres. They had spent an average of 29.5 years on their current farm, and 65% made between $50,000 and $249,999 in farm income in 2014. For additional details and survey analysis, see Dentzman [16]; Ervin et al. [20]; and Frisvold et al. [21].

We assessed growers' tillage use with two dependent variables; a binary yes/no variable indicating whether the respondent used tillage at all (addressing Research Question 2a), and a categorical variable indicating the proportion of fields tillage was used on (addressing Research Question 2b). For the proportion variable, we dropped respondents who had used no tillage. This allowed us to first assess the impact of herbicide resistance on the choice to till at all, and second on the intensity of tillage for those who did till. Our tillage proportion variable consisted of five categories; less than 20 percent, 20–39 percent, 40–59 percent, 60–79 percent, and 80–100 percent of fields. A logistic regression was used to determine the impact of independent variables on the binary tillage variable; an ordered logistic regression was used on the categorical tillage variable. The analysis was completed using the logit and ologit commands in STATA 15 (College Station, TX, USA).

There were five independent variables of interest. First, we included a binary indicator of the respondent's *awareness* of weeds resistant to a single herbicide on their own farm. The binary indicator was complimented by a 3-point categorical measure indicating the respondent's *concern* about weeds resistant to a single herbicide on their farm. An additional two indicators measured awareness and concern as above but for weeds resistant to multiple herbicides. Finally, we included an index of herbicide-resistant weeds on respondents' farms (Index of Weeds on Farm), with 0 indicating none, 1 indicating one species, 2 indicating two species, 3 indicating three species, and 4 indicating four or more species. Control variables included indicators of crops grown; time availability to manage weeds; use of pre-emergence, post-emergence, and post-harvest herbicides; income; age (correlated with years of farming experience); total acres operated; gender; and the state in which the respondent farmed (see Table 1 for details). Independent variables were considered significant at the $p < 0.10$ level due to the exploratory nature of our study and consistency in result trends during model testing and development. Additionally, results were corroborated using data from the other two phases of our study [17].

2.4. Research Question Three

Our third research question, on whether community management can conserve no-till systems while also addressing herbicide resistance, was investigated with preliminary data from work with four wheat-growing communities in the Pacific Northwest. The community data focus on a different region and dominant crop than our focus group or survey data. For these reasons, it is less generalizable than our other results. However, as an exploratory study, we may draw some conclusions regarding the potential for community management to succeed in a region where conservation tillage has been rapidly adopted [7,8]—a case study that has significant value for understanding the types of herbicide resistance management most likely to protect vulnerable soils. Still, it should be noted that any trends identified are based on an incomplete and ongoing research project, and furthermore may not be relevant to farmers not involved in dryland wheat systems in a region with highly erodible soils.

As part of ongoing research in the Pacific Northwest to determine the specific herbicide resistance management strengths, weaknesses, and needs of the wheat-growing community, we identified three communities in the region in which to establish a Community Herbicide Resistance Management Initiative. These communities were identified via relationships built at the Tri-State Grain Growers Convention as well as through extension educators at the University of Idaho and Washington State University. They include (1) the Palouse region of Washington and Idaho, (2) the Camas Prairie region of Northern Idaho, and (3) Northern Douglas County, Washington. Each region is involved in dryland wheat cultivation and has begun experiencing herbicide resistance issues within the past 10 years. Thirty-seven total individuals are participating, including growers, extension educators, conservation districts, Natural Resource Conservation Service (NRCS) representatives, state Noxious Weed Boards, commodity group members, and agricultural retailers.

Table 1. Survey question wording and coding.

Independent Variables	Question	Response Options	Recoding
Used Tillage	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? Tillage	0 (Did Not Use); 1 (<20%); 2 (20–39%); 3 (40–59%); 4 (60–79%); 5 (80–100%)	0 (Did Not Use/Missing); 1 (Used)
Proportion of Fields Tilled	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? Tillage	0 (Did Not Use); 1 (<20%); 2 (20–39%); 3 (40–59%); 4 (60–79%); 5 (80–100%)	1 (<20%); 2 (20–39%); 3 (40–59%); 4 (60–79%); 5 (80–100%)
Dependent Variables			
Grows Cotton	What types of field crops were planted on your farming operation in 2016? Cotton	0 (Did Not Plant); 1 (Did Plant)	N/A
Grows Soybeans	What types of field crops were planted on your farming operation in 2016? Soybean	0 (Did Not Plant); 1 (Did Plant)	N/A
Grows Wheat	What types of field crops were planted on your farming operation in 2016? Wheat	0 (Did Not Plant); 1 (Did Plant)	N/A
Grows Hay	What types of field crops were planted on your farming operation in 2016? Hay	0 (Did Not Plant); 1 (Did Plant)	N/A
No Time to Manage Weeds	Please indicate to which extent you disagree or agree with each of the following statements concerning the weed management practices used on your farming operation: I do not have adequate time for managing weeds on my farm.	1 (Strongly Disagree); 2 (Somewhat Disagree); 3 (Neither Disagree nor Agree); 4 (Somewhat Agree); 5 (Strongly Agree)	0 (Disagree/Neither); 1 (Agree)
Uses Pre-Emergence 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? Pre-Emergence Herbicides	0 (Did Not Use); 1 (<20%); 2 (20–39%); 3 (40–59%); 4 (60–79%); 5 (80–100%)	0 (Did Not Use/Missing); 1 (Used)
Uses Post-Emergence 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? Post-Emergence Herbicides	0 (Did Not Use); 1 (<20%); 2 (20–39%); 3 (40–59%); 4 (60–79%); 5 (80–100%)	0 (Did Not Use/Missing); 1 (Used)

