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The Promise of a Multi-Disciplinary, Mixed-Methods Approach to Inform Insect Pest Management: Evidence From Wyoming Alfalfa

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Pest management strategies involve a complex set of considerations, circumstances, and decision-making. Existing research suggests that farmers are reflexive and reflective in their management choices yet continue to employ curative rather than preventative strategies, and opt for chemical over biological solutions. In this piece, we detail work from a two-year, multidisciplinary, mixed-methods study of insect pest management strategies in alfalfa in Wyoming, integrating data from four focus groups, a statewide survey, and biological sampling of production fields. We outline how these different sources of data together contribute to a more complete understanding of the challenges and strategies employed by farmers, and specifically on biological pest control. We applied this approach across alfalfa hay and seed crop systems. Relatively few farmers acknowledged biological control in focus groups or surveys, yet biological exploration yielded abundant parasitism of common pest alfalfa weevil. On the other hand, parasitism of seed alfalfa pest *Lygus* was far less common and patchy across fields. It is only in integrating quantitative and qualitative, biological and social data that we are able to generate a more complete portrait of the challenges and opportunities of working with farmers to embrace a preventative paradigm. In doing so, we offer insights on possible barriers to the adoption of preventative insect management strategies and provide a case study of integrating social science and biophysical techniques to better understand opportunities to expand biological pest control in cropping systems.

Keywords: alfalfa weevil, parasitoid, biological control, *Lygus*, farmer decision-making, mixed-methods, *Hypera postica*, *Medicago sativa*

INTRODUCTION

Farmer decision-making has long been an area of interest to scientists to increase efficiency and provide useful scientific insight to assist growers. Recent research has paid growing attention to the need to integrate social and biological understandings of insect pests (Lamp et al., 1991; Summers, 1998). Such work has the benefit of being attentive to grower needs and practices, so that interventions may be designed in a way that incorporates realistic considerations and so that information is responsive to producer needs and interests. Further, insect pest management can be more sustainable by moving away from an overreliance on chemical treatments toward more preventative forms of insect pest management. Such preventative practices can include, but are not limited to, conservation or augmentative biological control (Landis et al., 2000) and systems-level diversification of an agroecosystem, for instance via increased crop or habitat diversity across spatial and temporal scales or integration of crop and livestock systems (Kremen and Miles, 2012). These preventative approaches are in contrast with preventative prophylactic pesticide applications common in many conventional cropping systems (i.e., calendar sprays, seed treatments). Promotion of such practices to encourage reduced pesticide use must empower farmers in farmer-centered communication and outreach strategies (i.e., Matteson, 2000). However, pest management research rarely integrates both quantitative and qualitative social data analysis techniques, commonly termed a "mixed-methods approach" (Cresswell and Plano Clark, 2011) with biophysical measures of actual pest pressures in the field.

Integrated pest management (IPM) is likely the most widely recognized framework for employing multiple pest management strategies to reduce reliance on chemical control (Peterson et al., 2018). Classically, it is defined as a systems-approach to pest management with the aim of reducing pests below defined threshold levels "by using methods that are effective, economically sound, and ecologically compatible" (Pedigo, 1989). However, recent attention by pest management scientists has largely turned to reflect on whether IPM is actually being employed as originally intended with think pieces such as "Whatever Happened to IPM?" (Peterson et al., 2018) and discussion of new IPM paradigms for the "modern age" (Dara, 2019). Pest management is in its essence a human enterprise, and Gott and Coyle (2019) pose that engaged and effective communication is critical to adoption of IPM. For example, farmer awareness of insect natural enemies in one case depended on prior education and management experience (Wyckhuys and O'Neil, 2007).

BACKGROUND

Alfalfa *Medicago sativa* L. is an important crop in the Western United States and much of the globe. Insect pests are a costly challenge to producing both quality alfalfa hay and seed crops, with alfalfa weevil *Hypera postica* (Gyllenhal) (*Coleoptera*: *Curculionidae*) and *Lygus spp.* (*Hemiptera*: *Miridae*), respectively, identified as particularly problematic pests in these distinct management systems. Alfalfa seed production differs from hay production in several biologically relevant ways. Seed production fields have lower alfalfa plant density per area than hay production fields. Producers harvest the seeds thus allowing alfalfa to mature beyond the vegetative plant stage typical in forage fields. Seed producers have the additional challenge of balancing chemical management with pollinator conservation, both of which are crucial for production of a high-yielding seed crop. *Lygus* plant bugs include a few closely related species whose nymphs and adults primarily feed on terminals, buds, flowers, and developing seeds, hence their particularly pernicious role in seed production (Blodgett, 2006). Growers of both hay and seed crops primarily rely on chemical control of alfalfa insect pests, although the type and timing of management disturbances differ greatly across these systems.

Both adult and larval alfalfa weevil feed on alfalfa, but the majority of defoliation is accomplished by late-instar larvae in the early season, usually in the first cutting (Pellissier et al., 2017). Hay alfalfa is typically harvested three to four times per growing season, while alfalfa seed is harvested only once. Hay growers apply insecticides to reduce weevil populations if needed, possibly based on existing economic thresholds for larval abundance. Seed growers generally rely heavily on chemical control for pests, applying neonicotinoids or pyrethroids for pest control three to five times per season (**Figure 1**). Right before bloom, seed growers may do a "pre-bee clean up" chemical application before release of alfalfa leafcutter bees *Megachile rotundata* F. (Hymenoptera: Megachilidae). In August, many seed growers will then use an herbicide as a desiccant to defoliate their field and get ready for seed harvest. Insecticides are not only costly to growers, but repeated applications could lead to resistance in target pests, leading some Extension educators to recommend chemical rotation (e.g., Long and Getts, 2018). These products are also highly toxic to non-target organisms like pollinators and natural enemies (Evans et al., 1993). Products approved for certified organic production, such as spinosads, may be less toxic to bees but are both more expensive than conventional products and less effective (Godfrey et al., 2005). Certified organic production of alfalfa in Wyoming is rare, which further limits adoption of biopesticide substitutions.

Though several parasitoid releases have occurred over the past century for biological control of the alfalfa weevil in particular, persistence, and activity of those parasitoids has been patchy and limited in this region (Brewer et al., 1997; Rand, 2013). Suggestions for promoting natural enemies within alfalfa fields are limited to strip harvesting, which is agronomically inefficient, and reduced pesticide use, which carries the risk of direct losses in the first cutting and carryover losses in the subsequent cuttings due to reduced plant vigor (Latheef et al., 1988). Recent evidence showed that provisioning of floral resources near alfalfa plots enhanced parasitoid abundance and richness, although biocontrol of alfalfa weevil specifically was unchanged (Pellissier and Jabbour, 2018).

