doi:10.2489/jswc.2023.00109

Understanding barriers to adoption of sustainable nitrogen management practices in California

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Abstract: Achieving sustainability in agricultural nitrogen (N) management relies on farmers' decisions to reduce fertilizer inputs and adopt conservation management practices. Understanding the drivers and barriers to farmers' adoption of improved N management practices is critical to developing effective management and policy approaches on this intractable challenge. Existing research on farmer behavior has assumed that any barrier to adoption will result in lower practice adoption rates, without fully understanding how barriers may vary across different management practices, farm and farmer types, and stages of adoption. By leveraging two farmer survey data sets (total n > 1,900), this study diagnoses key barriers to adoption across 11 different N management practices and a large diversity of farmer and farm types across the California Central Valley. We find resource constraints, technical knowledge, and uncertainty emerge as key barrier types that differentially affect farmers at various stages of adoption. On a practice-by-practice basis, uncertainty barriers appear greatest for nonadopters of a practice, whereas practice adopters are more likely to report resource barriers. Across management practices at the farm level, farmers with higher self-reported conservation orientations are more likely to report being affected by all barrier types, as compared to their peers with lower self-reported conservation orientations. Our findings demonstrate that barriers to adoption are more complex than simply the factors that predict lower adoption, as both adopters and nonadopters experience barriers. Furthermore, factors that typically predict higher adoption, such as conservation motivation, do not insulate a farmer from facing barriers to adoption. We consider how adopters are likely to go through a learning process while moving from considering to fully implementing a new practice, during which different barriers to behavior change may be encountered. We argue that interventions intended to motivate farmer adoption of improved management practices need to take more nuanced approaches to understanding how barriers to adoption are likely to vary across stages of adoption, farm and farmer type, and specific management practices.

Key words: adoption—barriers—decision-making—nitrogen—stewardship motivation—uncertainty

Use of nitrogen (N) fertilizers is a distinguishing characteristic of industrialized agriculture systems globally, with fertilizer inputs largely responsible for dramatic increases in crop yields over the past century (Vitousek et al. 2013). Excess N that is not taken up by the crop may be lost to the surrounding environment and contribute to nonpoint source water pollution and greenhouse gas emissions (Kanter 2018; USEPA 2017; Good and Beatty 2011). Extensive agronomic research has demonstrated that by implementing the right suite of conservation management practices on the farm, N use efficiency can be improved without sacrificing crop yields (Snyder 2017; Wu and Ma 2015). These suites of practices can include developing an N budget that helps to track N inputs and N uptake by crops (Muhammad et al. 2009); applying the 4Rs Nutrient Stewardship Strategy, an industry-developed educational framework to identify the right rate, right time, right amount, and right place for fertilizer applications (Mikkelsen 2011); using available monitoring and sampling technologies such as soil moisture sensors, or taking leaf/tissue or soil samples to measure nitrate (NO_3^-) status to make data-informed input decisions (Sanchez et al. 1995; Dinnes et al. 2002; Agostini et al. 2010; Diacono et al. 2013; Khalsa and Brown 2019); water use efficiency practices (Lopus et al. 2010; Taylor and Zilberman 2017); as well as more holistic soil health practices, such as cover cropping and use of compost or organic amendments (DeVincentis et al. 2020; Khalsa and Brown 2017).

Many researchers and agricultural policy stakeholders suggest current adoption of N management practices is inadequate to address N pollution problems (Rudnick et al. 2021; Osmond et al. 2015; Ribaudo 2015; Wade et al. 2015). These communities seek to understand what motivates or presents barriers to farmers' adoption of improved management practices in order to design effective behavioral interventions such as regulatory or incentive programs (OECD 2018). The existing literature on farmer decision-making predominantly focuses on farm- and farmer-level characteristics that *positively* influence or motivate adoption of conservation management practices (Prokopy et al. 2019), with empirical studies focused on better understanding and characterizing barriers to adoption being substantially more limited (Ranjan et al. 2019a). As one recent systematic review of the adoption literature points out, "quantitative research has not focused

Received July 29, 2022; Revised December 2, 2022; Accepted February 20, 2023.

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enough attention on barriers to adoption… [with] most independent variables included in adoption studies hypothesized to be positive predictors" (Prokopy et al. 2019).

We aim to address this research gap by explicitly focusing on understanding the barriers that California farmers report experiencing during their adoption of 11 different N management practices. We focus on the following three key research questions:

1. How do the barriers farmers report experiencing vary across different N management practices?
2. How do practice adopters and nonadopters differ in what types of barriers they report experiencing?
3. How do different farm and farmer characteristics influence the types of barriers farmers report experiencing?

We explore these questions by integrating two different farmer survey data sets (*n* = 1,916 in total) collected in the California Central Valley from 2018 to 2019.

Background on Barriers to Adoption. Achieving high levels of adoption of improved N management practices requires that farmers engage in a complex process to consider new management practices; acquire the knowledge, skills, and resources necessary to implement the practices; modify the practices to appropriately fit their specific farm conditions; and then scale up adoption across their farm. At every stage of this process, a farmer may face motivational, cognitive, or practical drivers or challenges (Vanclay 1992). While decades of farmer decision-making research has illuminated how significantly behavioral drivers can vary across contexts and practices being adopted, a few characteristics stand out for fairly consistently predicting higher levels of conservation practice adoption: larger farm size, greater farm income, higher education levels, larger information networks, previous use of conservation practices, and more positive attitudes toward environmental stewardship and conservation practices (Prokopy et al. 2019; Ranjan et al. 2019a; Liu et al. 2018; Carlisle 2016; Baumgart-Getz et al. 2012; Prokopy et al. 2008; Knowler and Bradshaw 2007). This literature also tends to assume that the factors that negatively correlate with adoption behaviors can be understood as "barriers to adoption." Commonly identified negative predictors of adoption, which are often factors in the opposite direction of the drivers above, include limited access to capital, land rental, lower education, older age or more years of farming experience, lack of access to information, lack of experience with or negative perceptions of conservation practices, perceptions of increased risk associated with practice adoption and risk adversity, and identify or value orientations that prioritize profits or production above social and environmental values (Prokopy et al. 2019; Ranjan et al. 2019a; Reimer et al. 2012).

Yet, by considering only the factors that correlate with low or no adoption to constitute barriers, current research underappreciates adoption as a *process* of behavior change, where it is reasonable to imagine barriers may be encountered throughout the process, and that farmers can overcome barriers and still end up adopting the practice of interest. Understanding when barriers influence the adoption process, which barriers are manageable versus insurmountable, and how different farmers are impacted by different barriers may provide key insights as to how to effectively design interventions that increase and sustain adoption of necessary conservation practices.

An additional gap in current research is in understanding how farmers may face different types of barriers with different types of conservation practices. Diffusion of Innovations literature suggests the characteristics of different innovations, such as its complexity, divisibility or trialability, compatibility with other management practices, economics, and risk are important characteristics to consider in determining how difficult the innovation will be to adopt (Vanclay 1992; Rogers 1962). For example, cover crops are thought to be a relatively complex practice with a temporal delay between costs and benefits, and can be challenging to make compatible with cash crop planting timing. For corn (*Zea mays* L.) and soybean (*Glycine max* [L.] Merr.) farmers in the Midwest, economic barriers, return on investment concerns, labor requirements, and concern about timing with planting cycles have all been identified as barriers to adoption to cover cropping (Roesch-McNally et al. 2017; Doran et al. 2022; Beetstra et al. 2022). On the other hand, when it comes to reducing N application rates, midwestern farmers report uncertainty as to how crop yields will be impacted and risk adversity to any yield losses as key barriers to adoption (Reimer et al. 2020). Furthermore, even for farmers motivated to reduce their environmental impact, access to information that facilitates learning how to best reduce fertilizer applications can be limited given that many crop advisors are fertilizer industry representatives with incentives that conflict with recommending reduced N rates (Stuart et al. 2012; Schewe and Stuart 2017). These different challenges or barriers may arise at various stages of adoption including consideration, learning, trialing, implementation, and maintenance (Rogers 1962; Vanclay 1992). Empirical studies explicitly focused on understanding how or when in the adoption process farmers experience different barriers are extremely limited, especially given methodological challenges associated with longitudinal or panel studies that would facilitate studying adoption as a process over time (Doran et al. 2022). We rely on the limited available research that suggests that barriers to adoption vary across practices and affect different stages of the adoption process to ground our hypotheses for this study.

Barriers Vary across Practices and Actual Adoption Behavior. Our first hypothesis reflects a general prediction that key barriers to adoption will vary across different management practices. This builds off early applications of Diffusion of Innovation literature applied to agricultural adoption that focused on understanding how characteristics of different agricultural innovations would influence their adoptability (Vanclay 1992; Pannell et al. 2006). A more recent assessment of different barrier types influencing the adoption of climate-smart agriculture practices provides a typology of possible barrier types, including cognition barriers (i.e., lack of problem recognition), interest barriers (i.e., lack of motivation or interest in trying new practices), practical barriers (i.e., cost, labor, equipment, or fit with operation), and information barriers (i.e., lack of technical knowledge or information on how to implement a practice) (Kipling et al. 2019). We expect to see barriers across this typology emerging as farmers report on what challenges their adoption of the 11 different N management practices of focus.