Table 1. *Cont.*

Independent Variables	Question	Response Options	Recoding
Uses Post-Harvest 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? Post-Harvest Herbicides	0 (Did Not Use); 1 (<20%); 2 (20–39%); 3 (40–59%); 4 (60–79%); 5 (80–100%)	0 (Did Not Use/Missing); 1 (Used)
Aware of Weeds Resistant to a Single Herbicide	Are you aware of the presence of any weeds on your farming operation that are resistant to a single herbicide?	1 (No); 2 (Not Sure); 3 (Yes)	0 (No/Not Sure); 1 (Yes)
Aware of Weeds Resistant to Multiple Herbicides	Are you aware of the presence of any weeds on your farming operation that are resistant to multiple herbicides (i.e., multiple herbicide sites of action)?	1 (No); 2 (Not Sure); 3 (Yes)	0 (No/Not Sure); 1 (Yes)
Concerned about Weeds on Farm Resistant to a Single Herbicide	How concerned are you about the presence of weeds resistant to a single herbicide on your farming operation?	1 (Not at All Concerned); 2 (Not Very Concerned); 3 (Somewhat Concerned; 4 (Very Concerned)	1 (Not Concerned); 2 (Somewhat Concerned); 3 (Very Concerned)
Concerned about Weeds on Farm Resistant to Multiple Herbicides	How concerned are you about the presence of weeds resistant to multiple herbicides on your farming operation?	1 (Not at All Concerned); 2 (Not Very Concerned); 3 (Somewhat Concerned; 4 (Very Concerned)	1 (Not Concerned); 2 (Somewhat Concerned); 3 (Very Concerned)
Index of Weeds on Farm	Which of the following weeds that you may see on your farming operation do you believe have or may become resistant to herbicides that you commonly use? (List of 16 weeds; option to specify additional)	0 (No); 1 (Yes)	Composite variable adding all weed species on farm; continuous with possible values from 0 weeds to 17 weeds; actual values ranged from 0–4 weeds
Income	What was your household income before taxes in 2014?	1 (Less than $15,000); 2 ($15,000–24,999); 3 ($25,000–48,999) 4 ($50,000–$99,999); 5 ($100,000–$249,999); 6 ($250,000–$499,999); 7 ($500,000 or more)	1 (Less than $50,000); 2 ($50,000–99,999); 3 ($100,000–249,999); 4 ($250,000 or more)
Age	How old are you?	Self-entered in years	N/A
Total Acres Operated	Of the acres of field crops that were planted in 2016, how many acres did you own? How many did you rent?	Self-entered in acres	Added acres owned and acres rented
Gender (0 = Men; 1 = Women)	Are you male or female?	0 (Male); 1 (Female)	N/A

Each group meets once per month, currently via the virtual videoconferencing platform Zoom, to discuss issues of herbicide resistance management in their community. Objectives and outputs include a guiding document, letter of commitment, community management plan, progress and assessment plan, and any grant applications the community decides to pursue. The ultimate goal of this ongoing project is to establish resources and capacity for building a coordinated community weed management program across the PNW.

Data from these groups are in two primary forms. First, a background interview is conducted with each participant to understand their interest in community management, experience with herbicide resistance, any preventative or mitigation actions they have taken, and any ideas for how to advance community management. Second, each monthly meeting is audio and video-recorded. At these meetings, participants are led in their discussion by the facilitator and a Community Herbicide Resistance Management Toolkit. The facilitator takes active notes on the discussion for each question addressed in the Toolkit.

At the time of writing, two community groups (Camas Prairie and Douglas County) have had one meeting each; the Palouse group has had two. Seventeen interviews have been conducted. As this is an ongoing project, data collection, transcription, and analysis are incomplete and evolving. Therefore, while we report quotations, themes, and impressions from our interviews and group meetings, these are not representative of the overall project and signify emerging data on how community management may be able to aid in maintaining conservation tillage while also dealing with the threat of herbicide resistance.

3. Results and Discussion

3.1. Research Question One

We employed focus group data to answer our first research question; how growers view tillage as an option for controlling herbicide-resistant weeds. During coding, the ways in which growers talked about tillage (growers used both the terms “tillage” and “cultivation” interchangeably) were sorted into three thematic categories: (1) as a stop-gap measure that they are hesitant to use, (2) as a viable option that is sometimes unfairly demonized, or (3) as an impractical or irresponsible method for controlling herbicide-resistant weeds. We review each of these themes, with representative quotations, in turn.

3.1.1. Tillage as a Stop-Gap Measure

The first theme often emphasized respondents’ hesitancy to till, while simultaneously holding onto the possibility of tilling as a solution for herbicide resistance. As an Iowa grower put it:

> “We do cultivate. I know that’s a dirty word in a lot of cases [. . .] it’s not something I want to do, look forward to doing, but we do it if we need to.”

They recognized the negative impacts of tillage, that it is not always culturally acceptable, and that they would rather not have to till. However, they also reported that they did till when they felt they needed to in order to control weeds when herbicides were ineffective.