Our focus group analysis suggests that growers are interested in preventative strategies, and that they are concerned about chemical treatment in a variety of ways: cost, questions of interests and bias on the part of chemical companies, as well as the effects on beneficial insects, including pollinators and natural enemies (Noy and Jabbour, 2020). However, chemical and other curative approaches provide much needed flexibility, which is prized among farmers handling complex and sometimes competing considerations of when to perform management events such as planting and harvest. We argue that it is important to consider different sources of data (quantitative and qualitative, sociological and biophysical) and incorporate grower perspectives with intention if the goal is to pursue agricultural redesign that is preventative, "nature-friendly," and does not threaten biodiversity. Such work must include producer perspectives, insight from agricultural professionals and advisors,

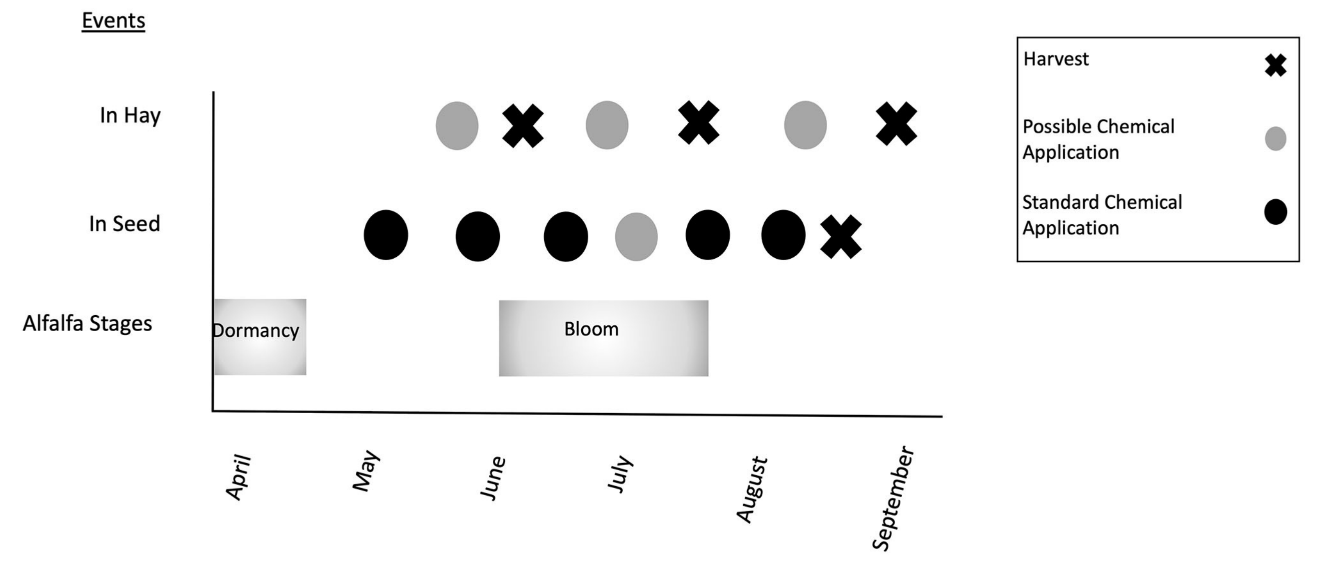

FIGURE 1 | Comparison of typical management practices in alfalfa hay and seed crops.

and field-based biophysical data to present a full picture of the current pest challenges and the effects, both positive and negative, of shifts to preventative, agroecological methods. These methods have the potential to be more efficient, cost-effective, and environmentally sound but must triangulate biological information with grower perspectives in order to craft an approach that will be useful and embraced by the primary stakeholders: growers.

MATERIALS AND METHODS

Our analysis draws from a multidisciplinary, mixed-methods study of insect pest management in Wyoming alfalfa production with data collected over approximately 2 years. "Mixed-methods research" is a methodological approach in the social sciences which refers to the integration of quantitative and qualitative data within a research project and draws on interpretation from both data sources (Cresswell and Plano Clark, 2011). Our study involved the collection of both biological and social data, including qualitative and quantitative data. The project was motivated by our interest in gaining an understanding of the prevalence of and motivation across management strategies of insect pests among Wyoming alfalfa farmers. Therefore, we sought to collect data on farmer perspectives as well as insect management strategies and practices. We conducted four focus groups, surveyed over 600 alfalfa farmers, and collected biological data about insect pests and biocontrol from both commercial production fields and research farms. In other publications (Pellissier, 2016; Jabbour and Noy, 2017; Noy and Jabbour, 2017, 2020; Pellissier and Jabbour, 2018) we have conducted detailed analysis drawing from single data sources only. Here, we integrate all three data sources and describe how these data build and inform one another to enhance our understanding of insect pest management of Wyoming alfalfa.

We draw on three sources of data: first, focus groups in four counties to understand farmer challenges and decision-making; second, surveys of Wyoming alfalfa farmers to gather information about growers' perceptions of pests and farm characteristics; and third, samples from production fields capturing the prevalence of pests and naturally-occurring biological pest control. For our social data, elaborated below, we chose to conduct focus groups because this method is especially good at illuminating participant perspectives, giving priority to their language and concepts and their framework for understanding the world (Kitzinger, 1994). Focus groups are generative and collaborative, and therefore they are less centered on individuals but instead on information-sharing where participants provide an audience for one another. Researchers are able to observe discussion and shared meanings. Survey data on the other hand allow more generalizable insight. However, this breadth comes at the expense of depth. Questionnaires then allow the collation of individual responses and discernment of patterns. Ideally, samples are representative of the populations from which they are drawn which allows a baseline understanding of trends. The overall project—including the survey and focus groups—was reviewed and approved by the University of Wyoming Institutional Review Board on November 14, 2013. Finally, we collected samples from production fields to provide biological evidence of the prevalence of biological pest control. We summarize the overall project design, a concurrent mixed-methods design including social and biological data, in **Figure 2**.

Focus Group Data

Our focus groups served two purposes: first, to generate important interactional information on insect pests and management strategies in their own right, and second, to validate the survey instrument which would be administered

