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RESEARCH ARTICLE

How can policymakers and researchers develop effective insect resistance management guidelines? A quantitative and qualitative study of Brazilian farmers' perspectives and attitudes

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Societal Impact Statement

Today, over 80% of the US and Brazil row crop acreage has plants expressing insecticidal proteins to prevent the damage caused by caterpillars. These plants (crops expressing *Bacillus thuringiensis*, Bt, toxins) have brought several benefits to farmers, the environment, and society. However, these can be eroded when insects develop resistance to these toxins. Researchers and regulatory agencies have developed tactics that should be followed by farmers to avoid resistance but with limited efficacy. Our research provides recommendations for researchers and policymakers that are based on farmers' perspectives, thereby offering changes for current guidelines to successfully manage insect resistance and protect Bt crops' efficacy.

Summary

- Genetically engineered crops expressing insecticidal proteins produced by *Bacillus thuringiensis* (Bt) have brought numerous benefits; however, pest resistance evolution poses a threat to the sustainability of this technology. Insect resistance management (IRM) for Bt crops has been defined as a wicked problem as it involves sociobiological complexities. A main challenge in IRM is the adoption of non-Bt refuge, which is one out of the few strategies amenable to human intervention.
- This study investigated farmers' perspectives on information sources and IRM practices in Brazil using quantitative and qualitative data collection. A total of 145 farmers responded to online Qualtrics surveys, and 13 farmers participated in person to open-ended interviews.
- This study demonstrates that farmers rely on strong social networks for information exchange and that sources with expertise based on local field experience are the most reliable channels of communication. We identified new challenges for refuge adoption such as the need to spray insecticides for pests not targeted by Bt and the intangible aspect of resistance evolution. Based on results of sources of information and perspectives on IRM practices, we discuss strategies that may be successful in delaying insecticide resistance evolution based on local contexts.

- This is the first study to investigate Brazilian farmers' perceptions on information sources and IRM strategies using qualitative data. Our results provide important elements to orient research development and decision-making in biotechnology policies for the agricultural sector in Brazil and other similar contexts.

KEYWORDS
B. thuringiensis, farmers' decision-making, refuge adoption, sources of information, technology adoption, transgenic crops

1 | INTRODUCTION

Studying farmers' perceptions and attitudes is fundamental for pest management as it links sociological influences on ecological systems. Among the many challenges that farmers face for crop production, the management of insect resistance to *Bacillus thuringiensis* Berliner (Bt) crops merits a special analysis as it involves social, economic, biological, and regulatory complexities (Gould et al., 2018). Since its initial release in the United States in 1996, the adoption of genetically modified plants with the expression of insecticidal proteins from Bt has been increasing around the world (James, 2019). The wide adoption of this technology can be attributed to its number of operational, environmental, and ecological benefits (Agroconsult, 2018; Alves et al., 2009; Barros & Degrande, 2012). However, these benefits have been undermined by the evolution of insecticide resistance of insect pests to Bt toxins. Even though resistance evolution is a biological process that evolves from insect-plant-insecticide interactions, pest management is a human activity that can drive insecticide resistance in the first place.

Insecticide resistance management (IRM) relies on the combination of tactics that aim to avoid or delay the evolution of resistance in a preventive fashion, and many countries have adopted various forms of governance for the IRM of Bt crops (Carrière et al., 2020). Among the factors influencing resistance evolution, including pest genetics, biology and ecology, and resistance management, only resistance management is amenable to human intervention. Out of these, a main IRM tactic is the planting of non-Bt refuge. When planting non-Bt refuge, the goal is to reduce the selection pressure for a proportion of the population (Bates et al., 2005), creating opportunities for resistant insects (that survived in the Bt field) to mate with susceptible insects (from the refuge) rather than having resistant insects only mate with one another and pass on their genetic resistance to the next generation. Indeed, for certain pests, studies have shown that resistance development to Bt toxins is associated with lack of refuge adoption (Huang et al., 2011; Tabashnik et al., 2008, 2013).

Governmental regulations with different levels of enforcement have been created to increase refuge adoption by farmers (Carrière et al., 2020); for example, in the US Cotton Belt, the Environmental Protection Agency requires farmers to plant 20% refuge when using Bt crops (USEPA, 2021). However, regardless of enforcement levels, refuge adoption by farmers varies significantly across different landscapes (Carrière et al., 2020). For example, refuge adoption has been reported to be of over 70% in the US Midwest (Hurley et al., 2005) and 40% in the US Southeast (Reisig, 2017). The lack of refuge compliance has been associated to the availability of refuge from neighbor farms, operational difficulties, lack of importance attributed to IRM, lack of problems with Bt target pests, and availability of non-Bt refuge varieties (Hurley et al., 2005; Kaup, 2008; Reisig & Kurtz, 2018; Smith & Smith, 2014).

One way to better understand farmers' behavior toward IRM and consequently develop programs to increase the planted area of refuge is to analyze the sources of information farmers trust and rely on to make agronomic decisions. Farmers balance many considerations while running their operations, and they must consider economic and environmental conditions that are outside of their control while also weighing information in the quest to optimize economic return relative to input, convenience, and unreasonable risk of crop losses. Regarding the support for adoption of new technologies and practices such as IRM, Monge et al. (2008) reported the importance of extension personnel on the dissemination of information, but several other information sources in farmers' network can also have an impact on their decision-making. Narayanam and Narahari (2011) showed that the connections that people make in a network have a large impact on how ideas and information spread. While extension personnel are crucial to share information, studies of various geographies indicate that other farmers and agronomists/sales representatives are often the top sources of knowledge for farmers (Andow et al., 2017; Crawford et al., 2015; Kaup, 2008). However, most studies focus on quantitative surveys, and the reasoning behind farmers' preferred sources of information is currently lacking in Brazil.

Therefore, the goal of this study was to investigate farmers' perspectives on information sources and IRM practices focusing on Brazilian farmers that grow soybean and corn. Our specific goals were to both identify and understand the reasons behind farmers' preferred sources of information and to investigate their attitudes and beliefs toward IRM recommendations and factors that have the potential to promote refuge adoption. To do this, we used quantitative and qualitative data collection methods to investigate general trends and in-depth information behind farmers' perspectives on these issues. Our research contributes to the literature in three ways. First, it is the first to study Brazilian farmers' perceptions on sources of information and attitudes toward IRM using qualitative data. Overall, results show that farmers rely on strong social networks and interactions with community-rooted stakeholders for information exchange. Farmers perceive that information based on local field experience is the most reliable type of information. We identified new factors that influence farmers' perceived value of Bt crops and refuge adoption, which include the need for insecticides to control pests not targeted by Bt toxins, and the non-tangible aspect of resistance evolution. Second, this study adds to the literature that investigates the role of human behavior by contrasting responses collected from surveys and interviews and by demonstrating the importance of using both data collection methods to study complex issues in agriculture. Third, this study provides important elements to orient research development and decision-making in biotechnology policies for the agricultural sector in Brazil and potentially other contexts by expanding from farmers' preferred sources of information and by arguing that there is a need to consider geographical heterogeneities, including the consideration of region-specific culture and market and local pest management practices.

