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Universities Council on Water Resources
1231 Lincoln Drive, Mail Code 4526
Southern Illinois University
Carbondale, IL 62901
Telephone: (618) 536-7571
www.ucowr.org

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Developing a Simple Strategy for Roadside Spring Water Disinfection in Central Appalachia

*Hannah Patton[1], Leigh-Anne Krometis[1], Ben B. Faulkner[2], Alasdair Cohen[3], Erin Ling[1], and Emily Sarver[4]

[1]*Biological Systems Engineering, Virginia Tech, Blacksburg, VA;* [2]*Civil and Environmental Consultants, Inc., Bridgeport, WV;* [3]*Population Health Sciences, Virginia Tech, Blacksburg, VA;* [4]*Mining and Minerals Engineering, Virginia Tech, Blacksburg, VA; *Corresponding Author*

Abstract: Several studies have highlighted issues of unreliable access to safe drinking water in the Appalachian region. In some cases, residents turn to roadside springs as a practical, and culturally valuable, drinking water source. However, public reliance on roadside springs for potable use can present concerns, as bacterial contamination of spring water has been documented throughout Appalachia. This study aimed to 1) develop a simple, low-cost protocol using household bleach to inactivate total coliform and *E. coli* in untreated roadside spring water; 2) provide educational materials at local roadside springs to inform users of this simple treatment strategy; and 3) assess spring user perceptions of the educational materials via a short survey. Laboratory scale trials emulating typical spring water collection and storage conditions investigated the use of household bleach (7.4-7.5% sodium hypochlorite) for total coliform and *E. coli* bacteria inactivation and free chlorine residual maintenance in spring water over time. Results showed that 2 drops (approximately 0.10 mL) of household bleach from an eyedropper per 1 gallon of spring water provided adequate total coliform and *E. coli* disinfection, while maintaining free chlorine levels below typical taste thresholds and providing sufficient residual over a 1-month trial period. An infographic communicating the disinfection protocol and a corresponding survey were created and distributed at roadside springs in rural regions of southwestern Virginia and southern West Virginia. The majority of spring user survey respondents (80%) reported that the infographic was generally helpful, and over half of respondents stated that they would use the bleach protocol.

Keywords: *drinking water, spring water, disinfection, free chlorine, total coliform, E. coli*

One in four people worldwide do not have access to safely managed drinking water (Ritchie and Roser 2021). In the U.S., although nearly 100% of the population is reported to have access to safe drinking water, issues related to drinking water quality, reliability, cost, and equity of access persist (Allaire et al. 2018; Mueller and Gasteyer 2021). Though the specifics of any environmental health concern often include locally unique aspects, problems with safe drinking water access in the U.S. are generally clustered in regions or communities characterized by similar contextual factors observed in struggling regions across all nations. For example, in Appalachia, a mountainous 531,000 square-kilometer region in the eastern U.S. (Pollard and Jacobsen 2021), the maintenance of essential water infrastructure is limited by socioeconomic, geographic, and geotechnical challenges (Cook et al. 2015; Arcipowski et al. 2017). Though shaped by different nation-specific histories, multiple authors have noted that factors such as steep topography, high poverty rates, and unique geography in rural mountainous regions present difficulties in the provision of safe drinking water and appropriate wastewater treatment (Browne et al. 2004; Wescoat et al. 2007).

Not surprisingly, rural mountainous regions often lag behind non-mountainous regions in the establishment and maintenance of drinking water

Research Implications

- Roadside spring water, while consistently testing positive for total coliform and *E. coli*, is often utilized as a drinking water source in the Appalachian region.
- Under conditions mirroring those used to collect and store roadside spring water in the Appalachian region, 2 drops of regular, unscented household bleach (7.4-7.5% sodium hypochlorite) successfully deactivated total coliform and *E. coli* in 1 gallon of roadside spring water and maintained a free chlorine residual of between 0.2 mg/L and 2 mg/L for the 1-month trial period.
- Efforts to provide information on spring water quality and bleach disinfection via infographic were considered to be helpful, however, only half of survey respondents reported that they intended to use the bleach disinfection protocol.
- Feedback suggests that while the infographic may be a useful tool in addressing roadside spring water use, broader discussion of risks associated with spring water use and efforts to improve in-home piped water infrastructure are necessary to reduce health risks.

infrastructure, and the Central Appalachian region is no exception (Browne et al. 2004; Wescoat et al. 2007). In some regions of Central Appalachia, upwards of 10% of homes lack complete plumbing (Krometis et al. 2017). While more recent data are not yet available, in 2005, 75% of the population in the Appalachian region had access to community water systems, behind the national level of 85% (Hughes et al. 2005). *Community water systems*, private or publicly owned systems providing piped drinking water to at least 15 service connections or that serve at least 25 people, are regulated by the U.S. Environmental Protection Agency's (EPA) Safe Drinking Water Act (SDWA; Tiemann 2017). Homes in Appalachia without access to community water systems most commonly rely on private wells for in-home water. *Private wells*, groundwater systems that serve no more than 25 people at least 60 days of the year and have fewer than 15 service connections, do not fall under the purview of the SDWA (CDC 2014). Private well systems generally do not employ treatment (Smith et al. 2014) and, as a result, the presence of health-based and aesthetic contaminants in private well water at the point-of-use (POU) is common (Shiber 2005; Pieper et al. 2015; Law et al. 2017; Patton et al. 2020). Issues with POU water quality are not confined to homes with private wells. Indeed, small, rural community water systems often struggle to comply with the SDWA regulations due to limited financial, technical, and human resources available for operation and maintenance needs (Hughes et al. 2005; Allaire et al. 2018; Marcillo and Krometis 2019).

Multiple studies report that Appalachian households without adequate access to drinking water of sufficient quality and quantity rely on alternative sources to satisfy daily potable water needs (Blakeney and Marshall 2009; McSpirit and Reid 2011; Arcipowski et al. 2017; Page et al. 2017; Krometis et al. 2019; Patton et al. 2020; Cohen et al. 2022). Though often preferred by homeowners (Blakeney and Marshall 2009; Arcipowski et al. 2017), reliance on bottled water presents a costly alternative in a region where the mean per capita income is significantly lower than the national average (Pollard and Jacobsen 2021). Given a lack of confidence in household water and the cost of alternatives, some residents of the Appalachian region collect a portion, or all, of their household drinking water from roadside "spout" springs, i.e., unimproved and untreated environmental waters often located along roads where road cuts have intersected with shallow groundwater aquifers or where mine pools are discharging (Swistock et al. 2015; Krometis et al. 2019; Patton et al. 2020; Sinton et al. 2021). Notably, recent surveys of regular roadside spring users revealed that the majority have access to in-home tap water but perceive roadside spring water to be of higher quality (Krometis et al. 2019; Patton et al. 2020). Although it is difficult to quantify the total population dependent on these water sources, Swistock et al. (2015) reported that 30% of Pennsylvania residents attending local Cooperative Extension programming had consumed water from a roadside spring at some point, and that 12% consumed spring water annually.

Reliance on roadside springs for potable use does present some concern, as bacterial contamination appears ubiquitous across regions. Krometis et al. (2019) reported that 99% (n = 83) of roadside spring samples collected from 21 springs in five Central Appalachian states were positive for total coliform bacteria and 86% of samples were positive for *E. coli*. Swistock et al. (2015) detected not only total coliform and *E. coli* in seasonal samples collected from Pennsylvania roadside springs (n = 37), but also *Giardia* and *Cryptosporidium* contamination in a small subset of samples (n = 10). This is especially concerning given previous reports of *Giardia* outbreaks linked to consuming roadside spring water in New York (Bedard et al. 2016). A broader examination of roadside springs throughout western New York determined that 86% of springs failed at least one U.S. EPA SDWA drinking water standard, most often for fecal indicator bacteria, which presents an immediate health risk (Sinton et al. 2021).

Despite the likelihood of poor or inconsistent water quality, it is critical to recognize that these springs, and the collection of spring water, is a common practice and is culturally valued in many rural Appalachian communities (Westhues 2017; Krometis et al. 2019; Patton et al. 2020). More importantly, in a study directly comparing the home water quality of spring users in some Central Appalachian communities with water from their preferred roadside spring, Patton et al. (2020) reported that in many cases, increased concentrations of metals associated with taste and aesthetic issues (e.g., iron, manganese) were much more common in tap water than spring water. Given that household POU options may be less palatable, the expense of bottled water, documented preference for the aesthetic qualities of spring water, and the associated cultural significance of roadside springs, it is not surprising that efforts to close access points to roadside springs can be met with resistance (Bedard et al. 2016; Williamson 2018).

The U.S. EPA and the Centers for Disease Control and Prevention (CDC) recommend the use of bottled water, boiled water, or bleach-disinfected water in situations where regular water service is interrupted and/or water may be unsafe to drink due to the presence of fecal indicator bacteria (U.S. EPA 2017; CDC 2021). As previously mentioned, bottled water is a costly drinking water alternative that some in the Appalachian region are unable to afford. Moreover, as noted in multiple studies (Swistock et al. 2015; Krometis et al. 2019; Patton et al. 2020; Sinton et al. 2021), many spring users collect water in bulk and may be unable or unwilling to boil all the spring water before using it. In developing countries, chlorination of drinking water via sodium hypochlorite has been found to be a successful method of disinfecting drinking water that helps to decrease levels of coliform in drinking water (Sobel et al. 1998; Firth et al. 2010) and related diarrheal episodes in homes (Quick et al. 1999). Sodium hypochlorite, the active ingredient in chlorine bleach, is a well-established disinfectant that has been used since the 1820s as a disinfecting and bleaching agent (Ponzano 2007). The CDC and the Pan American Health Organization (PAHO) have developed a chlorine-based intervention called Safe Water System that utilizes sodium hypochlorite (the active ingredient in bleach) for in-home disinfection of drinking water (CDC 2003). The present study aimed to: 1) develop a simple, low-cost protocol using household bleach to inactivate total coliform and *E. coli* in untreated roadside spring water; 2) provide educational materials at local roadside springs to inform users of this simple treatment strategy; and 3) assess spring user perceptions of the educational materials via a short survey. Laboratory scale trials emulating typical water collection and storage investigated the use of name-brand and store-brand household bleach in varying quantities to determine effectiveness in *E. coli* bacteria inactivation and maintenance of free chlorine residual in spring water over time.

Methods

Disinfection Protocol Design

Four 1-month trials were completed between August and October of 2021 assessing the effect of household bleach brand and volume on levels of total coliform, *E. coli*, free chlorine, and total chlorine in locally collected spring water samples (Table 1). The 1-month trial duration was chosen because previous studies documenting roadside spring use found that most surveyed spring users

Table 1. Variables assessed in each of the four trials of bleach disinfection of roadside spring water completed. NB = name-brand, SB = store-brand.

Trial Number	Bleach Brand	Bleach Treatment Volumes (per 1 gallon of water)	Number of Samples	Spring Sampled	Trial Duration
1	NB	0 tsp, 1/4 tsp	8	Spring 1	1 Month
2	NB	0 tsp, 1/8 tsp, 1/16 tsp	12	Spring 1, Spring 2	1 Month
3	NB	0 drops, 3 drops, 2 drops, 1 drop	4	Spring 1	1 Month
4	NB, SB	0 drops, 2 drops	6	Spring 1	1 Month

collected water from springs at least once a month (Krometis et al. 2019; Patton et al. 2020). Based on this information, one month was considered a realistic amount of time that an individual may store spring water at their home before running out and/or collecting a fresh batch. Trials included assessment of one type of unscented name-brand bleach (Clorox) and one type of unscented store-brand bleach (Dollar General). The brands were chosen based on the types of chlorine-containing household bleach that are readily available at commercial stores in southwest Virginia and southern West Virginia.

Bleach volumes tested varied from 1/4 tsp (~ 0.6 mL) to 1 drop per 1 gallon of roadside spring water. Drops were dispensed from a disposable plastic eyedropper designed to distribute approximately 0.05 mL per drop (Table 1). While the CDC recommends the addition of 1/4 to 1/8 tsp (~ 0.6 to 1.2 mL) of unscented household bleach per 1 gallon of water, the U.S. EPA recommends 6 to 8 drops (~ 0.3 to 0.4 mL) of unscented household bleach per 1 gallon of water (U.S. EPA 2017; CDC 2021). The objective of assessing different bleach volumes was to determine the smallest quantity of bleach that could be added to spring water that would both inactivate total coliform and *E. coli* bacteria and provide a suitable free chlorine residual to protect water that is being stored for longer than 24 hours, as previous studies suggest that spring water is often stored for multiple weeks (Krometis et al. 2019; Patton et al. 2020). The CDC recommends free chlorine residual levels between 0.5 and 2.0 mg/L one hour after disinfection, and greater than 0.2 mg/L 24 hours after disinfection (CDC 2020). Individuals can taste or smell chlorine in drinking water at concentrations well below 5 mg/L, and even as low as 0.3 mg/L (Crider et al. 2018; WHO 2022). The study aimed to maintain a residual below 2.0 mg/L as this is considered the taste threshold for free chlorine (CDC 2020) and spring users frequently cite the taste of spring water as a reason for preferring it over their home drinking water (Swistock et al. 2015; Krometis et al. 2019; Patton et al. 2020; Sinton et al. 2021). A primary concern is that if an excessive quantity of bleach is added to the spring water and impacts taste, spring users may decide not to follow the dosing regimen to disinfect their spring water—and potentially opt for no treatment at all.

