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The road less traveled: Assessing the impacts of farmer and stakeholder participation in groundwater nitrate pollution research

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Abstract: After decades of effort and investment to promote the use of agricultural best management practices (BMPs) to address nutrient losses from farms, the level of adoption of most BMPs remains relatively low. One increasingly common response has been to involve stakeholders more directly in research on local water quality challenges, with twin goals of improving the science and engaging local residents in the diagnosis of problems and development of effective responses. This paper uses qualitative and quantitative data to assess the impacts of a multiyear nitrate (NO_3^-) leaching study in a central Montana watershed that used a highly participatory research and outreach approach. For decades, the Judith River watershed has experienced groundwater NO_3^- levels that exceed safe drinking water standards, and many local residents install expensive water treatment devices, purchase drinking water from private vendors, or drink contaminated water. The project is notable for engaging local farmers, community leaders, and agency staff in the design, implementation, and interpretation of research to identify the sources of NO_3^- and to understand the effectiveness of alternative management practices in reducing NO_3^- leaching into groundwater. Two advisory groups regularly met with the science team to develop research questions, structure field research activities, select management practices, discuss interpretation of data, and design outreach efforts. Evidence of project impacts was gathered through interviews with our local collaborators and from a comparison of pre- and postproject surveys of the broader farm operator population in the watershed. The qualitative results suggest that the people most involved in the project became much more engaged with and concerned about how to address the local NO_3^- problem. The project's research findings were also more compelling to stakeholders because farmers had been involved in designing and interpreting the data, and the research had been conducted under real-world farming conditions. Survey results collected in the final year of the project showed that farmers in the watershed were familiar with and had very positive impressions about the project, and their levels of awareness and concern about NO_3^- issues rose over the course of the project. However, widespread changes in farmer behaviors had not been detected three years into the project, and the impact of the project on long-term NO_3^- contamination trends in the region is still uncertain.

Key words: crop rotations—Montana—nitrogen leaching—participatory research

Much of the dramatic growth in agricultural productivity over the last 60 years has been attributed to the increased use of industrially fixed nitrogen (N) fertilizers, which rose 20-fold between 1945 and 2002 (Fixen and West 2002). Combined with other changes in cropping, tillage, and fertilization patterns, there has been growing recognition that farming practices have been responsible for fundamental changes in the global N cycle (Cassman et al. 2002). Because harvested crops typically utilize only 50% of the applied N in the field, much of the available N is lost through leaching to groundwater aquifers, usually in the form of nitrate (NO_3^-), or is converted through denitrification and released to the atmosphere mainly as dinitrogen gas (N_2) but also as nitrous oxide (N_2O), a potent greenhouse gas (Robertson and Vitousek 2009). Nitrate contamination of groundwater has become a critical public health concern because elevated NO_3^- levels in drinking water can cause cancer and impact the development of fetuses and young children (Ward et al. 2005). They can also disrupt aquatic ecosystems (Rabalais et al. 2002).

Despite growing attention to N losses from farming systems, efforts to address the problem have met with mixed success (Ribaudo 2015). A central focus for many nutrient management programs is fertilizer use, with widespread emphasis on what many call the 4Rs: placing fertilizers at the right rate, from the right source, in the right place, at the right time (Davidson et al. 2016). Despite concerted efforts to develop and promote advanced nutrient management practices, adoption rates for many best management practices (BMPs) remain relatively low (Perez 2015; Weber and McCann 2015), and measurable improvement of water quality at the watershed scale has been slower than expected (Gassman et al. 2010; Lemke et al. 2011; Pearce and Yates 2015).

This paper summarizes results of a participatory research project conducted in the Judith River watershed (JRW) in central Montana. Numerous groundwater wells in shallow aquifers of the JRW have levels of NO_3^- that exceed federal drinking water standards, and long-term monitoring suggests that these levels have been steadily growing for several decades (Schmidt and Mulder 2010; Sigler et al. 2018). Prior to the research reported here, agriculture had been identified as the likely source of elevated

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NO_3^- levels (Bauder et al. 1993; Schmidt and Mulder 2010), and the Montana office of the USDA Natural Resources Conservation Service (NRCS) had initiated programs to incentivize adoption of BMPs designed to reduce NO_3^- leaching to groundwater (MT NRCS 2017). Our project utilized an intensely participatory approach that engaged local farmers, community leaders, and agency staff directly in the design, implementation, interpretation, and communication of scientific field research on N leaching. We wanted to test the hypothesis that engaging local stakeholders in the research would lead to greater understanding and ownership of the groundwater NO_3^- problem, and help identify innovative management strategies that were both effective and likely to be adopted.

This paper presents qualitative and quantitative evidence about the impacts of our project on changing farmers' awareness, understanding, and concern about local groundwater NO_3^- issues, and the extent to which farmer behaviors in the JRW have changed in response to the effort. The results provide guidance to future participatory research efforts to address agricultural environmental problems.

Drivers of Farm Conservation Behavior. Most agricultural conservation programs in the United States use recommendations from scientific researchers to identify BMPs that reduce environmental risks and emphasize voluntary education- and incentive-based policies that encourage farmers to use these BMPs (Dowd et al. 2008). To motivate producer use of BMPs, a range of education and extension efforts are often employed to raise awareness and concern about the underlying environmental problems and to disseminate scientific information about the pros and cons of various BMPs. Common modalities include the use of one-on-one farm visits, technical reports, factsheets, websites, social media, workshops, on-farm demonstrations, and other public outreach events (Black 2000; Lemke et al. 2010; Peterson et al. 2017). Because many conservation practices are not expected to generate financial returns to producers, public cost-sharing programs are frequently used to defray expenses associated with adoption of new BMPs (Reimer 2015; Shortle et al. 2012).

Empirical studies of farmer conservation behavior have shown that effective BMP implementation depends substantially on the acceptance of the practice and understanding of the value of the practice by the farm operator (Osmond and Gale 1995; Prokopy et al. 2008; Busse et al. 2015). Without accepting and understanding the purpose and value of a BMP, farmers are unlikely to maintain the installation and may divert their efforts to other needs viewed as being more valuable to the operator (Jackson-Smith et al. 2010). Farmers also recognize that BMP programs are affiliated with local, state, or federal agencies, and producers' attitudes about the governmental partner can shape their willingness to engage with the conservation program (Armstrong et al. 2011; Mase et al. 2015).