The potential need for tillage, despite not wanting to, was echoed many times over—particularly in Iowa and Minnesota—although some participants from Arkansas mentioned it as well:

> “I think we have to broaden our thinking. Certainly we all know there’s problems with tillage and so forth, and so on. But it doesn’t mean that it can’t be used.” (Iowa)
>
> “Never say never.” (Minnesota)
>
> “Nobody wants to hear this, I know it, but that cultivator might come back into play [. . .] never say never.” (Arkansas)

Likewise, two growers from Minnesota had this conversation:

> Participant 1: "And I just think, in my mind, you know there might be a day when I'm going to invest in a cultivator."
>
> Participant 2: "God, I hope not. [laughter]. I got one parked in the weeds, yet, but I don't want to get it out [laughter]."

Part of this hesitancy was due to concerns over soil quality, although, according to several growers in Iowa, "conservation compliance is kind of playing a role there, too" such that growers who might otherwise employ tillage are prevented from doing so.

Other deterrents to tillage were the time and financial burdens of purchasing, refurbishing, and operating a cultivator. One grower explained that he knew a family of cotton growers who went to no-till for a variety of reasons, "not the least of which is time management, and also investment in, you know, diesel fuel and stuff like that" (Iowa).

3.1.2. Tillage as Useful but Demonized

In contrast to the above respondents, there were also those who thought tillage was both viable and desirable, but unfairly demonized to the point that they were not allowed to use it. The theme was sometimes related to restrictions imposed by the local Natural Resource Conservation Service, as in the following quotations:

> "I have reached out to them and I have found that there is so much variability from one NRCS district to the next, but the general statement – if we're talking about tillage, if you talk about mechanical control, even if you talk about stuff like rotary hoeing, nope, it can't be done; not part of the equation. So, my sense is that at least locally they really don't appreciate the situation." (Iowa)
>
> (North Carolina):
>
> Participant 1: "Yeah, and there's actually been some research done on suppression of pigweed following tobacco with the herbicides and the tillage, burying the seed deeper and whatnot, so. . . "
>
> Participant 2: I guess NRCS doesn't see that as part of the management, cultural practices, preference anyway."

Likewise, other growers mentioned that some NRCS districts had begun allowing tillage to control herbicide-resistant weeds but with conditions and caveats about planting cover crops immediately after:

> "And they worked with the NCRS guys, and got dispensation for significant tillage in some of those fields. But there was quid pro quo. You know, they could plow it down, which has an immediate benefit. But then they had to put out cover grow to help. . . " (Iowa)

This, in their minds, made tillage a less viable option due to the expense and loss of earning potential when planting a cover crop. These restrictions cause growers significant frustration: one participant in Iowa vented that, "Well, down here, if you need a tillage to out, they'll throw you in jail, you know?"

3.1.3. Tillage as Ineffective or Irresponsible

Other growers, however, did not think that tillage was a good tool for herbicide resistance management, and was the third major tillage-related theme to come out of the focus groups. In several instances, growers even explained that tillage might make for worse weed control, depending on how it was done:

> "And there's some cases where people say, as far as weeds are concerned, vertical tillage is worse than no-till [for weed control]." (Iowa)
>
> "I believe in my opinion, [no-till has] done better. Because we had a spot in the field where we did till, and then some we didn't. And the weeds grew more where we did [till] than where we were no-tilling." (North Carolina)

> "I've seen a few people cultivating fields. When you open it up, you know, if you don't have that canopy, they're going to come easier after that, when the first rain comes." (North Carolina)

A more common reason for citing tillage as impractical for weed control, however, had to do with the difficulty of implementation. The large—and growing—amount of land producers are managing was frequently cited as a barrier:

> "Because acre-wise, the majority of people couldn't cover their acres to cultivate." (Iowa)

> "I don't envision a 10,000 acre operation getting the cultivators back out. I don't know if I see that one coming. I think I would retire before I could get a cultivator back out." (Iowa)

> "I don't see a 30,000 acre farm cultivating." (Minnesota)

> "Yeah, we can hardly get the spraying done, much less putting a cultivator out there. It takes a lot of time." (Minnesota)

Besides the limitations of farm size and time commitment, growers also mentioned that there was a lack of sufficiently trained labor they could hire to run a cultivator. Finally, some growers rejected even limited or infrequent tillage as an option due to concerns over soil health:

> "So you kind of get into a catch-22 where—and I've even heard some people recommend, you know, we might have to go to cultivating, or working the ground, or something, and there's some ground that, in my mind, shouldn't be worked." (Iowa)

Overall, it seems that producers run the gambit when it comes to utilizing tillage to manage herbicide resistance. Few saw it as a completely rational, unproblematic solution. However, most considered tillage to be a viable, though sometimes distasteful, tool they could fall back on if herbicide resistance could not be controlled through other methods, i.e., herbicides. Research findings in Australia and the U.S. support the position that conservation tillage is linked to the availability of effective herbicides [4–6,9–13]. Yet some growers challenged such a contention, instead stating that tillage would be ineffectual at controlling herbicide resistance for a variety of reasons including farm sizes, labor availability, or agronomic conditions. Conservation tillage was uncoupled from effective herbicides, an unexpected contention given the existing literature.

In order to further understand these differing perspectives, we turn to our quantitative survey data and the variables that significantly predicted tillage use on a broader scale.