1.1 | IRM in Brazil

Brazil stands out as an important landscape to study farmers' perspectives on resistance management practices and sources of information in the context of IRM. First, Brazil is ranked as one of the world's largest producers of economically important crops such as corn (*Zea mays*) and soybean (*Glycine max*). In Brazil, the adoption of Bt crops has led to yield increases, reduction in the use of insecticides and fuel savings, job creation, and less environmental impacts (Agroconsult, 2018). Of the total area planted with corn and soybean in this country, 79% and 62% express Bt toxins, respectively (Agroconsult, 2018). In addition to corn and soybean, the Brazilian landscape also has cotton and sugarcane expressing Bt toxins, which, in addition to tropical conditions that provide ideal temperature and environmental conditions for insects to undergo multiple generations in a year and multiple plantings of Bt crops in a year, create a scenario favoring rapid resistance evolution (Bernardi et al., 2016; Fatoretto et al., 2017). Several Lepidoptera of economic importance have developed field-evolved resistance to Bt toxins in Brazil, and major concerns are associated with feeding by fall armyworm, *Spodoptera frugiperda* (J.E. Smith) (Farias et al., 2014; Omoto et al., 2016).

In addition to biotic factors that favor resistance, Brazil has a different regulatory system for refuge compliance of regulations in other geographies (Carrière et al., 2020). In Brazil, the National Technical Committee for Biosafety (CTNBio) assesses the biosafety of modified crops, but it does not evaluate or regulate issues related to resistance management, and IRM is not mandatory (Bernardi et al., 2016; Carrière et al., 2020). Resistance management practices for Bt crops are promoted by technology providers and academic and government researchers (e.g., EMBRAPA) (CIB, 2018; IRAC, 2017). These include educational materials for farmers such as information distributed through lectures on events, field days, and websites.

In Brazil, adoption rates following IRM guidelines are reported to be of 25% (Fatoretto et al., 2017; Resende et al., 2014). Since the introduction of Bt crops, one of Brazil's agricultural industry's main challenges has been refuge compliance (Fatoretto et al., 2017). Results from Resende et al. (2014) show that the low refuge adoption can be explained by the fact that many farmers do not fully understand the function of planting refuge for resistance management. The study highlights that one of the challenges for the adoption of refuge in Brazil is because the practice is mandatory not by law but by contracts with technology providers, giving the false impression that the problem of resistance is a problem that technology providers need to solve (Resende et al., 2014). Overall, studies that have investigated refuge adoption in Brazil and farmers preferred information sources that are limited to surveys. Quantitative methods for data collection are used to test specific hypotheses; they are quicker, are more cost-effective to execute, and can collect results from large sample sizes. In contrast, qualitative research is more suitable for exploratory purposes, and the depth and richness of results obtained using interviews cannot be obtained with quantitative data alone.

2 | MATERIALS AND METHODS

Given that our goal was to assess farmers' perspectives on sources of information and on IRM practices in Brazil, the study targeted soybean and corn farmers as participants, using surveys and interviews. Details of how and why these methods were applied are described on the sections below. For both surveys and interviews, farmers voluntarily registered to participate in the study. Data were collected in Portuguese and translated to English by Author 1, who is a native Portuguese speaker. Before the study was initiated, a human subject research protocol (#20943) was submitted and approved by North Carolina State University's Institutional Review Board.

2.1 | Surveys

First, we performed data collection using a structured questionnaire by Qualtrics. From April to July of 2021, recruitment material, including a link for the survey, was sent to farmers through WhatsApp groups that had agriculture as the focus of the group and had farmers and agronomists as members. These WhatsApp groups were first identified by Author 1 personal and professional connections, and through these initial connections, she sought additional groups to recruit participants. The recruitment material detailed the main goals of the study and stated that only soybean and corn farmers were eligible to participate. Each participant voluntarily completed the survey on a Qualtrics web-based platform using their personal computer or smartphone. The survey had a total of 30 questions where 28 were multiple-choice or yes/no answers and two were descriptive (Supporting Information S1). The descriptive questions asked participants to list their city and state and to list the role of three people that were the most influential in their management decisions. Farmers were instructed to indicate the role of these people instead of their names to protect privacy (Supporting Information S1). Overall, questions covered demographics, perspectives on sources of information, overall farm management, and perspectives on IRM (viz., Bt plant-incorporated protectants and refuge strategy) (Supporting Information S1). A quality control question was used to validate answers; non-validated responses were deleted from the analyses. For the descriptive results, mentions of different information sources were calculated for the following categories: agronomists, social media, university researchers, family, other farmers, self-experience, and consultants. Grouping was done by looking at the full list of answers and examining for overall trends and by referring back to the list of sources of information in the multiple-choice question. When a response included two categories, "my agronomist daughter" for example, scores were given to both the agronomist and the family groups. Answers that were only mentioned one time and were not listed on the multiple-choice question were not included in the results because of lack of relevance of that source of information.

2.2 | Interviews

Results from surveys were limited to multiple-choice answers. Therefore, we further conducted interviews to understand farmers' perspectives and attitudes, following the same questions used on surveys but in a semi-structured format. A semi-structured interview is a type of interview in which the interviewer asks few predetermined questions while the rest of the questions are not planned in advance (Krueger, 2014). The interviewer follows a guideline but is able to follow topical trajectories in the conversation that may stray from the guide when it seems appropriate. The use of surveys beforehand allowed us to analyze major trends and then formulate questions for semi-structure interviews that investigated issues in more detail. The purpose of collecting qualitative data is to identify themes associated with the responses to questions of interest and not to gather quantitative information about what proportion of farmers have specific beliefs or attitudes (Krueger, 2014). The statements collected during interviews by our study may not represent the full scope of farmers' perceptions on information sources and IRM practices, but they bring in-depth information that we have categorized into themes to reveal novel perspectives behind farmers' attitudes.

To collect data, potential participants received an invitation for the study through WhatsApp and voluntarily replied to Author 1 by providing a name and phone number. The invitation contained details on the study such as objective and requirements to participate. Respondents from interviews were contacted through a family farm network of Author 1 as she was local to the region and had friends and family that are farmers. Once a list of interested potential participants was available, Author 1 selected them based on a representative range of farm age and size (Table 1). Each participant received a phone call or text from Author 1 to schedule a day and place for the interview. Interviews were held with Author 1 at farmers' properties and lasted an average of 2 h, with one participant at a time. During the interview, Author 1 gave more details on the objectives of the study and obtained a signed consent form from the participant to be interviewed; interviews were audio recorded. In general, questions were the same used in the Qualtrics survey (Supporting Information S1) but with an open-ended response as described above. Notes were taken during the interview in a notepad or in her cell phone, which were kept with Author 1 for confidentiality purposes.