Spring Selection and Sample Collection

For each trial, water was collected from a roadside spring in Virginia (Spring 1) that is regularly used by local residents for potable water (Table 1). This spring consistently tested positive for total coliform and *E. coli* in a previous study, with maximum detected levels of 2,149 MPN/100 mL and 583 MPN/100 mL, respectively (Krometis et al. 2019). Compared to the 21 roadside springs previously sampled, water samples collected from this spring yielded the highest recorded total coliform and *E. coli* levels in the study (Krometis et al. 2019). For trial 2, water was also collected from a second roadside spring in West Virginia (Spring 2) which, while less frequently positive for fecal indicator bacteria (Patton et al. 2020), is another known popular location for the collection of drinking water. The turbidity of spring water collected and tested during this study was between 0.0 and 0.13 NTU, which is considered low (USGS 2018).

Sample collection and storage were designed to emulate the practice of spring users collecting roadside spring water as closely as possible. All bleach dosing trials were conducted in spring water collected and stored in one-gallon plastic milk jugs (Figure 1). Anecdotally, these vessels are commonly used for the collection and storage of spring water for drinking (Figure 1). Prior to spring water collection, plastic jugs were washed with dish soap and tap water to simulate what would be available for cleaning in a home. Each jug was rinsed three times with spring water prior to collecting samples to eliminate any residual chlorine that may have been present in the tap water used for cleaning. After collecting the spring samples, the plastic jugs were capped and transported to the laboratory for immediate analysis. Throughout the study, spring water-filled jugs were capped and stored on a countertop out of direct sunlight in a ~ 20°C room, in keeping with common spring water storage conditions in households (Figure 1). Additionally, samples were not transported on ice because spring water is not commonly iced when transported by local residents.

Water Analyses

Upon returning to the lab and prior to the addition of bleach, spring samples were tested for bacteriological contaminants and initial chlorine levels. After initial testing, bleach was added to the sample using either a 1/4 or 1/8 tsp kitchen measuring spoon, or a plastic eyedropper (Thermo Fisher Scientific, Waltham, MA). After the addition of bleach, the water jugs were inverted three times. Following inversion, bacteria and chlorine levels were measured at 5-minute, 30-minute, 1-day, 1-week, and 1-month post-bleach intervals. In each trial, control samples were not dosed with bleach. The 5-minute, 30-minute, and 1-day post-bleach measurement intervals were selected to determine

Figure 1. Left – Collected roadside spring water stored in one-gallon plastic jugs in the home of a spring user in Central Appalachia. Right – Roadside spring water sample being collected for this study in a one-gallon plastic milk jug (original photos).

the minimum reasonable contact time required for disinfection. One-week and 1-month post-bleach intervals were selected because multiple authors report spring users collecting water at least once a month and often, once a week (Krometis et al. 2019; Patton et al. 2020; Sinton et al. 2021). These time periods also allowed for the investigation of potential bacterial regrowth during prolonged storage.

Samples were tested for free and total chlorine before bleach treatment and at the post-bleach treatment time intervals using a HACH DR300 Pocket Colorimeter (HACH, Loveland, CO). Bacteriological analysis of spring water samples before and after bleach treatment was completed for total coliform and *E. coli* via the Colilert-defined substrate method (www.idexx.com, Westbrook, MN).

Infographic Creation and Distribution

After the disinfection protocol design process was completed, an infographic (Figure 2) featuring spring water quality information and the disinfection protocol was created for distribution at five local roadside springs in southwestern Virginia and southern West Virginia that are frequently used for drinking water collection. The front side of the infographic features information on the potential for spring water to contain bacteriological contaminants, as well as a link to a public website with recent bacteriologic data from the spring. The front side of the infographic also included a link to a website that provides periodically updated water quality reports for local springs that have been sampled. The back side of the card features the simple bleach protocol to disinfect spring water. The goal during infographic development was to provide spring users with useful information about spring water quality and disinfection delivered in an objective, easily accessible, and discreet manner. Local contacts reviewed the language to ensure it was not inflammatory and was easy to understand.

Postcard-sized infographics were printed and laminated so that the spring users could keep the infographic for an extended period of time. Infographics were placed in a plastic sandwich bag along with one disposable plastic eyedropper (i.e., the same used in all trials) so that spring users would have access to an appropriate tool to help measure out the correct bleach quantity. Additionally, a postcard-sized, pre-addressed anonymous survey was included in the bag. The bags were distributed in plastic bins at five local springs beginning in December of 2021 with the goal of continuing distribution every few months.

Survey Development and Distribution

To assess spring user response to the infographic, a brief anonymous survey was designed (Figure 3). The survey included questions regarding spring use, previous knowledge of spring water quality, and reception of the infographic. Questions were kept brief, anonymous, and easily understood so that spring users would be more inclined to complete and return the survey. The purpose of the survey was not to further examine motivations

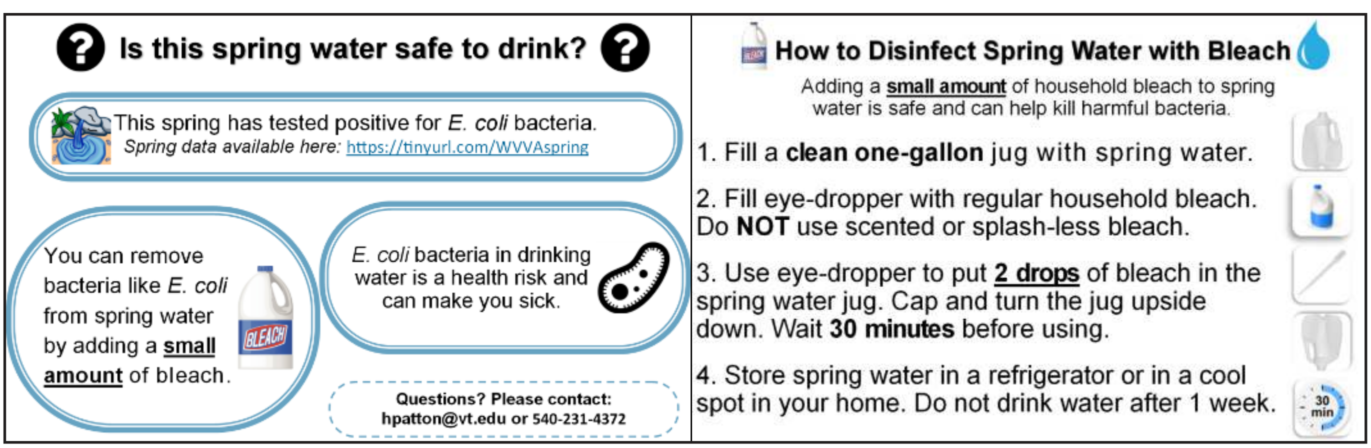
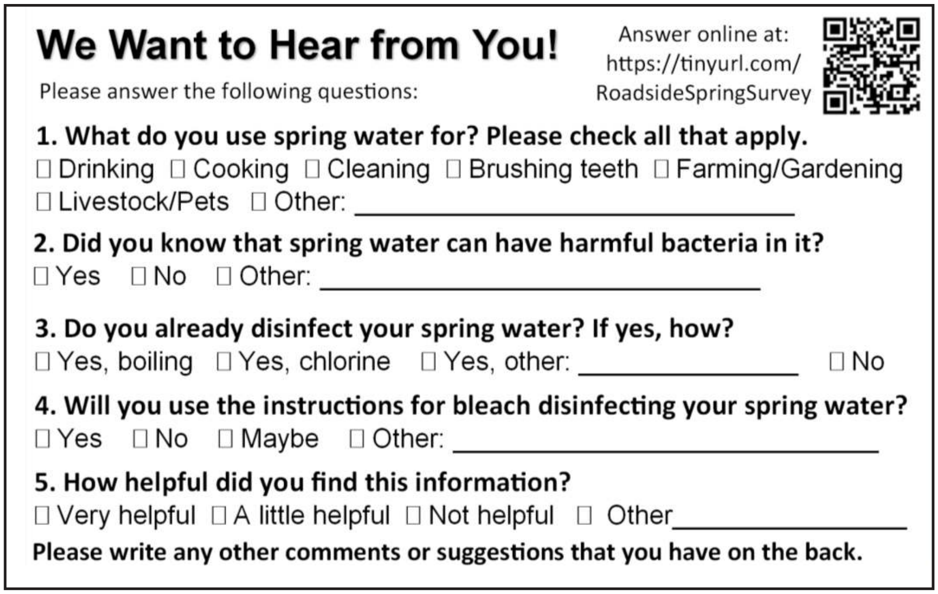


Figure 2. Left – The front side of the infographic featuring information on spring water quality. Right – The back side of the infographic featuring the protocol for bleach disinfection of spring water.



We Want to Hear from You!

Please answer the following questions:

Answer online at: https://tinyurl.com/RoadsideSpringSurvey

1. What do you use spring water for? Please check all that apply.

☐ Drinking ☐ Cooking ☐ Cleaning ☐ Brushing teeth ☐ Farming/Gardening ☐ Livestock/Pets ☐ Other: ________________

2. Did you know that spring water can have harmful bacteria in it?

☐ Yes ☐ No ☐ Other: ________________

3. Do you already disinfect your spring water? If yes, how?

☐ Yes, boiling ☐ Yes, chlorine ☐ Yes, other: ________ ☐ No

4. Will you use the instructions for bleach disinfecting your spring water?

☐ Yes ☐ No ☐ Maybe ☐ Other: ________________

5. How helpful did you find this information?

☐ Very helpful ☐ A little helpful ☐ Not helpful ☐ Other________

Please write any other comments or suggestions that you have on the back.

Figure 3. Postcard-sized, pre-addressed anonymous survey distributed with infographic and plastic eyedroppers at local roadside springs.

for spring use, but to assess the success of the infographic in providing useful information to spring users. As previously mentioned, the survey was postcard-sized, included in plastic sandwich bags with the infographic and a plastic eyedropper, and distributed at five roadside springs local to southwestern Virginia and southern West Virginia. The survey included a return address and postage as well as a link to an online version of the survey. This allowed spring users to choose the survey format (paper or online) that was more convenient for them to complete and return.

Results and Discussion

Chlorine Residual

As previously stated, a specific study aim was to determine the minimum volume of household bleach that could be added to 1 gallon of spring water to inactivate total coliform and *E. coli* bacteria and maintain a free chlorine residual of between 0.5 and 2.0 mg/L 1-hour post-disinfection, and at least 0.2 mg/L 1-day post-disinfection, in accordance with CDC (2020) recommendations. Identifying the minimum quantity necessary for addition would ensure that taste and/or aesthetic issues were minimized, thus maximizing the potential adoption of this strategy by regular spring users.

Spring water dosed with CDC recommended bleach quantities of 1/4 and 1/8 tsp per 1 gallon (~ 3.79 L) of water yielded free chlorine levels of at least 8.8 mg/L throughout the duration of the trial time period, the maximum measurement range for the HACH colorimeter (Figure 4). Exceedance of the free chlorine residual taste threshold (2.0 mg/L) is of particular concern, given repeated reports that spring users prefer the taste of spring water to home or alternative drinking water sources (Swistock et al. 2015; Krometis et al. 2019; Patton et al. 2020). Halving the 1/8 tsp recommendation to 1/16 tsp bleach still yielded free chlorine levels that reached the maximum measurement range of 8.8 mg/L for the duration of the trial period.

The bleach volume of 1 drop from a plastic eyedropper (0.05 mL) successfully maintained a free chlorine residual below 2.0 mg/L for the duration of the trial period. However, 1-week post-disinfection the residual fell to 0.17 mg/L, below the CDC recommended range. This is of concern because previous studies regarding roadside spring water use found that individuals often collect spring water weekly or monthly, suggesting that collected spring water may be stored for several weeks prior to being used (Swistock et al. 2015; Krometis et al. 2019; Patton et al. 2020; Sinton et al. 2021). Bleach volumes of 2 and 3 drops from a plastic eyedropper (0.10 and 0.15 mL, respectively) yielded free chlorine levels that were greater than zero but less than the maximum detection limit, for the duration of the trial time period. While the free chlorine residuals for 2 and 3 drops exceeded the CDC recommended maximum of no greater than 2 mg/L at the 5-minute and 30-minute post-disinfection time points, at the 1-day post-disinfection time point, the free chlorine residual of the 2 drop trials decreased to 2.0 mg/L. This residual remained within the CDC recommended range of 0.2 to 2.0 mg/L for the remainder of the trial duration.