3.2. Research Question Two

Farmers' attitudes and experiences with herbicide-resistant weeds, including whether they are likely to adopt or expand tillage for weed control, were assessed using survey data. Of 787 respondents who answered the question on tillage use, 76.4% reported that they had used tillage to control weeds on their farm in the past two years. Of those 601 respondents who used tillage, 36.1% used it on 80–100% of their fields. The remaining categories were relatively evenly distributed, with 13–18% per category. Looking at our independent predictor variables, 74.3% of respondents were aware of weeds resistant to a single herbicide on their farm, and 30.4% were aware of weeds resistant to multiple herbicides. 94.5% were concerned or very concerned about their single-resistance weeds; 86.6% were concerned or very concerned about their multiple-resistance weeds. Only 6.7% of respondents were not concerned about any resistant weed species on their farm; the remainder were relatively evenly split between concerns over one, two, three, or four or more weed species. For these and additional descriptive statistics, see Table 2.

Table 2. Descriptive Statistics.

Dependent Variables											
	No		**Yes**								**Total**
Used Tillage	186	23.6%	601	76.4%							787
	<20%		20–39%		40–59%		60–79%		80–100%		
Proportion of Fields Tilled	89	14.8%	79	13.1%	108	18.0%	108	18.0%	217	36.1%	601
Independent Variables											
	No		**Yes**								**Total**
Grows Cotton	750	89.5%	88	10.5%							838
Grows Soybeans	146	17.4%	692	82.5%							838
Grows Wheat	444	53.0%	394	47.0%							838
Grows Hay	807	96.2%	32	3.8%							839
No Time to Manage Weeds	698	85.9%	115	14.2%							813
Uses Pre-Emergence Herbicides	97	11.6%	742	88.4%							839
Uses Post-Emergence Herbicides	60	7.2%	779	92.9%							839
Uses Post-Harvest Herbicides	491	58.5%	348	41.5%							839
	No or Not Sure		Yes								
Aware of Weeds Resistant to a Single Herbicide	211	25.7%	611	74.3%							822
Aware of Weeds Resistant to Multiple Herbicides	571	69.6%	249	30.4%							820
	Not Concerned		Somewhat Concerned		Very Concerned						
Concerned about Weeds on Farm Resistant to a Single Herbicide	45	5.5%	209	25.5%	567	69.1%					821
	Not Concerned		Somewhat Concerned		Very Concerned						
Concerned about Weeds on Farm Resistant to Multiple Herbicides	108	13.4%	203	25.1%	498	61.6%					809

Table 2. *Cont.*

	Dependent Variables										
	No		**Yes**								**Total**
	Not Concerned About Any Weeds		Concerned About 1 Weed Species		Concerned About 2 Weed Species		Concerned About 3 Weed Species		Concerned About 4+ Weed Species		
Index of Weeds on Farm	56	6.7%	167	19.9%	241	28.8%	182	21.7%	192	22.9%	838
	<$50,000		$50,000–99,000		$100,000–249,000		$250,000+				
Income	107	12.8%	251	29.9%	326	38.9%	155	18.5%			839
	Min.	Median	Mean	Max.							
Age	23	59	57.7	92							839
Total Acres Operated	0	1000	1381.2	20,000							839
	Man		Woman								
Gender	802	98.20%	15	1.8%							817

Before our analysis, we created a correlation matrix with all of our independent variables. One variable, years of farming experience, was eliminated from further analysis due to a very high correlation coefficient (0.734) with our farmer age variable. All remaining correlation coefficients were well below our preestablished minimum of 0.70 [22], with the exception of concern about single resistance and concern about multiple resistance, which had a moderate correlation of 0.541.

3.2.1. Likelihood of Adopting Any Tillage

We first used a logistic regression to investigate variables that significantly predicted growers using tillage at all (a 0/1 binary variable; Table 3, Column 1). Of our five predictor variables, two significantly impacted whether the respondent had tilled to control weeds in the past two years. First, awareness of weeds resistant to a single herbicide increased the likelihood of tillage with an odds ratio of 1.72 ($p < 0.10$). *Concern* over weeds resistant to a single herbicide, however, *decreased* the likelihood of tillage with an odds ratio of 0.68 ($p < 0.10$). Significant control variables included growing soybeans (1.76; $p < 0.10$), using post-harvest herbicides (0.55; $p < 0.05$), and respondent age (0.98; $p < 0.05$).

Table 3. Factors impacting tillage, a logistic regression on tillage used; ordered logistic regression on the proportion of fields tilled.

	Tillage Used (No/Yes) (*n* = 750)	Proportion of Fields Tillage Used on (*n* = 577)
	Odds Ratio	**Odds Ratio**
Grows Cotton (0/1)	0.97	0.76
Grows Soybeans (0/1)	1.76 *	1.11
Grows Wheat (0/1)	1.42	0.86
Grows Hay (0/1)	1.04	0.64
No Time to Manage Weeds (0/1)	1.13	0.93
Uses Pre-Emergence Herbicides (0/1)	1.1	0.39 **
Uses Post-Emergence Herbicides (0/1)	1.2	0.54
Uses Post-Harvest Herbicides (0/1)	0.55 **	0.79
Aware of Weeds Resistant to a Single Herbicide (0/1)	1.72 **	1.44 *
Aware of Weeds Resistant to Multiple Herbicides (0/1)	0.79	0.64 **
Concerned about Weeds on Farm Resistant to a Single Herbicide (1–3 Scale)	0.68 *	0.70 **
Concerned about Weeds on Farm Resistant to Multiple Herbicides (1–3 Scale)	0.95	1.27 *
Index of Weeds on Farm (0–4)	0.96	0.92
Income (Categorical)	0.98	0.87
Age	0.98 **	0.99
Total Acres Operated	1.00	1.01
Gender (0 = Men; 1 = Women)	1.20	1.26

Note: Binary dummy variables for each state were included as controls but are not shown due to space. ** = $p < 0.050$, * = $p < 0.10$.