More generally, the idea that agricultural environmental problems are relatively tame puzzles that have straightforward technological solutions has been increasingly questioned. Rather, many agricultural environmental problems (like NO_3^- pollution in groundwater) represent good examples of "wicked problems"—problems that are rooted in complex coupled human-natural systems, and are difficult to address without an appreciation for linked drivers and outcomes of behaviors that extend well beyond the environmental issue of interest (Batie 2008; Rittel and Webber 1973). For example, farmers typically seek to maximize a complex suite of goals, only some of which relate to environmental stewardship (Jackson-Smith 2010; Reimer et al. 2012). Programs to promote BMP use have benefited by recognizing differences among farm operators, and increasingly try to target different BMPs and programs toward diverse audiences (Mase et al. 2012; Nowak et al. 2006; Shepard 1999). Farming systems are also embedded in specific and varying landscape and climate contexts, and the same behaviors adopted in different locations (or across diverse rainfall or temperature conditions) may produce quite different environmental outcomes.

These insights have led many to suggest that expert-led efforts to develop and promote the use of specific agricultural BMPs for use by farmers are limited by the lack of a good fit between a BMP and the nuanced social, economic, and environmental context within which individual farmers make decisions. In other words, one should not expect a single solution to complex problems like NO_3^- pollution—both because the technologies that best fit with the social and biophysical context will differ across landscapes (and among farms) and also because each BMP is likely to introduce tradeoffs between environmental performance and other socially important goals or outcomes, like farm profitability, landscape aesthetics, etc.

The Case for a Participatory Approach. In response to these complexities, a growing number of scholars and practitioners are promoting the use of a transdisciplinary model in which scientists and nonscientists collaborate to take advantage of the different forms of knowledge and experience each group has with respect to wicked problems (Brown et al. 2010; Hirsch Hadorn et al. 2008). There have been many different approaches to engaging key actors or stakeholders in scientific research and modeling efforts (Ashby et al. 1996; Langsdale et al. 2013; Voinov and Bousquet 2010). While the details of each approach vary, the most impactful efforts have used participatory engagement both to improve the accuracy with which human behaviors are represented in scientific models, and the relevance of research and modeling to key stakeholders and decision makers (Morton and Brown 2011).

The success of a participatory scientific research effort is usually measured by the degree to which actors understand, view as legitimate, and use the results in their resource management decisions (Ashby et al. 1996). In the context of addressing wicked problems, it is also important for participants to feel comfortable contributing their insights and experience to the science team and perceive that their insights and experience are relevant to ensure that complex system outcomes are appreciated in the research process (Hirsch Hadorn et al. 2008). For example, successful inclusion of landowners and managers at early stages of watershed conservation projects can provide important feedback that might influence the selection of BMPs that are most likely to work and be accepted by land managers, the location of representative sample sites, and the most effective way to design extension and educational programs (Bentrup 2001; Johnson 2009). More interactive and personal interactions between program staff and farmers can also boost effective BMP development and adoption (Lemke et al. 2010; Perez 2015).

Description of Study Area and Project. The JRW (HUC 10040103) is a watershed in central Montana that receives runoff from the Little Belt and Big Snowy mountains and drains north into the Missouri River. Most of the nonmountainous portion of the

7,200 km^2 watershed is in agricultural land use, with small grains, forages, and pasture dominating the landscape. Rainfall averages 390 mm y^{-1} at the town of Moccasin (WRCC Gauge #245761), and very little of the farmland is irrigated. The watershed encompasses two counties (Fergus and Judith Basin). According to the 2012 Census of Agriculture, these counties were home to roughly 1,100 farms with an average farm size of almost 1,100 ha, and most gross farm income in the area came from the sale of beef (~58%) and wheat (*Triticum aestivum* L.) (~26%) (USDA NASS 2013). Typical cultivated crop rotations involve winter wheat followed by spring wheat or barley (*Hordeum vulgare*), and then a year when fields are left fallow. Here, the term "fallow" indicates that no crop is planted, no fertilizer applied, and weeds are prevented with herbicide application. In the resulting absence of transpiration (water utilization by plants), soils store water and produce plant-available, leachable NO_3^--N from soil organic matter through the processes of mineralization and nitrification. Some farms also rotate in oat (*Avena sativa*), pea (*Pisum sativum*), and lentil (*Lens culinaris*). No-tillage and reduced-tillage are the dominant cultivation practices. The area is on the western edge of the Great Plains, and is characterized by economic dependence on farming and services, relatively low economic diversity, and unchanging or declining populations.

Participatory Research Approach. The research presented below was part of a larger USDA-funded project (fall of 2011 to summer of 2015) to better understand and develop effective responses to the problem of rising NO_3^- concentrations in groundwater wells in the JRW (John et al. 2017; Miller 2013; Sigler et al. 2018). A primary goal of the project was to empower local farmers and community leaders by giving them important roles in the design and implementation of the scientific research and fieldwork components of the effort. To do this, we created two advisory groups. The first was a 15-person advisory committee (AC) consisting of six representatives of local, regional, and state conservation and health agencies; two local agricultural extension agents; the superintendent of the local Montana State University agricultural research center; a county commissioner; and five farmers (two of whom also ran agribusinesses in the basin). The AC met on an annual basis (five total meetings, including an initial meeting in November of 2011 and a final meeting in June of 2015). The AC received regular updates about research activities and emergent findings throughout the year via email and mail from our project team. AC members were also consulted individually for their expertise when appropriate, and to assist the research team with outreach efforts.

The second advisory group was the Producer Research Advisory Group (PRAG), which consisted of six local farmers who were asked to meet three to four times a year to intensively collaborate with the research team on the design and implementation of the project. Some PRAG meetings were held in conjunction with the annual AC meeting, and PRAG members typically attended these AC meetings. Three PRAG members served as hosts for the field work by undertaking three years of field trials on their farms to evaluate the impacts of recommended BMPs, and by allowing the research team to collect samples and install instruments on their fields. Farmers in the PRAG were recruited from a list generated by local key informants, and included producers from different subregions across the watershed and farmers at different career stages. A few were explicitly selected to represent producers who our local contacts suggested could be expected to be skeptical of the project and/or not regularly serve on conservation agency boards or project advisory groups.

At their initial meetings, the AC and PRAG members were introduced to the project, which included a review of evidence of high NO_3^- concentrations in local wells and an emphasis on the importance of local input and control. We specifically asked them to identify areas of concern and uncertainty regarding the drivers and potential effective responses to the NO_3^- problem. As a group, we also discussed how we could use our project resources to address the following three types of research questions:

1. What are the most important sources of NO_3^- in groundwater in the watershed?
2. How effective are various BMPs in mitigating NO_3^- leaching?
3. Which BMPs are most likely to be adopted by producers in the region?