Lantagne et al. (2014) analyzed the performance of the U.S. EPA recommended dose of bleach for drinking water disinfection in the event that bottled or filtered water is unavailable (approximately 1/8 tsp or 8 drops in 1 gallon (~ 3.79 L) of water). Similar to the present study, the authors dosed water collected in one-gallon vessels, but utilized water from various sources including tap water, surface water, well water, and rain barrels. The authors determined that 24-hours after dosing, 81% of samples dosed with 2 mg/L of sodium hypochlorite fell between the desired free chlorine residual range of 0.2 mg/L (the CDC recommended minimum free chlorine residual level) and 4 mg/L (the SDWA Maximum Contaminant Level for free chlorine). Sodium hypochlorite doses of 4 and 7 mg/L resulted in only 69% and 14% of samples remaining within the desired free chlorine residual range, respectively, suggesting that these doses are too high. Lantagne et al. (2014) concluded that existing U.S. EPA recommendations for the chlorine disinfection of drinking water need to be adjusted to lower, more accurate doses, especially given recent chlorine increases in commercially available bleach. The Lantagne et al. (2014) results are consistent with the results of the present study where 2 drops (0.10 mL) of bleach in 1 gallon of spring water, equivalent to approximately 1.95 mg/L of sodium hypochlorite, provided a sufficient chlorine residual of between 0.2 and 2 mg/L 24-hours after dosing.

Notably, after determining that 2 drops of bleach provided an appropriate free chlorine residual within the desired range for 1 gallon of spring water, an additional trial was completed testing the volume using name-brand and store-brand bleach to account for any differences in chlorine strength. Bleach brand testing was completed due to concerns about varying chlorine levels in commercially available bleach (Lantagne 2009). In the current study, differences were negligible (see Supplementary materials, Figure S1). Figure 4 represents results from the name-brand bleach trials. Both name- and store-brand bleach

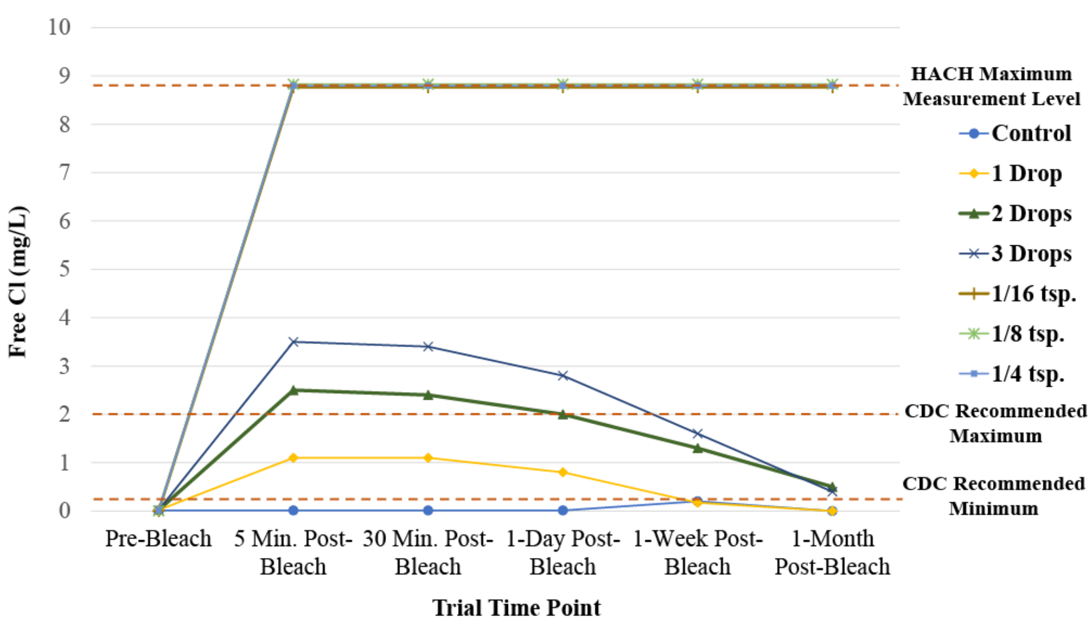


Figure 4. The relationship between bleach dosage (per 1 gallon of spring water) and free chlorine measured in collected spring water over time. (n = 2 for ¼ tsp, 1/8 tsp, 1/16 tsp; n = 5 for 2 drops; n = 1 for 1 drop and 3 drops).

effectively inactivated total coliform and *E. coli* in spring samples for the duration of the trial period, and both provided a sufficient chlorine residual.

Total Coliform and *E. coli*

All quantities of added bleach at or above 2 drops per gallon successfully inactivated total coliform and *E. coli* in the spring water and prevented regrowth for the duration of the study (Figures 5 and 6). As all coliform levels in samples prior to the addition of bleach exceeded 1000 MPN/100 mL, this represents an approximately 2-3 log-scale inactivation. Total coliform appeared to regrow when an insufficient residual (below 0.2 mg/L) was maintained, given detection at 1-week and 1-month post-disinfection in the spring water treated with 1 drop of bleach. *E. coli* levels in pre-disinfection spring samples were notably lower than that of total coliform (1.5 to 54.5 MPN/100 mL), which aligns with typical observations at roadside springs in this region (Krometis et al. 2019), and no *E. coli* regrowth was observed under any of the bleach regimes. As 2 drops of bleach appeared effective both in inactivation of fecal indicator bacteria and maintenance of an appropriate residual below the CDC (2020) taste threshold, this quantity was selected for infographic recommendation.

Survey Results

Ten individuals responded to the surveys left at the five springs. The majority (70%) reported using the roadside spring water for drinking and cooking. Survey respondents also reported using roadside spring water for cleaning (30%), brushing teeth (30%), and for use with livestock/pets (50%). When asked whether they had previous knowledge of the potential presence of harmful bacteria in spring water (Figure 7), survey responses were split relatively evenly between yes and no. Despite 50% of survey respondents stating that they knew that roadside spring water could have harmful bacteria in it, 80% of respondents reported that they do not disinfect their spring water prior to using it.

With regards to infographic reception, 70% of respondents found the infographic content to be very helpful, 20% found the content to be not helpful, and 10% found the content to be a little helpful (Figure 8). Additionally, 60% of respondents stated that they would use the provided instructions for bleach disinfecting their spring water, 10% reported they would not use the instructions, and 10% reported they might use the instructions (Figure 8). One individual reported that they may reconsider use of roadside spring water entirely while another individual was skeptical about the safety of adding bleach to drinking water.

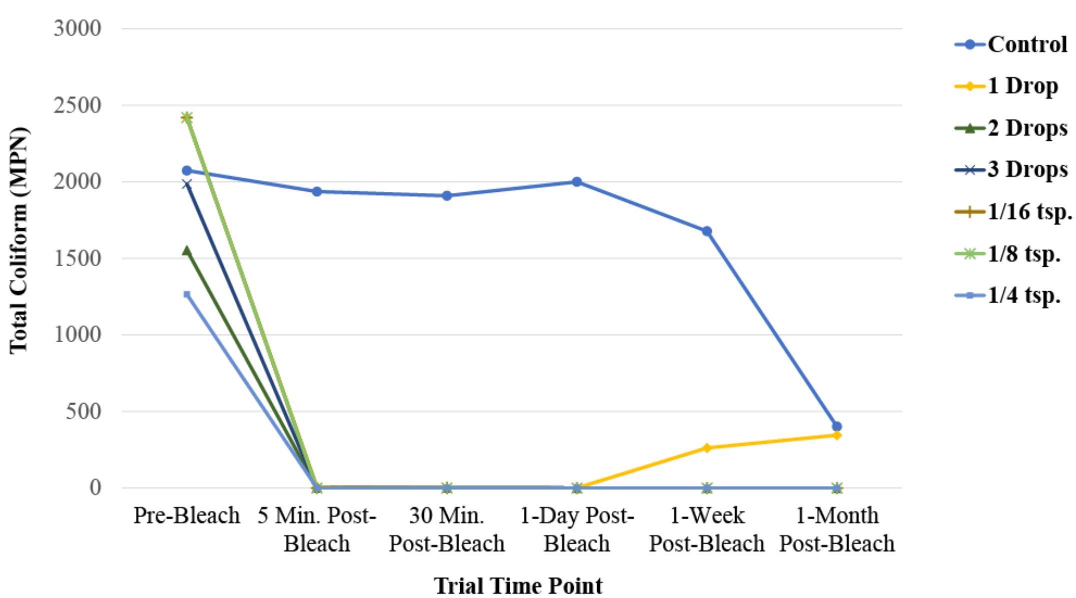


Figure 5. The relationship between bleach dosage (per 1 gallon of spring water) and total coliform bacteria measured in collected spring water over time. (n = 2 for ¼ tsp, 1/8 tsp, 1/16 tsp; n = 5 for 2 drops; n = 1 for 1 drop and 3 drops).

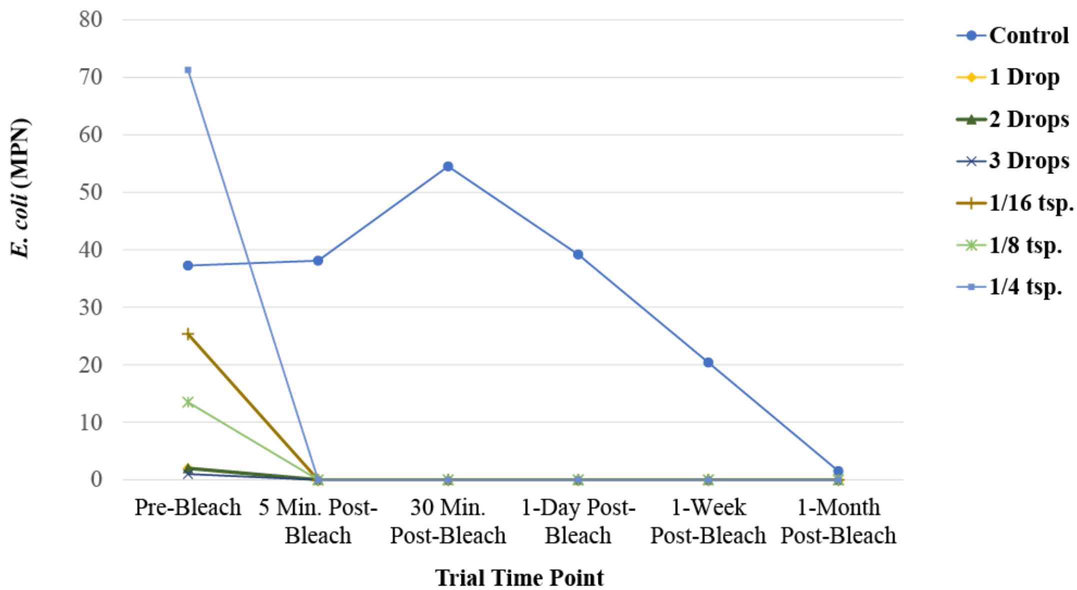


Figure 6. The relationship between bleach dosage (per 1gallon of spring water) and *E. coli* measured in collected spring water over time. (n = 2 for ¼ tsp, 1/8 tsp, 1/16 tsp; n = 5 for 2 drops; n = 1 for 1 drop and 3 drops).

Though most survey respondents reported finding the infographic at least a little helpful, only a little over half of survey respondents stated that they would use the provided disinfection instructions and eyedropper. This feedback, and the individual response highlighting that spring users may be unsure of the safety of adding bleach to drinking water, suggests that the infographic may need more information on the safety of the addition of small amounts of bleach to drinking water, coupled with information on the dangers of adding too much bleach. Ideally, more widespread outreach and educational efforts in the area, discussing common water contaminants and health impacts, would encompass this information and information on home drinking water quality.

Limitations

We did not test bleach varieties with less than 7.4% sodium hypochlorite. Our disinfection protocol was developed using name-brand and store-brand household bleach with 7.4 to 7.5% sodium hypochlorite. This sodium hypochlorite concentration reflects the concentration of most commercially available regular household bleach products in the U.S. of between 5 and 9% (WS DOH 2015; CDC 2022). Certain varieties of commercially available household bleach, such as scented or splash-less products, have lower sodium hypochlorite concentrations (1 to 5%). The infographic emphasizes the use of regular household bleach and not splash-less or scented varieties because of the higher concentration of sodium hypochlorite in regular household bleach.

Commercial household bleach has a shelf life of approximately six months, after which the product begins to degrade, becoming 20% less effective each year after it is produced (Ono 2006). The timeline of this study did not allow for the degradation of bleach to be factored into the scope of the experiment. The authors recommend that individuals interested in using bleach to disinfect their roadside spring water use new bleach bottles or bottles opened within six months and that have not exceeded any manufacturer printed expiration dates.