TABLE 1 Results of demographics (age and area planted) of farmers that participated in the study by answering to online surveys and to interviews. In the survey, farmers indicated their age and the area they farmed in hectares in a multiple-choice question. In interviews, farmers' age and area planted were collected in the recruitment material

Parameter	Number surveyed, percent of total (145)	Number interviewed, percent of total (13)
Age		
18–27	68 (46%)	1 (8%)
28–37	32 (22%)	4 (31%)
38–47	20 (14%)	4 (31%)
48–57	20 (14%)	3 (22%)
>68	5 (4%)	1 (8%)
Area planted (hectares)		
<100	47 (32%)	2 (15%)
100–300	30 (21%)	4 (31%)
300–600	24 (17%)	3 (23%)
600–900	9 (6%)	1 (8%)
>900	35 (24%)	3 (23%)

To analyze the qualitative data, a color-coding method was used to identify answers that fit into the different categories. Categories were predetermined, based on the objectives of the study: "sources of information," "refuge adoption," and "factors promoting adoption of refuge." The category "perception on the value of Bt" was created after analysis of statements and relevance to the study. As statements were analyzed, major themes were identified based on the frequency of similar beliefs or thoughts. Statements that mentioned specific soybean or corn trade names (e.g., Xtend, Enlist, and Intacta) were replaced by Bt soybean and Bt corn, respectively, for data protection. Farmers' statements were then organized into four main categories (Note S2, Note S3, Note S4, and Note S5), and results from interviews presented below were obtained through analyses of these statements by category.

3 | RESULTS AND DISCUSSION

The data presented below are based on responses from a total of 145 farmers that responded to the online Qualtrics survey and 13 farmers that participated in person to open-ended interviews. The age and the area planted by respondents are presented in Table 1. Results are presented in four sections: sources of information, perceptions on the value of Bt, refuge adoption, and factors promoting adoption of refuge. For each of these sections, we present main results obtained from Qualtrics surveys and interviews and discuss and compare them to the available literature.

3.1 | Sources of information

Results from multiple-choice answers showed that researchers, other farmers, and self-experience are the preferred sources of information for farmers (Figure 1). On the Qualtrics survey's descriptive question, agronomists and other farmers were the sources of information mentioned most frequently by farmers (Table 2). Similarly, analyses of statements collected during interviews indicate that farmers use other farmers, agronomists, family members, and self-experience as preferred sources of information. Comparing results from the multiple-choice and descriptive questions in the Qualtrics survey, the low ranking given for agronomists in the first may be because this category was broken down to agronomists from cooperatives and agronomists from seed dealers in the multiple-choice questions. Researchers were mentioned less often as preferred sources of information during interviews in comparison to results from multiple-choice questions. This discrepancy between responses collected during the Qualtrics survey and interviews may be attributed to the way farmers interpreted the question (e.g., preferred source as the most desirable source or as the most used source of information) or because of a response bias of respondents taking the survey (Grimm, 2010). For example, for the Qualtrics survey, respondents were introduced to the researcher leading the study, which may have influenced them to say something that in their perspective was desirable (e.g., researchers are a preferred source of information). In contrast, farmers that participated in the interviews were introduced to the researcher as a farmer's daughter, family, or friend interested in their perspective.

Overall, our study shows that farmers rely on social connections to exchange knowledge concerning farm management. This is demonstrated by the number of times that farmers mentioned family and friend in conjunction with other roles in the survey's descriptive question (Table 2) and by analyses of statements collected during interviews. Information exchange during social interactions was mentioned by 6 out of 13 farmers interviewed. For example, one farmer mentioned "we share our experiences with farmers at family reunions and while we are around in the city [e.g., informal talking while running errands]," indicating that information sharing is multidirectional and that farmers receive information organically, without necessarily seeking a formal knowledge transfer. Another farmer said "I believe that we learn a lot by having simple day-to-day conversations with people. There is a lot of information being exchanged; it's like gossiping about what is working or not working in the farm," indicating that farmers value the simplicity of informal information exchange among groups and that expertise is passed along based on individuals' experience.

Results from sources of information on surveys and interviews showed that farmers value self-knowledge in farming experiences that are both actual and ongoing (Figure 1). During interviews, farmers said that they "know what works and what doesn't by experience," that their "farm functions as a test site," and that they "tend to prefer certain varieties based on experience with them in the field." These statements indicate that farmers greatly value local experiential knowledge as they see it as having practical, personal, and local relevance. Further reinforcing farmers' value on farming experience, our results indicate that farmers have other farmers as the main contact for information exchange. The preference for receiving information from fellow farmers seems to be based on trust in the honesty of the recommendation, as a farmer said that "the most trustworthy source of information is other farmers because they receive no advantage by saying something" and because products are validated based on a

TABLE 2 Results of farmers' preferred sources of information responding to the question "Who are the 3 most influential people in your management decisions? Cite only your occupations and/or your relationship with these people" in the online survey. Responses were descriptive (e.g., farmers typed their three most influential people in management decisions in the answer line), and results presented in the table describe the most cited categories on sources of information

Sources of information	Number of mentions*
Agronomists	84
Family	70
Researchers/professors	36
Other farmers	34
Friend	32
Consultants	29
Self-experience	11
Social media	4

*The number of mentions reflects the total count of mentions based on 145 respondents; that is, if a farmer wrote "my daughter that is an agronomist," one mention is given to family, and one mention is given to agronomist.

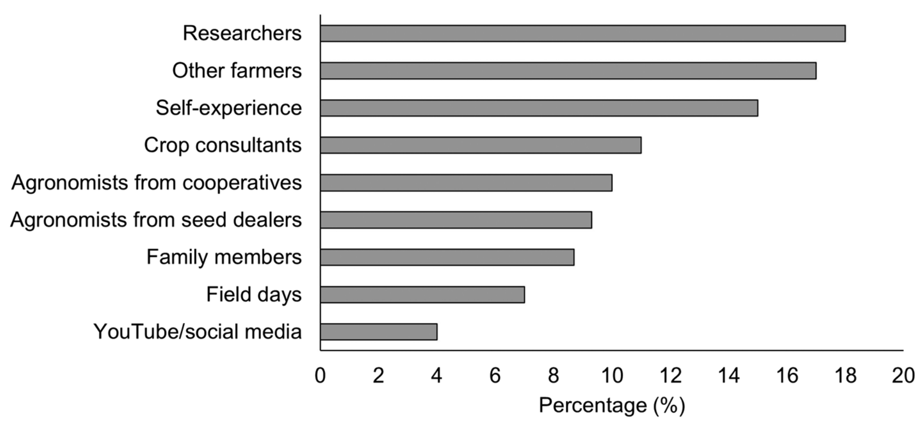

FIGURE 1 Farmers' responses to the question "From the list below, select three sources that you consider most important for your crop decisions" using online surveys. The question presented multiple-choice answers that were preestablished based on literature. Answers presented in the figure are based on 145 participants.

non-biased source, as another farmer stated that "farmers can be viewed as researchers because they try out something before telling you; if something doesn't work, they have no reason to tell you about it." Local information and expertise, often based on experience rather than scientific findings, are particularly important in farming, where farmers are subject to conditions that are not only unpredictable (weather and rainfall) but also mutually constitutive (weather affects insect populations) and localized (neighbor's management practices may impact pest prevalence in neighbor fields) factors.