Researcher interactions with the AC and PRAG influenced the team's research design choices, including selection of treatments and research fields and configurations of field instruments. Based on their detailed input, trials were conducted between spring of 2012 through fall of 2015 at the field scale (~32 ha) and focused on comparing standard farming practices (three-year rotation of chemical fallow, winter wheat, spring wheat; spring broadcast urea fertilizer) with three alternative practices with potential to reduce NO_3^- leaching. These alternatives included two fertilizer management techniques: split-application of N in the spring to include a posttillering application, and the use of a slow-release form of N fertilizer. Previous work in the region suggested that in fallowed fields, the lack of crop roots to use N generated by decomposing organic matter can increase the risk of leaching (Campbell et al. 2008; O'Dea et al. 2013). Based on this, we also included an alternative crop rotation practice (planting pea instead of fallowing).

The project team also monitored water movement and extensively sampled soils and crops on the study farms, and sampled surface and groundwater across the watershed (John 2015; John et al. 2017; Miller 2013; Sigler et al. 2018). Although we saw potential for all three practices to have beneficial impacts, our field trials (and materials included in our publicity and outreach efforts) demonstrated relatively modest impacts for two fertilizer BMPs (split application in the spring, and slow-release forms of N), but found that planting annual legumes (like pea) in lieu of fallowing showed the greatest promise for both reducing NO_3^- leaching and sustaining farm income (John et al. 2017). Analysis of water composition and NO_3^- abundance in soil, groundwater, and surface water samples informed quantitative models of NO_3^- leaching losses at the landscape scale, and supported the observation that replacing fallow fields with a crop has strong potential to reduce NO_3^- leaching (Sigler et al. 2018).

Outreach Efforts. To disseminate insights gained from our participatory research project, the project team engaged in several forms of outreach and education targeting farmers and the general public. We regularly encouraged PRAG and AC members to proactively discuss the emerging findings from the project with their peers in the watershed. We participated in demonstrations and distributed information at three field days hosted by the local Montana State University agricultural research center (in 2012, 2013, and 2015) and held our own field day on two of our cooperating PRAG members' farms (in summer of 2014), where the farmers presented findings from data collected from their fields to an audience of farmers from across the watershed. We developed a project website with regularly updated materials, authored several press releases that generated multiple articles in local and regional newspapers, and participated in several live radio programs that are widely listened to by area farmers (MSU EWQ 2017). Finally, between October of 2014 and July of 2015 we distributed hard copies of four two- to four-page newsletters through local extension and government offices, agribusinesses, and other gathering places. These newsletters included brief text, photos, and graphics to provide an overview of our activities, as well as discussion of our research findings about the major research themes developed over the course of the project: processes and timing of NO_3^- leaching, sources of NO_3^-, and performance of various BMPs. Copies of the newsletters were also posted on our project website.

Materials and Methods

We used both qualitative and quantitative methods to assess evidence of changes in farmer awareness, understanding, and concern about NO_3^- pollution issues, and trends in the use of BMPs that the project deemed effective and viable in this region.

Qualitative data were obtained from semistructured interviews with PRAG and AC members conducted after the project concluded. The interview schedule included a set of common questions that asked respondents to reflect on their experience with the project, including open-ended questions about the degree of their involvement, perceived challenges, and most important accomplishments of the project, as well as their observations about how involving local farmers impacted the trajectory of the research and outputs. Interviews were conducted in person or over the phone by two graduate students, and respondents were promised that their feedback would be kept confidential. Graduate students were trained in qualitative interviews as part of their graduate coursework and supervised by faculty with extensive experience gathering qualitative data. Interviews were recorded and transcribed and then systematically analyzed by the lead author using an open coding process to identify dominant and alternative themes and patterns in the responses to each answer (Corbin and Strauss 2008). Results of the analysis were checked by other members of the research team to ensure that conclusions accurately characterized the general tenor of responses. Interviews were completed with 15 people: all 6 PRAG members and 9 of the 15 AC members (4 of the original AC members had moved on to new employment and were no longer active in our meetings).

Quantitative data were provided by random sample farmer surveys conducted in late winter/early spring (January through April) in both 2012 and 2015. The surveys were developed by the project team with significant input from the AC and PRAG members. Surveys and questions were formatted using guidelines for best practices (Dillman et al. 2014). Questions covered topics including the use of various farming practices, motivations for farm management decisions, awareness and concern about water quality issues, and other related topics.

In both survey years, we generated our sampling frame from a publicly available list of all persons who received USDA Farm Services Agency (FSA) payments for participation in federal farm programs in Judith Basin and Fergus counties (in FY2010 or FY2013 and FY2014, respectively). Program payment recipients with mailing addresses outside of Judith Basin and Fergus counties were excluded. Because nearly all commercial farming operations in this region participate in at least one type of federal farm program, this list is viewed by local experts as very inclusive of the active farm population. This list included more than 2,000 names, but duplicate listings and addresses allowed us to consolidate to a sampling frame of roughly 1,000 possible recipients. This compares to an estimate of roughly 1,088 total farms that provided information in the 2012 US Census of Agriculture, which suggests that the FSA list included most farms in these counties.

From that list, we randomly sampled 1 in 3 (n = 309) farms in 2012. From these, 69 were disqualified because they no longer farmed their own land (or because they were nonoperator landlords only, in which case we replaced them with the person responsible for operations on most of their land). From the remaining 240 sampled operations, we received completed surveys from 139 farms for a 57.9% response rate. The 2015 sample included 413 newly randomly selected addresses (50% of the nonduplicate FSA program recipients with Montana mailing addresses). Of these, 106 turned out to have already been included in the original 2012 sample, including 42 nonrespondents from 2012. In addition, we resurveyed the remaining 75 respondents from the 2012 survey who were not selected in our new 2015 random sample (thus resurveying all 139 respondents from 2012). Of the total 488 sampled farms, 74 were disqualified operations (for reasons stated above), leaving an adjusted sample size of 414. A total of 209 responded, for an overall 50.5% response rate.

A comparison of survey respondent characteristics with published results of the 2012 Census of Agriculture suggests that both 2012 and 2015 survey respondents generally represent the greater farm community in Fergus and Judith Basin counties, although there was a modest tendency to over-represent large-area wheat producers. Given the estimated size of the farm population in these two counties (roughly 800 working commercial farms that gross more than US$10,000 a year), and the number of respondents (139 and 209), our results are expected to be accurate to within roughly +/– 6% (Dillman et al. 2014).