This bleach disinfection protocol is targeted at inactivating total coliform, *E. coli*, and other chlorine-vulnerable pathogens commonly found in spring water. Chlorine disinfection of drinking water is not effective in removing chlorine-resistant waterborne pathogens, such as *Cryptosporidium* (U.S. EPA 1999; CDC 2022), has low to moderate success in inactivating *Giardia* (CDC 2022), and thus should not be used in an attempt to disinfect drinking water that is suspected to be contaminated with chlorine-resistant pathogens. The inactivation of waterborne pathogens that are not bacteria, such as viruses, was also not tested during this

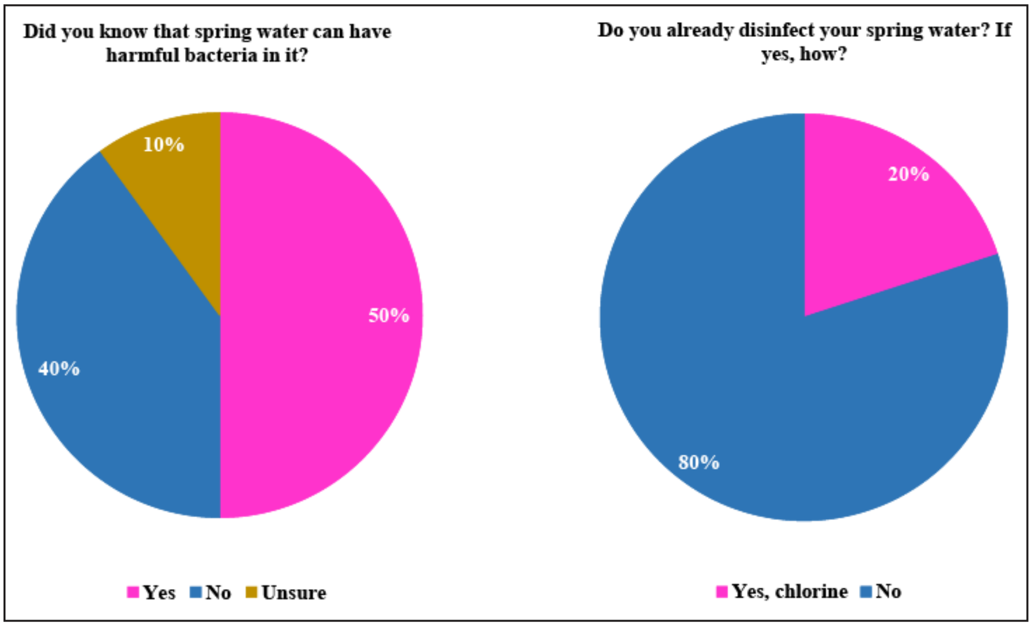


Figure 7. Survey responses collected regarding perception and use of roadside spring water.

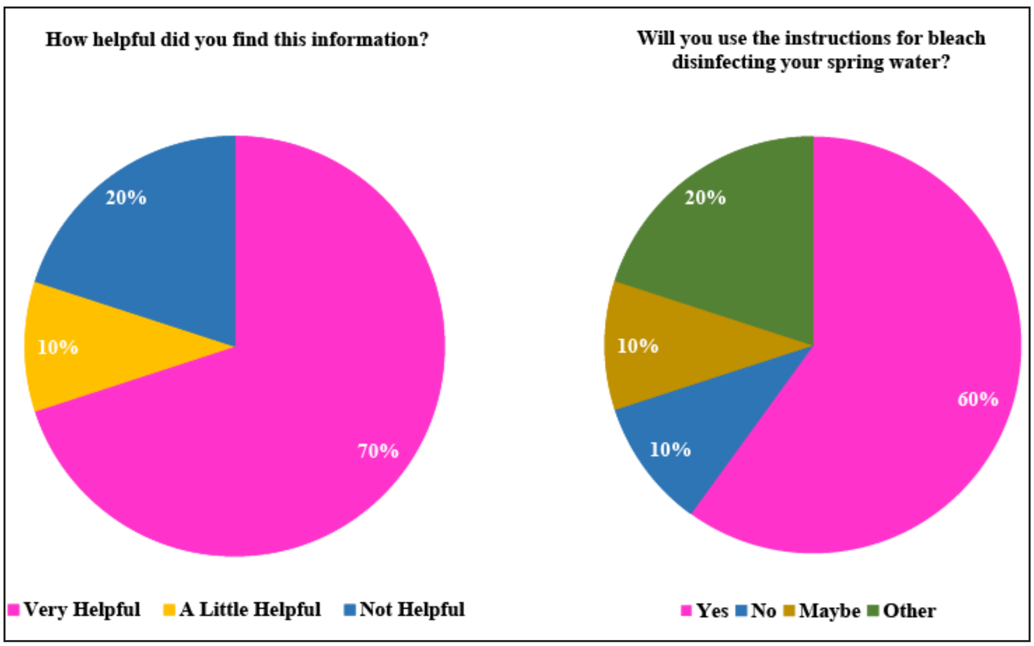


Figure 8. Survey responses collected regarding perception and use of the distributed infographic.

study. Additionally, it should be noted that bleach disinfection is less effective in turbid water (> 10 NTU; Crump et al. 2004; Lantagne 2008). The turbidity of the water tested was between 0.0 and 0.13 NTU. Turbidity values of less than 10 NTU in water are generally considered to be low (USGS 2018). For this reason, we feel that bleach disinfection of spring water in the Central Appalachian region can be an effective tool for the inactivation of bacteria such as total coliform and *E. coli*. This disinfection method was not tested on spring water with higher turbidity, therefore, any future attempts to apply this method to spring water in other regions and/or to alternate water sources must consider water turbidity, among other water quality parameters.

Our survey sample from infographic distribution was convenience-based, as only spring users who received and/or viewed the infographic information received the option to take the survey. However, based on the generally mixed responses to the infographic depicted in the survey data, we feel that it may be reasonable to draw general conclusions about infographic reception from the survey results. We do, however, caution against using this survey data to generalize spring users' reception to bleach disinfection, whether in Appalachia, across the entire United States, or in other countries.

Conclusion

Roadside springs are a common drinking water source for some households in the Central Appalachian region. Previous studies across multiple states indicate that users may prefer the taste and aesthetics of the spring water to other available drinking water sources, lack trust in their household drinking water, and/or lack access to in-home drinking water entirely. Based on previous studies assessing roadside spring water quality in the Central Appalachian region, consumption of untreated roadside spring water can pose a health risk to spring users due to the presence of total coliform and *E. coli*, among other bacteria and pathogens. However, as at-home water options may be unpalatable and/or spring water consumption may have cultural significance, education dissuading spring water use entirely may be ineffective and poorly received. Bleach disinfection of roadside spring water can provide a simple, accessible POU treatment option for households reliant on roadside spring water. This study demonstrates that 2 drops of household bleach from an eyedropper provided sufficient disinfection and free chlorine residual in 1 gallon of roadside spring water for up to one month. Efforts to provide information on spring water quality and bleach disinfection via infographic were considered helpful but only half of survey respondents reported that they intended to use the bleach disinfection instructions. Additional research on the risks associated with spring water use, as well as efforts to expand water infrastructure and improve in-home piped water quality, is needed to better understand and help reduce associated health risks in Central Appalachia and elsewhere where untreated spring water is used as a source of drinking water.

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Author Bio and Contact Info

Dr. Hannah Patton (corresponding author) has a Ph.D. in Biological Systems Engineering from Virginia Polytechnic & State Institute. Hannah has a B.S. in Environmental Engineering from Saint Francis University, an M.S. in Biological Systems Engineering from Virginia Tech, and an M.P.H. from Virginia Tech. Hannah is an Engineer in Training and is Certified in Public Health. Hannah's graduate research focused on drinking water quality and point-of-use water treatment in the Central Appalachian coalfields and other rural areas. Hannah can be contacted at hpatton@vt.edu or by mail at Seitz Hall, RM 200, Virginia Tech, 155 Ag Quad Lane, Blacksburg VA 24061.

Dr. Leigh-Anne Krometis is an Associate Professor and Elizabeth and James E. Turner Jr. Faculty Fellow of Biological Systems Engineering at Virginia Tech. She holds a Ph.D. in Environmental Engineering and has conducted research on home water quality in Central Appalachia for over ten years. Dr. Krometis can be contacted at krometis@vt.edu or by mail at Seitz Hall, RM 308, Virginia Tech, 155 Ag Quad Lane, Blacksburg VA 24061.

Ben B. Faulkner is a Biologist from Princeton, WV. His career has focused on coal and metal mining water quality and land reclamation. He can be reached at BenBFaulkner@gmail.com or by mail at 171 Willowbrook Rd., Princeton, WV 24740 or through the WV Mine Drainage Task Force at www.WVMDTaskForce.com.

Dr. Alasdair Cohen is an Assistant Professor of Environmental Epidemiology in the Department of Population Health Sciences at Virginia Tech. He conducts research on drinking water (contamination, treatment, and supply), sanitation, wastewater, and health in rural areas, with a focus on developing and improving safe water programs. Dr. Cohen can be contacted at alasdair.cohen@linacre.oxon.org or by mail at Virginia Tech PHS, 205 Duck Pond Dr., Blacksburg VA 24061.

Erin Ling is a Senior Water Quality Extension Associate in the Biological Systems Engineering Department at Virginia Tech. She coordinates the Virginia Household Water Quality Program, which provides water testing and education to Virginia's 1.6 million private water supply users through Virginia Cooperative Extension offices statewide. Erin develops and disseminates educational Extension resources to youth and adult audiences and works with collaborators to conduct applied research focused on drinking water quality. She can be reached at ejling@vt.edu or by mail at 1230 Washington St. SW - HABB1 302F Virginia Tech, Blacksburg VA 24061.

Dr. Emily Sarver is Stonie Barker Professor and Graduate Program Director in the Department of Mining and Minerals Engineering, and adjunct faculty to the Via Department of Civil and Environmental Engineering at Virginia Tech. Her research sits at the intersection of resource extraction and the environment, with a focus on both community wellbeing and occupational health. She also teaches at both undergraduate and graduate levels on the topic of sustainable development. Dr. Sarver can be contacted at esarver@vt.edu or by mail at Holden Hall, RM 393, Virginia Tech, 445 Old Turner Street, Blacksburg VA 24061.

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Supplementary Figure

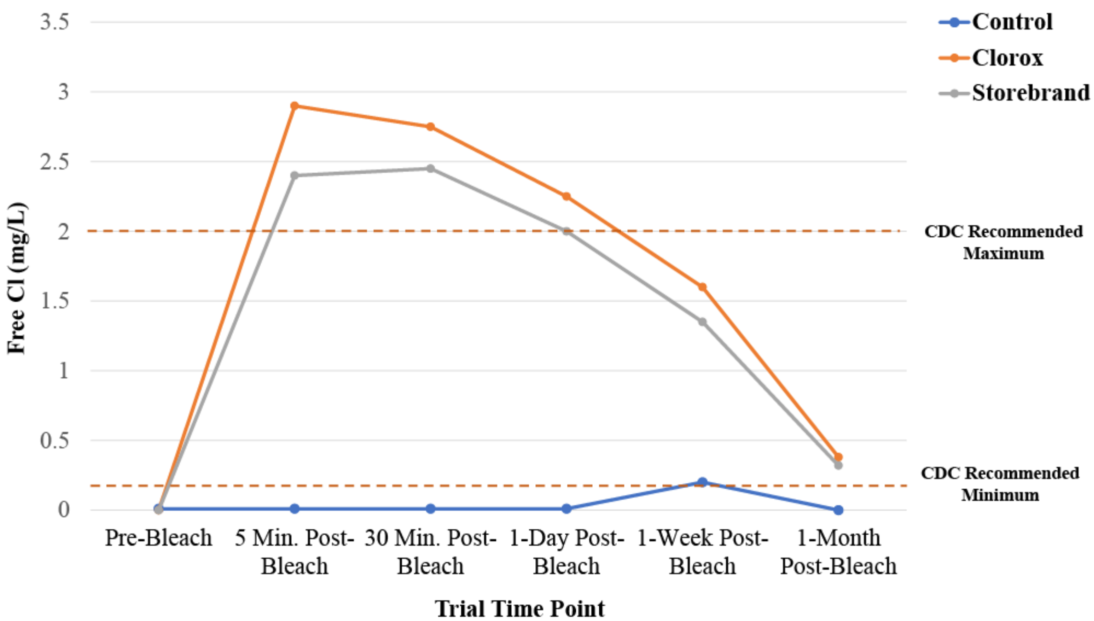

Figure S1. The relationship between bleach brand (2 drops per 1 gallon of spring water) and free chlorine measured in collected spring water over time.

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"So That We Can Save the Earth from Dying": Highlights from a Middle School Environmental Field Day

*Kenton Sena[1], Jill Abney[2], Hannah Ruehl[2], and Chris Barton[3]

[1]Lewis Honors College, University of Kentucky, Lexington, KY
[2]Center for the Enhancement of Learning and Teaching, University of Kentucky, Lexington, KY
[3]Department of Forestry and Natural Resources, University of Kentucky, Lexington, KY
**Corresponding Author*

Abstract: Continued urbanization is likely to reduce human-nature experience, transforming human-dwelt spaces into increasingly artificial environments and removing humans from interaction with non-human living things and their ecosystems. In urban spaces, outdoor experiential educational activities can help students increase their familiarity with the outdoors and get their hands dirty. This case study reports on an environmental field day for middle school students from an urban Kentucky middle school. Students rotated through three activities (picking insects out of leaf packs, testing water quality, and planting trees), then completed a brief survey designed and administered by their faculty. Students rated the tree planting activity more highly than the other two activities ($p < 0.0001$), suggesting that this activity was more accessible, interesting, and engaging to a broader range of students. However, student qualitative responses to the water quality and leaf pack activities demonstrated an ability to make connections between those activities and the broader world, such as the importance of their stream-water quality for the Gulf of Mexico, or the implications of finding pollution-tolerant insects for understanding stream health. Overall, we recommend planning field days with multiple activities that offer various entry points for students with a range of prior experience of nature. We also emphasize the potential for these sorts of activities to help students develop a sense of awe or wonder in nature—seeing and handling things they never considered before but now experience as profound and interesting. These observations are consistent with the literature demonstrating the need for human-nature experience (especially in urban areas) to support developing a sense of affectivity for the environment and interest in taking environmentally beneficial actions, as well as the role of place-based experiential education in helping students bridge that gap.