Practice-Specific Barriers Hypothesis (H1): Farmers will name different barriers as most challenging for different management practices.

Another popularly employed theoretical framework in farmer behavior research is the Theory of Planned Behavior/Reasoned Action Approach (Azjen 1991; Fishbein and Ajzen 2010), which posits that behavior is driven by intentions. Though less commonly integrated in farmer behavior research, theory on motivation suggests that perceived barriers to an intended behavior act as an intermediary factor dampening the effect of intention on actualized behavior (Gollwitzer and Oettingen 2012). To our knowledge, however, few empirical studies have focused on quantifying the intermediary effect of perceived barriers to adoption of management practices on farmers' actual adoption behaviors. Giampietri et al. (2020) provide one example where higher perceived barriers result in reduced intentions to adopt crop insurance, as a strategy promoted to enhance resilience to environmental and economic changes. Doran et al. (2022) provide further supporting evidence, showing that farmers in later stages of cover crop adoption reported fewer overall barriers to adoption. Our second hypothesis is consistent with this framework, assuming farmers' reporting more barriers will be less likely to have already adopted the practice of focus.

Adopter Hypothesis (H2): Farmers who adopt a practice will report significantly fewer barriers than nonadopters.

Barriers Vary across Farmers and Farm Types. Farmers that have different types of operations and personal characteristics including values, knowledge, and experiences would also be expected to face different types of barriers. We predict similar characteristics to those that decrease adoption would also make a farmer more likely to perceive or be impacted by different barriers to adoption. For example, farmers who lack access to financial capital, diverse informational sources, or who are renting land have been found to be more susceptible to resource barriers like cost and labor (Ranjan et al. 2019b; Stuart et al. 2018; Wreford et al. 2017). Technical knowledge has been identified as a significant barrier for older farmers who are less likely to be technologically savvy and are more resistant to change (Wiebold et al. 1998; Prokopy et al. 2019) and for farmers with limited access to information sources (Stuart et al. 2012). Recent studies have demonstrated that farmers accessing more information and a larger number of information sources overall have been found either likely to report fewer barriers to adoption (Doran et al. 2022) or have greater likelihood of overcoming their named barriers to adoption (Upadhaya et al. 2021). Risk and uncertainty barriers emerge in the empirical literature as perceived risks to crop yields associated with practice adoption (Reimer et al. 2020) and lack of clarity on the economic payoffs and time to return on investment (Hillis et al. 2018; Ghadim et al. 2005; Cary et al. 2001). Uncertainty and risk perceptions have been shown to decrease as farmers engage with learning about a practice and better understand how the practice will help them achieve their operational goals (Pannell et al. 2006; Marra et al. 2003). In their study of farmers in different stages of adoption, Doran et al. (2022) found farmers with higher environmental concern or a higher stewardship identity were likely to be in later stages of adoption, which we assume to indicate a later stage of learning about the practice and likely lower levels of uncertainty. Considering these recent studies on barriers alongside the characteristics known to decrease adoption, we develop the following hypotheses on what farm and farmer types we predict will be more likely to report experiencing different barrier types:

- *Resource Hypothesis (H3): Farmers with lower farm income, smaller farm size, and/or renting land will be more likely to report resources as barriers to practice adoption.*
- *Technical Knowledge Hypothesis (H4): Older farmers, smaller farms, and/or farmers with limited information networks will be more likely to report technical knowledge as a barrier to practice adoption.*
- *Uncertainty Hypothesis (H5): Farmers with lower environmental problem recognition and stewardship motivation will be* more *likely to report uncertainty as a barrier to practice adoption.*

Materials and Methods

Nitrogen Management and Policy Context in California. The California Central Valley is a vast and diverse, input and technology-intensive agricultural region, with more than 400 different commodity crops in production across 9 million irrigated acres (3.6 million ha) (California Department of Food and Agriculture 2018). Improved N management has become a strong focus of agricultural policy and extension in California in recent years, as N pollution threats to drinking water have grown (Harter et al. 2012). This has led to a heightened interest among research, extension, and policy stakeholders in understanding farmers' barriers to adopting N management practices (Tomich et al. 2016; CDFA FREP 2020).

California also provides an interesting research context as it is the first state in the United States to adopt and implement a regulatory program to address agricultural nonpoint source pollution. The Irrigated Lands Regulatory Program (ILRP) requires mandatory participation of all irrigated agricultural operations across the state and is implemented through watershed-scale groups known as Water Quality Coalitions, which most farmers participate in to meet regulatory compliance. Key components of the program include mandatory education and reporting elements that track fertilizer use and voluntary adoption of management practices for improved N use efficiency (Central Valley Regional Water Quality Control Board 2020). This regulatory context provides the backdrop encouraging widespread adoption of management practices and prompting interest in understanding farmers' "barriers to adoption." We focus on evaluating the barriers to 11 different N management practices that are identified as centrally important management practices by the ILRP: developing an N budget, leaf testing, soil testing, split fertilizer applications, organic matter amendments, cover crops, N testing of irrigation wells, evapotranspiration-based irrigation scheduling, pressure chamber, soil moisture probes, and checking irrigation systems for distribution uniformity.

Integrating Two Survey Data Sets. This paper integrates farmer survey data from two waves of data collection conducted in the Central Valley between 2017 and 2019: a survey distributed in-person at ILRP-mandated farmer education meetings ("Meeting Survey") and a survey distributed via postal mail ("Mail Survey"). The two survey instruments offered the opportunity to study farmer behavior and barriers to practice adoption at different levels of granularity, assessing if and how we can measure barriers across different management practices, farm and farmer types, and actual adoption behaviors. For example, in the Meeting Survey, we were able to measure barriers at a practice-specific level and evaluate the direct relationship between the adoption decision on a specific practice and the reported perceived barriers around that practice. These practice-specific measures provide valuable information about how decision-making can vary across a large number of different management decisions farmers make; however, collecting this type of data increases the response burden on participants. Thus, in the Mail Survey effort, where we also aimed to measure other farm operation characteristics and farmer socio-behavioral characteristics such as attitudes, beliefs, and information networks, we decided to ease the response burden on participants by asking about overall barriers to adoption of any N management practices, rather than measuring barriers on a practice-specific level. This level of measurement allowed us to assess how perceived barriers relate to other farm and farmer-type characteristics, but we could not parse these behavioral interactions at a practice-specific level. Multiple measures of practice adoption and reported barriers to adoption also help to avoid common-source bias that is a prevalent challenge in survey-based research.

Both survey instruments were developed and distributed through a collaborative process that involved contributions and feedback from a diverse network of agricultural extension, policy, and industry stakeholders. The survey populations were defined by boundaries of Water Quality Coalitions across the Central Valley and sought to represent the agronomic and operational diversity present in the region (see map in figure 1). Additional details on data collected in each instrument follows.

Figure 1

Map of regions surveyed in both survey efforts. Meeting Surveys were conducted in the dotted region in 2017 (covering San Joaquin County and Delta Water Quality Coalition and East San Joaquin Water Quality Coalitions) and striped region in 2019 (covering the seven South San Joaquin Water Quality Coalitions). The Mail Survey was conducted in the crosshatched (Colusa-Glenn Subwatershed Program) and dotted regions in 2018.

Meeting Survey. We distributed short surveys to all attendees at Water Quality Coalition annual education meetings, including seven meetings in the North San Joaquin Valley in winter of 2017 and seven meetings in the South San Joaquin Valley in winter of 2019. The survey instrument was very brief to facilitate quick real-time responses from meeting attendees who voluntarily participated. It focused on gathering adoption data on 11 different N management practices and asking farmers what factors they perceived as barriers or motivators to their adoption of each practice. Two different lists of factors were provided—one of potential barriers or "challenges to adoption" and one as potential motivators or "benefits considered in adoption," where the options provided were informed by preliminary scoping interviews with farmers and technical assistance providers reviewing the survey tool to ensure relevant items were included. On both lists, respondents were asked to select all that apply, allowing them to select "yes/no" on each benefit or barrier. Binary response options were used to minimize the respondent burden, since we were asking about barriers and benefits on 11 distinct management practices. On the barriers question, respondents were also provided with the option "Adopted with no challenges," allowing our analysis to distinguish between those who had adopted a practice and still indicated challenges on that practice, those who had adopted a practice but did not report any challenges, those who did not adopt the practice and reported challenges, and those who did not adopt and did not report challenges. Additionally, five short questions about characteristics of the respondent's farm operation were also included in order to characterize adoption by crop type, farm size, and irrigation system. The data set offers granularity on barriers to adoption at a practice-specific level, but is limited by lack of data on farmer demographic or socio-behavioral characteristics (see Khalsa et al. [2022] for more details on survey methods and respondent demographics). We collected 950 usable responses in total, constituting an approximate 35% response rate of meeting attendees. Respondents were found to be fairly representative of the Water Quality Coalitions' total membership, on the basis of farm size and primary crop type. Respondents were entirely anonymous and thus we are not able to match responses to Mail Survey respondents.