Results and Discussion

Evidence of Impacts from Project Participants. We begin by summarizing results of qualitative interviews conducted with PRAG and AC members at the end of the project. Overall, those interviewed indicated that the project significantly influenced their understanding of the dynamics of, and potential responses to, NO_3^- leaching into local groundwater. They also felt that the participatory process was a critical mechanism to ensure that the research was grounded in producer experiences and constraints, and to ensure that farmers' voices were present within the project recommendations. One elaborated on the importance of the participatory approach in generating understanding by the farmers on the project:

> For me the best thing was [the PRAG]… their realization because they're knowledgeable, influential people here in the central Montana farming community. I think it really helped them understand this whole soil-water interaction, water movement process, how things happen in surface water and then groundwater and the nutrients that go along with that. I think it just really cemented in their minds all of those processes, how they

fit together and the control that they do have over some of those processes.

Two questions in the semistructured interviews asked respondents to reflect on the "best things" about the project, first for them personally, and second in terms of the overall outcomes or accomplishments. We also asked them to discuss what they learned from the project that they didn't know going in. For all members of the PRAG, the best thing about the project usually referenced their first-hand experience with the scientific process and opportunities to learn more about the dynamics of N in their local farming systems. One noted that "being involved directly, seeing what was going on, actually meant a lot more to me than just reading the numbers." Another said,

> One of the best things was being able to actually use…people that have done research…there are a lot of times in farming that things happen and, you know… Joe Blow down at Coffee is trying to put an answer to it, and we don't know what it is. We're all just taking guesses, and here at our fingertips is an immense… wealth of knowledge that needs to be used and so that was pretty cool.

Most PRAG members, and the AC members who were farmers, cited examples of things that they learned about "how we are part of the system that creates nitrates," and, "that there are ways that you can minimize leaching." Most respondents also gave answers that were consistent with the substantive findings of the scientific team's observations that (1) crop rotations (replacing fallow with pea in the small grain rotation) were most successful at decreasing leaching in the field, particularly because high decomposition rates of organic matter (OM) in fallow fields release plant-available N (mineralization), but living plant roots are not present to utilize that N or stored water; and (2) fertilizer BMPs (like split application and slow release N) had less consistent environmental and economic benefits.

PRAG members also noted that their experiences on the project demonstrated how hard it is to get simple answers to the question of NO_3^- sources and how best to respond. One mused that "weather makes a big difference on what happens out here," and another appreciated that "it takes a hell of a long time to find a norm." Many concluded that many more years of research might be required to really understand how well different BMPs work under different weather conditions.

The AC members who worked in agricultural extension programs also appreciated how the participatory model got producers directly involved in the research and gave them "insight into how the university works, how we come up with the recommendations that I so often give [farmers]." Interestingly, the AC members who work for local or state agencies charged with addressing natural resource problems were much less likely to suggest that they personally benefited from their participation compared to the farmers or extension agents. This may reflect that these professionals tend to have more extensive formal education in relevant scientific fields and many indicated that results of field measurements were similar to what they expected. That said, almost all the AC members expressed surprise at the findings that crop rotations (and soil OM mineralization processes) may be a more important driver than the type or timing of chemical fertilizer applications.

In terms of their assessments of the "biggest things the project achieved," the PRAG and AC responses were more diverse. Most focused on the knowledge the project generated about the underlying physical processes linking fertilization, crop rotations, soils, precipitation, and NO_3^- leaching. Many highlighted how the farmers involved in the project now recognize that "there is a nitrate problem in the groundwater," and that "producers have some control over the groundwater nitrates by their crop management."

Some emphasized the impact of the project on broader community awareness and concern about the NO_3^- issue. One PRAG member said, "…it has really opened up conversations even outside of this watershed on the nitrate issue, and so people in the surroundings areas are aware and concerned and want to be proactive." An AC member suggested that the best thing to come out of the project was "a lot of information and awareness of what's contributing to the nitrates in the community."

A handful of AC and PRAG members focused more on the lingering questions and uncertainties that remained after the project funding had run out. One noted that "the one variable that affects [nitrate leaching] a lot is…precipitation. They can't control that." Another reiterated, "two or three years doesn't really give you a good idea of what's actually happening long term."

Our respondents were also invited to identify the biggest challenges about the project (for themselves or overall), and to discuss any concerns they had about the project. The biggest challenges cited by both PRAG and AC members reflected logistical issues—finding time to keep records and taking days off to attend project meetings. Producers also talked about the complexities of carrying out research on a working farm, including the difficulties related to consistently implementing BMPs in the face of soil variability, weather patterns, and coordinating other field operations across the different years of the study.

Almost every interviewee noted that their biggest concerns related to how the research results might be used by environmental regulatory agencies. This concern made many participants wary of getting involved at the project's outset. The underlying concern was that the government might ban or severely restrict the use of N fertilizer, something that most respondents felt would threaten the very existence of their farms and communities. This typical comment was summarized by one participant:

> A pretty big concern of mine is that this information would get turned out there and if it wasn't fully described and laid out, that it would, could end up… turning bad against what we were trying to do. But at the end of the day, I think that the producers involved made it very clear that that was a concern and the researchers involved made sure that they did everything they could to just lay the information out looking at it from all sides…by the end of it [the researchers] put together some very good information that is not, that is not finger pointing information. It's simply data that's saying that well here's what our research found and here are some things that we think are potential but are other than producer related. So I think it alleviated the concern and the way they presented the data, they did a good job of trying to present the data in a way that was nonthreatening and nonjudgmental so that if somebody was to read it that the first thing they wouldn't take away is that "oh my gosh these farmers are terrible horrible people."

Perhaps fortuitously, our on-farm field observations and model results led to the conclusion that changes in crop rotations (especially the use of fallow under no-till conditions, combined with periods of heavy rainfall and deep soil moisture movement) were probably at least as important as commercial fertilizer applications in explaining rates of NO_3^- leaching (John et al. 2017; Sigler et al. 2018). At a minimum, the fact that fertilizer (alone) was not identified as the main culprit opened up opportunities for farmers to let down their guard and engage in conversations about how their overall farming systems were impacting local environmental conditions. Indeed, by including them in the discovery of the results, most ended up recognizing that commercial fertilizer practices likely play a role, but this realization was not associated with being "painted in an unfair light" by people from outside of the area.

Finally, the 15 interviewees were asked how the involvement of local farmers in the research impacted the science/findings and the overall success of the project. Both PRAG and AC members noted that inviting farmers to participate in the design and execution of the research "gave [researchers] welcomed access to the land." While several recognized that working with actual farmers at the field scale introduced complexities for the researchers, the participating farmers also reported they felt findings were more accurate and believable precisely because they were made under more realistic farming conditions.