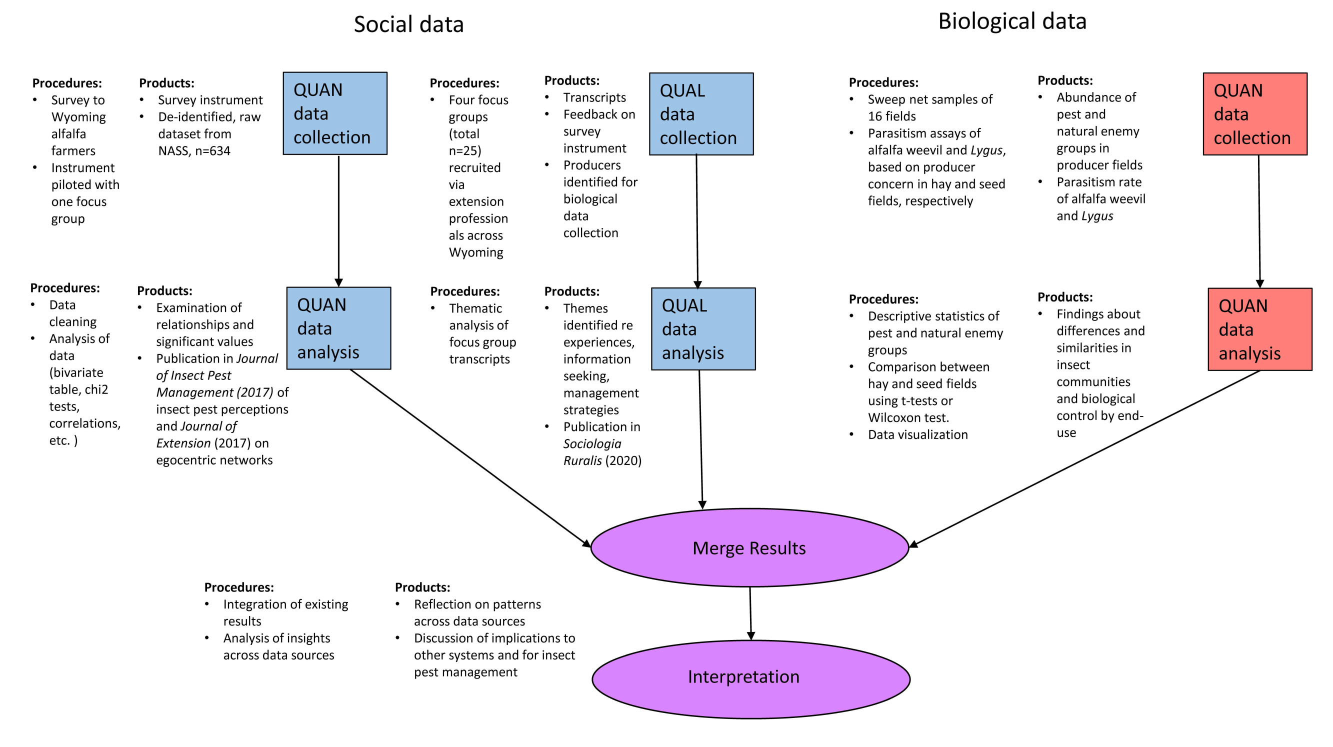

FIGURE 2 | Overview of mixed-methods research design and outcomes for overall project on alfalfa insect pest management in Wyoming.

to the population of alfalfa growers in the state. As such, we strategically selected four Wyoming counties with variation in markets and production circumstances, including diversity in end-use market (e.g., hay vs. seed).

We conducted focus groups in Spring 2014 and Fall 2015 in four counties in Wyoming (**Table 1**). Informed consent was obtained from all individual participants included in the study and we have assigned pseudonyms to both the counties and the individual growers to protect grower privacy. We chose to conduct these focus groups in counties across the state to include diversity in field size, markets, and agronomic conditions. We relied on a county-based Extension educator to help recruit producers, seeking diversity along farm characteristics and experience among participants. A short survey administered before the focus group gathered information about the growers and their operations (**Table 1**). In the focus groups, we asked questions about grower experiences, insects pests, information seeking, and management strategies. Each focus group was audiorecorded, transcribed, and the data analyzed thematically.

Survey Data

We designed and administered a survey (**Supplementary Material**) via the United States Department of Agriculture-National Agricultural Statistics Service (USDA-NASS) which had a master list of alfalfa producers in Wyoming. We designed the survey instrument to examine the priorities and perceptions of Wyoming alfalfa producers with a focus on insect pests, particularly to establish a baseline for this group as no systematic information had been collected prior to our study despite the importance of this crop in the state. The survey included questions about respondents' socio-demographic characteristics; farm size, production, and output; alfalfa insect pests and pest management; and questions about respondents' social networks. We sought feedback from four Extension professionals when crafting our survey instrument. We then piloted the survey with a focus group consisting of six alfalfa producers (East County in **Table 1**).

We received data from 634 surveys completed by farmers. USDA-NASS mailed the survey to a total of 3,141 farmers (of 3,246 in their confidential total roster because the U.S. Postal Service was unable to locate 105) in Wyoming in March 2015. Eighty-three surveys were returned uncompleted because farmers reported they did not grow alfalfa, were not farming, refused to respond, and/or asked to be removed from the survey list. Via USDA-NASS, we sent one postcard reminder, 2 weeks after the initial survey was mailed to attempt to maximize the response rate (Dillman et al., 2014). Of eligible respondents, we had a 20.7% completion rate. Raw data from returned surveys were entered by USDA-NASS staff and de-identified data were provided to us for analysis.

Biological Data

During summer 2015, biological data from alfalfa production fields was collected with a focus on estimation of rates of biological pest control. In our region, no biological assessment of biocontrol rates of alfalfa weevil had been completed in alfalfa since 1996 (Brewer et al., 1997) and none had ever occurred, that we know of, to document prevalence of native *Lygus* parasitoids.

TABLE 1 | Descriptive statistics for focus group respondents.

County	East	South	North	Middle
Date of focus group	January 2014	February 2014	February 2015	March 2015
Number of participants	6	9	7	3
Average acres for total dryland crop production	23.33	50	0	0
Average acres for dryland alfalfa	6.67	12.5	0	0
Average acres total irrigated crop production	883.33	396.88	1022.11	234.33
Average acres irrigated alfalfa	537.5	318.75	274.22	126.67
Average acres total rangeland	12.5	4115.38	415.67	143.33
Alfalfa produced for	Primarily hay	Primarily hay, some feed	Half seed, half on feed, and hay	Hay and on farm feed

Collection of these in-field biological data in concert with the focus groups and surveys allowed us as researchers to evaluate which preventative measures were both most feasible and most likely to have impact upon investment of future research by scientists and future time, effort, and finances of producers.

We collected biological data from a three-county area in Wyoming where both alfalfa hay and seed production occur. Fields were identified with the help of Extension educators and crop advisors in these counties, including a subset of fields of the participants in one of our previous focus groups who indicated willingness. Fields were at least 4 km apart from one another. We collected insects from eight seed fields and eight hay fields twice in summer 2015: in early June (June 1–5, 2015) and in mid-July (July 14–17, 2015). These sampling periods were selected based on growing degree day models and discussion with area crop scouts. Early June was the best time to measure parasitism of alfalfa weevil larvae and mid-July was the best time to measure parasitism of *Lygus* nymphs.

Insects were sampled using sweep nets (Al Ayedh et al., 1996; Rand, 2013). In each field, we collected six 50-sweep samples, at least 20 m from the field edge, with each sample 10 m apart. Samples were sealed in gallon size plastic bags, with a paper towel added to collect extra moisture, and stored in a cooler with ice until return to the lab. Herbivore insects in the following categories were identified and counted: alfalfa weevil adults and larvae, *Lygus* nymphs and adults, and aphids (*Hemiptera*: *Aphididae*). Natural enemies in the following categories were identified and counted: lady beetle larvae and adults (*Coleoptera*: *Coccinellidae*), damsel bugs (*Hemiptera*: *Nabidae*), green lacewings (*Neuroptera*: *Chrysopidae*), and spiders (*Araneae*). In the lab, a subset of alfalfa weevils (in June sampling) or *Lygus* (in July sampling) were counted and removed across all six subsamples per field to complete parasitism assays as described below.

Parasitism rates of alfalfa weevil larvae were estimated through a rearing assay. We collected 100 third and fourth-instar alfalfa weevil larvae from each field, or as many as we could if abundances were low, to measure parasitism rates by *Bathyplectes* parasitoid wasps (Al Ayedh et al., 1996). These parasitoids have distinctive cocoons that can be easily identified, with a single cocoon per larva. Weevil larvae were placed in paper bags with two stems of freshly harvested alfalfa, replaced with fresh alfalfa every 2 days until weevils reached the adult stage. At this time, samples were examined and the number of parasitoid cocoons and adult weevils were tallied to calculate the parasitism rate [percent parasitism = parasitoid cocoons/(parasitoid cocoons + adult weevils)]. Larvae that died before reaching adulthood or parasitoid cocoon stage were not included in the estimate.