The descriptive question in our survey and our interviews identified that agronomists, who are represented by seed and chemical sales representatives from retailers, are a major source of information for farmers in our study (Table 2). A farmer mentioned that farmers "have a lot to worry about and instead of getting information from each category [weed sciences, soil sciences, entomology, and plant pathology], it's easier to have a summarized recommendation from a trusted agronomist," indicating that experience, in particular, was prized given the localized nature of challenges and the relationship between weather, weeds, insect pests, water availability, and market demands. Another farmer mentioned that "retailers have the largest social network with many personnel in the field," indicating an advantage that agronomists bring information based on experience with multiple farmers in a region and because compared to other information sources (e.g., researchers, consultants and technology providers' representatives), there is a substantially larger number of sales representatives within a region, so they have the opportunity to make connections to farmers more often than other sources, being able to build relationships and trust. Another farmer said that "agronomists help us a lot because they will come and help us scout and identify what is damaging our crops," meaning that farmers value agronomists' assistance such as scouting and recommendations at no cost. A farmer referred to agronomists by saying that "they know how to sell and win over people, many farmers develop social interactions with agronomists, they go to the same events and do other things besides talking about agriculture," demonstrating that the agronomists are embedded within farmer communities and their social networks, as that these attributes facilitate their professional performance as sales representatives. Furthermore, agronomists seem to co-occupy roles with strong social ties with farmers, as many farmers indicated that they have family members and friends that are agronomists.

Regarding farmers' perspectives of researchers as sources of information, a farmer said that "researchers are the ones that have the most technical knowledge of things," indicating the value of in-depth knowledge that researchers have on specific disciplines. Another farmer stated that farmers are "thankful for researchers because without them, farmers wouldn't have information about anything," demonstrating that farmers believe scientists are a key component on the development of new technologies to farmers. However, many farmers interviewed in our study indicated that researchers are less accessible or difficult to contact, as demonstrated by the statement "I wish we had more contact with researchers from universities, but I only have the opportunity to talk to them like two or three times in a year." Also, as indicated by statements collected during interviews, researchers were not mentioned as the primary sources of information for farmers, which may be because, in comparison to other sources, researchers are not embedded within farmers' social interactions. Another explanation of why farmers did not mention researchers as a primary information source may be because researchers do not interact with them in a continuous or frequent basis, which may be associated to a bigger region that researchers cover in comparison to agronomists and because researchers' appointments are not solely focused on extension but on teaching and research as well.

This is the first study investigating sources of information of farmers in Brazil using qualitative analyses. Our results provide in-depth analyses on the reasoning behind farmers' preference for certain sources of information, which align to preferred sources observed by studies conducted in other countries. Similar to our results, Resende et al. (2014) reported that seed dealers/retailers were ranked as the top information sources for farmers in Brazil, but the study does not explore the reasoning behind this choice. In the US, multiple studies have reported that farmers' learning relies on firsthand experiences and grower-to-grower information sharing is particularly effective (Eckert & Bell, 2005; Franz et al., 2010; Noy & Jabbour, 2020; Sutherland & Darnhofer, 2012). In the Midwestern US, Andow et al. (2017) reported that farmers had consultants and seed dealers as their primary contact and had more confidence in people they had worked with a long time. Similar to our results, farmers appreciated the independent, unbiased input and knowledge of Extension but that the communication was more difficult (Andow et al., 2017). In North Carolina, organic farmers mentioned networking (face-to-face interaction with other growers, individuals, neighbors, or family members) as the most effective source of information (Crawford et al., 2015). In Pakistan, information from friends and fellow farmers was ranked to be the most effective of sources, followed by pesticide agencies, and extension field staff (Ashraf et al., 2015). Special emphasis is given to a study conducted by Wood et al. (2014), which identified three major themes regarding farmers' most valuable contacts in New Zealand: (1) the value of knowledge delivered in person, (2) the sharing of farmer experience, and (3) farmer empiricism. Finally, results presented above align with the theory of the reflexive producer, where farmers use both locally produced lay knowledge and the imported knowledge of experts for decision-making (Kaup, 2008).

3.2 | Perception on the value of Bt

Results from surveys indicated that insect suppression is one of the major reasons that farmers choose to plant Bt crops, in addition to yield potential (Figure 2). Similar results were obtained from interviews where farmers indicated that they prefer varieties with the latest technologies on herbicide resistance and Bt toxins and with specific agronomic characteristics such as yield, maturity, and yield consistency under stress conditions. During interviews, a farmer mentioned that "all of our corn is Bt … because of the operational efficiency with Bt, security about the crop and the harvest, decreased

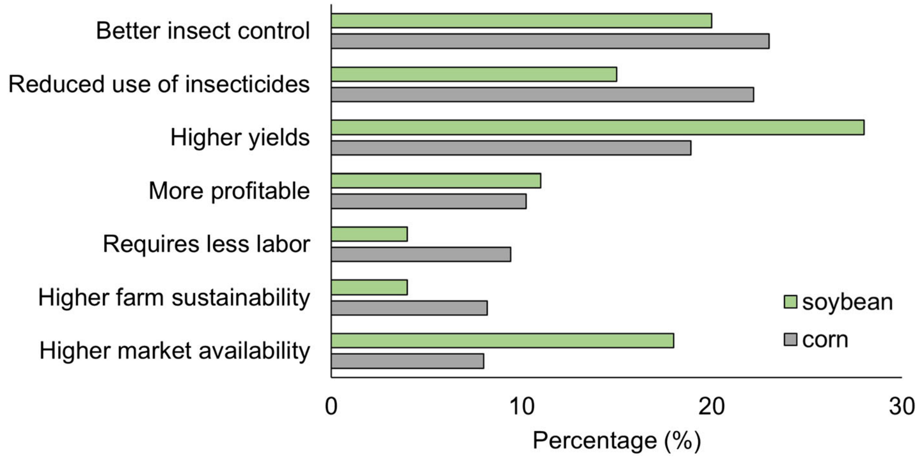

FIGURE 2 Farmers' selections on the reasons for planting corn and soybean expressing *Bacillus thuringiensis* toxins (Bt crops) based on 145 respondents using online surveys. The survey had two separate questions for corn and soybean. For corn, the question asked is "What are the top 3 reasons for you to plant Bt corn (Yieldgard, Herculex, Viptera 3, PowerCore, VT Pro 3, Leptra, Optimum Intrasect, and Agrisure)?". For soybean, the question asked is "What are the top 3 reasons for you to plant Bt cultivars (ex: Intacta or Conkesta)?".