Moreover, because farmers were involved from the beginning in deciding which management practices to test in the field plots, they were able to pick BMPs that they felt could be practical when implemented on a commercial scale. One PRAG member emphasized this point:

> Well I think [farmer participation] was necessary. I mean, the researchers were very—they were quite clear. They expected us to be open with our own ideas, and to try to figure out some– they encouraged us (by asking), "Is there something missing here? Is there something else?" They didn't want to be the ones giving the ideas. They expected it to come from the ag community, so I think it was very important to have them in there and the farmers be involved in it, 'cause most of the farming practice ideas came from the farmers.

Similarly, both PRAG and AC members suggested that the research is likely to have more impact in the broader community because it was informed by the perspectives of local farmers. One PRAG member discussed this at length:

> It's understood that this project was studied with local farmers making local decisions, I think it helps people soften up to the research and the understanding that, you know, this wasn't just scientific ideas put together, force-fed, here's what we need to do. Now this was boots on the ground, producers that live here, work here, and make a living off of this land …And so by having it on location and in three different locations I think it really brought a, I don't know what you want to call it, I call it, a hometown feel to it.

A producer on the AC added that "It adds... local credibility to the researchers where they have people help doing the work every day growing the crops; it's not just a small deal trial here and there. These guys are using full fields and crop rotation and what not to try to prove what's right." Another AC member noted:

> I think it definitely changed the direction of the treatments that we were going to do. Rather than someone at the university saying what would be best, we had a lot of input from farmers on what they were willing and able to do. So I'm hopeful as we get through the next couple years that our recommendations will be much more palatable because farmers had some input to say this is something, these are the types of changes we're able and willing to make.

Evidence of Changes in the Broader Farm Community. To capture evidence of impacts of the project on the broader farming population in the watershed, we gathered information on awareness and evaluation of the Judith River Watershed Nitrogen Project (JRWNP) using the 2015 farmer survey. The 2015 instrument included a page of questions that asked respondents whether they were familiar with the JRWNP, and if so, whether they had positive impressions of the project. Findings are presented in table 1. Because much of the practical work of our research project was designed to help wheat growers better manage N inputs, and since high NO_3^- are concentrated on landforms where small grains are grown, we also break out the results separately for the wheat and nonwheat producer respondents. Overall, nearly half of the farmers who responded said they had heard about our project prior to receiving the 2015 survey. Wheat growers were nearly twice as likely to be familiar with the JRWNP (61% versus 34%).

Among those aware of the project, most heard about it from their county extension agent (or other government official), from reading about the project in a newspaper, or by reading one of our newsletters. A large fraction of wheat farmers (43%) also heard about the JRWNP at one of our field day presentations. Wheat farmers were also more likely to have heard about it from the local farmers who were hosting research on their farm. Roughly 20% of wheat farmers (and 10% of nonwheat farmers) say they had told other farmers about the project.

Based on what they had seen or heard, a majority (64%) of those who knew about the project had a favorable impression of our efforts, and only 3% had an unfavorable impression. This did not differ by type of farm. Similarly, more than 80% of those who had heard about the project said that it "had changed their understanding of how NO_3^- get into the groundwater in this area."

If the respondent had heard about the project, they were asked how the project had affected their use of various management practices. Results are summarized in figure 1. After factoring out those who said they already used these practices before the JRWNP began, most indicated that the project either made them more likely to use, or actually prompted them to begin using, each type of practice. The self-reported impact of the project was most notable for the practices of (1) considering NO_3^- leaching when making farm decisions, (2) using slow release forms of N, (3) testing drinking water for NO_3^-, and (4) changing crop rotations. However, in all four cases, the percentage who stated that the project made them "more likely" to use the practices was greater than the percentage who actually adopted them.

A final measure of farmer perceptions of the JRWNP is reflected in the levels of agreement with a series of statements about a range of possible project outcomes (table 2). Generally speaking, farmers who responded to the 2015 survey were strongly in agreement that involving farmers in the research was the most positive aspect of the project. A majority wanted to know more about

Table 1
Awareness and perceptions of the Judith River Watershed Nitrogen Project (JRWNP) among 2015 random sample survey respondents.

	Nonwheat growers (n = 85)	Wheat growers (n = 72)	All farms (n = 160)
Before getting the survey, percentage who have heard about the JRWNP	34.1	61.1 ***	46.5
Of those aware of the project (%)			
Where did you hear about it?			
From county extension agent or other government agency	55.2	54.5	54.8
Reading newspaper	48.3	54.5	52.1
Newsletters or brochures	37.9	36.4	37.0
Attending field days	17.2	43.2 *	32.9
From other farmers	17.2	29.5	24.7
Contacted directly by project staff	13.8	25.0	20.5
Local farmers hosting research on their farm	6.9	22.7 ***	16.4
Radio program	24.1	9.1	15.1
From crop advisors or local agribusiness	6.9	6.8	6.8
Percentage who told other farmers about the JRWNP	10.7	20.5	16.7
Based on what you've heard or seen, what is your general impression of the JRWNP?			
Very unfavorable	0.0	2.3	1.4
Unfavorable	0.0	2.3	1.4
Neutral	35.7	31.8	33.3
Favorable	53.6	54.5	54.2
Very favorable	10.7	9.1	9.7
Based on what you've heard or seen so far, how has the JRWNP changed your understanding of how nitrates get into groundwater in this area?			
No impact	17.9	13.6	15.3
Small change	39.3	40.9	40.3
Moderate change	42.9	43.2	43.1
Major change	0.0	2.3	1.4

Notes: Chi-square test of wheat vs. nonwheat growers significant differences (*$p \leq 0.05$; ***$p \leq 0.001$). Estimates of population characteristics should be accurate to within ±6%.

research results (62%) and expected the project to produce useful information in the future (74%). There was also a perception that the project is likely to benefit both farmers and the local community (58% and 70% agreement, respectively). While more than half of respondents were not sure (or neutral about) whether the JRWNP had *already* produced useful information, farmers were six times as likely to say that it had generated useful outputs (36%) than said it had not (6%). Interestingly, though the participatory aspects made the project more attractive and convincing to most farmer respondents, less than a third said that they would want to participate in participatory projects like the JRWNP.

To document changes in awareness and concern about water quality issues (particularly NO_3^- contamination of area groundwater) among farmers in the watershed, we compared results of the 2012 and 2015 surveys. Table 3 summarizes perceptions of water quality among both wheat and nonwheat farms in 2012 and 2015. The last three columns present changes in the estimated proportion of the farm population in each category across the three-year period. Initially, the proportion of farmers who perceive groundwater as only "poor" or "fair" increased slightly over the three-year period, particularly for deep groundwater on the respondent's farm and among wheat producers.