Mail Survey. The Mail Survey was distributed to farmer members in three Water Quality Coalitions in the North San Joaquin Valley in 2018. Mailing lists were built using the coalitions' mailing lists when provided, supplemented with the county Agricultural Commissioner databases of commercial agricultural operations in compliance with Pesticide Use Reporting requirements, and the USDA Organic INTEGRITY Database for organic operations (USDA 2018). We followed a modified Dillman method (Dillman et al. 2008), with four mailings. The survey included 30 questions covering farmers' adoption of the same N management practices, factors considered to be barriers or priorities in general adoption decisions (i.e., not practice-specific), environmental problem recognition and attitudes, values and motivations (e.g., stewardship versus production-motivated), perceived control related to N pollution, information sources on N management, demographic, and farm operation characteristics. The survey aimed to measure more variance on the impact of different barriers and motivators on adoption decisions generally by using a five-point Likert scale (1 = never to 5 = always influences adoption), but it did *not* measure these factors on a practice-specific basis. It did capture significantly more detail on farmer demographic characteristics (e.g., income, age, race, gender, and education) that were not measured in the Meeting Surveys. We collected 966 usable responses, constituting an average response rate of 20% across the three regions after adjusting for possible noneligible addresses included in our mailing lists (American Association for Public Opinion Research 2016). See Rudnick et al. (2021) for more details on survey methods and respondent demographics. Respondents were found to be fairly representative of the full farming populations in the surveyed regions on the basis of primary crop grown and farm size, when compared to USDA 2012 Census of Agriculture data (see tables S3 through S5 in the supplemental materials). The average farm size of our Mail Survey respondents is 355 ac (143 ha; minimum <1 ac [<0.4 ha], maximum ~12,000 ac [~4,800 ha]). In aggregate, our survey respondents manage 329,800 ac (133,465 ha) of land across the Central Valley, approximately 35% of the area of the study area. Seventy-nine percent of respondents own their land; 80% of respondents are male; and 84% of respondents identify as White or Caucasian, 4% as Hispanic or Latino, and 3% as Asian or Asian American. Sixty-one percent of respondents have at least some college education. On average, respondents have 35 years of farming experience, and the median gross farm income bracket is US$100,000 to US$200,000. Our response rate is equivalent to that in other recent mail surveys on similar topics conducted with farming populations (Denny et al. 2019; Wilson et al. 2014; Arbuckle and Rosman 2014).

All data collection methodologies were reviewed and approved by the Internal Review Board at University of California Davis. Question wording from both survey instruments is included in table S1 in the supplementary materials for all variables used in this analysis.

Analysis Approach. By leveraging two sets of survey data, this paper provides a novel opportunity to quantitatively assess what factors farmers perceive as barriers across 11 different N management practices and evaluate what socio-behavioral characteristics predict the likelihood of a farmer reporting experiencing a barrier, across a large number of respondents and diverse agricultural operations. The unit of analysis for all exploratory analyses and hypothesis testing is an individual farmer.

We leverage the Meeting Survey data for our analysis of H1 to evaluate how key barriers vary across 11 different N management practices. Key barriers were constructed as latent variables, combining multiple factors measured on the survey (e.g., resource barrier is combination of cost, labor, and supplies/equipment measures [table S1]). Barrier variables were constructed as binary measures, with a 1 on any barrier indicating the presence of at least one of the contributing factors (e.g., if farmer selected cost as a barrier, but not labor or supplies/equipment for the leaf testing practice, resource barrier = 1), and a 0 on any barrier indicating the absence of all contributing factors (e.g., if the farmer did not select cost, labor, or supplies as a barrier, resource barrier = 0). We made the decision to keep barriers as a binary variable rather than count variable of the contributing components because we felt this was a more consistent measure of whether the farmer experienced the different key barrier types (resource, uncertainty, or technical knowledge) at all. We learned that some respondents had confusion as to whether the different barrier factors should be considered as mutually exclusive of one another, or not. For example, labor can be a key component in the cost of implementing any practice. Some farmers indicated to us that they selected both "cost" and "labor" as barriers to demonstrate the impact of labor costs on their adoption decisions, whereas other farmers only indicated one or the other factor.

To assess our practice-specific hypothesis (H1), we use the Meeting Survey data to qualitatively compare how key barriers differ across each of the 11 N management practices of focus for all respondents.

To assess our adopter hypothesis (H2), we subset the Meeting Survey data into adopter and nonadopter groups for each management practice and compare the different groups' reported rates of each key barrier, evaluating differences using a Mann-Whitney test.

We leverage the Mail Survey data set, which provides greater detail on socio-behavioral and demographic farmer characteristics, to evaluate our hypotheses on which farm/farmer types will be more susceptible to each key barrier type (H3, H4, and H5). The Mail Survey measured barriers that generally affect adoption of N management practices on a five-point Likert scale, but did not measure barriers on a practice-specific basis. We averaged across individual survey items to again create latent variables for each key barrier (resources, technical knowledge, and uncertainty), on the same five-point scale. We used confirmatory factor analysis and calculated Cronbach alpha scores to verify internal consistency between the survey items; all alpha scores were greater than 0.70, a widely accepted cut-off point indicating internal validity (Santos and Reynaldo 1999) (table S1).

To evaluate our hypotheses, first, we use descriptive statistical analyses including Student's t-test and Analysis of Variance (ANOVA) to compare the average rating of each key barrier across farmer demographic groups (education level, income, land tenure, farm size, age measured as years of experience, race, and gender).

We also estimate three individual cumulative ordered logistic regression models ("ordered logit"), with partially relaxed assumptions about proportional odds, for each of the three key barriers. The latent barrier variables (resources, technical knowledge, and uncertainty) serve as the ordered dependent variables (1 = never a barrier, 5 = always a barrier) for each model. Explanatory variables included in the models include farmer demographics (education level, income, land tenure, age, and farm size); different types of information networks including agriculturally oriented information networks (irrigation district, water quality coalition, Pest Control Advisor, Certified Crop Advisor, County Agricultural

Commissioner, County Farm Bureau, and commodity organization), environmentally oriented information networks (Resource Conservation District, Cooperative Extension, USDA Natural Resources Conservation Service, and California Department of Food and Agriculture Fertilizer Research and Education Program), and informal/peer networks (own experience, family, field crew, and other farmers) (groupings modified based on Arbuckle et al. 2015); environmental problem recognition; stewardship motivation; and perceived behavioral control. We include a count variable to control for the number of practices adopted (table S1).

Ordered logistic regression models require the data to meet the proportional odds assumption, otherwise known as the parallel lines assumption, indicating that predictor variables have the same effect on different levels of the dependent variable (e.g., age has a consistent effect on reporting technical knowledge as a barrier, where each additional 10 years of experience increases the likelihood of a farmer moving from technical knowledge being "never" to "rarely" to "sometimes" to "often" to "always" a barrier). If the proportional odds assumption is violated, coefficient estimates can be biased both in direction and magnitude. To test the proportional odds assumption, we ran Wald tests on each standard ordered logit model and Brant tests (Brant 1990 to test each specific variable included in the model. All three of our barrier models failed to meet the proportional odds assumption overall, and multiple predictor variables failed individually on each key barrier. Partial proportional odds (PPO) models allow for this assumption to be relaxed for a subset of variables in the model by estimating a single coefficient for covariates that meet the proportional odds assumption, and multiple coefficients for each level of the ordered dependent variable for the covariates that do not meet the proportional odds assumption (Peterson and Harrell Jr. 1990). This is a more efficient alternative to relaxing the proportional odds assumption on every coefficient, which may result in a large inflation in the number of total coefficients being estimated. The PPO method does have potential limitations, including a lack of clear theoretical grounding for which explanatory variables may operate consistently versus differently across the dependent variable scale. This can limit meaningful interpretation of the model results, and calls to question what the appropriate alpha level threshold on the Brant and Wald tests should be (i.e., should one follow the standard 0.05 alpha cutoff to relax the proportional odds assumption, or is a higher level of significance more appropriate) (Fullerton and Xu 2011). Furthermore, including additional coefficients in a model increases the likelihood of type I errors. Finally, we admit that reporting and interpreting the PPO results is less straightforward than the interpretation of a traditional proportional odds model, as it requires considering the relationship between the independent and dependent variables differently, at different points along the scale. This can muddle key patterns and confuse research audiences who are already digesting the results of complex analyses. While we recognize these limitations, we choose to leverage the PPO modelling approach and estimate the models for all three barriers consistently, applying liberal proportional odds relaxations for all variables that violated the assumption in any of the three key barriers models, which included education, years experience farming, perceived behavioral control, and environmental problem recognition. We conducted multiple robustness checks, comparing different model specifications that included the proportional odds model as well as different variations on which variables should be granted relaxed slopes, and compared how results varied across these model specifications. Our reported results and key takeaways are robust across many different model specifications and iterative proportional odds adjustments (figure S4).