Keywords: *place-based education, ecology, environmental education, urban forestry, urban streams*

Globally, many people find themselves living seemingly separate from nature as the human population is increasingly concentrated in cities. In fact, nearly 70% of the world's population is expected to live in urban areas by 2050 (Eurostat 2016). This ongoing human migration from rural to urban spaces is associated with human disconnection with nature, termed the "extinction of experience" (Soga and Gaston 2016). As nature scholars, we know that this distinction is arbitrary—humans are a part of nature. However, our built environment can separate us from experiences with the natural world. And yet, human experience of nature is critical for mental health and well-being (Bratman et al. 2015; Hunter et al. 2019), and is associated with increased affectivity for nature and environmental action (Zaradic et al. 2009; DeVille et al. 2021). Conversely, disconnection from nature may lead to a lack of interest in nature, or, more problematic, a distaste for nature's less convenient or (to some) less aesthetic realities, such as bugs. In addition, these feelings of disconnection from nature also limit our ability to recognize the impact of human behavior on the environment.

Soga and Gaston (2016) describe decreased opportunity to interact with nature as a key cause

Research Implications

- Middle school students were invited to participate in an environmental field day.
- Activities included tree planting, picking insects from leaf packs, and testing water quality.
- Students tended to prefer the tree planting activity, but demonstrated higher levels of learning from the other activities.

for the decline in human-nature experience, a factor closely associated with urbanization. Urban dwellers have less opportunity to interact with nature because they are less able to access quality greenspace, both due to loss of greenspace to urban development (Dallimer et al. 2011; Zhou and Wang 2011) and degradation of remnant greenspace (Foo 2016) through fragmentation (Li et al. 2019), species invasions (Johnson et al. 2020; Santana Marques et al. 2020), pollution (Peters 2009; Liu et al. 2022), and biodiversity loss (Turner et al. 2004). This lack of access is exacerbated by social and economic inequalities—members of under-resourced communities and minoritized racial and ethnic groups often have less access to high quality greenspace (Wen et al. 2013; Dawes et al. 2018; Spotswood et al. 2021). Extended to an environmental education context, urban students, and especially those from under-resourced and minoritized communities, may have negative assumptions about or predispositions toward nature due to a lack of previous positive experience of nature—that is, they might immediately assume that stream-dwelling insects are gross without giving them a chance to be cool.

Because of the critical importance of nature experience for human wellness and the many barriers restricting access to greenspace for urban dwellers, especially for members of under-resourced communities, increasing opportunities for positive interaction with greenspace in urban areas and increasing the quality of that greenspace, are essential. Urban forest restoration can improve air quality (Kroeger et al. 2014), sequester carbon (Teo et al. 2021), increase biodiversity (Simmons et al. 2016), mitigate the urban heat island effect (Kroeger et al. 2018), and manage stormwater (Pataki et al. 2021). Moreover, engaging in urban restoration activities can enhance affectivity for nature—a key leverage point for reversing the loss of human-nature experience (Whitburn et al. 2018). For students with a negative attitude toward nature, caring for their own community greenspaces, through activities such as planting trees and assessing water quality, may help them overcome those preliminary misgivings and develop a more positive affectivity. The tree they plant, which may grow throughout their lifetime, is worth them getting a little muddy.

Place-based, experiential environmental education programs in K-12 classes are uniquely positioned to engage urban students in caring for their local community greenspaces, both enhancing greenspace quality and improving student attitudes toward nature. Students participating in experiential learning programs outdoors generally report positive attitudes toward their experiences (James and Williams 2017), emphasizing their appreciation of out-of-classroom learning (Genc et al. 2018). These programs also support increased environmental knowledge (Hoover 2020), more developed environmental attitudes (Genc et al. 2018; Hecht and Nelson 2021), and changed environmental behaviors (Hoover 2020). Importantly, place-based environmental education can be especially impactful for students from under-resourced schools (Stevenson et al. 2014; Stern et al. 2022), although with exceptions (Wyner and Doherty 2021). Furthermore, as James and Williams (2017) note, experiential learning can be more accessible and impactful for students with learning differences or difficulties, emphasizing the importance of place-based outdoor learning in ecology and the environment for inclusive education. However, implementing experiential learning programs in K-12 curriculum can prove difficult if educators lack confidence in aligning place-based programming with standards (Merritt and Bowers 2020; Wright et al. 2021). Overall, local stewardship activities, such as water quality assessment and tree planting, may be good entry points for educators hoping to integrate place-based opportunities in their curriculum. In addition, introducing students to noticing and caring about their local greenspace may help students discover an appreciation for the outdoors that transcends the curricular experience, resulting in changed attitudes toward and voluntary engagement with nature. Students who initially dismissed stream-dwelling insects as gross may be more willing to get in the creek and flip rocks the next time they visit their local park.

This case study reports on a field day engaging 167 eighth grade students in water quality sampling, stream health assessment, and tree planting activities at a local urban forest and stream site. These eighth graders attend a middle school in the second largest city in Kentucky. The majority of this middle school's student population are listed as both minority students (68%) and as economically disadvantaged (69%) (USNWR 2021). According to a 2013 study examining the 85-square mile urban service area, a tree canopy covers at least 13,000 acres (25%) of that space (Davey Resource Group 2015). Student participants completed a post-trip survey to reflect on their experiences, including rating their preferred activity (tree planting, water quality, and leaf pack) and sharing something they learned from each activity. We reviewed survey results to address the following research questions: 1) Did students prefer one activity over others? and 2) Did student self-reported learning vary across these activities?

Methods

A team of middle school educators, local government employees, and faculty from the local state university hosted this field day at a community forest within a local park. This forest was planted as part of a community tree-planting event in 2000 and has since developed a closed canopy and vertical forest structure (overstory trees, understory shrubs and trees, and a shade-tolerant understory herb layer). Additionally, the forest is experiencing significant pressure from invasive plants such as Amur honeysuckle (Sena et al. 2021). The field day consisted of three stations (tree planting, water quality, and leaf pack stations) which students rotated through in three different groups throughout the course of the day. At the tree planting station, led by the local government urban forestry division and a local non-profit organization whose mission is to restore forests, students used dibble bars to plant native trees in an area of the forest where invasive species had recently been cleared. Station leaders emphasized the importance of trees for ecological health and human well-being. At the water quality station, led by faculty and students from a local university, students analyzed stream-water samples for turbidity, pH, nitrate, phosphate, and dissolved oxygen. Station leaders emphasized stream connectivity—that upstream processes influence downstream water quality, eventually leading to the Gulf of Mexico—as well as sources of water pollution and the influence of underlying geology on surface water quality. At the leaf pack station, led by faculty and students from a local university, students picked through leaf packs that had been incubating in the stream for several weeks, finding and identifying individual insects using forceps, hand lenses, and field guides. Station leaders emphasized that some insects are sensitive to pollution and will not survive in a polluted stream, while other insects are more tolerant to pollution. Students spent 15 – 20 minutes at each station, then ate lunch in the field before returning to school.

After the event, faculty at the partnering school developed and administered a survey to evaluate student attitudes toward the activities, as well as what they learned during the event. Survey responses were shared with the project team with all identifiers removed; a preliminary Institutional Review Board (IRB) review designated this project as Not Human Research (NHR). Survey questions are summarized in Table 1. Questions 1-3 asked students to rate their attitudes toward each activity (tree planting, water quality, and leaf pack) on a scale of 1 – 5, with 1 being the worst and 5 being the best. Question 4 asked students to rank the activities from their most favorite to their least favorite. Finally, questions 5-7 invited students to share something they learned from each activity, and question 8 asked students to reflect on why scientists were interested in studying stream health at this site. We note that the survey was developed and administrated by the middle school to collect routine feedback on the field trip; it was not developed from the outset as a research instrument. In some cases, in hindsight, some questions could have been rephrased to more rigorously assess the research questions, or survey design could

Table 1. Survey items list for student post-activity reflection.

Survey Question	**Options**
Rate how you felt about the tree planting activity.	1 – 5, with 1 being worst and 5 being best
Rate how you felt about the water quality activity.	1 – 5, with 1 being worst and 5 being best
Rate how you felt about the insect activity.	1 – 5, with 1 being worst and 5 being best
Which activity did you like the best, second best, or least?	Ranked activities 1 – 3, with 1 as favorite and 3 as least favorite
What did you learn while planting trees?	Free response
What did you learn at the water quality station?	Free response
What did you learn from the leaf packets?	Free response
Please explain why scientists are interested in the health of the stream at Masterson Station.	Free response

have been adjusted to improve data quality (e.g., students were able to rank multiple activities as their "favorite"). Furthermore, given the large number of students who responded "I don't know" or "I don't remember" to the qualitative questions, adding a brief description or picture of each activity to help students remember the activity in question may have helped to jog their memory. With these limitations in mind, we believe the survey results give insight into developing and implementing a field day for middle school students, supporting future efforts to engage students with diverse backgrounds and varying levels of prior nature experience in learning and living in the natural world.

Quantitative data (feelings toward each activity; activities ranking) were analyzed using a Kruskal-Wallis test, with follow-up pairwise comparisons using a Wilcoxon test with a BH adjustment (Benjamini and Hochberg 1995). Qualitative data (responses from the free response questions listed in Table 1) were coded independently by two members of the project team and discrepancies reconciled. The codebook for this process was developed with attention to students' tendencies to offer responses demonstrating varying levels of thinking and different experiences of content proficiency. We designed our coding scheme to loosely mirror Bloom's Taxonomy, a hierarchical classification of learning outcomes commonly used in K-12 lesson design (Table 2) to consider which activity, if any, lent itself to higher levels of cognition.

Results

To examine students' attitudes toward the activities individually, students were asked to rate each activity on a scale from 1 – 5 (with 1 being the worst and 5 being the best). Student reactions to the tree planting activity tended to cluster in the 4 – 5 range, with a few outliers in the 2 – 3 range (Figure 1). With the water testing and leaf pack activities, student responses tended to be more spread out, with the denser areas of reactions clustering around option 3. This preference for the tree planting activity was significant ($p < 0.0001$), with students rating the tree planting activity higher (4.25) than both water quality (3.31) and leaf pack (3.15) activities (Table 3).

Consistent with student ratings of each activity individually, student ranking of activities from favorite (1) to least favorite (3) demonstrated a preference for the tree planting activity (Figure 2;

Table 2. Codebook for student open-ended responses.

Code	Definition	Examples	General Correlation with Bloom's Taxonomy
Recalls basic properties	Student lists something descriptive or identifiable about the trees, water system, bugs, etc.	"Snails can live in the leaves." "The biodiversity in the river." "How much acidity there is."	Remember (Recall facts and basic concepts)
Identifies step(s) in a process	Student mentions a step or steps in the processes shown that day like how to plant a tree or how to evaluate water quality.	"You have to dig a big hole."	Understanding (Explain ideas or concepts)
Makes connections to larger, local natural ecosystems	Student articulates awareness of the connection between multiple natural and manmade details.	"The stream can easily be polluted from the sections from the stream that are in high populated areas." "I learned that the water quality is decided by a lot of things and because we live in Kentucky we have limestone that also affects the river."	Applying (Use information to make connections)
Articulates causal impact of humans (& vice versa)	Student makes conclusions about humans' causal impacts on the environment or the environment's impact on humans.	"That its easy to do something small that can make a big difference in the future."	Analyzing (Draw their own conclusions)
Evaluates quality or reality	Student makes an evaluative statement about the cleanliness of the water, whether it is drinkable, the number of trees, etc.	"It has a D rating."	Evaluating (Argues a perspective)
Establishes global conclusions	Student indicates some awareness of broader/global interconnectivity either through discussing places/ environments not necessarily addressed in the stations or through the creation of plans for improving the environment.	"It can flow to the Gulf of Mexico killing some fish." "Trees help the carbon dioxide in the atmosphere decrease."	Creating (Imagining or formulating additional applications and global connections)
Reflects on social connections formed in environmental work	Student makes reflective comments about the experience of the activities and the connections they made with other learners.	"Idk but I did have fun doing that. I felt adventurous." "Quite calming talking with friends while working."	Multiple (Evaluative, reflective, creative)
No appropriate code	Use this code if none of the others fit. Usually when no possible interpretation of the response is possible.	"Bugs"; "Yes"; "Water source"	NA
I don't know/NA	Student indicates lack of certainty about learning anything.	"I wasn't paying attention." "Don't know."	NA
Nothing	Student indicates they learned nothing.	"Nothing"; "Nothing it was horrible"	NA

Note: Students were asked "What did you learn while planting trees?"; "What did you learn at the water quality station?"; and "What did you learn from the leaf packets?". The chart also includes definitions, example responses, and each code's perceived connection to Bloom's Taxonomy of levels of thinking.