3.2.2. Likelihood of Increasing Percent of Fields Tilled

Next, we employed an ordered logistic regression to determine which variables significantly predicted growers using tillage on an increasing proportion of their farmland (Table 3, Column 2). Our predictor variables showed a similar trend to our first regression; awareness of weeds resistant to a single herbicide increased the likelihood of more tillage

(1.44; $p < 0.10$), while concern over weeds resistant to a single herbicide decreased the likelihood of more tillage (0.64; $p < 0.05$). In this regression, two additional predictor variables were also significant. Awareness of weeds resistant to multiple herbicides on respondents' farms decreased the likelihood of more tillage (0.70; $p < 0.05$), while concern about weeds resistant to multiple herbicides had the opposite effect and increased the likelihood of more tillage (1.27; $p < 0.10$). The only significant control variable was using pre-emergence herbicides (0.39; $p < 0.05$.

Awareness and concern over herbicide-resistant weeds appear to impact tillage use but in complex ways. Consideration of awareness and concern regarding single and multiple-resistance weeds as a scale of intensity helps provide clarity. We might consider awareness to be less intense than concern, and single resistance to be less intense than multiple resistance. Our scale, then, would run from awareness of single resistance on the low end up through concern about single resistance, awareness of multiple resistance, and finally to concern about multiple resistance on the high end. Conceptualized as such, the relationship between tillage and herbicide resistance intensities is parabolic (Figure 1).

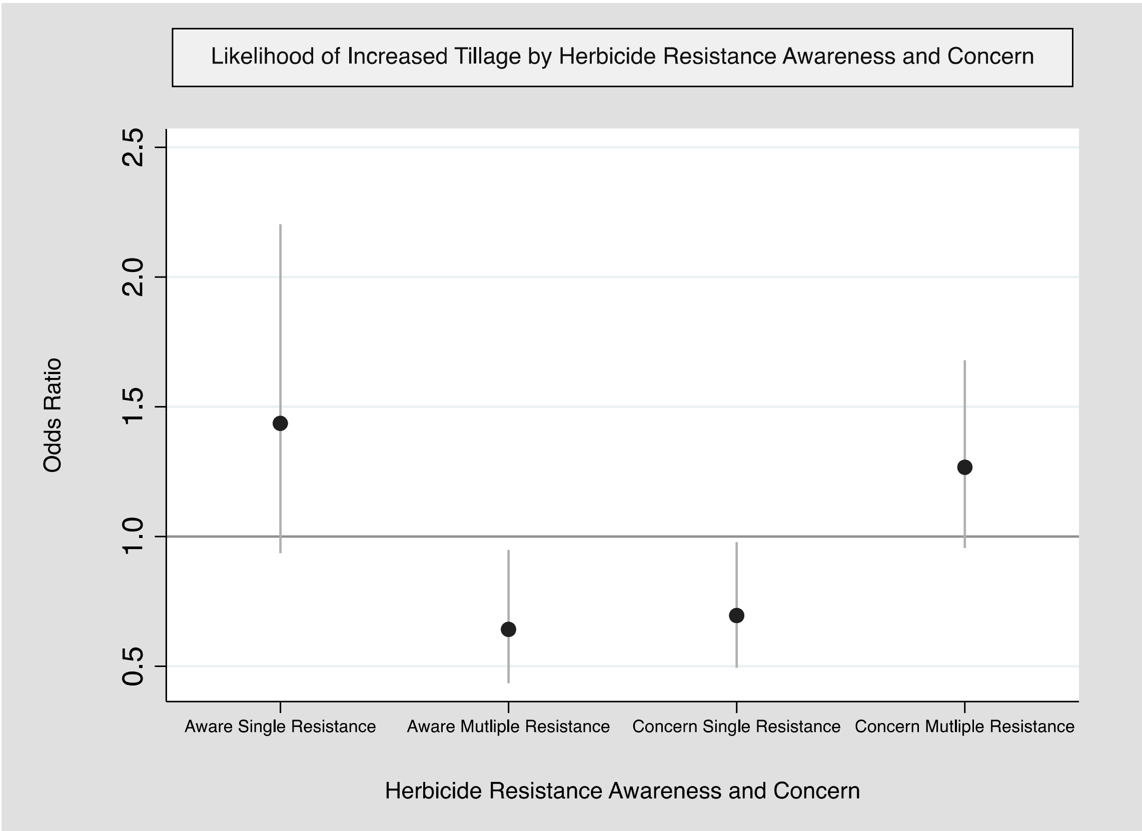

Figure 1. The parabolic relationship between awareness/concern and tillage.

Initial awareness of single herbicide resistance predicts increased tillage or even initiates it where it previously did not exist. When this awareness develops into a more intense concern, however, tillage decreases. The trend continues when growers become aware of weeds resistant to more than one herbicide, but then reverses; growers *concerned* about resistance to multiple herbicides *increased* the proportion of fields they till to control weeds.