We used stepwise deletion and evaluated model fit statistics including log-likelihood and Akaike information criterion (AIC) to determine the most parsimonious model specification that included key explanatory variables of interest. All coefficients are presented in exponentiated form as odds-ratios to facilitate interpretation, where values greater than one indicate a positive relationship between the predictor and dependent variable, and values less than one indicate a negative relationship (table S2 and figure S3).

Recognizing that our models contain a large number of explanatory variables that allow us to test multiple hypotheses (H3, H4, and H5) at once, we evaluate a Bonferroni correction to our statistical significance level (standard significance level of $p < 0.05$) to account for multiple comparisons. The Bonferroni correction helps to guard against the bias of repeated testing effects, where there is an increased likelihood of determining that at least explanatory variable is significant by pure chance. To account for this inflated likelihood of error, the Bonferroni method lowers the desired significance level by dividing the standard alpha value of 0.05 ($p < 0.05$) by the number of hypothesis tests being conducted (in our case, 11 explanatory variables and 1 control variable means 12 independent tests), to determine a new threshold of significance ($p < 0.004$). These adjustments provide a conservative estimate for new significance thresholds and associated confidence intervals (see figure S5 and table S6 for comparison of standard versus Bonferroni-adjusted confidence internals). Our results are fairly robust under the adjusted significance thresholds and we report on a few coefficients with confidence intervals that fall extremely close to the significance threshold, given the conservative Bonferroni adjustment.

As a final robustness check, we also fit ordered logit models using all individual barrier items from the survey as dependent variables, rather than our latent key barrier variables. We compare these model estimates for the items that load into each key barrier; results yield similar coefficient estimates (figure S6).

Results and Discussion

We organize our results around our three key research questions. First, our exploratory analysis of the Meeting Survey data diagnoses the key barrier type farmers report in their adoption of 11 different N management practices (H1). Second, we further leverage the Meeting Survey data to evaluate our adopter hypothesis (H2) and characterize differences in the barriers named by adopters and nonadopters of each practice. Finally, we analyze our Mail Survey data using descriptive cross-group comparisons and PPO ordered logit models to evaluate our three barrier-specific hypotheses (H3, H4, and H5) to determine which types of farmers and farm operations are most likely to experience resource, technical knowledge, and uncertainty barriers, respectively. Interpretation and implications of the results follow.

Barriers to Adoption Vary across Management Practices. At the full farm level, approximately half of farmers report that resources (52%) or uncertainty (49%)

barriers always or often influence their adoption decisions. Comparatively, only 28% of farmers report that technical knowledge always or often acts as a barrier to adoption. However, the most prevalent barriers differ when zooming in to individual management practices, providing support for our practice-specific barriers hypothesis (H1). Resource barriers were dominant on 7 of the 11 practices: soil testing, split application, leaf testing, irrigation well N testing, distribution uniformity, moisture probes, and pressure bomb. Uncertainty was the greatest barrier reported for the four other practices: N budget, organic matter use, cover crops, and evapotranspiration (ET)-based irrigation scheduling. Technical knowledge barriers were reported by more than 20% of farmers for ET-based irrigation scheduling and pressure bombs, but it was not the most prevalent barrier for any practice (figure 2).

Barriers Reported Vary Based on Practice Adoption Behavior. Our adopter hypothesis (H2) predicted that farmers who adopted a specific practice would report fewer overall barriers than farmers who did not adopt the practice. Our findings demonstrate support for this prediction, showing that across nearly all management practices, nonadopters reported higher rates of all three key barriers than adopters, though for some barrier-practice dyads these differences were small and insignificant (exceptions to the trend include adopters naming higher resources barrier on N budget and technical knowledge barrier on cover crops) (table 1).

Interestingly, we find that when practice adopters *do* report barriers, they tend to name resource barriers as most frequently influencing their adoption, whereas nonadopters indicate uncertainty most frequently. Few exceptions to this overall trend include adopters naming uncertainty as a slightly greater barrier than resources for cover crops, adopters naming resources and technical

Figure 2

Total percentage of farmers reporting key barriers to adoption on each of the 11 conservation nitrogen (N) management practices. Resource barriers are in black, technical knowledge barriers are in grey, and uncertainty barriers are in white (data source: Meeting Survey data set, all respondents: *n* = 950).

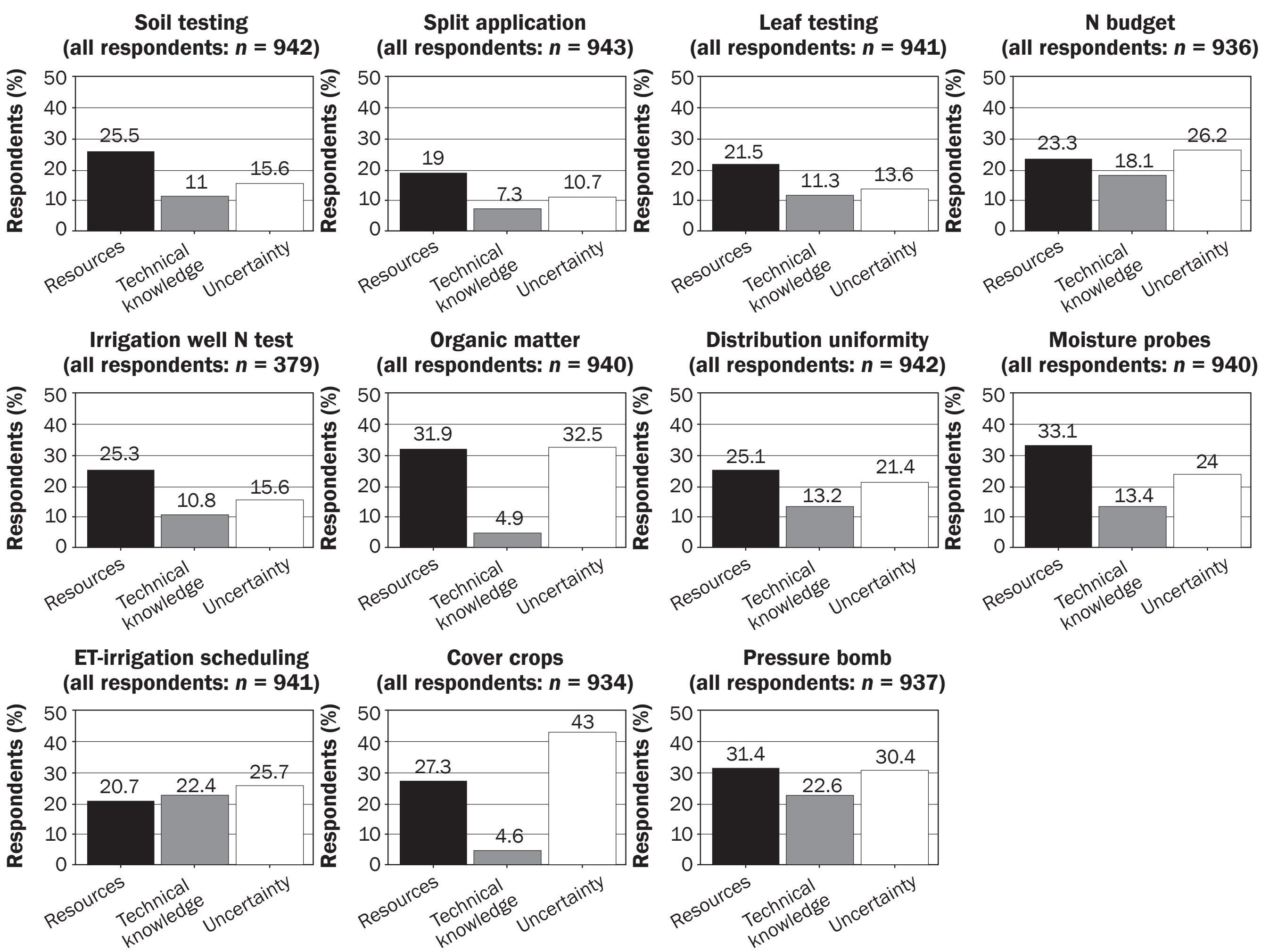


Table 1

Percentage (%) of adopters and nonadopters reporting uncertainty, resource, and technical knowledge barriers on 11 distinct nitrogen (N) management practices. Practices are ordered from highest to lowest rate of adoption, with adoption rates reported in parentheses after the practice name. Differences in barrier rates reported between adopters and nonadopters evaluated with Mann-Whitney tests, where $p < 0.05$ indicates a significant difference in reported barrier rates between adopter and nonadopter groups.