Parasitism rates of *Lygus* nymphs were estimated based on dissection. We collected 100 *Lygus* nymphs from each field, or as many as we could if abundances were low, placed them immediately in 80% ethanol, and dissected at a later date to quantify parasitism rate by native *Peristenus* parasitoids (Day et al., 1999).

Arthropod community data was log-transformed and examined using multivariate analysis with "vegan" package in R (Oksanen et al., 2019). Differences in arthropod community composition were visualized through principal components analysis. The effect of sampling round (1 = June, 2 = July), end use (hay, seed), and the interaction between sample round and end use on arthropod communities was tested using a PERMANOVA. Parasitism rates of alfalfa weevil were compared between hay and seed fields using a *t*-test with the base package of R (R Core Team, 2020). Due to non-normality of *Lygus* parasitism data, we used a non-parametric Wilcoxon test.

RESULTS

Focus Group Data

The focus groups yielded rich data on grower perspectives, challenges, and solutions. Elsewhere, we have discussed findings from these focus groups as they pertain to farmer views on expertise and sources of information (Noy and Jabbour, 2020). We found that growers reported using chemical treatment for insect pests to maximize crop yields and importantly, flexibility, rather than to save on time, or labor. However, they used spraying and other pest management strategies in coordination, seeking advice from trusted experienced contacts, including Extension personnel. Our analysis revealed that neighbors function both as sources of information and as variables to consider. For example, spray timing was influenced by what neighbors were doing, sometimes in order to utilize the same plane (and save costs) for aerial spraying (Lawrence, Middle County) and also due to insect mobility, as one respondent explained: if your neighbor sprays but you do not, the insects often migrate to your field (Ned, South County).

Here, we focus on growers' discussion of insect pest management in the focus groups, and in particular, mentions related to biological control. The issue of biological pest control came up several times during the focus groups, in North and East counties. North County included farmers who grew alfalfa for seed in addition to hay and on-farm feed, the only focus group for which this was the case (**Table 1**).

Both Grant and Richard agreed that *Lygus* species are the biggest "killer for seed" (Richard, North County) and was particularly problematic because it "builds up resistance so quick" (Grant, North County). In this discussion, they noted that *Lygus* builds up resistance to some pesticides, while other pesticides are not preferred because they kill pollinators. Further, Grant noted that damsel bugs in the family Nabidae are also important to protect because they are predators of aphids, *Lygus* and other soft-body insects. Richard chimed in with mention of "ladybugs." Grant further emphasized that "with the correct management, we can limit the use of insecticides and let the beneficials do the controlling of pests, but we can't always count on that." He goes on to discuss pest populations "exploding" as a result of both insecticide resistance and non-target effects on natural enemies.

Therefore, producers report being constrained in what they can spray. Cole, in East County, noted the importance of being sensitive to neighbors, reporting that four neighbors had honey bees, and he needed to give them warning before spraying pesticide to allow for them to take precautions. Another solution was to spray at night when the bees were less active or spray earlier in the season to avoid "hurting the beneficials" (Cole, East County).

In East County, growers noted that contemporary pesticides are less effective than previous ones, as evidenced in the following exchange:

> Tim: When we had herbicides that were highly persistent, and insecticides, you could spray the border of your field and that, that insecticide would still be killing grasshoppers 30 days later, we don't have access to any of those insecticides that are that persistent anymore but it hasn't been that long ago, probably 15 years ago, and I forget what we were spraying for the insecticide at the time but you could spray them, spray the borders of those fields and the outside, outside the field, and you could hold those grasshoppers for the entire season with one spraying but—
> Matt: Doesn't the University, has the extension office in the University have a program, you know if you get to your grasshoppers early enough and they're still in the nymph stage you can spray'em, what is that? That they'll do a cost share on—
> Art: Biological control so they don't molt
> Matt: Right, do you, you have to get them
> Interviewer: Is it a fungus or something different?
> Art: Stops their instar and they can't molt
> Matt: Their exoskeleton is just they get stuck in there and then they die
> Art: You can't do it over the second instar
> Matt: Right. Yeah, you have to be, I mean [cross talk] it has to be a certain stage [cross talk] when you see grasshopper a small one you have to be very diligent at your timing or, or that, that insecticide won't work.
> Gabe: But they'll only cost share on grassland, they won't do it on farm ground
> Matt: I've cost shared, I've done it on my borders
> Gabe: Really? Cause I talked to'em and—
> Matt: Cause that's on your borders, on the outside that's where a lot of times the grasshoppers are anyways, and they'll cost share on your borders.

The above exchange provides several important insights: first, cost is clearly a concern given discussion of cost-sharing. The cost-share program described is not referring to a biological control product *per se*, but rather a recommended pesticide at the time of the focus group that is an insect-growth regulator with a more specific target than some of the generic pesticides previously used. Thus, they may be associating this "softer chemistry" with biological control due to the reduced non-target effects. Second, growers are aware of the decreased toxicity of the newer options, even if they may miss the "good old days" of using more potent pesticides.

Survey Data

While the focus group data allowed us to generate interactive data and refine our survey instrument, we aimed to get a broader view of the challenges experienced by alfalfa farmers across the state, motivating a mixed-methods approach. Surveys necessarily sacrifice depth in the interest of breadth, but in combination with focus groups yields a comprehensive approach. Elsewhere we have discussed some sections of the survey (Jabbour and Noy, 2017; Noy and Jabbour, 2017). Here, we present additional information about why alfalfa weevil and *Lygus* were labeled as most problematic (**Table 2**), elaborating on our published work (Jabbour and Noy, 2017). Understanding the perceived impact of pests is important for those seeking to promote biological control methods that are most appropriate. Overall, Wyoming farmers considered alfalfa weevil (65% of respondents), grasshoppers (18% of respondents), and aphids (7% of respondents) as their most problematic insect pests. Although alfalfa seed production is an important industry in Wyoming, there are far fewer producers who grow alfalfa seed than alfalfa hay. Only 2% of survey respondents (12 individuals) produced seed.

In previous analyses of these data we found that while 5.5% of respondents reported trying biological control strategies for alfalfa weevil, only 7.7% of those that had tried it found it to be the most effective management strategy (Jabbour and Noy, 2017). For grasshoppers, the second most problematic pest, only 2.3% of respondents had tried biological control while for aphids this number was 10.9%. Alfalfa weevil was identified as the most problematic pest by 65% of respondents and was one of the pests we focused on in biological data collection. Although the survey responses from seed producers were minimal, any seed producers that identified a most problematic pest selected *Lygus*. This observation, paired with the focus group discussions referenced above, highlight that predominant insect concerns in alfalfa seed production center on this insect. Here, we provide additional information from the survey on why farmers considered these

TABLE 2 | Commonly mentioned themes by Wyoming alfalfa producers to explain problematic nature of insect pests in hay (alfalfa weevil) and seed (*Lygus*) production.