efficacy of commercial [i.e., foliar] insecticides, and less genetic development [i.e., breeding and traits] with non-Bt varieties," indicating that the reasons he plants Bt crops are because of insect suppression and the operational benefits of not spraying insecticides and because of the perception that Bt varieties have higher yields than non-Bt ones. Another farmer said, "we plant 100% of our area with Bt corn … we are in a tropical region, very warm weather, and high pressure of Spodoptera, it's very difficult to manage," indicating that Bt crops are used as a prophylactic tool to control high densities of insect pests. Similar to our results, Resende et al. (2014) and Agroconsult (2018) reported that the main reasons Brazilian farmers choose to plant Bt crops are to control damaging insects, increase flexibility in farm management, reduce use of insecticides, and increase yields. Studies elsewhere have reported a similar trend regarding farmers' intentions to plant Bt crops such as reduced risk to yield robbing insects, higher yield, ease of use, more convenience, reduced use of insecticides, and environmental concern (Kaup, 2008; Pilcher et al., 2002; Skevas et al., 2009; Useche et al., 2009).

Analyses of statements above also illustrate farmers' use of Bt crops as a preventive tool to decrease risks associated to crop damage by insects. Risk management is an important driver behind the use of Bt crops because farmers make planting decisions before knowing the severity of pest infestations. Also, more security with a crop may be a key advantage given that there are many insecurities associated with farming (e.g., weather events) and because farmers historically experience high insect pressure. This confirms previous findings from Maia and Silveira (2014) in a study with farmers in Brazil, which showed that risk perception tends to be higher with farmers that choose to plant Bt seeds than those that plant non-Bt varieties. Kaup (2008) also shows that one of the main reasons farmers choose to plant Bt corn is because they anticipate having insect problems.

In addition, our results from surveys and interviews showed that farmers attribute a higher value of Bt to corn than in soybean (Figure 2). For example, a farmer stated that "Bt has more value in corn, because we have more challenges to spray for fall armyworm; for the beans, we spray more in conventional soybeans; for Intacta [a trade name for a type of Bt soybeans], we need to worry about Spodoptera," indicating that differences in the value attributed to Bt in corn and in soybean may be due to the feeding behavior of caterpillars, including *S. frugiperda*, on these crops. In corn, many caterpillars feed inside the corn ear beneath the husk or bore into the whorl or stalk, protecting them from external hazards such as foliar-applied insecticides. In addition, Bt corn hybrids currently available in Brazil express Cry1, Cry2, and Vip toxins, whereas Bt soybean varieties express only Cry proteins; these Cry proteins have moderate toxicity to some species of caterpillars, including *S. frugiperda*, and field-evolved resistance has been reported for some species (Bernardi et al., 2016; Farias et al., 2014; Omoto et al., 2016). The attributed Bt value difference farmers place in different crops is also observed with corn and cotton in the Southern US, where farmers likely perceive a higher value of the Bt technology in cotton than in corn, which is explained by the potential damage caused by Heliothinae pests between these crops (Gassmann & Reisig, 2023; Reisig & Kurtz, 2018).

At least half of the farmers interviewed in our study demonstrated a good understanding of the impact of different Bt traits to manage insects. For example, a farmer stated, "we know that fall armyworm is resistant to many of the proteins; in corn the only hybrids that still provide a good control are the ones with Viptera [i.e., hybrids expressing a Vip toxin]. In soybean, the proteins were never 100% effective, and now with resistance, we need to use other control methods. I am curious to see how the new varieties [i.e., varieties expressing Cry1Ac + Cry1F, and Cry1A.105 + Cry2Ab2 + Cry1Ac] will perform," indicating knowledge of how specific Bt toxins such as Cry and Vip impact insects that feed on corn and soybean. Another farmer stated that "there is a lot of variation in the number of insecticide applications across different technologies. For some of the older technologies [i.e., hybrids expressing Cry1 and Cry2 toxins], we spray up to 4 times, which is the same number of applications that we have for non-Bt corn. For newer technologies such as Vip, we don't spray specifically for Spodoptera," indicating that insecticide sprays are managed in response to the insect control that different Bt toxins provide.

Even though our results show that most farmers perceive the value of Bt proteins, farmers mentioned that multiple insecticide sprays are necessary to manage non-caterpillar insects not targeted by Bt on both Bt and non-Bt crops. The need for insecticide applications for other nontarget pests may play a role in reducing farmers' attributed value of this technology for insect suppression (e.g., whether Bt or insecticides are controlling caterpillars). This problem is demonstrated by statements such as “we have had a lot of problems with planthoppers recently, so we need to spray insecticides anyway,” indicating less value for Bt because insecticides are required to other nontarget pests “anyway,” and “I usually don't think about insects when I am buying Bt soybean; there are always left over insects, and we always spray some insecticide, even on Bt soybean; and you know, we have a zero tolerance of insects on crops,” indicating farmers historically experience high insect pressure in their fields and, in addition to risk aversion, some of them will use prophylactic foliar insecticide treatments as a way to decrease risks associated with damage from insects not targeted by Bt. This is the first study that reports the impact of insecticide applications for insects not targeted by Bt toxins on farmers' perceived value to Bt crops. This finding is very important as it likely impacts farmers' behavior toward IRM.

Finally, in addition to insecticide sprays for other insects, in some instances, farmers have associated a skepticism on the performance of Bt traits to historical failures of insect control with Bt crops. For example, one farmer said “we know that the technology works [referring to Bt soybean and corn], that it reduces the population of insects, but we don't trust it much, like we are always suspicious. Look, we never know when the technology is going to fail, is it this or next year? So, we still spray insecticides to guarantee full production,” and another farmer said, “farmers had a very bad experience when the Bt technologies with Cry failed and caterpillars destroyed the crops, so we still spray insecticides on top of Bt because we don't fully trust the technology.” These statements indicate that, based on previous experience, there is a fear that resistance will cause big crop losses in a year; farmers thus spray insecticides as a kind of insurance to make sure pests are under control. However, because farmers did not mention resistance in these statements, it is unclear whether they attribute “technology failure” to insecticide resistance or to other reasons, such as low toxicity levels of specific Bt toxins to insects.

3.3 | Refuge adoption

A total of 56% respondents of our Qualtrics survey indicated that they plant corn non-Bt refuge. However, no interviewed farmer indicated that they planted refuge as recommended by the guidelines. The different levels of refuge adoption collected from surveys and interviews may be attributed to the smaller sample size collected from interviews because of response bias of respondents on surveys or because of how the question was asked on the survey (viz., the question asked whether farmers planted corn refuge but not if they followed recommended planting guidelines). This is demonstrated by a survey that found that 70% of farmers planted corn refuge in Brazil (Resende et al., 2014). However, when asked about spatial and percentage requirements, only 31% of farmers indicated following these guidelines. In addition, similar to responses collected on our surveys, 14% of farmers indicated planting refuge in a separate area, and 27% indicated planting refuge in land with lower yield potential (Resende et al., 2014). The estimated adoption of refuge by 20% of farmers in Brazil by Fatoretto et al. (2017) may be accurate.