Management practice (adoption rate)	Uncertainty (%)			Resource (%)			Technical knowledge (%)		
	Adopters	Nonadopters	*p*	Adopters	Nonadopters	*p*	Adopters	Nonadopters	*p*
Soil testing (80%)	12.12	37.36	*<0.001*	24.58	29.67	0.295	9.41	20.88	*0.001*
Split application (78%)	5.83	38.31	*<0.001*	17.92	23.85	0.144	6.76	10.09	0.216
Leaf testing (78%)	7.46	47.40	*<0.001*	18.74	32.35	*0.002*	10.24	16.67	0.055
Irrigation well N test (72%)	8.26	29.17	*<0.001*	17.94	28.10	*0.028*	7.12	15.63	*0.005*
Nitrogen budget (65%)	19.11	44.22	*<0.001*	22.99	22.77	0.950	14.95	25.12	*0.001*
Organic matter	17.68	53.63	*<0.001*	30.62	32.62	0.576	5.50	3.90	0.334
Distribution uniformity (52%)	10.10	36.71	*<0.001*	23.91	25.49	0.645	11.11	15.69	0.086
Moisture probe (49%)	11.61	39.45	*<0.001*	24.37	44.33	*<0.001*	11.06	16.20	0.051
ET-based irrigation (48%)	12.91	41.24	*<0.001*	15.27	26.91	*<0.001*	15.48	30.55	*<0.001*
Cover crops (39%)	25.67	56.00	*<0.001*	22.88	29.92	*0.037*	4.70	4.31	0.806
Pressure bomb (32%)	18.33	37.00	*<0.001*	28.74	31.48	0.458	14.12	28.31	*<0.001*

knowledge as about equally important barriers for ET-based irrigation scheduling, and nonadopters naming resources as a slightly greater barrier than uncertainty for irrigation well N testing and moisture probes. There is a moderate negative trend between the overall adoption rate on a practice and the proportion of farmers who indicate any barrier to adopting the practice, though this is strongest for uncertainty, where the proportion of farmers indicating uncertainty strongly decreases as the adoption rate on a practice increases (figure 3).

Barriers Affect Different Types of Farmers. We used the Mail Survey data to compare how reported barriers to overall adoption at the farm scale (i.e., not practice specific) vary across farmer and farm operation characteristics, including gender, race, education level, farm income, farm size, land tenure, and years of farming experience (i.e., proxy for age). Resource barriers were reported significantly more often by non-White farmers, as compared to White farmers ($p < 0.1$). Technical knowledge barriers were reported significantly more often by non-White farmers ($p < 0.05$), farmers without any college education ($p < 0.01$), smaller and lower income farms ($p < 0.05$) and owner-operators, as compared to nonland owning operators ($p < 0.01$). Uncertainty barriers were reported significantly more often by male farmers, as compared to female farmers ($p < 0.05$) and by farmers with relatively high gross farm income (US$500,000 to US$1 million), as compared to all lower farm income brackets ($p < 0.01$) (see table S1 for full descriptive statistics).

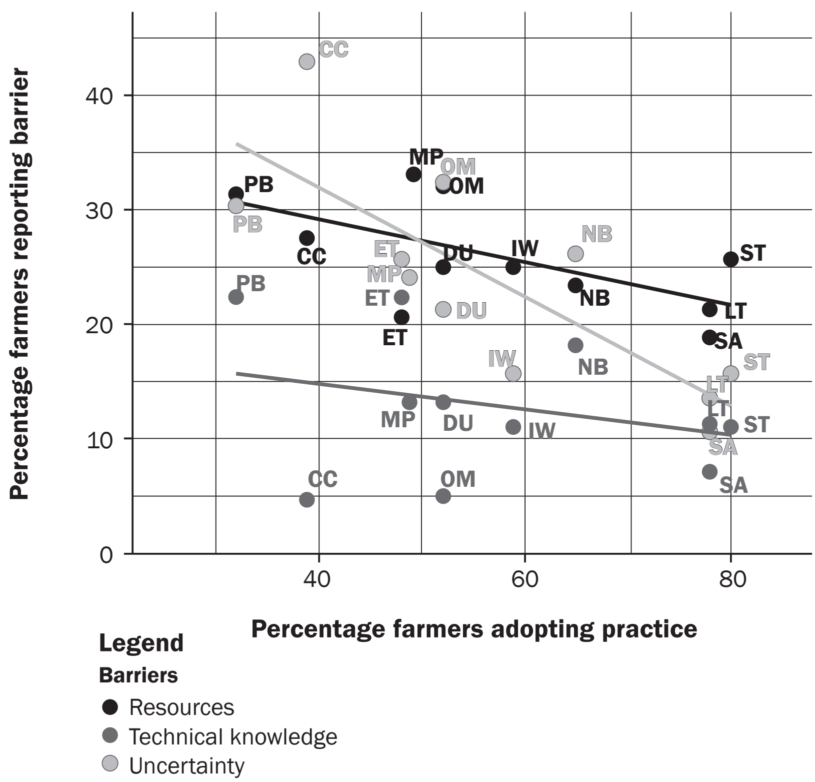
Partial Proportional Odds Model Results. PPO models allowed for the control of the farmer demographic variables, farm operation characteristics, and actual adoption behaviors, in order to evaluate the effect of specific factors hypothesized to influence the likelihood of reporting each barrier to practice adoption. We report results in terms of predicted probabilities, which holds all independent variables constant at their median value and allows us to observe the marginal change in the likelihood of a farmer reporting a specific barrier, given a single unit change in the hypothesized explanatory variable(s) (table 2).

Resource Barriers Are More Often Reported by Farmers with Higher Stewardship Motivation and Relying on Informal Information Networks. The resource hypothesis (H3) predicted that farmers with lower financial capital (i.e., lower farm income, smaller farm size, and land renters) would be *more* likely to report resources as a barrier to their practice adoption. We did not find support for H3, seeing no significant effects of financial capital variables on a farmer's likelihood of reporting resource barriers. However, we did find that farmers with higher stewardship motivation and problem recognition were significantly *more* likely to report resource barriers. Furthermore, farmers seeking information from *informal* sources (e.g., peers, family, field crew, and past experience) appear *more* likely to report resource barriers (though the significance of the informal information sources coefficient falls just barely outside of the Bonferroni-adjusted 99.6% confidence intervals).

Technical Knowledge Barriers Are More Often Reported by Farmers Operating Smaller Farms, with Agriculturally Oriented Information Networks, Higher Stewardship Motivation, and Problem Recognition. The technical knowledge hypothesis (H4) predicted that older farmers, smaller farms, and/or farmers with more limited information networks would be *more* likely to report technical knowledge barriers. Our technical knowledge PPO model results show moderate support for H4. Consistent with our hypothesis, smaller farms were *more* likely to report technical knowledge as a barrier (though the significance of the farm size coefficient falls just barely outside of the Bonferroni-adjusted 99.6% confidence intervals). With regards to information networks, farmers seeking information from agriculturally oriented information sources (e.g., farm bureaus, irrigation districts, and commodity organizations) were 29% *more* likely to report technical knowledge as a barrier with each additional information source. Other information networks did not have a significant impact on reporting technical knowledge barriers. In addition to the variables we hypothesized in H4 and consistent with the resource barrier results, we found that farmers with higher self-reported stewardship motivation and problem recognition were significantly more likely to report technical knowledge barriers.

Figure 3

Percentage of farmers reporting each key barrier (resources in black, technical knowledge in dark grey, and uncertainty in light grey) on each practice compared to practice adoption rate. Each data point represents one practice-barrier dyad (e.g., soil testing-resources barrier), and is labelled with practice abbreviations: CC = cover crop, DU = distribution uniformity, ET = evapotranspiration-based irrigation, LT = leaf testing, IN = irrigation well nitrogen (N) testing, MP = moisture probe, NB = N budget, OM = organic matter, PB = pressure bomb, SA = split application, and ST = soil testing. The relationship between barrier frequency and practice adoption is most clear on uncertainty: the frequency of farmers naming uncertainty as a barrier decreases dramatically with increased practice adoption (data source: Meeting Surveys; *n* = 950).



Uncertainty Barriers Are More Likely to Be Reported by Farmers with High Environmental Problem Recognition and Stewardship Motivation. The uncertainty hypothesis (H5) predicted that farmers with *lower* environmental problem recognition and stewardship motivation would be *more* likely to report uncertainty as a barrier. The uncertainty PPO model results contradict our hypothesis, showing that farmers with *higher* problem recognition and stewardship motivation are significantly *more* likely to report uncertainty barriers. As reported above, this unexpected pattern was consistent across resource, technical knowledge, and uncertainty barriers (figure 4). We also find farmers relying on environmentally oriented information sources were *less* likely to report uncertainty as a barrier with each additional information source (though again the significance of the environmental information sources coefficient falls just barely outside of the Bonferroni-adjusted 99.6% confidence intervals).

Discussion and Implications of Results. Our results at both the practice-specific and overall farm scales demonstrate that barriers to adoption are more complex than simply the factors that correlate with nonadoption. We find that key barriers to adoption differ across specific management practices (H1) and based on whether the farmer has or has not adopted the specific practice (H2). At the farm scale, our results show that farmers across the board—from the typical "laggards" (i.e., slow or nonadopters) to "early adopters"—report different types of barriers influencing their adoption decisions. For example, our results show that farmers with higher self-reported stewardship motivation and environmental problem recognition, which typically would be associated with a conservation-orientation and who may be assumed to adopt more, are more likely to report that all barrier types affect their adoption. Thus, understanding what types of barriers farmers face on different practices and at different stages of adoption appears to be a critical lynchpin to developing solutions to help farmers effectively and persistently adopt conservation practices.