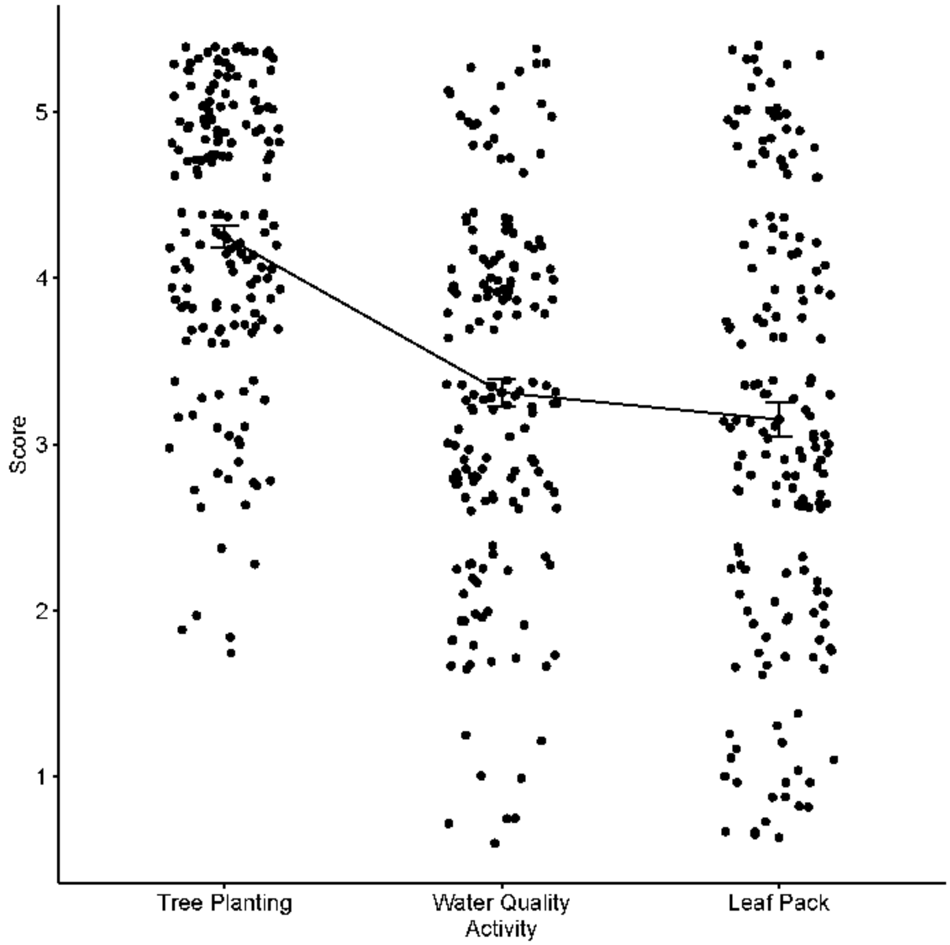

Figure 1. Student responses to "Rate how you felt about" each activity; students ranked each activity from 1 – 5 (with 1 being worst and 5 being best).

Table 3. Descriptive statistics for quantitative student survey responses.

Activity	Mean Score (± SD)*	Mean Rank (± SD)
Tree	4.25a ± 0.83	1.95 ± 0.91
Water Quality	3.31b ± 1.05	2.14 ± 0.66
Insect	3.15b ± 1.29	2.08 ± 0.77
Kruskal-Wallis chi-squared	87.2	3.50
Kruskal-Wallis p	< 0.0001	0.1738

*"Score" indicates student response to survey question "Rate how you felt about the activity." "Rank" indicates student response to "Which activity did you like the best, second best, or least?" "SD" = Standard Deviation. Means with different letters are significantly different ($p < 0.05$) across activities.

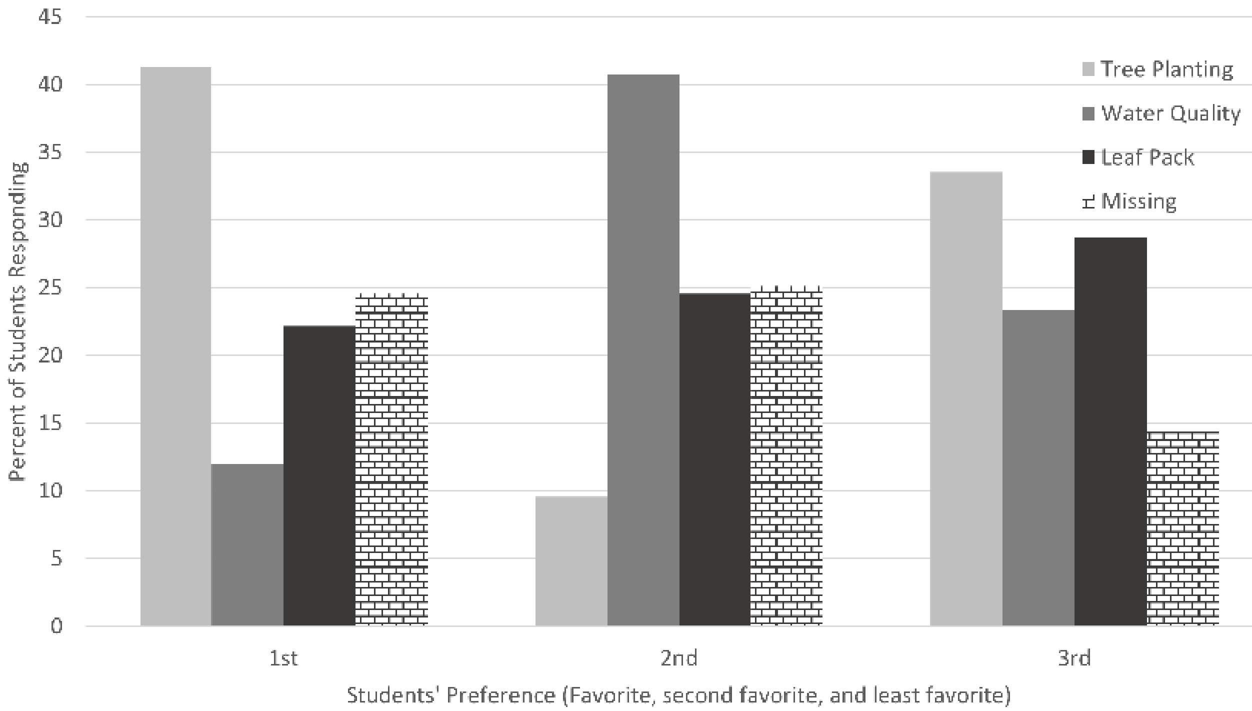

Figure 2. Student responses to "Which activity did you like best?" by percentage. Students were asked "Which activity did you like the best, second best, or least?" and were given the opportunity to choose 1 – 3 for each activity. The percentage of students with "NA" responses above either were missing that rank for any of the activities or had duplicates for that rank.

Table 3). When students were invited to rank which of the three activities they liked the best, 41.3% of students chose the tree planting activity, 22.2% of students indicated the leaf pack activity, and 11.9% of students chose the water testing activity. The most popular second place activity was the water testing activity (40.7%) followed by the leaf pack activity (24.6%). Interestingly, students tended to either rank the tree planting activity first or third, with only a small percentage (9.58%) ranking it second. We should note that the design of the question led to a lot of inconclusive data for this survey item because ranks were either duplicated or missing with 24.6% of responses for first, 25.2% of responses for second, and 14.4% of responses for third being uninterpretable. In some cases, for instance, students ranked all three activities as number one. These insufficient data indicate that the design of that survey item should be altered for clarity in future iterations of the survey.

Student qualitative responses demonstrated that field day activities supported a spectrum of learning experiences for students. For example, for the tree planting activity, many students shared that they learned how to plant trees ("I learned how to plant a tree") or about the significance of trees for human and environmental health ("Planting trees can change the environment and is important"). Other students remarked on some aspects of trees that they had not known before, such as the length or complexity of root systems ("Trees have very long and complicated roots at just a young age") and the names of trees ("I learned the names of trees..."). Students differed in their perspectives about whether planting trees was easy or hard ("It isn't that hard to plant trees" vs. "It was NOT as easy as I thought it would be"). When reflecting on the water quality activity, students shared about the significance of stream-water quality for human and environmental health ("We should know how clean or dirty our water is, because we literally drink out of it" and "They need good water quality for the animals"), and understood that humans are largely responsible for poor water quality ("The water is very dirty, mostly because of us and what we put in it"). They also recalled various aspects of the test methods demonstrated ("If the color looked darker the water could be bad but if it looked lighter the water is good") and noted the connectivity of our streams to both local and global earth and environmental systems ("The waters here are effected by limestone" and "The stream flows to different rivers in the us [sic] and then into the Mississippi River then to the Gulf of Mexico"). Finally, students reflecting on the leaf pack activity shared some degree of surprise at the number of insects in the stream ("There are lots of different bugs in the river...") and noted the importance of looking closely to find said insects ("Insects are small and aren't always big enough to see"). A number of students also commented about using insect community data to better understand stream health ("I learned that the insects on a leaf can help you determine the water quality"). In answer to the final qualitative question ("Why scientists are interested in the health of the stream..."), students noted human health ("It can get into the water that the homes use and they could end up drinking it or using it"), environmental health ("Because they want to make sure the stream is clean and not bad for the environment"), and their intersection ("Because we live in this part of the world and we love to see animals and bug [sic] that live in that stream"). Several students specifically noted that the study stream was connected to global environmental issues like climate change ("To help stop climate change by planting more trees so the trees can absorb the carbon dioxide that's in the atmosphere and the trees can give us the oxygen"), the Dead Zone in the Gulf of Mexico ("The algae blooms that happens in the Atlantic ocean it start in the streams and it could cause a big problem"), and global environmental health generally ("So that we can save the earth from dying").

When coding students' open-ended responses, the different activities inspired some notable differences in what students learned from the individual activities. Unsurprisingly, most of

Table 4. Number of student responses coded by level of thinking per activity.

Bloom's Connection	**Code of Student Response***	**Tree Planting Activity**	**Water Quality Activity**	**Leaf Packet Activity**	**Total by Code**
Remembering	Recalls	33	54	64	112
Understanding	Identifies	66	32	11	109
Applying	Makes connections	11	11	8	30
Analyzing	Articulates impact	7	16	3	19
Evaluating	Evaluates quality	7	38	11	56
Creating	Establishes conclusions	2	4	2	8
Multiple	Reflects, imagines	1	0	0	1
NA	I don't know or nothing	4	9	22	35
NA	No appropriate code	2	5	5	12

*See full code text in Table 2. On occasion, responses were coded with multiple codes so the totals above do not equal the number of student participants (N=167).

the responses about what was learned from all three activities were identified as primarily remembering and understanding basic facts and steps (Table 4). But when we looked at these two categories of responses by activity, we noticed that students were more likely to demonstrate understanding of a process with the tree activity. Responses demonstrating an understanding of process occurred less often in reference to the water quality station and least often in reference to the leaf pack station.

Where the tree activity inspired more students to share experiences of understanding, especially as they related to the process of planting trees or the physical features of trees, students were more apt to demonstrate evidence of analysis and evaluation as a result of the water quality station. While the water station included an inherent quality of evaluation as a result of the testing process students used, it also often led students to cite connections to invasive species and the broader global connectivity of different water systems. Student responses indicate that they seemed to have the most trouble with the leaf pack activity. When asked about their learning related to that station, students were more likely to say “I don’t know,” “nothing,” or “I don’t remember.”

Discussion

Overall, the results in all three activities highlighted how interaction with nature through varied opportunities can increase affectivity for nature (Zaradic et al. 2009; Whitburn et al. 2018; DeVille et al. 2021), environmental knowledge (Hoover 2020), and a recognition of the need for environmental action due to a growing understanding of the relationship between nature and humanity (Genc et al. 2018; Hecht and Nelson 2021). Specifically, student reactions to this middle school field day illuminate the potential benefits of a curated series of inquiry-based, hands-on activities targeting environmental education broadly and water education more specifically. The place-based, experiential activities highlighted in this study utilized tenets of inquiry-based pedagogies which, although lacking a centralized definition, generally employ a rethinking of the traditional educational model to create opportunities for students to ask questions, make connections, evaluate evidence, and solve problems (Brown 2017). These activities made space for students to engage in moments of environmental action by evaluating local water sources, getting their hands dirty, and asking questions about their local landscape. In their post-activity reactions, students indicated an awareness of local and global connectivity, environmental cause and effect, human/environmental interdependence, and – on a few occasions – nature’s ability to help us connect with ourselves and others.

Most open-ended responses about what students learned during the tree planting activity recalled basic attributes of trees or the process of planting them. Nearly all these responses were also positive or neutral, absent of any abhorrence to digging or working in the dirt. Despite the commonality of trees and a growing urban tree canopy in our area, responses indicated that many students were notably lacking in knowledge about trees. For instance, one student articulated a new-found awareness about the structure of a seedling, stating that “The branch looking things are actually the roots and you have to plant that part of the tree.” Similarly, students described the process of tree planting as “not that hard” and something that can be done “without seeds,” revealing students’ inexperience with how trees are cultivated. Someone with experience interacting with trees might assume the identification of the roots to be an unnecessary step, but for a student first encountering a tree as a seedling that observation is noteworthy and essential. The popularity of the tree activity in the rankings, combined with students’ abilities to identify and understand steps in the tree planting process in their open-ended responses, suggest that the tree activity provided an accessible entry point for students, regardless of background and previous experience with nature. Regardless of whether students had limited experience with seedlings or planting trees before the experience, general awareness of trees provided a key foundation for their learning. The logical nature of the activity also likely increased student confidence in what they learned through that activity. The tactile process of identifying an appropriate place, digging the hole, identifying the roots, and burying them effectively required little global awareness beyond a likely source of water. On the other hand, the water quality and leaf pack activities required more complex steps of recognizing causation, unseen environmental factors, and global connectivity, which challenged student confidence in formulating conclusions and identifying what they learned. The results from the tree planting survey support the existing theories that experience with nature can increase the affective feelings toward nature (Whitburn et al. 2018; DeVille et al. 2021) and increase environmental knowledge (Hoover 2020).