Based on responses from the Qualtrics survey, the main reasons for farmers to plant non-Bt crops are because the seed is cheaper and because of concerns with insecticide resistance (Figure 3). Comparison of results from the survey and interviews is difficult because of the lack of interviewed farmers who indicated planting refuge. Investigating the reasons farmers choose to plant non-Bt soybean, farmers indicated that “some farmers still plant non-Bt soybean because of the seed price” and “because of historical familiarity with it and that, in a bad year, they tend to yield more as they are more robust than new technologies.” For corn, farmers indicated that “sometimes I would buy refuge corn since the seed is cheaper” and that “we plant corn refuge in an area with less yield potential and no irrigation, because there is less investment of breeding on refuge corn.” These results indicate that seed price, familiarity with cultivars, agronomic characteristics, and stable yield potential of non-Bt varieties in comparison to Bt varieties are the main reasons farmers choose to plant non-Bt crops.

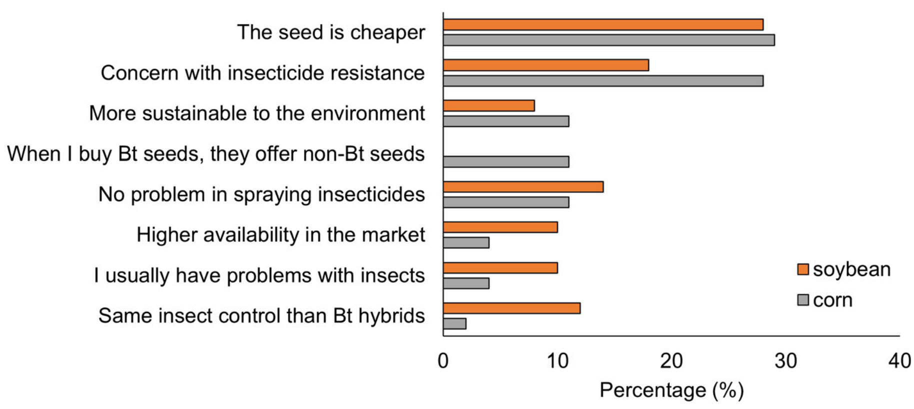

FIGURE 3 Farmers' selections on the main reasons for planting conventional corn and soybean varieties based on 145 respondents using online surveys. The survey had two separate questions for corn and soybean. For soybean, the question asked is “Why do you plant conventional or non-Bt (e.g., soybean not genetically modified to express *Bacillus thuringiensis* proteins) soybeans? Select 3 options.” For corn, the question asked is “What are the 3 main reasons you plant corn refuge?”.

Results from the Qualtrics survey showed that farmers' main reasons for not planting refuge were a lack of understanding of the value of refuge because it requires more labor and because Bt hybrids have higher yields (Figure 4). During interviews, farmers indicated operational difficulties as a main reason for not planting refuge, as demonstrated by statements such as "farmers do not plant refuge because it brings more complexity to the system; it can bring benefits, but if it adds more work to our plate, it will be more difficult" and "farmers don't plant refuge because of operational difficulties; it's basic, managing everything in the same way is easier." Also, in many instances, farmers indicated that they do not plant refuge corn hybrids because they do not yield as much as Bt corn. In addition, a farmer said that "if you spray a specific herbicide in the Bt corn, you will kill the refuge [i.e., the perception that refuge plants don't have the specific herbicide-resistant traits that Bt corn has]," indicating that the lack of specific traits on refuge is a barrier for its implementation.

Finally, analyses of statements collected during interviews identified that the lack of perceived gravity of the problem of insecticide resistance and farmers' overall focus on short-term solutions are additional barriers to the implementation of refuge. For example, a farmer stated that "farmers don't see the need for refuge because they don't see resistance as something tangible, [that is to say] not something that you see happening. It's something that happens bit by bit, we don't plant refuge and we slowly have resistance. If it was a chronic or active problem, we have a pest problem, and we have to solve it, then the grower takes action to do it" and "the problem is that farmers don't see resistance as a big problem, we know that if we have resistance to Bt, we can still control caterpillars with insecticides." These statements indicate that a barrier on the perception of the problem of resistance stands on the fact that insecticide resistance development is not something tangible. Further complicating the problem is that if the caterpillars evolve resistance to Bt, there are foliar insecticides that are still effective. Often times, resistance can be measured in the laboratory, but it might require a few years of lag time for field damage to be observed in the field (Tabashnik et al., 2013). This may diminish farmers' perception regarding the problem of resistance and the urgency to solve it. The use of a refuge strategy in IRM is a preventive long-term strategy to delay resistance evolution and the consequent loss of efficacy of Bt proteins. Overall, farmer's decisions tend to be based on short-term economic concerns (Agroconsult, 2018; Carrière et al., 2020), and as demonstrated in statements such as "many farmers wait for the next step [e.g., new pest solutions]; there is no desire to do it if there is no economic loss in the moment; they think about the immediate profit," farmers' short-term perceived costs of planting refuge outweigh the perceived long-term benefits provided by adopting this particular IRM practice.

This is the first study that investigates the reasons farmers choose to plant non-Bt varieties and why they choose not to plant refuge in Brazil; thus, comparison of our results is limited to studies from other countries. Regarding the reasons farmers choose to plant non-Bt varieties, the positive impact of reduced seed price and concerns with insecticide resistance have been reported elsewhere (Bourguet et al., 2005; Kaup, 2008; Kruger et al., 2009), but in addition to these, we report familiarity with non-Bt varieties and tolerance (e.g., the ability of a plant to cope with variable weather conditions) as factors influencing farmers' preference for non-Bt crops. Although, it should be clear that these factors are associated with farmers' intentions to plant non-Bt crops instead of planting refuge (as it has specific spatial arrangement requirements), these results are important as they can be used to promote planting of non-Bt crops for IRM. Similar to our findings, factors associated with a lack of refuge adoption such as operational costs, difficulties in applying the coexistent regulations, lack of high-yielding varieties (Bourguet et al., 2005; Hurley et al., 2005; Kaup, 2008; Kruger et al., 2009; Skevas et al., 2009), and lack of hybrids with specific traits (Reisig et al., 2021) have been reported elsewhere. The impact of the non-tangible aspect of resistance management on farmers' refuge adoption is a novel finding of this study.