Barriers Vary with Specific Practices and Stages of Adoption. Resource constraints, such as cost and labor, are an often-cited and obvious barrier to adoption (Ranjan et al. 2019a). While we find that resources are the primary barrier on 7 of the 11 management practices we studied, it was not the most prominent barrier for all practices. For a subset of practices (N budget, organic matter use, cover crops, and ET-based irrigation scheduling), technical knowledge and uncertainty of how the practice may impact crop yield, return on investment, and nutrient efficiency were greater concerns for farmers than the resources required to implement the practice. Our qualitative field work revealed these practices as being known as more complex, difficult to trial, less familiar or mainstreamed, and perceived to have higher uncertainty as to how the practice will impact yields and returns (table 3). This is consistent with Diffusion of Innovations theory that acknowledges the importance of an innovation's characteristics in determining its likely adoption patterns and other empirical farmer adoption literature that identifies nonfinancial barriers associated with practices that are harder to understand or measure the immediate effects of, such as cover crops (cf. Reimer et al. 2020; Beetstra et al. 2022).

The most prominent barrier for a specific practice also varied significantly between the farmers who had already adopted the practice versus those who had not. Adopters of the practice reported resource barriers as most impactful to their adoption decision, whereas nonadopters reported uncertainty barriers most frequently. Considering adoption as a process that occurs across iterative learning stages helps interpret this pattern (Ghadim and Pannell 1999). First, a farmer engages in conceptual learning, involving collecting and integrating new information and updating prior beliefs about associated costs and benefits of an innovation (Pannell et

Table 2

Results from three partial proportional odds models for key barriers: uncertainty, resource, and technical knowledge. Coefficient estimates for all predictor variables are reported in exponentiated form (odds-ratios). Confidence internals reported are adjusted based on a conservative Bonferroni correction to show a 99.6% confidence interval (alpha = 0.004). See supplementary materials for results reported at standard 95% confidence interval (Data: Mail Survey).

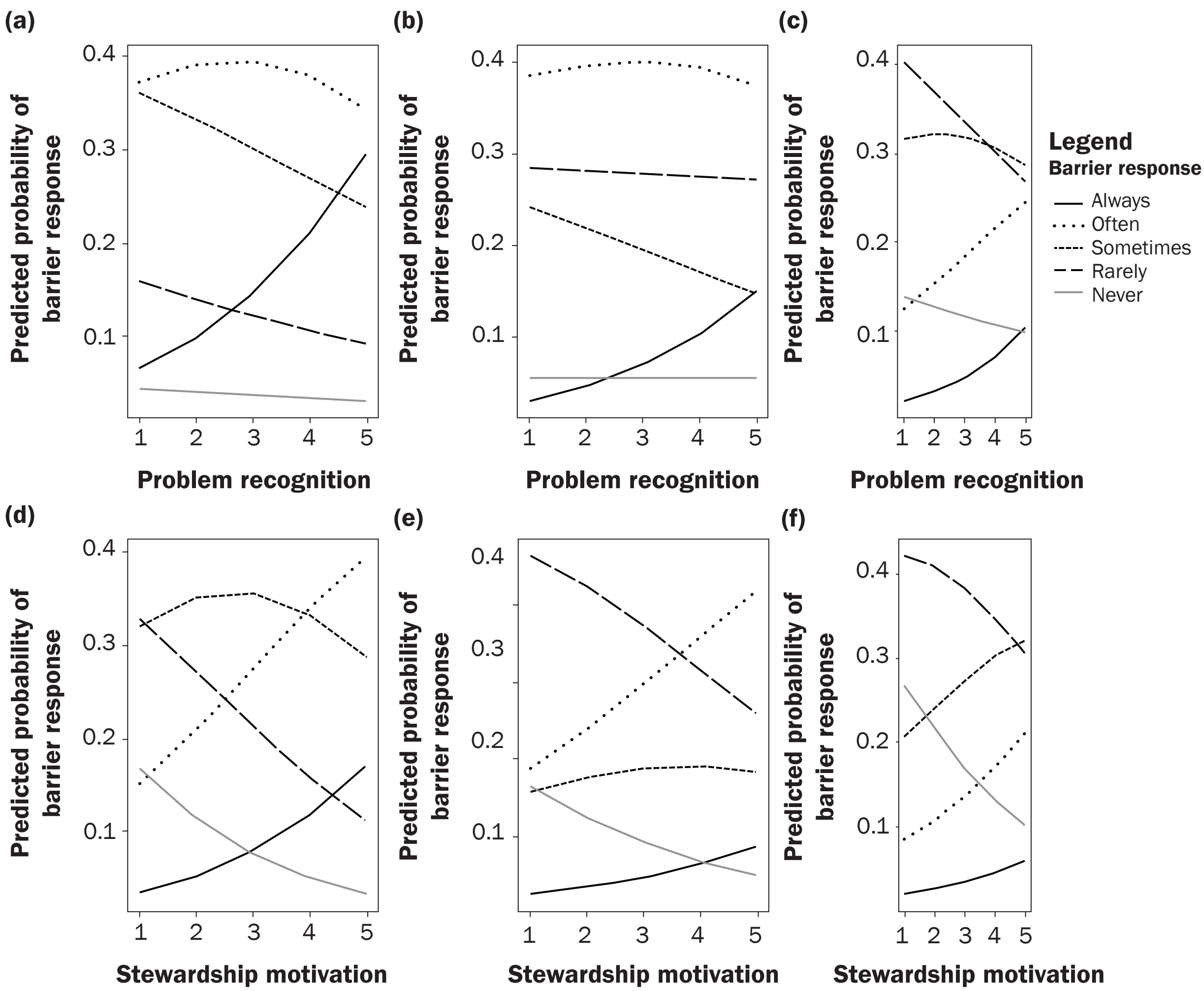
	DV = uncertainty barrier			DV = resources barrier			DV = technical knowledge barrier		
Predictor variable	**Odds-ratio**	**0.20%**	**99.8%**	**Odds-ratio**	**0.20%**	**99.8%**	**Odds-ratio**	**0.20%**	**99.8%**
Education:1	1.385	0.551	3.482	1.514	0.657	3.490	0.749	0.370	1.518
Education:2	1.230	0.694	2.179	0.862	0.516	1.438	0.703	0.428	1.154
Education:3	0.848	0.519	1.384	0.759	0.468	1.229	0.685	0.396	1.185
Education:4	0.742	0.394	1.399	0.540	0.265	1.102	0.840	0.330	2.140
Income	1.069	0.903	1.267	0.996	0.840	1.181	1.039	0.878	1.230
Owner-operator	1.332	0.772	2.299	1.135	0.655	1.968	1.308	0.758	2.258
DecadesinAg:1	1.049	0.801	1.376	1.089	0.852	1.393	1.126	0.925	1.371
DecadesinAg:2	1.122	0.950	1.325	0.996	0.860	1.154	1.019	0.884	1.175
DecadesinAg:3	1.030	0.894	1.186	0.985	0.857	1.132	1.011	0.862	1.187
DecadesinAg:4	0.962	0.798	1.159	0.965	0.781	1.191	0.815	0.617	1.075
Farm_acres (log)	1.033	0.875	1.218	1.066	0.903	1.259	0.886	0.751	1.045
Info Network_Ag	1.067	0.907	1.254	1.078	0.916	1.270	1.319	1.119	1.554
Info Network_Env	0.812	0.630	1.047	0.967	0.749	1.249	0.862	0.669	1.111
Info Network_Informal	1.132	0.916	1.399	1.201	0.971	1.485	0.966	0.782	1.194
Stewardship Attitude	1.544	1.257	1.897	1.401	1.142	1.718	1.345	1.098	1.648
PercBehaveControl:1	0.940	0.654	1.351	1.047	0.758	1.446	0.935	0.712	1.228
PercBehaveControl:2	0.818	0.644	1.038	0.868	0.704	1.070	0.895	0.732	1.094
PercBehaveControl:3	0.982	0.803	1.200	0.928	0.762	1.131	0.985	0.786	1.234
PercBehaveControl:4	1.165	0.881	1.542	1.207	0.873	1.669	1.356	0.869	2.114
ProbRecog:1	1.097	0.693	1.734	1.000	0.661	1.514	1.100	0.784	1.543
ProbRecog:2	1.161	0.872	1.547	1.014	0.786	1.309	1.195	0.934	1.529
ProbRecog:3	1.232	0.962	1.578	1.118	0.877	1.424	1.334	1.005	1.771
ProbRecog:4	1.571	1.115	2.212	1.544	1.044	2.283	1.535	0.932	2.528
# Practices adopted	1.026	0.935	1.126	0.987	0.899	1.085	0.994	0.906	1.090
(Intercept):1	0.699	0.084	5.838	0.750	0.105	5.371	1.109	0.201	6.113
(Intercept):2	0.181	0.039	0.840	0.430	0.102	1.812	0.254	0.061	1.053
(Intercept):3	0.032	0.007	0.144	0.129	0.031	0.539	0.033	0.006	0.173
(Intercept):4	0.002	0.000	0.013	0.002	0.000	0.022	0.002	0.000	0.034
Overall model fit statistics									
Residual deviance		1,949.63			1,937.64			1,950.52	
Log-likelihood		−974.82			−968.82			−975.26	
Prop. odds assumption (Brant test)		0.008			0.002			0.05	

al. 2006). As farmers learn about the innovation, uncertainty is expected to decrease and they are able to more accurately assess how the innovation will help them achieve their operational goals (Pannell et al. 2006; Marra et al. 2003). If the farmer believes the innovation will help them advance their operational goals, they are expected to begin experimenting with and trialing the innovation (Pannell et al. 2006). Experiential learning stages involve investment of time and capital, which means resources (or lack thereof) could become a more salient and significant barrier to advancing in this stage of learning. During experimentation, farmers gain a more accurate approximation of actual costs and benefits of implementation and may determine the cost outweighs its benefits, or vice versa. While experimenting with the innovation, farmers also gain a better understanding of the technical knowledge or skills needed to implement or refine the innovation to suit the specific characteristics of their farm. If trials and experimentation go well and the farmer believes they can effectively implement the innovation to further their goals, they are expected to expand adoption across the operation (Barr and Cary 2000).