There are a few possible explanations for the changes in trends around tillage. It may be that, when first dealing with the threat of herbicide resistance, growers turn to tillage for preventative management. This is supported by previous research, D'Emden and Llewellyn [4], Schlegel et al. [6], Thomas et al. [9], and Llewellyn et al. [10] all found that herbicide resistance issues predicted growers shifting from no-till to conventional tillage. However, as the herbicide resistance increases in severity and concern increases to moderately high levels, respondents to our survey were less likely to use tillage, abandoning it for other management techniques. No previous studies have linked awareness and concern about herbicide resistance directly to tillage use or intensity. Results from our focus groups, however, indicate several reasons farmers who are relatively highly concerned about herbicide resistance may not employ tillage—they may view it as ineffective, too difficult or expensive, or too harmful to the environment. Alternatively, the causal direction may be reversed; growers using no-till may be more aware/concerned about herbicide resistance than those who do not, and only resort to it in extreme cases of multiple resistance.

Finally, in cases where growers are highly concerned about weeds resistant to multiple herbicides, they are more likely to use tillage on a greater proportion of their fields—potentially as an emergency stop-gap measure as described in our focus groups. This may reflect the growing interest in strategic, single, or occasional tillage that has occurred over the last several years [6,14,15]. It is possible that growers who are highly concerned about weeds resistant to multiple herbicides are experimenting with some of these newer, less disruptive forms of tillage for weed control. Because we did not specify the type of tillage in our questionnaire we cannot provide support for this hypothesis, but encourage further study.

3.3. Research Question 3

Finally, we look at our Community Herbicide Resistance Management groups for insight into how community management may be able to maintain conservation tillage systems while also managing herbicide resistance. Of the growers involved in these groups, the majority practice conservation tillage or no-till agriculture. It is first significant that these are the types of growers who are interested in this project and willing to contribute their time and ideas. Growers practicing conservation tillage may be especially concerned with herbicide resistance and looking for alternative, collaborative approaches to manage it. This supports the correlation in our survey data between no-till and moderately high awareness/concern about herbicide resistance.

Participants' significant concern directed at herbicide resistance was often explicitly related to tillage, with one grower in Douglas County, WA reporting that "herbicide resistance is probably the single thing that scares me the most under our no-till farming systems". Participants in each community group mentioned that some growers in their region use herbicide resistance as a justification for using conventional tillage and that growers who do not use conservation tillage take the issue of herbicide resistance less seriously. More to the point, they generally agreed that growers dedicated to conservation tillage are forced to contend with the issue of herbicide resistance more directly and therefore develop innovative, integrated methods for dealing with it. As one grower put it "no-till people feel the pain of herbicide resistance most".

Such pain appears to drive some degree of cooperation, as evidenced by the types of growers involved in our Community Herbicide Resistance Management Initiatives. Specific to the PNW, growers' interest in cooperative management may in part be a result of STEEP, which fostered a strong community of local conservation tillers and still exists broadly as the Pacific Northwest Direct Seeder Association. Community organization is known as an effective approach to reducing tillage by facilitating communication between early adopters or long-term no-tillers to those looking to adopt reduced or no-till practices on their own farm. Conservation tillers in the PNW are already aware of the benefits of community management and may be more willing to try a similar approach for managing herbicide resistance.

Indeed, participating growers have been extremely creative and innovative in our discussions of how to manage resistance. Many have already added new rotations, such as canola, to their operation. They mix herbicide modes of action and are interested in using cutting-edge technology such as drones, mechanical weeders, weed seed terminators, electric weeding machines, and biological controls to diversify their weed management practices. Several groups have discussed cooperative ownership of equipment such as a

Weed-It (a reflectance activated sprayer system) or Harrington Seed Destructor (a combine-mounted hammer mill that destroys weed seed that passes through it). Additional ideas have included an emergency weed management fund growers can apply for when health emergencies, natural disasters, or other factors impact their ability to manage weeds. One group wrote a grant proposal to pay incentives to growers who have fewer than 10 Russian thistles smaller than a volleyball per 100 acres. The energy and innovation in herbicide resistance management by dedicated conservation tillers gives credence to the findings in our survey that moderately high levels of concern about herbicide resistance are related to lower proportions of farmland tilled.

What, then, might we make of our finding that awareness of single herbicide resistance and concern about multiple resistance increases tillage use? Why did many of our focus group participants reference going back to tillage as a viable option to deal with herbicide-resistant weeds? Based on discussions in our community groups, two primary reasons for this trend emerge. While these are based on preliminary data in a specific cropping region of the U.S., they offer an exploratory look at the types of thought processes that go into the decision to control herbicide-resistant weeds through tillage.

First, several growers in our Palouse group stated that when they first were dealing with a serious infestation of herbicide-resistant weeds, "we tried to plow our way out of the problem". This is again in line with findings from previous findings from Australia and the U.S. [4,6,9,10]. However, this same participant went on to clarify "That didn't work". Instead, they went back to reduced tillage, only using it when absolutely necessary for herbicides that need to be incorporated with the soil. They emphasize that tillage is less effective at controlling weeds than a more integrated and nuanced approach. This supports the trend found in our survey data, where initial awareness increases tillage but, as awareness and concern develops, tillage decreases back down. Growers may initially react to herbicide resistance with tillage, but subsequently, till less as they gain more experience with managing herbicide-resistant weeds. When serious infestations break out, however, they may practice targeted and less disruptive forms of tillage to get back on track. Again, this fits with our survey finding that very high concern may lead to more tillage.