A growing percentage of farmers indicated awareness of elevated NO_3^- levels in local groundwater (an issue that was at the forefront of our outreach efforts). The proportion who said they had heard "some" or "a lot" about the issue rose by more than 11%, and the rise was most rapid among wheat farmers (despite being more aware than nonwheat farmers in 2012). Similarly, a larger proportion of respondents indicated they believed that the elevated groundwater NO_3^- level is a relatively new phenomenon (becoming a problem in the last 10 to 50 years), and the percentage of farmers who said it is not a problem dropped by more than 10%.

Finally, the percentage of respondents who indicated that they were concerned or very concerned about NO_3^- in drinking water or area groundwater increased over the life of our project (increasing by up to 8%). Nonwheat growers began the period with lower levels of concern, but their concern about NO_3^- rose more quickly than among wheat farmers.

A comparison of results from the 2012 and 2015 surveys also allowed us to assess whether the project's collaboration with local farmers and communication products impacted local farmer understanding of the processes causing elevated groundwater NO_3^- (table 4). The largest changes reflect a decline in the percentage of farmers who see livestock wastes or rain/snow as sources of NO_3^- pollution, and an increase in the proportion

Figure 1
Percentage of random sample 2015 farm survey respondents who are aware of the Judith River Watershed Nitrogen Project (JRWNP) reporting whether they have made any changes in their use of various farm management practices at least partly because of information they heard through the JRWNP (n = 71).

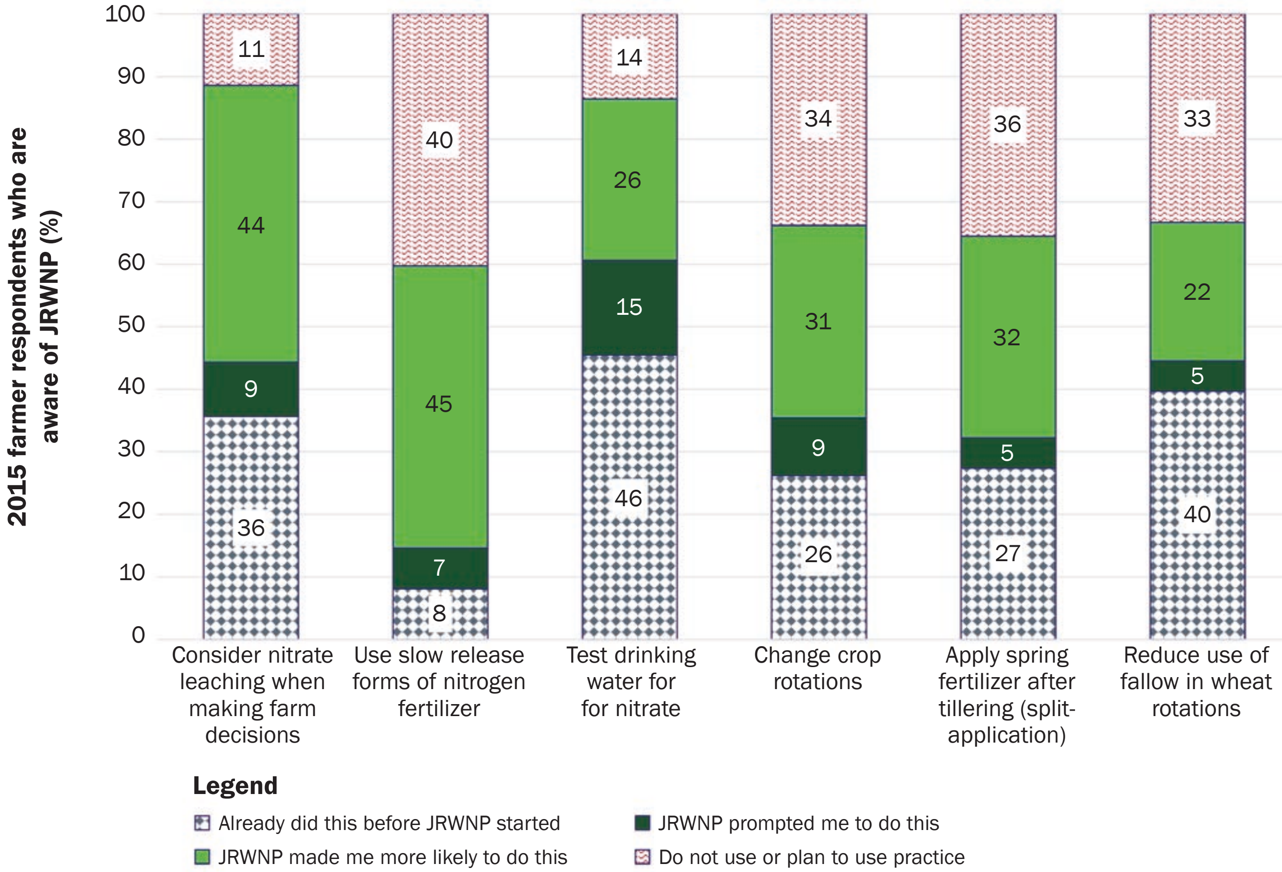

Table 2
Percentage of 2015 farm survey respondents who agree or disagree with statements about the Judith River Watershed Nitrogen Project (JRWNP) (n = 155).

	Respondents (%)				
Statement	**Strongly disagree**	**Disagree**	**Neutral**	**Agree**	**Strongly agree**
Involving farmers in the research is a positive part of the JRWNP	0.7	2.6	15.1	42.5	39.2
I want to know more about the research results of the JRWNP	1.3	2.0	34.9	33.6	28.3
The JRWNP is likely to produce useful information in the future	1.3	2.6	21.8	53.3	21.1
The JRWNP is good for farmers in this area	1.3	3.9	36.8	40.8	17.1
The JRWNP will help our community	2.0	4.0	24.5	53.6	15.9
The JRWNP will improve water quality in this watershed	2.7	2.0	36.7	44.0	14.7
The JRWNP is an example of a good use of tax dollars	2.6	5.3	39.8	37.7	14.6
The JRWNP has already produced useful information	1.3	4.7	57.7	28.9	7.4
I want to participate in participatory projects like the JRWNP	4.7	5.4	57.7	19.5	12.8

Table 3
Perceptions and concerns about water quality, 2012 and 2015 survey respondents, and estimated change in population proportions between the two survey years.