	Alfalfa weevil	*Lygus*
Agronomic & economic	• Decreased yield and quality • Timing (always there) • Chemical control costly	• Extensive damage to blooms and seed • Limited effective insecticide chemistries available
Biological & weather	• Pest biology • Link with weather • Landscape perspective	• Insecticide control of this pest can also harm pollinators • Multiple generations

TABLE 3 | Growers who have tried biological control by farm acreage.

Alfalfa acreage	Number of respondents	Percent of respondents	Number of respondents who have tried biological control	Percentage of total respondents who have tried biological control
1–50	321	50.6	12	3.7
51–100	103	16.3	11	10.7
101–200	103	16.3	11	10.7
201–500	72	11.4	9	12.5
501–100	30	4.7	3	10
1,000+	5	0.8	1	20
Total	634	100	47	7.4

two pests particularly challenging. These details may provide information about possible openings for preventative and biological control research and interventions, underscoring the importance of integrating biological and social data.

Challenges of Alfalfa Weevil

Respondents listed a variety of agronomic challenges when explaining why they thought alfalfa weevil was the most problematic insect. These challenges included decreased alfalfa yield and quality and challenges related to timing, either within the season or across years. Chemical control was repeatedly indicated as necessary although costly. The biology of alfalfa weevil was referenced by those who either thought that it was the only insect that caused problems in alfalfa or a particularly abundant pest. Respondents described alfalfa weevil as the "only real damaging pest" or the "only insect we encounter." Two respondents stated that alfalfa weevil was most problematic because of the behavior of their neighbors, with one stating "I am surrounded by large producers that may choose not to chemically control these insects." Another reported, "my neighbors don't spray. Last year, my neighbor's fields were full of weevil which moved to my field. We cut the hay and found thousands." They are inferring that insect movement between fields of different landowners is important.

Challenges of Lygus

Although far fewer survey respondents identified *Lygus* as their most problematic pest, they consistently pointed to similar reasons for identifying it as such. The main agronomic challenge was the considerable damage to bloom and seed stages of alfalfa. Chemical control was again repeatedly discussed centered on efficacy including mention of "lost chemistries" to regulation and suspicions of insecticide resistance development in *Lygus*. The challenge of using chemical control while protecting pollinators was cited including mention of the limited number of effective "bee-safe" insecticides available and the need to time applications around leafcutter bee activity (i.e., night applications).

Management Strategies and Biological Control of Alfalfa Insect Pests

We found that for alfalfa weevil, grasshoppers, and aphids, insecticide and early harvest were the most common practices that producers reported having tried (Jabbour and Noy, 2017). For alfalfa weevil, respondents reported using insecticide (55.2% of responses), early harvest (35.3%), and biological control most often (4.3%). These response rates shift when respondents indicated which management practices are most effective against alfalfa weevil, with most respondents indicating insecticides are most effective (79.9%), with biological control lagging in popularity (7.7%), followed by early harvest (4.8%). For both grasshoppers and aphids, insecticide was identified as the most effective tool and the one used most often.

Our results indicate that 7.4% of respondents (47 of 634) had ever tried biological control (for any insect pest). These results suggest that many growers have not tried biological control strategies and rely heavily on insecticides and chemical control. Our focus group data suggests that they value chemical control because of the flexibility it allows, and its effectiveness. There seems to be an interest in biological control, though limited exposure to it, and our data suggests that focusing on flexibility and effectiveness may be useful strategies to highlight when appealing to growers.

Here, we focus on biological control in particular to better understand which growers are best acquainted with this practice. Although inferences should be undertaken carefully because of small sample size, we generally find that as alfalfa acreage increases, the percent of respondents are more likely to have tried biological control (**Table 3**). However, because around half of our respondents have smaller farms this may be a particularly important group to target with information about biological control. Our focus group results suggest that perhaps this group is less likely to focus on biological control because of dependence on neighbors (e.g., sharing aerial insecticide spraying) or otherwise being constrained by neighbors' behavior. Therefore, such efforts should proceed cooperatively and communally.

Of the 47 respondents who indicated trying biological control, 38 identified a pest that was most problematic. 60.5% ($n = 23$) of those 38 indicated that alfalfa weevil was most problematic, 10.5% ($n = 4$) indicated aphids, while only 5.3% ($n = 2$) indicated grasshoppers. Again, these small numbers should be viewed with caution in terms of generalizability but suggest that there is room

TABLE 4 | Alfalfa end use of famers who have tried biological control, $n = 47$.

End use	Sample size	Percent (of 47)
For on-farm hay	38	80.85
For off-farm hay	21	44.68
For off-farm seed	3	6.38
For on-farm hay and off-farm hay	15	31.91
For on-farm hay and off-farm seed	1	2.13
For off-farm hay and off-farm seed	2	4.26

Our survey gave respondents the first three options: on-farm feed, hay, and seed. Respondents could select any combination of the three. The latter three categories were calculated based on those responses.

to consider biological control, especially among alfalfa farmers struggling with aphids, and grasshoppers as they are a small proportion of those who have tried biological control.

We also examined reports of trying biological control according to end-use of the crop, including all combinations of the responses for on-farm hay, and seed and hay marketed off-farm (**Table 4**). On-farm hay was included as a distinct survey option, because we hypothesized that those who market their hay to others may have different priorities than those who grow hay to feed their own on-farm animals. Those that had tried biological control were mostly growing alfalfa for on-farm hay while under half were growing it for off-farm hay markets and very few were growing it for seed. This again suggests that future research should examine this disparity and in particular not only why so few alfalfa farmers have tried biological control but whether and how end-use has affected their practice. Only 1% of survey respondents were certified organic.

Altogether, our survey results suggest that there may be demand for pest management strategies beyond traditional pesticide use. However, there may be a variety of reasons that farmers have not or will not try biological control. Chemical solutions are popular for a variety of reasons: flexibility of timing, effectiveness, etc. but there are also concerns with resistance, cost, needing to factor in neighbors' behavior, etc. Further, our data suggest that only a small minority of Wyoming alfalfa farmers have tried biological insect pest management strategies. This, again, suggests the time is ripe for introducing such practices. However, in order to be successful efforts will need to be sensitive to the existing context, network, and the challenges posed by different insect pests and investigate the barriers across end-use.

Egocentric Network Data

Another component of the survey (**Supplementary Material**) elicited egocentric network data: we asked growers to identify "the five people you have most often discussed farming with within the last 12 months" and then asked whether they received and/or gave advice about alfalfa farming and/or farming in general, information about these "alters" (people named) in terms of whether they were friends and how they knew this person (e.g., neighbor, extension professional etc.). As we discussed elsewhere (Noy and Jabbour, 2017), growers on average listed 1.76 alters (people they turned to from advice). We further found that advice networks were characterized by friendship and that the most common category of alters were neighbors. This suggests that advice networks are localized and not only professional, but often personal (Noy and Jabbour, 2017). We note that this suggests an opportunity for experts including Extension professionals and Weed and Pest personnel to provide advice and information, but that they will likely need to build personal relationships before becoming trusted advisors. This was confirmed by our focus group findings (Noy and Jabbour, 2020). This may be particularly important for disseminating information that is viewed as trustworthy about biological control and targeting central "nodes" in the network, people who are broadly trusted and densely connected to try biological control may facilitate its use across networks of growers—which was bolstered by discussions of trust and expertise in the focus groups as well.