By considering this framing of adoption as a learning process, we can make more sense of our findings about adopters and nonadopters' greatest barriers. Prior to adopting a practice (i.e., practice nonadopters), farmers would be expected to experience high uncertainty, as our results show. At this stage, any reported barriers may be more accurately characterized as *perceived* barriers. Doran et al. (2022) find similar results, with farmers reporting uncertainty barriers being less likely to be

Figure 4

Plots for all three barrier partial proportional odds (PPO) models show the probability of reporting each barrier ([a and d] uncertainty, [b and e] resource, and [c and f] technical knowledge) at different levels (always to never, shown with different dashed lines), given different levels of social-behavioral predictor variables: (a, b, and c) environmental problem recognition and (d, e, and f) stewardship motivation. The plots show that as both problem recognition and stewardship motivation increase (from 1 = never to 5 = always), the likelihood of reporting uncertainty, resources, or technical knowledge as always a barrier increases and the likelihood of reporting uncertainty, resources, or technical knowledge as rarely or never a barrier decreases. For each model, all other predictor variables are held at their median value (data source: Mail Surveys; *n* = 966).



in advanced stages of cover crop adoption. As the farmer engages in learning about and experimenting with a new practice, they gain a better understanding of what implementation requires in terms of resources (e.g., cost, labor, and supplies/equipment) and technical knowledge. This aligns with our findings that practice adopters are more likely to name resource barriers, which may be more accurately characterized as *experienced* barriers at this stage. An updated theoretical and applied understanding of barriers to adoption as hurdles that can be dynamic and change throughout different stages of learning or experimenting with a new practice has important implications on designing effective outreach and intervention programs that target the specific barriers that farmers are likely to face at different stages of adoption.

Barriers Vary for Different Farm and Farmer Types. In addition to evaluating barriers between adopters and nonadopters on specific practices, we also evaluate the impact of farmer characteristics that are frequently studied in adoption literature on the likelihood of naming key barriers to overall adoption of N management practices. Our descriptive analyses show that farmers with less financial resources (i.e., smaller farms, lower income farms, and owner-operators), less information access (i.e., limited information networks; no college education), and non-White farmers report experiencing more barriers overall. These findings were consistent with past adoption literature that suggests limited financial, informational, and social capital can be key inhibitors of adoption (Prokopy et al. 2019; Ranjan et al. 2019a). Specific to the California context, it is important to understand owner-operators typically represent family owned and operated farms, which have a smaller average area

Table 3
Summary of findings on how barriers vary across farm types and stages of adoption.

Barrier	Description of barrier in farmers' words	Practices most affected	Types of farmers/farms most affected	Policy/extension tools to consider
Resources	*"[The pressure bomb] it's manual... and you have to do it often to make it worth it, it's just a labor intensive operation."* (San Joaquin Valley farmer) *"Farmers will look at the cost of implementing new practices versus risk of adoption compared to what they are comfortable with from years of past use...If you want people to [adopt] on N-related issues, [you] need to provide reason that resonates and show the monetary benefit of better N management... people forget that wastefulness wastes money too."* (San Joaquin Valley farmer)	• Soil testing for residual nitrate (NO_3^-) • Split application leaf testing for plant N status • Irrigation well testing for NO_3^- • Distribution uniformity check • Moisture probes • Pressure chamber	• Adopters • Non-White farmers • Larger informal information networks • Higher problem recognition and stewardship motivation	Provide estimates of implementation costs in dollars, labor, and time required. Provide estimated timelines for return on investments, and how sensitive those timelines are to input cost variability.
Technical knowledge	*"High tech computer stuff you got going on... irrigation systems that monitors it automatically and checks moisture in the field automatically... it's something I've heard of and would do, but don't know how."* (San Joaquin Valley farmer) *"I just think that there needs to be more support in the area of water and sustainability. Like the whole ball of wax. [We] need to have training sessions or bring your data....in and we will help you get through it."* (San Joaquin Valley farmer)	• ET-based irrigation scheduling • Pressure chamber	• Adopters • Non-White farmers • No college education • Small farms (<50 ac) • Lower farm gross income (<US$200K) • Owner-operators • Larger agricultural information networks • High problem recognition and stewardship motivation	Develop decision-support tools that convert raw data from in-field monitoring technologies into irrigation and fertilizer application recommendations. Calculate associated cost savings with input recommendations. Increase support for technical assistance providers, by funding more technical extension positions and supporting training opportunities for technical assistance providers.
Uncertainty	*"There is a lack of good information on N and cover crops... [how do different] species and cultivars effect N and the management approaches to retain and have available for the crop."* (Sacramento Valley farmer) *"Culturally, soil testing is a pain. Are the cost-benefits really higher? Where I sit the jury is still out. I can't see... how many tests do I need to do?"* (San Joaquin Valley farmer)	• Organic matter amendments • Cover crops • ET-based irrigation scheduling	• Nonadopters • Male farmers • High farm gross income (US$500,000 to US$1 million) • Larger informal information networks • Higher problem recognition and stewardship motivation	Outreach messages to nonadopters should clearly articulate the practice's return on investment,potential impacts to crop yields and efficacy of improving N use efficiency. Additionally, articulate potential benefits gained from the practice.

and lower average farm income, as compared to incorporated farm businesses that often have absentee landlords who own a much larger area and hire local operators to run the farm business.

Contrary to our hypotheses, however, our PPO models also reveal that farmers who report higher problem recognition and stewardship motivation are *more* likely to report all three key barriers, and that access to some information networks may also influence what barriers farmers report (table 2).

Conservation-Oriented Farmers Report Greater Barriers to Adoption. Our results show that both increased problem recognition and stewardship motivation had consistent effects increasing the likelihood of a farmer reporting all three barriers. This was a surprising finding, given the fairly consistent signal in current adoption literature that conservation value orientations lead to increased practice adoption behaviors, alongside our assumption that barriers to adoption would roughly follow characteristics that relate to low adoption (Prokopy et al. 2019; Ranjan et al. 2019a).

The first potential explanation for these results is a finding of some cognitive dissonance within stewardship-minded farmers who are making adoption decisions that are inconsistent with their values or beliefs (cf. Stuart et al. 2012). In our case, farmers may recognize that their self-reported stewardship priorities don't align with their actual adoption behaviors and aim to rationalize these differences by indicating high barriers that hinder them from adopting practices. Construal-level theory suggests one likely outcome of cognitive dissonance is an overemphasis of the explanation for the disconnect between value and action (Trope and Liberman 2010). In this way, reporting high barriers to adoption becomes a justification for farmers to explain why their adoption behaviors don't always reflect their stewardship values and priorities. This dissonance is worth further exploring to better understand true relationships between intended and actual behaviors, which are predicted to be highly correlated by the Theory of Planned Behavior (Azjen 1991), but are often less tightly related in empirical data. Stuart et al. (2012) report similar findings from a study of midwestern corn farmers who indicate high "self-acknowledged stewardship ethos" and express concern about the impact of N fertilizer on the environment, yet "they felt unable to address this concern" and indicated low willingness to adopt management practices that might threaten their crop yields.

Beyond a cognitive disconnect, prior research that suggests stewardship motivations act secondarily to economic motivations (Shaffer and Thompson 2013; Davidson et al. 2019) or require supplementary collective action to overcome the high resource costs of practice adoption (Lubell et al. 2011). In this way, stewardship-motivated farmers may have a more complex set of priorities that are considered in the decision to assess and adopt any new practice. This more complex cost-benefit analysis may result in stewardship-minded farmers reporting more barriers overall, as they struggle to assess if a management practice will optimize across their multiple goals. This explanation is supported by evidence from a recent study that aimed to better understand "types" of midwestern farmers that behave similarly in relation to conservation behaviors, developing the following distinct groups: "conservationist farmers," "deliberative farmers," "productivist farmers," and "traditionalist farmers" (Upadhaya et al. 2021). "Deliberative farmers" are characterized as being similar to Diffusion of Innovation Theory's "early majority" adopters (Rogers 1962), which "make up the largest proportion of adopters of a given innovation… but deliberate for some time before completely adopting a new idea" (Upadhaya et al. 2021). These deliberators tended to have high conservation motivations and utilization of environmentally oriented information sources, but also identify a high number of both economic and agronomic barriers associated with practices being considered for adoption (Upadhaya et al. 2021). If these farmer types are transferable across geographic contexts, the farmers in our study who reported high stewardship motivation, high problem recognition, and greater high barriers to adoption, could be classified as *deliberators* who more carefully consider the complex decisions associated with adopting a suite of N management practices. To reiterate, through this lens it makes sense that reported barriers to adoption do not necessarily correlate with nonadoption, rather they are factors being considered at different stages of learning about and contemplating a new management practice.