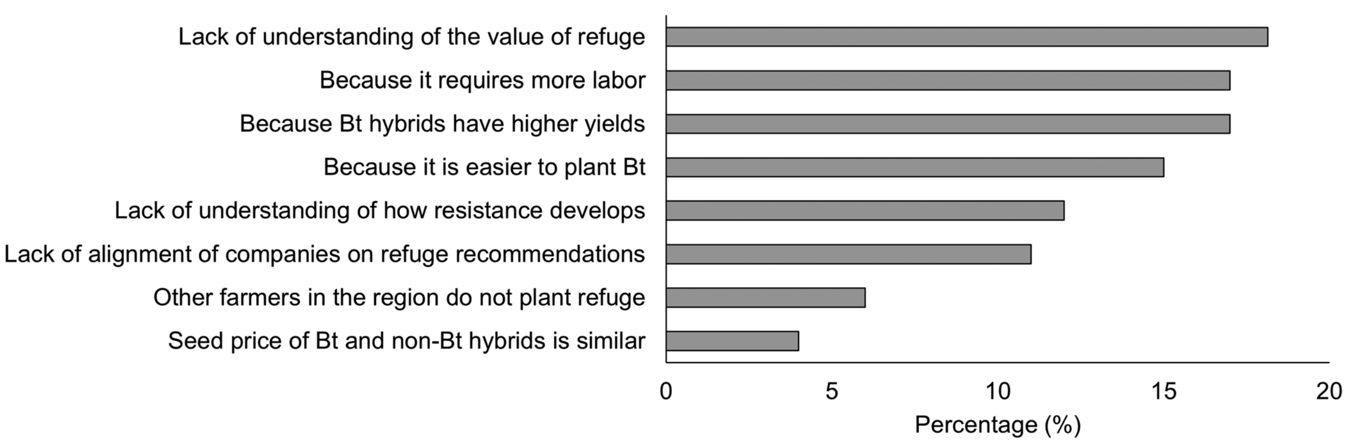

FIGURE 4 Results on farmers' responses to the question "In your opinion, why don't farmers plant refuge corn (e.g., plants not expressing *Bacillus thuringiensis* toxins, or non-Bt corn)? Select 3 options" based on 145 respondents using online surveys

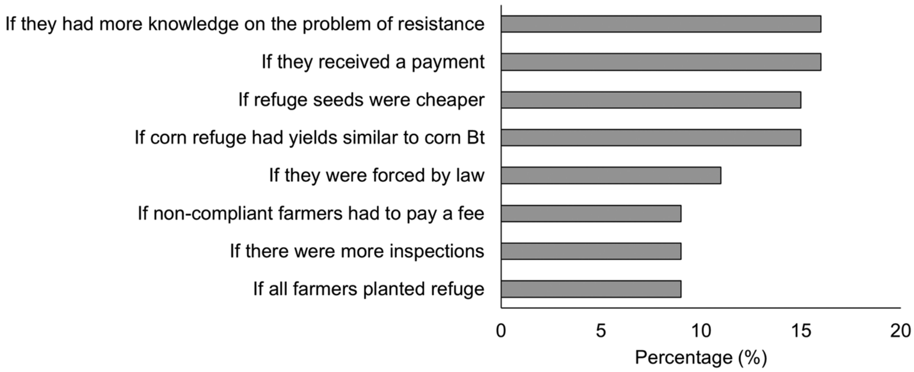

FIGURE 5 Results on farmers' responses to the question "What would make growers more likely to plant refuge corn (e.g., plants not expressing *Bacillus thuringiensis* toxins, or non-Bt corn)? Select 3 options" based on 145 respondents using online surveys

3.4 | Factors promoting adoption of refuge

In the Qualtrics survey, results showed that factors such as education, incentives as a form of payment or cheaper seeds, and availability of high-yield non-Bt varieties would make farmers more likely to plant corn refuge (Figure 5). Similar results were observed during interviews. For example, a farmer stated, "if we have hybrids with the same agronomic characteristics [as Bt hybrids], I think people would plant Bt." Statements such as "I think the government should give us some form of compensation for resistance management" and "farmers would plant refuge if refuge seeds were cheaper" indicate that monetary compensation may have a positive effect on refuge adoption by farmers.

Even though results from the Qualtrics surveys showed that other farmers' compliance would not make respondents more likely to plant corn refuge, four interviewees indicated that farmers would plant refuge if other farmers planted it. Doing so, they gave additional details such as "companies should talk to seed representatives and have them pick some of the biggest farmers in the region to offer refuge." These results align with other studies that show farmers perceive insecticide resistance as a common pool resource (Brown, 2018; Milne et al., 2015). In this scenario, if only few farmers plant refuge, the farmers that comply with refuge requirements bear the extra operational costs of planting refuge and the costs from resistance evolution. However, the impact of other farmers' refuge adoption on individual decisions seems to vary across individuals in our study, as two farmers indicated that "farmers are not influenced by their neighbors for resistance management" and that "other farmers planting refuge wouldn't make the change" in interviews. In addition, results from interviews allowed us to identify additional factors that may influence refuge adoption. One farmer mentioned that "the only form for the refuge to be adopted would be if we had a percentage of non-Bt corn that came in the bag [seed blend refuge]," whereas another farmer mentioned that "farmers tend to change what they are doing only if they have a big loss."

4 | CONCLUSIONS AND IMPLICATIONS

Our results extend the literature in rural sociology by underscoring the reflexive nature of Brazilian farmers' information search, validation, and utilization (Kaup, 2008). Our research demonstrates that Brazilian farmers' dynamics for information exchange rely on social networks and that expertise based on local field experience is the most effective factor to elicit a change in management practices. In this context, farmers and agronomists were viewed as valuable sources of information partly because of their deep embeddedness in the community, highlighting the importance of networks. In addition, this research shows that temporality can also influence how experience becomes expertise as farmers are oriented toward history and their own experiences, which may challenge uptake of new information with its focus on continuity and incremental progression. This is the first study that investigates farmers' perceptions on information sources in Brazil using qualitative data. Even though similar trends of farmers' attitudes toward sources of information have been reported elsewhere, our study is unique as it discusses the reasoning behind preferences and the implications of these on IRM practices in Brazil.

Our study brings important insights of opportunities and barriers for resistance management that have not been reported in the literature. First, our study revealed that the need for multiple insecticide applications for insects not targeted by Bt (e.g., whitefly, aphid, thrips, beetles, and leafhoppers) in Brazilian soybean and corn can undermine the role of Bt toxins on insect suppression because farmers have to spray insecticides to control other insects independently if target insects are suppressed by Bt. It is expected that this directly impacts farmers' perception of the value of Bt crops, making farmers less prone to spend money and time on conserving this technology by planting refuge. In addition, our study revealed that, despite refuge adoption or concern with insecticide resistance development, many farmers choose to plant non-Bt crops because they tend to be more tolerant to weather conditions and because of familiarity with certain varieties. Finally, a new finding of our research was that a barrier on the adoption of refuge was due to the non-tangible aspect of resistance evolution.