Biological Data

Parallel to the collection of social data, we conducted a series of biological studies in alfalfa. Other published work includes an experiment testing the effect of the conservation biological control approach of habitat management, providing different types of floral resources adjacent to alfalfa (Pellissier and Jabbour, 2018). We also explored landscape and local effects of non-crop habitat on weevil densities in production fields in southeastern Wyoming, where only hay alfalfa is grown, not seed (Pellissier, 2016). Here, we share biological findings from a different growing region in Wyoming that includes both alfalfa hay and seed production across the landscape.

Arthropod community composition differed significantly between sample rounds (1 = June, 2 = July), end-use of hay or seed, and the interaction between sample round and end use ($p < 0.001$ for all predictors). The first two principal components, visualized in **Figure 3**, explained 50.8% variance in arthropod community composition. The highest loadings on the first principal component (>0.4) were lady beetle adults, lady beetle larvae, and green lacewings. Along this component, communities in seed fields in July had the highest abundances of these natural enemies, as well as *Lygus* adults, distinctive from seed fields in June. Communities in hay fields, both in June and July, were clustered midway along the first principal component. The second principal component had highest loadings (>0.4) from alfalfa weevil adults and larvae, with hay samples clearly clustered according to sample date: more alfalfa weevils in June samples than July.

In our parasitism assays, we found evidence of biological control by parasitoids of both alfalfa weevil and *Lygus* in both hay and seed fields, although the parasitism rate varied widely between individual production fields (**Figures 4**, **5**). We sampled eight seed fields and eight hay fields, but only found alfalfa weevil larvae in four seed fields and seven hay fields. Parasitism of alfalfa weevil ranged from 0 to 47.5% across all fields assayed (percentage calculated from total of 22–92 weevils per field, mean of 67). Generally, parasitism of alfalfa weevil was higher in hay fields than seed fields, although this difference was not statistically significant ($t = 1.34$, $p = 0.22$). The smaller sample size in seed fields may reflect the earlier and more aggressive chemical management norms in seed production

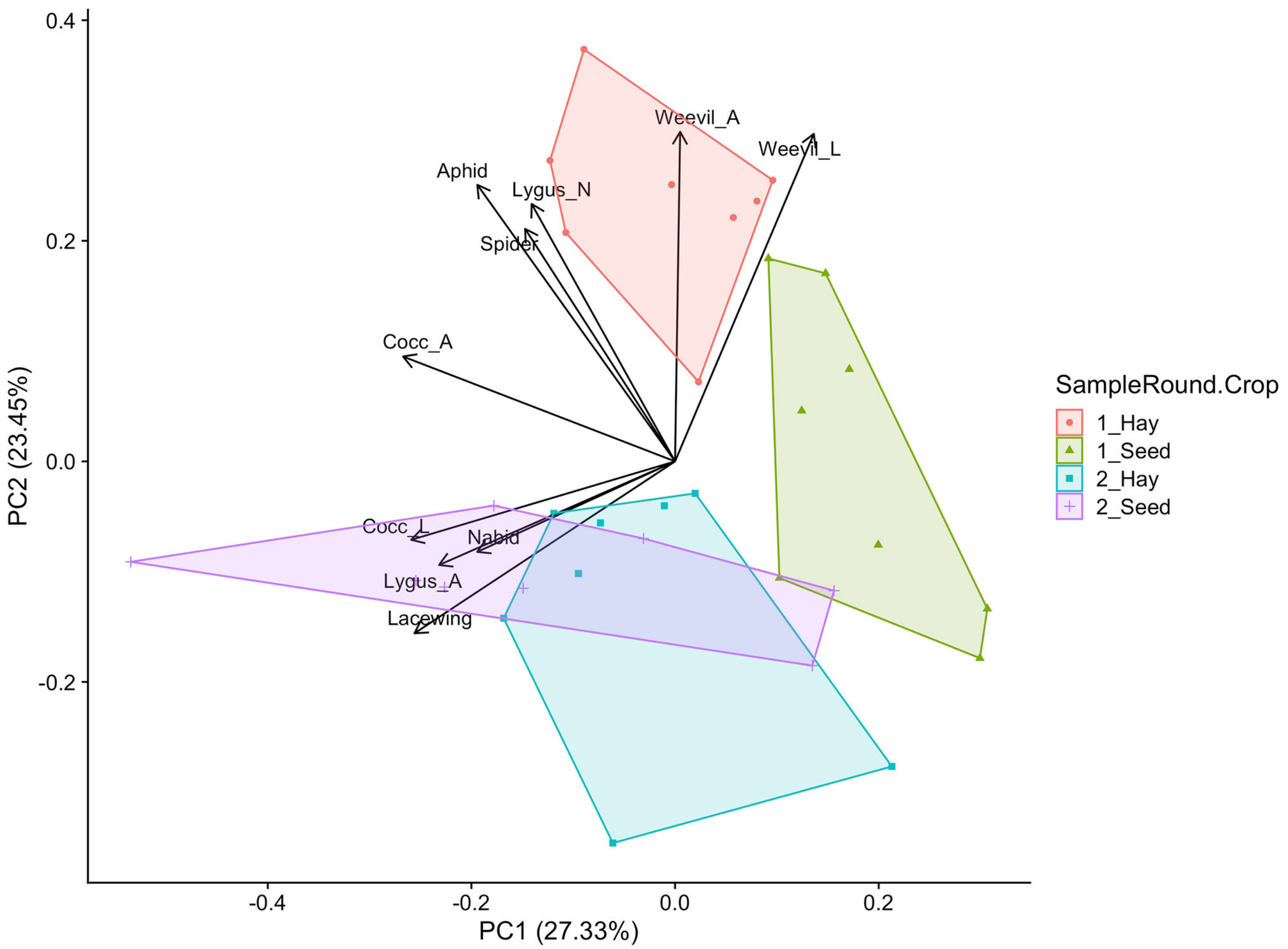

FIGURE 3 | Principal component analysis bi-plot of principal component (PC) 1 and 2. Color and shape distinguish samples according to crop type (hay or seed) and sample round (1 = June, 2 = July). Arrows indicate loadings of arthropod groups representing alfalfa weevil adults (Weevil_A) and larvae (Weevil_L), *Lygus* adults (Lygus_A) and nymphs (Lygus_N), lady beetle adults (Cocc_A), and larvae (Cocc_L) and other groups indicated by common name.

(**Figure 1**). As demonstrated by others (Al Ayedh et al., 1996; Rand, 2013), it is not rare for scientists to find evidence of alfalfa weevil parasitoids in the Western United States. This common biological occurrence contrasts with the producer perspective: parasitoid natural enemies were not mentioned in any of our focus groups or mail survey data. Producers were more likely to mention more visually apparent predators such as lady beetles when discussing biological control. This suggests that there may be important opportunities for education on these forms of biological control which may be best uncovered by research that takes a more holistic, system-based, stakeholder-centered approach—combining biological data with social data.

Parasitism of *Lygus* offers a different story (**Figure 5**). Again, we sampled 16 fields but only found *Lygus* nymphs in six hay and seven seed fields. We dissected anywhere from 5 to 100 nymphs per field, mean of 41 nymphs. Rates of parasitism were generally low or non-existent, and did not significantly differ between production types ($W = 14.5$, $p = 0.39$), with the exception of one seed field in which 85% of *Lygus* dissected were parasitized (29 out of 35 dissected). Some but not all of the fields sampled were managed by focus group participants. This field with evidence of high biocontrol activity was actually farmed by one of the growers from North County who spoke at length about biological control agents such as Nabidae in his field.