The water quality activity elicited some unique responses from students, elucidating how interactions with nature can increase and develop their environmental knowledge even if their responses to the activity were not wholly positive. Many of them made sometimes contradictory notes about what they learned from testing the quality of the water, such as the water "is mad nasty" to "the water is pretty clean," suggesting that many did not fully understand what testing the water demonstrated or were off put by the appearance of the water. Still, many students understood that they were testing the water for different qualities: acidity, cleanliness, and desirable quality ("It turns green when you add the pill and you want it to be green"). Others indicated that they had a new understanding of the ecological and systematic role of water by noting human actions around water can affect the rest of the ecosystem like "I saw that we need to take care of the world because we have a lot of animals and bug that need that water." Others expressed ideas on how to protect the water through human actions, such as planting trees and being mindful of what we put in water ("That the water ph [pH] has decrease in the past 20 years by planting trees"). Importantly, others reflected on how the quality of the water affected humans ("We can't drink the water it will make us sick"). Through the range of responses, we can see how students understood some of the nuances of the water quality activity by reflecting on its broader impact on themselves and both the local and larger ecosystem and that this change could move them toward changed environmental behaviors (Hoover 2020).

Similar to the water activity, student responses about the leaf pack activity ranged from negative responses related to the perceived "grossness" of bugs to statements about learning to observe the world around them more intentionally as well as understanding the connections between aquatic insect communities and the water in which they live. For example, one student noted that "...if you take out the leave you can see microscopic bugs that you may not have seen before," and another said "They are A LOTTTT of insects, small, tiny tiny, or huge!!! It made me slow down and observe more efficiently." These responses highlight a response akin to wonder—students seeing something that they had not seen before and thinking it was cool. This wonder is especially clear in the student who commented "I saw a iceapod [isopod] and i though it was so sick and that it was a cool experience and it was fu[n] looking at it close up." Students learned that insects are everywhere—they just needed to know how and where to look. One student shared that "Leaves provide food and shelter for insects and other animals," demonstrating an understanding of habitat, and another noted that "...there are insects everywhere and most are not harmful." The emphasis here on insects as not harmful speaks to a cultural fear or dislike of insects, clearly communicated by another student, who said "Them bugs are nasty." Finally, several students shared about the connections between stream-water quality and aquatic insects, noting "That knowing what type of insects there are in a creek we can know how the water quality is," and "...if you find a bug that is prone to live in polluted places in the water you test then that water is most likely polluted." Not only do these responses evidence higher-level thinking—making connections between observed phenomena and their broader implications that support the use of place-based, experiential learning activities (Brown 2017), but they also demonstrate that creating these opportunities for students, even when they may find the activity 'gross,' has benefits for their learning.

Conclusions

During all these activities, students were asked to use scientific processes to evaluate the quality, impact, or habitability of their local forest and stream ecosystems. Scholarship about the use of inquiry-based teaching in science education suggests that these methods help improve students' knowledge of science concepts and their use of science practices (Marshall et al. 2017). The tendency for many students to comment on the process itself as they reflected on what they learned suggests that perhaps teaching middle school students about water as an alterable and changing resource, reliant on human behavior and awareness, can go a long way in empowering students to be more environmentally attuned. For some of these middle schoolers, it may have been the first time they were encouraged to scrutinize the natural world around them. The pairing of the activities also cultivated student awareness of the interconnected and often reciprocal relationships between different parts of an ecosystem, both locally and globally. Where students seemed to struggle to go beyond recall, understanding, and general observations were when those connections required following longer threads of dependency and more complex systems of interaction (i.e., the leaf pack activity). Perhaps future iterations of those activities that explore those more complex connections would be well served by building in some additional scaffolding and points of entry.

Student reactions to this field day indicate that projects seeking to help students recognize their connection to nature should go beyond simple observation. Rather, asking students to touch, dig, and impact their surroundings on a small scale helps bridge the disconnect many of us feel with the natural world. These activities prioritizing water education helped students recognize how nature can help them connect with themselves and others. Based on their responses, a few students found some level of introspection during the activities. When asked what they learned, they spoke about how the process made them feel. These introspective statements, although rare, hint at students' growing awareness of the impact working and playing out in nature had on them. For instance, one student indicated that as they planted their tree "It's quite calming talking with friends while working." One student said "I loved it! And you don't have to dig a very big hole." Another stated an awareness of the uniqueness of moment stating, "Idk [I don't know what I learned] but [I] did have fun doing that. I felt adventurous." Notably, this was the first field trip these students had taken in nearly three years due to restrictions during the COVID-19 pandemic, which may also have added to the feelings of adventure and awe students experienced. These comments call to mind studies that demonstrate the power of nature to inspire awe and wonder which can support personal well-being (Anderson et al. 2018). We did not code for statements of feeling, awe, or broadening individual awareness of their connection to the environment, but these instances suggest that time spent guiding middle school students in environmentally informed, intentional, collaborative activities present exciting opportunities for students to learn more about themselves in connection with the planet.

Our interpretations of the findings from this student survey are potentially limited by some constraints of our coding scheme and our inability to always glean the precise meaning of student responses. While Bloom's Taxonomy is a commonly used hierarchy of categories of thinking, there are those that rightly interrogate and complicate this model (Ritchart and Church 2020). While mental moves of identification or understanding can seem, at first glance, to be introductory level skills, a more accurate hierarchy of habits of mind would account for variable levels of thought at all stages of Bloom's hierarchy. We acknowledge those limitations of the framework and intend our use of the basic Bloom's divisions as a starting point and a tool for considering the accessibility of particular activities for certain students.

Additionally, coders were limited by the brevity of student comments that occasionally prevented clear interpretation of meaning. There were also comments that indicated awareness of global or local connections that might have been the result of students remembering something the activity facilitator said, rather than them independently making connections or analyzing variables. Lastly, it is impossible to know for sure each students' personal experience with the environment outside of these activities. The area these students live in is unique—the city is relatively urban but includes a notable urban tree canopy and is surrounded by a protected region of farmland preserved from commercial development through the local urban/county government's Agricultural Conservation Easement program. In addition, restrictions during the COVID-19 pandemic may have altered students' utilization of outdoor spaces for social connection, leisure, and activity. As a result, while many of these students may not have extensive experiences with their natural surroundings, there are certainly possibilities for those encounters nearby. Furthermore, student responses to the leaf pack activity may have been constrained by differences in wording—the questions for that activity called it the "insect activity" and "leaf packet activity"—the lack of consistent terminology may have made these questions more confusing for students.

Finally, we note that students' quantitative scoring and ranking of activities demonstrated a clear preference for the tree planting activity over the leaf pack and water quality activities. Paired with qualitative responses describing the water and insects as varying degrees of "gross," this underscores the reality that students, perhaps particularly urban students, come into natural spaces with various presuppositions, tolerances, aesthetics, and biases. In this case, running multiple stations ended up being an excellent strategy to address this reality—students who may not have appreciated the leaf pack activity as much may still have gone home with a generally positive attitude toward the field day as a whole because of the tree planting activity. Conversely, we note that student responses regarding the water quality and leaf pack activities tended to suggest higher levels of thinking, such as making ecological and global connections—while these activities may not have been the general favorite, they were certainly meaningful in an educational context. Our findings further support offering a constellation of activities for a field day, scaffolded to be accessible to students with varying degrees of prior knowledge, as well as a spectrum of biases and presuppositions about nature.

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Author Bios and Contact Information

Kenton Sena, Ph.D. (corresponding author), is a lecturer in the Lewis Honors College at the University of Kentucky, where he teaches the Honors Foundations Seminar and additional honors courses in ecology and the environment. He holds a B.A. in Biology from Asbury University, and an M.S. in Forestry and a Ph.D. in Integrated Plant and Soil Sciences from UK. His research engages urban restoration and imagined ecologies. He may be contacted at kenton.sena@uky.edu or by mail at 1120 University Drive, Lexington, KY 40526

Jill Abney, Ph.D., is a Senior Faculty Instructional Consultant at the University of Kentucky's Center for the Enhancement of Learning and Teaching. Her pedagogical interests include exploring strategies for building community and belonging in the college classroom. She holds a Ph.D. in history from UK and her research examines the role of gender, power, and rhetoric in 19th century Britain. She may be contacted at jill.abney@uky.edu.

Hannah Ruehl, Ph.D., is a Faculty Instructional Consultant at the University of Kentucky's Center for the Enhancement of Learning and Teaching. Her doctorate is 19th century British literature, and she is currently pursuing a Master's in environmental science. Her research focuses on the overlap of the science of curiosity and the science of learning in the college classroom and explores the psychology of habit in changing environmental behaviors. She may be contacted at hru223@uky.edu.

Christopher D. Barton, Ph.D., is a Professor of Forest Hydrology and Watershed Management in the Department of Forestry and Natural Resources at the University of Kentucky. He is currently working in the areas of ecosystem restoration and water resource management. He is also the founder and president of Green Forests Work, a non-profit organization whose mission is to restore forests on degraded land in Appalachia and beyond. He may be contacted at barton@uky.edu.

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Case Study Article

Sea Grant Center for Great Lakes Literacy Shipboard Science Workshop Evaluation

Jennifer Hunnell[1], *Heather A. Triezenberg[1,2], Brandon C. Schroeder[3], and Meaghan J. Gass[4]

[1]Michigan Sea Grant, Michigan State University Extension, East Lansing, MI
[2]Michigan State University Fisheries and Wildlife Department, East Lansing, MI
[3]Michigan Sea Grant, Michigan State University Extension, Alpena, MI
[4]Michigan Sea Grant, Michigan State University Extension, Bay City, MI
**Corresponding Author*

Abstract: Youth have an important role in current and future Great Lakes stewardship. Educating youth and empowering them to be Great Lakes stewards requires educators to be knowledgeable and confident, and therefore more likely to engage in teaching Great Lakes literacy activities in their classroom, thus contributing to a Great Lakes-literate public. The Shipboard Science Workshop (SSW) for educators is a vessel-based professional learning opportunity aboard the U.S. Environmental Protection Agency's research vessel (R/V) *Lake Guardian.* During the week-long SSW, educators learn from professional scientists, Sea Grant staff, and each other about Great Lakes research through the lenses of place-based education (PBE) and Next Generation Science Standards (NGSS). The goals of the SSW are to (1) enhance understanding of scientific concepts, processes, or techniques; (2) influence changes in teaching practices, curriculum, or personal behaviors; (3) influence communication and promotion of pro-environmental behaviors with others; and (4) establish communities of practice, including educators, scientists, and SSW coordinators. Herein, we present the findings of a 10-month follow-up survey to evaluate the SSW efficacy from 2016-2019. Overall, the SSW appears to have achieved its goals. We discuss the implications of these results within the PBE framework for shifting educators' classroom approaches and empowering youth inquiry and leadership on complex Great Lakes issues.

Keywords: *professional learning, place-based education, Next Generation Science Standards, communities of practice, social network analysis, vessel-based education*

The Laurentian Great Lakes, a significant feature in North America, contain approximately 20% of the world's fresh surface water, including 95% of the United States' surface water, and are an important component of the water cycle, water systems, and watersheds (Center for Great Lakes Literacy 2023). The Great Lakes suffer from impairments from aquatic non-indigenous species, ecosystem changes, non-point source water pollution, nutrients, emerging contaminants, and climate change, among others. Remediating and restoring the Great Lakes is considered a complex environmental problem, or a wicked problem, because of the interconnectedness of the source, problem, and solution (Rittell and Webber 1973). The Great Lakes Water Quality Agreement outlines the restoration and protection efforts on behalf of the United States with the Great Lakes Restoration Initiative (GLRI) and associated focus areas, themes, actions, funding, and interagency collaboration as the mechanism to achieve the goals for the Great Lakes (Great Lakes Restoration Initiative 2019). GLRI focus area 5 objective 1 specifically addresses the need to educate the next generation about the Great Lakes ecosystem with accurate information to make informed decisions regarding the Great Lakes and their watershed (GLRI 2019). Bridging the science and policy gap for effectively addressing these complex Great Lakes issues is needed, and

Research Implications

- Educators can learn approaches to teach science, Great Lakes literacy principles, and place-based education practices effectively.
- Youth can be engaged in meaningful watershed education experiences and empowered as informed problem-solvers for Great Lakes issues today and in the future.
- The R/V *Lake Guardian* Shipboard Science Workshop is a unique educator professional learning opportunity that inspires educators.
- Communities of practice, also known as networks for collective learners, enhance the capabilities for teaching Great Lakes literacy and empowering stewardship using place-based education (PBE) frameworks regionally and locally.

youth have an important role in that now and in the future (Krantzberg 2004; Great Lakes Stewardship Initiative 2017).