Question	Respondents (%)								
	2012 survey (n = 139)			2015 survey (n = 160)			Change in population proportion, 2012 to 2015		
	Nonwheat farms	Wheat farms	Overall	Nonwheat farms	Wheat farms	Overall	Nonwheat farms	Wheat farms	Overall
Perceived water quality (WQ) as poor/fair on my farm									
Shallow groundwater	15.4	26.7	21.1	16.3	26.8	21.1	0.9	0.1	0.0
Deep groundwater	5.3	5.4	5.3	6.3	16.4	10.9	1.0	11.0	5.6
Perceived WQ as poor/fair in Judith River watershed									
Shallow groundwater	22.4	16.7	20.0	19.5	34.9	26.6	–2.9	18.2	6.6
Deep groundwater	5.4	7.4	6.2	7.7	9.2	8.4	2.3	1.8	2.1
Over last four years, how much have you heard about the issue of elevated nitrates (NO_3^-) in local groundwater?									
None	30.9	18.0	25.4	27.4	10.1	19.6	–3.5	–7.9	–5.8
A little	28.4	31.1	29.6	23.8	24.6	24.2	–4.6	–6.5	–5.4
Some	30.9	37.7	33.8	39.3	46.4	42.5	8.4	8.7	8.7
A lot	9.9	13.1	11.3	9.5	18.8	13.7	–0.4	5.7	2.4
Elevated NO_3^- levels in local shallow groundwater...									
Are not likely to ever be a problem	36.8	19.6	29.5	24.7	16.7	21.0	–12.1	–2.9	–8.5
Are not yet a problem, but could get worse if nothing is done	28.9	35.7	31.8	31.2	22.7	27.3	2.3	–13.0	–4.5
Have become a problem since settlement	2.6	3.6	3.0	2.6	4.5	3.5	0.0	0.9	0.5
Were here prior to pioneer settlement	5.3	8.9	6.8	6.5	12.1	9.1	1.2	3.2	2.3
Have become a problem in the last 50 years	13.2	19.6	15.9	16.9	28.8	22.4	3.7	9.2	6.5
Have become a problem in the last decade	13.2	12.5	12.9	18.2	15.2	16.8	5.0	2.7	3.9
Concerned or very concerned about NO_3^- in...									
My household drinking water	25.3	36.9	30.4	36.2	40.5	38.1	10.9	3.6	7.7
My livestock water source	21.1	35.7	27.3	28.4	37.6	32.6	7.3	1.9	5.3
Drinking water for nearby houses	26.3	39.6	32.1	35.8	44.8	39.8	9.5	5.2	7.7
Groundwater in Judith Basin (JB) and Fergus (F) counties	40.8	44.0	42.2	44.9	49.2	46.9	4.1	5.2	4.7
Surface water in JB and F counties	40.8	47.4	43.7	37.5	50.7	43.5	–3.3	3.3	–0.2

who point to agricultural fertilizers and bedrock. There was also a drop in the percentage who believed that decomposing OM in soil could be a source of NO_3^- (which ironically was a major potential source based on our research). The lack of consistency between our project messages and farmer perceptions may be partly due to the timing of the dissemination of our newsletter on the specific topic of "sources of NO_3^- in groundwater," which was unfortunately not ready for distribution until three months after we finished the 2015 survey effort.

We used the 2012 and 2015 surveys to test whether there were any changes in the factors producers consider when making decisions about the rate and timing of N fertilizer applications, as well as their use of BMPs that were the focus of the JRWNP research (table 5). The results suggest that producer decision making processes shifted over the life of the project. The most notable changes reflect a 13% growth in a desire to minimize costs, perhaps reflecting the relatively high cost of fertilizer compared to crop prices in 2015 (USDA ERS 2017). We also observed a similar increase of 11.5% in the proportion of farmers who said that accounting for soil OM is important or very important to them (one of the areas that was stressed in the JRWNP). There was a slight (but statistically insignificant) rise in the percentage who said they consider the risks

Table 4
Farmer perceptions about relative contributions of different sources to elevated nitrate (NO_3^-) levels in groundwater. Results show for 2012 and 2015 surveys and changes in estimated population proportions over the three-year period.

Based on what you've learned or observed, how important are each of the following possible sources of elevated NO_3^- in local groundwater?	Respondents reporting it as a moderate or major source (%): 2012 survey (n = 139) Nonwheat farms	Wheat growers	Overall	2015 survey (n = 160) Nonwheat farms	Wheat growers	Overall	Change in estimated population proportions between 2012 and 2015 Nonwheat farms	Wheat growers	Overall
Agricultural fertilizers	59.4	56.9	58.4	71.6	56.7	64.6	12.2	–0.2	6.2
Livestock wastes	25.0	32.1	38.0	22.7	21.2	22.0	–2.3	–10.9	–16.0
Decomposing organic matter in soil	17.6	28.5	22.3	14.9	18.7	16.7	–2.7	–9.8	–5.6
Bedrock	11.5	9.3	9.4	10.7	19.7	14.8	–0.8	10.4	5.4
Household wastes	16.9	14.5	15.9	13.5	10.5	12.0	–3.4	–4.0	–3.9
Rain and snow	17.6	17.9	17.7	8.0	13.4	10.6	–9.6	–4.5	–7.1
Wildlife	10.7	10.7	10.7	2.8	7.5	5.1	–7.9	–3.2	–5.6

of NO_3^- leaching when making fertilizer decisions, but many other considerations (maximizing yields, avoiding crop failure, and meeting crop yield goals) remained more important.

The ultimate impact of our project on water quality may be related to whether or not producers adopt new fertilizer or crop management practices that have the greatest potential for reducing NO_3^- movement to groundwater. A comparison of responses from the 2012 and 2015 samples show changes in rates of adoption of four practices by wheat farmers in the watershed (table 5). The results suggest no real change over the three-year period in the use of split application practices, only a slight increase in the use of annual legumes in place of fallowing, and notable growth in both the use of slow-release forms of fertilizer and cover crops on fallowed fields. Despite only a slight increase in the percentage of farmers who report using annual legumes as a fallow replacement, government statistics suggest that the planted area of pea in the two-county area actually increased almost five-fold from 2011 to 2016 (USDA NASS 2017). This growth in area (and anecdotal feedback from our PRAG members) suggests that those already planting annual legumes in 2012 greatly increased the amount of area devoted to annual legumes over the three-year period. As noted above, data from our on-farm plots did not demonstrate consistent benefits from split application methods or slow-release N products, but instead identified the use of alternatives to fallowing having the most potential to reduce NO_3^- leaching while maintaining farm profitability (John et al. 2017). In this sense, some, but not all, of the changes in producers' behavior in the watershed were consistent with our project's results and communication messages.