DISCUSSION

In this article we have sought to bring together insights from disparate biological and mixed-methods social data, combining qualitative, and quantitative data in the latter. Our project is an ambitious multidisciplinary one, and we take an approach we believe is both increasingly necessary and valuable in insect pest management, and agroecology more broadly. We must seek to understand farmer decision making and complexity from several angles if we are to meet the stated goal of making insect pest management more efficient, accessible, and less damaging to ecosystems. Multidisciplinary collaborations between biophysical scientists

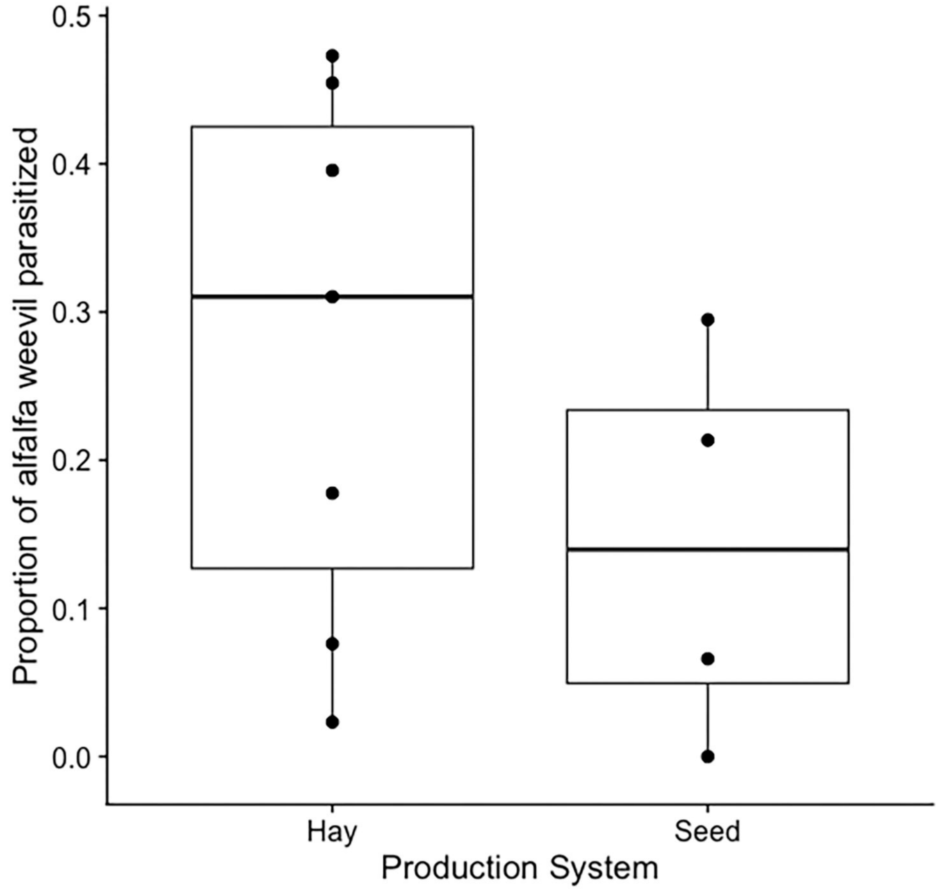

FIGURE 4 | Proportion of late-instar alfalfa weevil larvae parasitized by wasp *Bathyplectes curculionis* in June samples.

and social scientists are critical to best tackle research on environmental problems while building on foundations established in each discipline, using appropriate methodology and interpreting results rigorously (Martin, 2020). We propose that mixed-methods research, a social scientific approach which integrates contextual and relational understandings together with biological and entomological expertise is a valuable one. Underlying mixed-methods research—drawing from quantitative and qualitative data—within the social sciences is the contention that these data (in our study: survey and focus groups, respectively) provide a better understanding of the research issue than either approach alone (Cresswell and Plano Clark, 2011). For instance, quantitative approaches alone result in few consistent predictors of farmer adoption of conservation practices, but integration of qualitative approaches allow better understanding of this decision-making process (Ranjan et al., 2019). Using multiple methods that incorporate quantitative and qualitative data has also been touted as a recent and important innovation in evaluation of Extension programming (Edwards et al., 2019).

Our social data along with our biological data provide complementarity in our understanding of the challenges and successes Wyoming alfalfa farmers experience in insect pest management as well as opportunities for information dissemination, education, and strategies that farmers may be interested in but are underutilized for a variety of reasons. Although we have published some aspects of the study in isolation, we have brought new information from the surveys and focus groups about biological control to this article, as well novel biological data, to outline the project in its entirety and place the data and results in conversation with each other. We have demonstrated that efforts to promote biological insect pest management strategies must account for differences in insect communities across different end-use systems (biological data), that farmers do not seemingly assign much importance to parasitoid activity but are aware of predators (focus group and survey data), and that biological control has not been extensively deliberately employed but is naturally occurring in many production fields (survey, focus group, and biological data). We show that farmers rely on social networks, not only professional but also personal (family and friends) to make decisions (survey and focus group data), prizing chemical approaches for the flexibility they provide (focus group data).

Relying on survey data alone would have obscured the ways in which farmers make decisions, and not just who they turn to for advice, but why. The survey provided an important

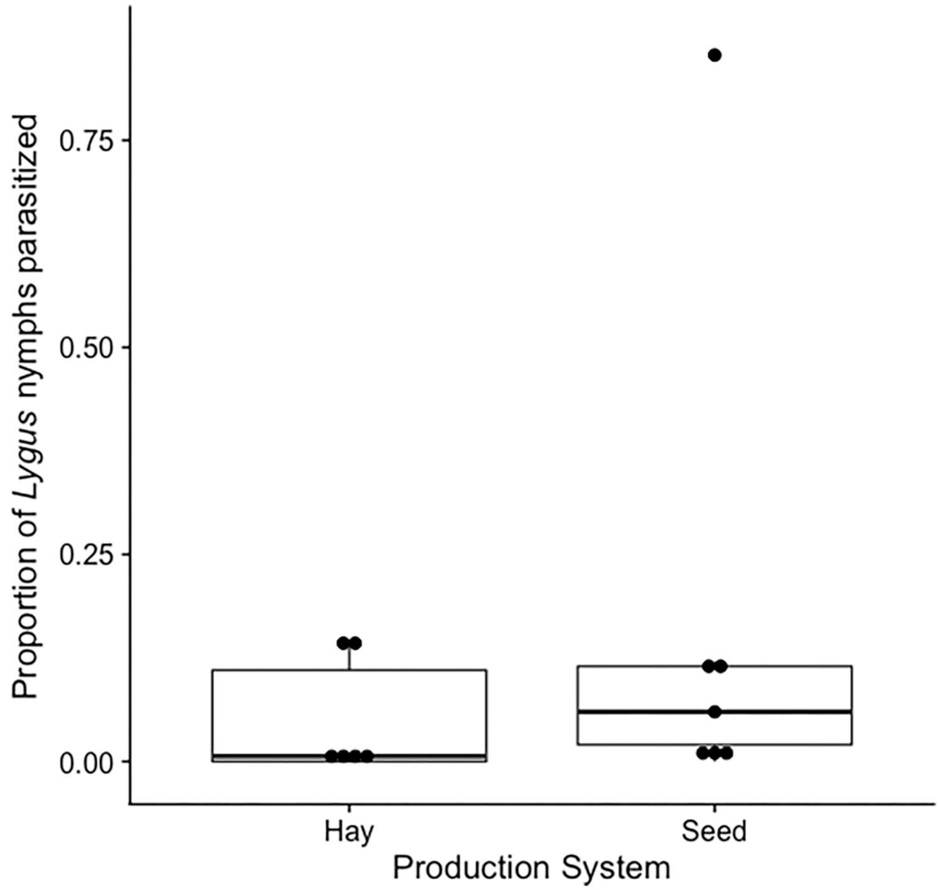

FIGURE 5 | Proportion of *Lygus* late-instar nymphs parasitized by wasps in July samples.