Besides focusing on information sources and IRM strategies, our study highlights the importance of using qualitative research in tandem with quantitative data collection to investigate complex issues in agricultural landscapes. The use of qualitative data collection in our research allowed us to collect data that were not expected on surveys and to have an in-depth understanding behind preferences and attitudes. Importantly, for some specific questions, we obtained different results from surveys and from statements collected during interviews.

In addition, our study shows that response bias can play a role on the data collected with both qualitative and quantitative methods, depending on the relationship or perspective that respondents have of the researcher conducting the study. Furthermore, participation being voluntary, we acknowledge that participants of our study may have greater than average interest in Bt crops and resistance management. To decrease this participant bias, further studies should offer benefits to participants or conduct surveys with farmers' members of agronomic groups.

4.1 | Research recommendations

Our study highlights the impact of specific guidelines and consequently extra operational efforts on refuge compliance. Farmers acknowledge the benefit of resistance management practices but stated that they tend to adopt technologies that make their farming operations easier or more flexible. Based on results presented here, even though some farmers would be willing to plant non-Bt varieties because of reduced seed price, familiarity with cultivars, and agronomic characteristics, they likely will not plant it according to refuge guidelines because of operational difficulties. One of the main reasons farmers choose to plant Bt crops is because it can lead to more flexibility and reduced costs in their farm operations. Thus, we believe that researchers should design and evaluate alternative scenarios based on region-specific practices where planting refuge would still be effective to delay resistance while removing the burden of resistance management from farmers. This could include using alternative non-Bt hosts when the planting or harvesting cycle does not coincide with corn (e.g., pigeon pea refuges in Australia [Whitehouse et al., 2017]) and by evaluating the impact of blended refuge on resistance evolution in the Brazilian context. Research could also consider planting corn refuge in different spatial schemes by taking into consideration local landscape parameters, such as land fragmentation. For example, a farmer may plant a larger area of non-Bt refuge plants that is centrally located to fields planted with Bt crops. Importantly, future research should investigate farmers' perspectives on alternative guidelines to ensure future recommendations would be suitable to local practices and landscape systems. Instead of using a top-down approach to implement IRM, research should be conducted based on multidirectional communication across parties involved. Finally, research conducted in a local-based approach should consider the impact of insecticide sprays to control pests non-targeted by Bt toxins on resistance development to Bt crops. Results based on different refuge strategies, spatial schemes, and biology of insects can inform resistance modeling development to predict the best solutions to fight resistance in a more local and realistic approach.

Our results indicated that a main barrier for refuge adoption is that farmers perceive Bt crops having a higher yield potential than non-Bt varieties. Therefore, research should focus on trials comparing agronomic characteristics of Bt and non-Bt varieties in a regional context. The choice of non-Bt varieties should focus on non-Bt varieties that have higher farmer adoption based on experience and tolerance to weather conditions. In addition, as farmers tend to focus on short-term profit, research should focus on evaluating the net profit of using Bt versus non-Bt varieties under low-, mid-, and high-level production systems (e.g., land fertility and irrigation) and by calculating costs with future insecticide resistance to make the problem into something more tangible. Furthermore, farmers indicated that they would be more prone to plant refuge if the seed was cheaper or if they had economic incentives. Future research needs to investigate prices and incentives in detail. To be successful, solutions need to be advantageous enough to change farmers' attitudes considering farmer heterogeneity but also practical based on technology providers or governmental perspectives (Ambec & Desquilbet, 2012).

4.2 | Policy recommendations

The main insight of our study on farmers' preferred information sources is that farmers rely on strong social ties and own experience for decision-making. This can be advantageous for farmers as it validates the use of new technologies through the sharing of local knowledge, but it may pose challenges for the adoption of external or new technologies that have not been yet experienced throughout the groups, such as non-Bt refuge. Therefore, we believe that stakeholders should use influential farmers as a pathway to disseminate information on IRM and that they should present results based on farm research-based experience. Entities could consider hiring local individuals with farming experience that can build a relationship with farmers and facilitate transfer of information.

Statements of farmers collected in our study illustrate that making farmers aware of the importance of the refuge is difficult, despite the fact that its adoption brings clear benefits in the future compared with the present and because resistance is something not tangible. However, *S. frugiperda* has evolved resistance to Bt toxins as early as 3 years when inadequate refuges are available (Tabashnik et al., 2013), demonstrating that economic and operational difficulties can arise very quickly. Therefore, education efforts should focus on the short-term costs of Bt resistance to make the issue of resistance something "real and actual." Interestingly, Brazil stands out for its success with programs on soil conservation practices, including no-till systems and soil carbon fixation, which also result in long-term economic benefits (Calegari et al., 2020). Even though soil improvement has a material quality or is something tangible in comparison to resistance evolution, investigation of soil conservation messaging and practices may offer insights of long-term strategies that could promote adoption of IRM practices. Also, because farmers have agronomists as a primary information source, it is important for extension entomologists to work closely with seed companies and seed dealers to disseminate information about IRM. Moreover, education efforts should focus on marketing of non-Bt varieties that have a fit for specific regions. This could be done by sponsoring non-Bt crops in yield contests and campaigns on IRM.

Because IRM strategies have been defined as a wicked problem given their sociobiological nature (Gould et al., 2018), IRM strategies should consider the heterogeneity of farmer culture and the landscape that they are embedded in to develop region-specific guidelines that better suit farm practices (Liu et al., 2007). IRM recommendations cannot be a "one size fits all" strategy, which overly rely on studies and modeling efforts conducted by the US Environmental Protection Agency (EPA), but should rather consider a smaller scale approach centered around particular geographies. Farmers rely heavily on their peers for decision-making, and they interact constantly on information settings. Therefore, a culturally based solution for IRM could have an emphasis on communities, where rules and guidelines can emerge to ensure a sustainable, shared management of resources, as well as one that is efficient from an economical and practical point of view of farmers in a local perspective (Ostrom, 1990).

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CONFLICT OF INTEREST

Daniela T. Pezzini currently works in a position at Bayer CropScience, which sells genetically engineered seeds expressing Bt toxins and insecticides. However, the study was conducted while I was a graduate student at NCSU, and no funding from any agricultural company was used to perform this study. Jason A. Delborne has no conflicts of interest. Whereas Dominic D. Reisig has received research support from companies that sell Bt crops and insecticides, this research was not funded by agricultural companies.

AUTHOR CONTRIBUTIONS

Daniela T. Pezzini, Jason A. Delborne, and Dominic D. Reisig designed the study. Daniela T. Pezzini collected the data. Daniela T. Pezzini analyzed the data with help from Jason A. Delborne and Dominic D. Reisig, and Daniela T. Pezzini wrote the manuscript with substantial help from Jason A. Delborne and Dominic D. Reisig.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available in the Supporting Information S1 of this article.

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SUPPORTING INFORMATION

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