A second explanation has to do with the level of commitment to conservation tillage. Many growers in our community groups are highly dedicated to conservation tillage, having used it continuously for decades and being involved in their regional Direct Seeders Associations. There is a strong no-till community, grown out of STEEP, to offer support and to keep them from resorting to tillage as an "out". However, there are also individuals in the communities who are only just starting to experiment with conservation tillage and are less dedicated to the practice. A member of the local conservation district, who is a part of one of our community groups, said that she has worked with growers making the transition to conservation tillage who have pulled back due to their inability to control herbicide-resistant weeds in a no-till system. Several growers in Douglas County expanded on this notion, explaining that new users of no-till do not have the management experience and system expertise to effectively control weeds at first. They must either engage and learn a new, complex management style, or give up and go back to conventional tillage—which is more likely if they are dealing with herbicide-resistant weeds they cannot manage. This again provides evidence of the connection between dedicated conservation tillage and concern about herbicide resistance.

While many members of our groups are frustrated with growers using conventional tillage, there is also a surprising amount of goodwill. Each group was asked whether conventional tillers should be included in our management group, or if we should focus only on those using conservation tillage. All responded that we should reach out to those using conventional tillage. While some part of this rationale is that weeds do not stop at the borders of conventional or conservation tillage operations, making them everyone's problem, there is also the strong desire to engage and even provide resources to those practicing conventional tillage. Our participants recognized that, especially for growers interested in transitioning to conservation tillage, a community of support and guidance would go a long way in making that transition successful. Community management should incorporate innovative herbicide resistance management practices while also supporting conservation tillage. Indeed, effective weed management tools, in a community context, could increase conservation tillage.

4. Conclusions

We found that many growers consider tillage to be a fail-safe measure to control weeds if herbicides do not provide adequate control. It is not necessarily a desirable option (due to labor, expense, and environmental concerns), but it is in their toolbox and they will use it if necessary and allowed. We also found a parabolic relationship in which awareness of weeds resistant to a single herbicide suggested increased tillage use, awareness of weeds resistant to multiple herbicides, and concern about weeds resistant to a single herbicide suggested decreased tillage use, and concern about weeds resistant to multiple herbicides suggested increased tillage use. Therefore, it appears that low and very high levels of awareness and concern promote tillage to control herbicide resistance, while a "sweet spot" of moderately high concern decreases tillage use.

There are a few apparent reasons for the observed trend. Our focus groups and community groups, as well as several previous studies [4,6,9,10], support the finding that some awareness of herbicide resistance results in increased conventional tillage. What was not apparent in previous studies, but is evident from our qualitative data, is that there is also a relationship between concern about herbicide resistance and a decrease in tillage. This can occur when growers find tillage to be an ineffective response to herbicide-resistant weeds, or avoid tillage due to labor, economics, environmental concerns, or agronomic philosophies. Finally, our results suggest that very high concern about weeds resistant to multiple herbicides may prompt growers to reconsider tillage as a weed management strategy. We suspect, but cannot test, that these highly concerned growers are experimenting with alternative tillage practices such as strategic, precision, and occasional tillage as is increasingly recommended [6,14,15].

Furthermore, based on our Community Herbicide Resistance groups in the PNW, it seems that conservation tillers are particularly concerned about herbicide resistance due to their reliance on herbicides and lack of tillage as a weed control option. The result, for those highly dedicated to conservation tillage, is a higher willingness to cooperate with other growers and find innovative management solutions. However, for those who are less dedicated, or experimenting with conservation tillage for the first time, the threat of herbicide-resistant weeds may be enough to make them give up on transitioning to conservation tillage more fully.

Community management has a role to play in enabling growers to manage herbicide resistance while also adopting or expanding conservation tillage practices. Our survey data provide evidence that levels of concern about herbicide resistance can actually decrease tillage practices—and our community groups bear this out for those already interested in conservation tillage. It is also very hopeful that our community groups are dedicated to reaching out to neighbors practicing conventional tillage to collaborate and learn more about each other's weed management practices. Community meetings are a place to start a dialogue between these groups, and they may serve the role of making conservation tillage seem more doable. As our participants explained, growers who are new to conservation tillage may initially struggle with weed management, but this can be overcome through sufficient knowledge, innovation, and support. Whether we will actually be able to engage growers using conventional tillage in our community groups remains to be seen; however, there is reason to expect that if these connections are made community groups can effectively provide support for adopting, expanding, or maintaining conservation tillage—potentially while integrating very specific alternative tillage practices—while also creatively and effectively managing herbicide-resistant weeds.

Author Contributions: Conceptualization, K.D.; methodology, K.D.; validation, K.D. and I.C.B.; formal analysis, K.D.; resources, K.D. and I.C.B.; writing—original draft preparation, K.D.; writing—

review and editing, K.D. and I.CB.; supervision, I.C.B.; project administration, K.D. and I.C.B.; funding acquisition, K.D. and I.C.B. All authors have read and agreed to the published version of the manuscript.

Funding: Funding was provided by the USDA APHIS (agreement no. AP19BRS00000G002), the Weed Science Society of America, and in part by the USDA National Institute of Food and Agriculture, Hatch project 1017286. The findings and conclusions in this publication have not been formally disseminated by the U.S. Department of Agriculture and should not be construed to represent any agency determination or policy.

Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki, and approved by the Institutional Review Board of Washington State University (18453-001, 9/16/20).

Informed Consent Statement: Page: 17 "Informed consent was obtained from all subjects involved in the study.".