baseline for who has tried biological control but does not provide grower perspectives on *why* they rely on chemical treatments so avidly. Similarly, relying only on focus group data does not allow us the broad understanding of which pests farmers found most problematic, and a broader, state-wide understanding of egocentric networks as well as how prevalent chemical and biological control are across the state and across end use. Finally, the biological data allowed us to deepen our understanding of pests and parasitoids across alfalfa end use (hay vs. seed) and triangulate information with grower perspectives.

In particular, we uncover an important opportunity for education about parasitoid conservation. The opportunity for education about cryptic biological control echoes the findings from a multidisciplinary collaboration in Washington. Apple producers had varying perceptions of the function of nocturnally-active earwigs, with some perceiving them as pests, and biological studies demonstrated their role as important aphid predators (Orpet et al., 2019). In our informal discussion with alfalfa producers, they have often asked about lady beetles, inquiring about the success of purchasing many lady beetles and releasing them in their fields. Commercially purchased and released lady beetles often disperse away from release sites quickly [as described in Cranshaw (2014)]. Generalist predators, including *Coccinellidae*, have not been found to impact alfalfa weevil populations, although they do suppress aphids in alfalfa (Rand, 2017) and can be active against *Lygus* as discussed in our focus groups.

Using survey, focus group, and biological data allows us to elaborate and clarify results across data sources. For example, although our quantitative, survey data suggests that only 7.4% (47/634) of survey respondents have tried biological control, our qualitative, focus group data provides context for this low percentage: suggesting that chemical control allows for more flexibility—especially in timing, coordination with neighbors, and is a tried-and-true strategy. Biological data documents the occurrence of biological control of important pests in production fields, but this activity is highly variable across fields and thus allows us to triangulate various farmer accounts of distinct experiences.

Even with our multi-disciplinary, mixed-methods approach, it is important to acknowledge that our starting focus on insect pest management is still simplified, and perhaps even reductionist, compared to the approach farmers must take in their work. Farmers solve problems across disciplinary boundaries. They engage in systems thinking, although producers who already have adopted conservation strategies are more likely to be systems thinkers than those who have not (Church et al., 2020). Similarly, Orpet et al. (2020) describe subjective perceptions of biological control strategies by producers that highlight a challenge in moving toward systems-level changes, regardless of whether producers are conventional or organic. For example, organic producers are more likely to adopt biopesticides rather than planting intercropped sweet alyssum as a conservation biological practice. When we completed our focus groups, prior to any open discussion or questioning, each participant completed a short written survey. We first asked them to discuss challenges to producing alfalfa, and nearly all of them mentioned non-insect pests and challenges with water and drought. The importance of these non-pest management challenges echoes the suggestion that we must not only demonstrate effectiveness of biological control, but also embrace practicality and the ability to address multiple management needs through suggested practices (Orpet et al., 2020).

Multiple management needs may interface with other non-insect pest management and conservation goals. Non-insect pests discussed were mostly vertebrates (we list names as expressed by participants): gophers, deer, birds, mice, racoons, skunks, and in one focus group, grizzly bears. This discussion highlighted the importance of these other animals to producers, also an issue at the interface of pest management and conservation. Birds, for example, have been documented as pests of crops (Kross et al., 2020) but also have been shown to contribute ecosystem services including, specifically, insect pest management in alfalfa (Kross et al., 2016). Alfalfa and other perennial forage crops are often highlighted as ideal cropping systems to advance conservation efforts in otherwise intensive landscapes (i.e., Strum, 2018). Through our framing of the problem and our respective areas of disciplinary expertise, data collected via the survey, focus groups, and entomological sampling addressed the specific focus of insect pest management. The opportunity remains to more broadly link management for biological control with other conservation-oriented goals (Sidhu and Joshi, 2016). In addition, IPM is not innately pollinator-friendly, and recent attention focuses on how to explicitly integrate both pest and pollinator management into a new "IPPM" (Egan et al., 2020).

Our work focused on the perspectives of producers themselves. Although they mention the importance of agricultural professionals such as crop advisors and Extension in both the network portion of the survey and the focus group discussions, we did not separately engage with those professionals to identify their perspectives. Comparison of priorities and perceptions across groups of different stakeholders in the agricultural industry can highlight commonalities and gaps between producers and the professionals who work with them (Jabbour et al., 2014; Wilmer et al., 2019; Boeraeve et al., 2020). Work to bridge these gaps can take the form of sociological research to define perceptions (i.e., Eanes et al., 2019; Boeraeve et al., 2020) or result from participatory, community-engaged research (i.e., Kerr et al., 2018; Wilmer et al., 2019).

This work demonstrates the value of designing research that both honors producer priorities (e.g., a focus on pests of concern) while pursuing scientist interests (e.g., quantification of parasitism). In our study, quantitative data has allowed us to examine trends and broad patterns while our qualitative data has allowed us to understand farmer perspectives and contextualize and interpret these findings. Such a mixed-methods approach, that blends social and biological data, has recently been shown to be fruitful in examples of biological control of apple pests in the United States (Orpet et al., 2019, 2020) and to evaluate social sustainability of biocontrol for dengue in Vietnam (Tran et al., 2015). It has also proven effective in other agroecological studies beyond insect pest management, for example Boeraeve et al. (2020) use survey, field data, and open-ended questions to understand landscape and ecosystem services in transitioning landscapes in Belgium while another recent study by Kerr et al. (2018) utilized focus groups, interviews, observations, surveys, and participatory agroecology experiments to examine perceptions and effects of climate change in Malawi. As we have discussed and demonstrated above, understanding insect pest management, and promoting preventative and biological control mechanisms is enhanced by collecting qualitative and quantitative, as well as social and biological, data. In order to design, develop, and understand biological insect pest management we must endeavor to advance not only the biological information, but also understand farmers' needs and motivations if we are to promote such strategies successfully and in ways that benefit growers.

DATA AVAILABILITY STATEMENT

The biological data will be made available by the corresponding author upon request.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by University of Wyoming Institutional Review Board. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

SN and RJ both conceptualized the manuscript, designed the research, collected and analyzed data, wrote, and edited the manuscript. Both authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2020.548545/full#supplementary-material

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.