This explanation may provide the clearest bridge to our earlier discussion considering adoption as a learning process. Research on agricultural innovative diffusion stages has suggested advancing between stages of practice adoption can be motivated by a farmer learning of an environmental problem or being motivated by their stewardship values (cf. Doran et al 2022); in fact, problem recognition may even be a necessary precondition to a farmer considering adoption of a new innovation (Pannell et al. 2006). For example, a farmer may not be motivated to investigate a complex new practice like cover cropping until gaining awareness of a local water quality problem and wishing to reduce their own farm's impact. These same internal motivations and values may prompt later stages of learning, contemplation, experimentation, and full adoption as well, which as previously discussed, may also reveal more experiential barriers related to costs and knowledge requirements. When considered this way, stewardship motivation and problem recognition may be the behavioral characteristics prompting farmers to engage more deeply with practices of interest, and through that engagement encountering more barriers. There is also recent but growing recognition that these pro-environmental behavioral factors are more complicated than assumed, influencing behavior differently based on the specific practice at hand or stage of learning or adoption the farmer is in (Lemken et al. 2017; Richens et al. 2018; Michels et al. 2020; Doran et al. 2022).

One farmer's explanation brings this to life, showing how their values provide motivation for changing their management, but the influence may be difficult to capture:

> Getting myself motivated would be a major [challenge]. If I have something that works, I feel like it's efficient and effective, I have a hard time changing. However, if it's obvious what I've been doing is harming the soil… or the environment, I will change. I would figure out how to do so quickly, because I live in this orchard… and I want to protect the people around me. (Central Valley farmer)

Limitations. First, we acknowledge that our interpretation of the patterns we see in reported barriers assumes that farmers responded to this question earnestly. We must consider the possibility that farmers perceived this survey, and particularly the question asking about barriers to adoption, as an opportunity to voice their greater frustrations related to the regulatory nature of N management in California that pushes farmers to use less fertilizer and/or adopt more costly conservation and efficiency practices. Indicating greater barriers to adoption may have also been perceived as an opportunity to advocate for additional resources and assistance in meeting regulatory requirements that are costly and perceived to potentially risk productivity levels.

Second, we also recognize a limitation in our ability to interpret when a respondent did *not* report a barrier, as we are unable to truly distinguish if the barrier was not ever encountered, or already overcome and therefore not reported. In our results, both reasons for not selecting a barrier are interpreted as the farmer "not being impacted by the barrier." However, these potentially competing processes are an important distinction and should be given further attention in future research. As with all survey research, there is a tradeoff in designing more elaborate questions to capture all potential explanations, and increasing the burden on the respondent, which tends to result in attrition or lowering response rates.

Third, consistent with all survey research, we recognize our results may be limited by relatively low response rates and may show a bias toward farmers who tend to be more engaged. While our sample is representative of our studied regions based on crop type and farm size, we know that survey research tends to elicit responses from farmers who are better connected and more engaged in extension and policy activities. Importantly, given the focus of this paper is on barriers, we might expect that the farmers who elected to participate in this survey may actually be facing *fewer* resource constraints and burdens on their time than their peers who did not participate. Thus, it is reasonable to suspect that barriers to adoption are more widespread than we report, particularly among the farmers who are less engaged and less participatory in educational and research activities. For example, we know there are multiple ethnic farming communities in the Central Valley for whom language and cultural differences present perhaps the largest barrier to accessing information and technical assistance on N management, and who are not well represented in our survey respondents. It is pertinent to recognize these underrepresented farmer communities are likely to face the strongest financial, technical knowledge, and resource barriers, both in their decisions to adopt more complex practices, and in their navigation of the N management regulatory programs at large (Mendez-Barrientos et al. 2020; Ngo 2017).

Finally, our analysis demonstrates both the utility and limitations to measuring barriers at two different scales. By measuring barriers at a practice-specific level on the Meeting Survey, we are able to evaluate the direct relationship between indicating a barrier and the adoption decision on the practice; however, we were not able to tie these to the robust socio-behavioral variables measured on our Mail Survey. The practice-specific measures provide valuable information about how decision-making can vary across different types of management practices. Yet, we recognize our study represents one snapshot in time and to truly understand the relationships between barriers and stages of adoption, it is important to collect data explicitly asking farmers about their stage of adoption (e.g., how long have you been using x practice) or a longitudinal research design is needed. Collecting these types of data increase the response burden, as we even saw a higher response burden when asking about practice-specific barriers. This often comes at a cost of measuring fewer other constructs. In our case, our different survey instruments provided the opportunity to measure the complexities of how barriers vary across 11 unique specific practices and actual adoption behaviors of those practices, and the socio-behavioral drivers that we expect to have an influence on perceived and experienced barriers, but these measures were not linked to one another. It is possible that the differences in our measurement granularity of the barriers contributes to some of the less expected results around stewardship motivation and problem recognition.

Summary and Conclusions

Achieving high levels of adoption of improved N management practices requires that farmers engage in a complex learning process to consider new management practices, acquire the skills, knowledge, resources or equipment necessary to implement the practice, and adapt the practice to fit their specific farm conditions. At every stage of this process, a farmer may face both perceived and actual challenges that must be overcome in order for adoption to be feasible. Past research modeling farmer decision-making has tended to refer to "barriers to adoption" only as the factors that negatively predict adoption of the practice. Recent other studies alongside the data we presented here make the case that barriers are likely to be faced throughout multiple phases of the behavior change process and by both practice adopters and nonadopters. We argue it is important for future research to continue to explicitly ask farmers what barriers they perceive and experience, when they encounter these barriers, and what they have done or may do to overcome these barriers. These are important frontiers for future farmer adoption research to explore in order to inform interventions that are effective in motivating and sustaining adoption.

Our integration of two distinct but related survey data sets allow us to evaluate barriers to adoption at different scales. At the specific practice scale, we gain more clarity as to how barriers differ across different types of management practices and how actual adoption behaviors influence what barriers farmers perceive and report, which provides insights for how extension and policy interventions may better support adoption. At the farm scale, we gain a better understanding of which types of farmers are more likely to report experiencing barriers: smaller farms, those with limited information networks, and those with higher self-reported stewardship motivation and environmental problem recognition. When taken together, we believe these findings at different scales are better understood by considering adoption as a learning process, during which different barriers are experienced at different stages of learning and adoption and considered to different degrees by different farmer "types."

This interpretation warrants future research attention that explicitly tests hypotheses around how different types of farmers learn and engage with new management practices, and how and what barriers they encounter at different stages of adoption. We advocate for additional research that investigates a larger number of practices, characterizing each practice by their adoptability characteristics (Vanclay 1992), and comparing these characteristics to the barriers farmers report experiencing to build a more sophisticated understanding of adoptability. Future research should also aim to measure what "stage" of adoption a farmer is in at the time of the survey and ask farmers directly how their motivations interact with the challenges they face through the adoption process.

Our findings have important implications for advancing the adoption of a holistic suite of N management practices in California. First, we saw clearly that farmers face different types of barriers across different management practices, which indicates that extension and policy approaches aimed to increase adoption should target the most prominent barriers for a *specific* practice; in other words, interventions need to be practice-specific. Second, our finding that adopters and nonadopters experience different barriers suggests that efforts aiming to increase adoption among nonadopters should first focus on reducing uncertainty around the specific practice, by providing the information that aims to estimate the practice's return on investment, potential impacts to crop yields and efficacy of improving N use efficiency, as well as any other potential benefits gained from the practice. Efforts that seek to sustain or expand adoption by targeting practice adopters and encouraging them to continue or expand their use of a practice should seek to understand the specific resource (e.g., equipment, infrastructure updates, inputs, labor, and time) or technical knowledge (e.g., use of new technology, field calibration, and data interpretation) demands that challenge the adoption of that practice, and then support the farmer in addressing those demands. Our research team's ideas on interventions to address each key barrier are included in table 3. Finally, we find that a wide variety of farmers experience barriers, including those with high stewardship motivations and problem recognition, which are characteristics traditionally thought to motivate adoption. This implies that barriers to adoption can affect farmers with widely differing motivations and value orientations, and it is critical to take these characteristics into account alongside the context of what stage of adoption a farmer is navigating, in order to anticipate what barriers are likely to be challenging adoption and design practice-specific interventions accordingly.

Supplemental Materials

The supplementary material for this article is available in the online journal at https://doi.org/10.2489/jswc.2023.00109.

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