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Livingston, M.; Fernandez-Cornejo, J.; Unger, J.; Osteen, C.; Schimmelpfennig, D.; Park, T.; Lambert, D.M. *The Economics of Glyphosate Resistance Management in Corn and Soybean Production*; Economic Research Report, No. ERR-184; US Department of Agriculture: Washington, DC, USA, 2015.
2. Norsworthy, J.K.; Sarah, M.W.; David, R.S.; Rick, S.L.; Robert, L.N.; Theodore, M.; Webster, K.W.B. Reducing the risks of herbicide resistance: Best management practices and recommendations. *Weed Sci.* **2012**, *60*, 31–62. [CrossRef]
3. Bonny, S. Genetically modified herbicide-tolerant crops, weeds, and herbicides: Overview and impact. *Environ. Manag.* **2016**, *57*, 31–48. [CrossRef] [PubMed]
4. D'Emden, F.H.; Llewellyn, R.S. No-tillage adoption decisions in southern Australian cropping and the role of weed management. *Aust. J. Exp. Agric.* **2006**, *46*, 563–569. [CrossRef]
5. Price, A.J.; Balkcom, K.S.; Culpepper, S.A.; Kelton, J.A.; Nichols, R.L.; Schomberg, H. Glyphosate-resistant Palmer amaranth: A threat to conservation tillage. *J. Soil Water Conserv.* **2011**, *66*, 265–275. [CrossRef]
6. Schlegel, A.; Holman, J.D.; Assefa, Y. A single tillage in a long-term no-till system on dryland crop performance. *Agron. J.* **2020**, *111*, 3174–3187. [CrossRef]
7. Kok, H.; Papendick, R.I.; Saxton, K.E. STEEP: Impact of long-term conservation farming research and education in Pacific Northwest wheatlands. *J. Soil Water Conserv.* **2009**, *64*, 253–264. [CrossRef]
8. Lyon, D.; Burce, D.; Vyn, T.; Peterson, G. Achievements and future challenges in conservation tillage. In Proceedings of the 4th International Crop Science Congress, Brisbane, Australia, 26 September–1 October 2004.
9. Thomas, G.A.; Titmarsh, G.W.; Freebairn, D.M.; Radford, B.J. No-tillage and conservation farming practices in grain growing areas of Queensland—A review of 40 years of development. *Aust. J. Exp. Agric.* **2007**, *47*, 887–898. [CrossRef]
10. Llewellyn, R.S.; D'Emden, F.H.; Kuehe, G. Extensive use of no-tillage in grain growing regions of Australia. *Field Crop. Res.* **2012**, *132*, 204–212. [CrossRef]
11. D'Emden, F.H.; Llewellyn, R.S.; Burton, M.P. Factors influencing adoption of conservation tillage in Australian cropping regions. *Aust. J. Agric. Resour. Econ.* **2008**, *52*, 169–182. [CrossRef]
12. Roberts, R.K.; English, B.C.; Gao, Q.; Larson, J.A. Simultaneous adoption of herbicide-resistant and conservation-tillage cotton technologies. *J. Agric. Appl. Econ.* **2006**, *38*, 629–643. [CrossRef]
13. Frisvold, G.B.; Boor, A.; Reeves, J.M. Simultaneous diffusion of herbicide resistant cotton and conservation tillage. *AgBioForum* **2009**, *12*, 249–257.
14. Blanco-Canqui, H.; Wortman, C.S. Does occasional tillage undo the ecosystem services gained with no-till? A review. *Soil Tillage Res.* **2020**, *198*, 104534. [CrossRef]
15. Obour, A.K.; Holman, J.D.; Schlegel, A.J. Strategic tillage in dryland no-tillage crop production systems. *Kansas Agric. Exp. Stn. Res. Rep.* **2019**, *5*, 4. [CrossRef]
16. Dentzman, K. Herbicide resistant weeds as place disruption: Their impact on growers' attachment, interpretations, and weed management strategies. *Environ. Psychol.* **2018**, *60*, 55–62. [CrossRef]
17. Creswell, J.W.; Plano-Clark, V.W. *Designing and Conducting Mixed Methods Research*, 3rd ed.; Sage: Newbury Park, CA, USA, 2017.
18. Morgan, D.L.; Morgan, S. *Successful Focus Groups: Advancing the State of the Art*; Sage: Newbury Park, CA, USA, 1993; Volume 156.
19. Mayring, P. *Qualitative Content Analysis: Theoretical Foundation, Basic Procedures and Software Solution*; Forum Qualitative Sozialforschung: Klagenfurt, Austria, 2014.
20. Ervin, D.; Breshears, E.; Frisvold, G.; Dentzman, K.; Everman, W.; Gunsolus, J.; Hurley, T.; Jussaume, R.; Norsworthy, J.; Owen, M. Farming attitudes toward cooperative approaches to herbicide resistance management: A common pool ecosystem service challenge. *Ecol. Econ.* **2019**, *157*, 237–245. [CrossRef]

21. Frisvold, G.B.; Albright, J.; Ervin, D.E.; Owen, M.D.K.; Norsworthy, J.K.; Dentzman, K.; Hurley, T.M.; Jussaume, R.A.; Gunsolus, J.L.; Everman, W. Do growers manage weeds on owned and rented land differently? Evidence from U.S. corn and soybean farms. *Pest Manag. Sci.* **2020**, *76*, 2030–2039. [CrossRef]
22. Mukaka, M.M. A guide to appropriate use of correlation coefficient in medical research. *Malawi Med. J.* **2012**, *24*, 69–71. [PubMed]