Table 5
Changes in the importance of factors behind nitrogen (N) fertilizer decisions and self-reported use of various best management practices (BMPs) among wheat farmer respondents in 2012 and 2015 surveys.

Question	Wheat farmers in 2012 survey (n = 60)	Wheat farmers in 2015 survey (n = 72)	Net change
Factors considered when determining N fertilization rate (percentage saying it is important or very important)			
Maximizing yield	86.0	89.4	3.4
Reduce risks of low yields or crop failure	81.4	83.1	1.7
Matching rate to crop yield goal	81.1	79.4	–1.7
Minimizing cost	59.7	73.0	13.3
Maximizing wheat protein levels	78.6	69.2	–9.4
Reduce risks of nitrate leaching	63.0	66.1	3.1
Results of recent soil tests	63.4	59.7	–3.7
Accounting for soil organic matter	43.4	54.9	11.5
Percentage reporting ever using this type of BMP			
Split application of N fertilizer	43.6	43.4	–0.2
Slow-release forms of N fertilizer	24.1	38.2	14.1
Plant annual legumes instead of fallowing	24.1	26.8	2.7
Plant cover crop on fallowed fields	15.1	25.0	9.9

Summary and Conclusions

Conventional approaches to outreach and extension in agricultural conservation programs in the United States have relied on top-down transfers of scientific knowledge to farmers through extension and outreach systems (Black 2000). The limited adoption of many conservation practices, and growing farmer skepticism about the value of scientific research, have led a growing number of outreach professionals to employ approaches that engage farmers in more collaborative processes (Arbuckle et al. 2015; Bentrup 2001; Johnson 2009; Osmond and Gale 1995). This can include relying more on local farmers and community leaders to design and implement conservation projects (Morton and Brown 2011).

While farmers are often increasingly involved in the outreach and implementation phase of conservation projects, it is much less common to involve farmers in the scientific research process itself (Ashby et al. 1996). While there is a strong tradition of farmer participatory research in many developing countries (Neef and Neubert 2011), this model is still relatively rare in the United States. Efforts to pursue more participatory approaches to research and modeling are premised on the idea that engaging people with practical and experiential knowledge can help scientists better understand the drivers of environmental or sustainability problems (Langsdale et al. 2013; Wiek et al. 2014). Moreover, having practitioners participate in the study of watershed problems and co-design appropriate responses is expected to increase local ownership of the problem, and help ensure recommendations will be embraced by land managers (Lemke et al. 2010; Perez 2015).

Feedback from the members of our AC and PRAG committees suggested that our participatory research process achieved many of the benefits that are expected from the literature. Farmers gained improved understanding of the need for changes in management practices and developed a higher degree of ownership over the underlying problem (Ashby et al. 1996; Brown et al. 2010). The fact that farmers had contributed to the design of field trials and were involved in data collection appears to have been more important than sharing tables of statistically significant results in generating farmer interest in and understanding of research findings. Collaboration between scientists and farmers led to higher levels of trust in the science and data (Busse et al. 2015), and results coming from the project were viewed as more credible among local farmers and community leaders than previous research.

Previous studies suggest that recognition of an environmental problem and being convinced that farm management decisions have an impact are important preconditions to motivating changes in farmer conservation behaviors (Morton and Brown 2011; Reimer et al. 2012). Postproject interviews with AC and PRAG members suggested that our farmer participants expressed increasing ownership over the NO_3^- problem, as well heightened awareness of how combinations of crop rotations, fertilization practices, and rainfall converge to generate pulses of NO_3^- from farm fields into shallow groundwater aquifers. Importantly, farmers were critical partners in characterizing the role played by factors above and beyond mere fertilizer use in driving NO_3^- leaching. In lieu of having the science team tell the participants what was going on, we developed an open process of joint discovery to test alternative hypotheses about the sources of NO_3^- and the effectiveness of various farm management practices. It appears that this approach had a strong impact on the beliefs, knowledge, and attitudes of nearly all project participants.

The process also provided an opportunity to address social and political perceptions that were historically the biggest obstacles to local farmer responses to high groundwater NO_3^- levels, particularly the perception that farmers were being unfairly accused of inappropriate behavior (in general) and excessive use of fertilizers (in particular), and fears that outside groups might use scientific monitoring data to regulate farmers' fertilizer management practices. By directly confronting these concerns and fears through face-to-face meetings and collaborative approaches to the design of the research, interpretation of data, and development of appropriate management responses, we witnessed a shift in the conversation away from fertilizers per se toward the dynamics of the broader farming system and the ways that decisions about crop rotations interacted with weather events to generate most of the NO_3^- leaching observed on our farmers' fields.

There is evidence that our participatory approach also strengthened the capacity and confidence of local knowledge and social networks that are important influences on farm management behaviors (Morton and Brown 2011). We did hear anecdotal examples of conversations between our farmer participants and their neighbors about the findings of the project, and the project team used local newspapers and radio media outlets and created print and online resources to disseminate information about the project including emerging research results. The 2015 survey provides evidence that a large share of farmers were aware of and had a positive impression of our project. Moreover, awareness, concern, and understanding of the NO_3^- issue also increased among the larger farm population, and survey respondents from across the watershed attributed some of those changes directly to our project's activities.

Ultimately, finding effective responses to most wicked agricultural environmental problems requires greater understanding of complex system dynamics that shape environmental processes and human behaviors (Batie 2008). This complexity is difficult to capture using conventional disciplinary scientific methods. The participatory approach used in this project is one example of an alternative that provides greater opportunities for scientists to benefit from farmers' intimate understanding of local agricultural landscapes (Cockerill and Tidwell 2006; Lemke et al. 2010; van den Belt and Blake 2011), and for farmers to gain insight about the scientific process. Farmer input helped the project identify management options that are compatible with complex social, economic, and environmental constraints (Ashby et al. 1996; Hirsch Hadorn et al. 2008; Reimer et al. 2012). Our process also demonstrates how a more open and collaborative approach can help break down historical social and political barriers among scientists, environmental policy makers, and the farm population.

While we can document increased awareness and concern about the NO_3^- issues among our core participants and the wider farm population, we have less evidence that this has translated into significant changes in farm management practices. We are aware of instances in which our collaborating farmers decided to try (or expand) their use of some of the more promising practices that emerged from our field studies, and growing interest in and use of cover crops and legumes in place of fallow among the broader farm community is consistent with messages disseminated from our project. Additionally, the project required a major investment of time and money from the USDA sponsors, the science team members, and our local farmers and community partners. Whether our approach could easily be reproduced with less funding, or whether the water quality or social capacity outcomes are worth this level of cost, remains unclear.

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