It is widely believed that elementary and secondary level teachers have the responsibility for developing environmental literacy in youth (Roth 1992). Integrating information on the Great Lakes into K-12 and nonformal teaching and learning settings is essential for a Great Lakes-literate society that: (1) understands principles and concepts about the characteristics, function, and value of the Great Lakes; (2) can communicate about the Great Lakes' influence on systems and beyond; and (3) is able to make informed decisions regarding the Great Lakes and their watersheds (CGLL 2023). With increased knowledge of the Great Lakes, and access to additional resources, educators can effectively incorporate Great Lakes literacy teaching and learning into their activities. The place-based education (PBE) framework is an established framework for facilitating youth learning and empowerment for problem-solving of complex Great Lakes issues, and has four main pillars: (1) set the focus; (2) establish foundations of place-based teaching and learning; (3) deepen impact; and (4) develop capacity for democratic participation (GLSI 2017). The Great Lakes Stewardship Initiative has championed PBE with schools and communities since 2007. These efforts established foundational case studies from across Michigan and contributed to the development of the aforementioned framework. The guiding principles for exemplary PBE inform the regional Center for Great Lakes Literacy (CGLL) approach (GLSI 2017). As an educational strategy for youth and community engagement, PBE has enhanced student learning and accomplished school improvement goals (Sobel 2004; Smith and Sobel 2010; Yoder 2012; Demarest 2015; Schroeder et. al. 2019). Similarly, PBE educational strategies can foster civic engagement values among youth committing to helping others, serving communities, and promoting understanding – i.e., they begin to believe that individuals do have the power to change society (Astin and Sax 1998; Gallay et al. 2016). As a result, youth engage in experiential learning and stewardship about the Great Lakes now and in the future.

Educators are a key partner for facilitating youth learning and empowerment for problem-solving of complex Great Lakes issues, and need professional learning opportunities with sustained support to adopt and implement PBE effectively. PBE reframes educators as student-centered learning process facilitators (i.e., guides on the side, rather than expert presenters), with relational support over time that results in adoption and transformation of teaching and learning practices, curriculum, and youth-community partnerships. As a result, educators facilitate learner-centered investigations of local environmental issues and student-led informed action, known as meaningful watershed educational experiences or MWEEs (National Oceanic and Atmospheric Administration Bay Watershed Education Training Program 2022). MWEEs include classroom and outdoor learning experiences that actively engage students in multi-disciplinary knowledge building and meaning making of the relationships between society and the natural world (NOAA BWET 2022). To facilitate relational support over time, educators are invited to join informal groups, known as communities of practice (COP), where people engage in collective learning along their professional learning journey (Wenger 2006).

We took a community-engaged research approach for this project, meaning we utilized foundational scholarship to inform evaluation design and some research questions, and engaged with partners to identify their interests and needs in the research questions and design (Doberneck et al. 2017). Following the Next Generation Science Standards (NGSS) approach, our partners (i.e., Great Lakes Sea Grant Program co-leaders) were most interested in what core scientific ideas, practices, and cross-cutting concepts were learned and applied with students using a PBE framework because of the Shipboard Science Workshop (SSW) experience (Next Generation Science Standards 2023). NGSS is a transformational approach to science education because they describe science as both knowledge and a process of building, refining, revising, and extending knowledge (NGSS 2023). They include behaviors (i.e., practices) that scientists use within their fields, the interrelationships in different scientific fields and knowledge (i.e., crosscutting concepts), and core disciplinary ideas (i.e., core science) (NGSS 2023).

In this manuscript, we (1) describe the research vessel (R/V) *Lake Guardian* Shipboard Science Workshop (SSW), a nonformal Great Lakes vessel-based education program for adults who may be formal or nonformal educators to learn about the Great Lakes and PBE (Williamson and Dann 1999); (2) evaluate the SSW at achieving its goals (Williamson and Dann 1999); and (3) discuss SSW as a PBE professional learning opportunity for enhancing teaching, learning, and curriculum, all necessary for increasing Great Lakes literacy and effective decision-making (Dann and Schroeder 2015; GLRI 2019).

Program Description

The Sea Grant CGLL hosts the SSW, a professional learning opportunity for educators to spend one week working and learning alongside scientists aboard the United States Environmental Protection Agency's (U.S. EPA) R/V *Lake Guardian* (CGLL 2023). The R/V *Lake Guardian* cruises a different Great Lake each year, with the Sea Grant program associated with the lake coordinating the SSW. Extension and education professionals from the seven respective Great Lakes Sea Grant Programs collaborate with the U.S. EPA on workshop planning, implementation, and evaluation. To date, approximately 225 educators and nearly 50 scientists and others have participated in the R/V *Lake Guardian* SSW since its inception in 2006 (K. Tepas, personal communication, February 10, 2023).

Aboard the R/V *Lake Guardian*, educators learn from professional scientists from federal or state agencies, universities, and Sea Grant programs, about science topics such as ecology, geology, geography, biogeochemistry, and weather, while learning about real-world Great Lakes issues. SSW participants also learn about the Great Lakes literacy principles (Table 1), modeled after the ocean literacy principles (Fortner and Manzo 2011). The SSW goals are to: (1) enhance understanding of scientific concepts, processes, or techniques; (2) influence changes in teaching practices, curriculum, or personal behaviors: (3) influence pro-environmental behavioral intentions and behaviors, including communication with others; and (4) establish communities of practice, including educators, scientists, and SSW coordinators. The desired outcomes from SSW participation are to enhance educators' capabilities for teaching Great Lakes science and to inspire stewardship of the Great Lakes using PBE and MWEE frameworks.

Interested educators (i.e., formal and nonformal) are invited to apply to participate in the SSW, with typically 15 participating in each research cruise per year. The application process includes personal and professional contact information, fields of teaching certification/licensure, years of experience, subjects and grade levels of audiences, work demographics (e.g., number of learners, percentages of students who are English language learners, percentage of free or reduced lunch, diversity of school population), personal statement, and name and email address of person providing a letter of recommendation. There is no cost to participate in the SSW. Upon completion of the SSW, participants receive a certificate of completion for professional development contact hours. Through a partnership with Ashland University, participants can apply for two graduate credits for an additional fee of $370. Currently, participating educators are eligible for a $500 stipend upon completion of the SSW requirements and support of up to $250 to offset travel expenses.

Table 1. Great Lakes Literacy principles (CGLL 2023).

Number	Principle
1	The Great Lakes, bodies of fresh water with many features, are connected to each other and to the world ocean.
2	Natural forces formed the Great Lakes; the lakes continue to shape the features of their watershed.
3	The Great Lakes influence local and regional weather and climate.
4	Water makes Earth habitable; fresh water sustains life on land.
5	The Great Lakes support a broad diversity of life and ecosystems.
6	The Great Lakes and humans in their watersheds are inextricably interconnected.
7	Much remains to be learned about the Great Lakes.
8	The Great Lakes are socially, economically, and environmentally significant to the region, the nation, and the planet.

In addition to adhering to safety protocols, SSW requirements include: (1) completing a pre-survey, a post-survey, an end of year survey, and pre-trip assignments; (2) participating in two SSW-related virtual meetings; (3) leading Great Lakes curriculum initiatives, field-based or laboratory scientific activities; and (4) sharing research and experiences with public audiences, classrooms or programs, professional association meetings, or other audiences.

Methods

We implemented a long-term post evaluation survey that consisted of 11 open-ended questions (Patton 2002). We utilized a modified tailored design method and emailed up to four invitations to complete an online survey (Appendix A) approximately 10 months after participating in the SSW occurring 2016-2019 (Dillman, Smyth, and Christian 2009). The Michigan State University Institutional Review Board reviewed and approved of the project on August 15, 2016 (# x16-1011e Category: Exempt 2).

To evaluate an enhanced understanding of scientific concepts, processes, or techniques, we asked open-ended questions about their teaching, curriculum, and communication as a result of SSW participation. The survey also asked about changes in pro-environmental behavioral intentions and behaviors, including communication with others (e.g., scientists and educators who were not part of the SSW), and any other comments about personal or professional activities or impacts stemming from their experience. The qualitative response data to open-ended questions were grouped by common themes (Rubin and Rubin 2005). This could be a common change in behavior, a specific scientific process, or post-SSW action taken. Those themes with the highest frequencies were summarized as main lessons for that particular year.

To assess the establishment of post-SSW COPs, we asked respondents to identify up to ten educators who participated in the SSW, up to three scientists, and up to three staff coordinators they have had contact with since participating in the SSW. Social network theory and analyses were used to reveal the extent of relationships among participants, indicators of established COPs. We used Ucinet 6 for Windows (version 6.620) (Muhr 2009) for social network analysis, which consisted of centrality calculations and netdraw sociograms. We calculated four centrality measures: (1) betweenness centrality, a measure of the extent to which a network actor (e.g., node) is in-between all other nodes influencing the entire network; (2) closeness centrality, a measure of the extent to which a node is near all other nodes directly influencing others in the network; (3) degree centrality, a measure of how many neighbor nodes a node has to influence; and (4) eigenvector centrality, a ranking measure of the number of connections a node has relative to other nodes influencing other nodes in the network (Scott 2000).

Results

Fifty-nine educators participated in the R/V *Lake Guardian* SSW from 2016 to 2019. Twenty-five completed the 10-month follow-up survey for a 42% response rate. Because survey respondents could identify individuals from the SSW that did not respond to the survey, network sociograms of post-SSW COPs included 51 educators, 12 scientists, and 7 SSW coordinators across all years. Of the eight Great Lakes literacy principles (CGLL 2023), our qualitative survey research appears to have covered all but principle two (natural forces formed the Great Lakes; the lakes continue to share the features of their watershed). Table 2 is a summary of the key themes from the qualitative analysis and trends across 2016-2019. Table 3 is a summary of the network descriptions and key roles in COPs.

Enhanced Understanding of Scientific Concepts, Processes, or Techniques

A variety of major scientific concepts were mentioned following SSW participation. These included basic ecological knowledge such as food webs, lake stratification, lake ecology, and identification of fish species (principle five; CGLL 2023). Scientific processes learned during the SSW centered around sampling methods, utilization of scientific methods, data collection protocols, instruments, and scientific resources, with survey respondents reporting gaining knowledge in these areas as a result of participation. When it came to water quality monitoring, respondents reflected on the importance of data and its impact on real world applications (principle seven; CGLL 2023). They were particularly impressed with the sampling equipment aboard the R/V *Lake Guardian*, such as the Rosette water sampler, and expressed excitement upon seeing it in action. This exposure to scientific methods and sampling practices resulted in respondents expressing increased confidence using scientific equipment.

Inspiring Place-based Education Approaches to Great Lakes Literacy, including Changes in Curriculum and Practices

This opportunity also impacted those who were shifting in their field of expertise, introducing them to environmental concepts with which they were unfamiliar.

> *"My background is in engineering and design of avionics displays and systems before I became a science teacher. My traditional affinity has been toward the physical sciences, with little personal interest in bio sciences. However, since I am now responsible for several life sciences/ bio courses I wanted to learn more about these areas from people who had made it their passion (so I could "catch" their excitement to transfer that to my students). The ... Shipboard Science Workshop was just the solution to helping me become passionate about teaching about living organisms and biological science. I am a better life science and biology teacher because of my experience on the* [R/V] *Lake Guardian..."*

For others, the content of the SSW revitalized their love of teaching, created excitement, and inspired new ideas for their classroom lessons. The opportunity to see scientific principles in action, and to work with, as one respondent put it, "world famous scientists" in a field setting left a lasting impact on several of the SSW participants. In the words of one participant:

> *"The Shipboard Science Workshop on the Lake Guardian is truly a unique experience. It allowed the scientist in me as an educator to flourish and grow. It challenged me to dig in and learn, explore, and be inquisitive to gain depth of knowledge on a topic that is extremely important to me as well as my community. At the same time the experience gave me resources to bring back to my classroom to use and share with my students. I definitely will continue to take advantage of any opportunities* [to] *gain more understanding and knowledge of the Great Lakes to share with my students and my community."*

There were also personal changes in regards to water and Great Lakes knowledge, with one participant altering their assumptions when it came

Table 2. Thematic summary from R/V *Lake Guardian* Shipboard Science Workshops, 2016-2019.

Survey Question Topic	Key Takeaways	Year(s) Reported
Major scientific concept learned	Harmful algal blooms	2016, 2018, 2019
	Water contaminants/microplastics	2018, 2019
	Role of food webs/importance of zooplankton	2016, 2017
	Lake stratification	2016, 2017
Major scientific process or techniques learned	Scientific equipment usage	2016, 2017, 2018, 2019
	Scientific data collection/techniques/protocols	2016, 2017, 2019
Changes in teaching practices or curriculum enhancements	Information integration into classroom lessons/ curricula	2016, 2018, 2019
	Supplemental knowledge/information expansion	2016, 2017, 2018
	Environmental field trip planning	2016, 2017, 2018, 2019
Changes in personal behaviors	Reduction/elimination of single-use plastics	2016, 2017, 2018, 2019
	Invasive species awareness	2016, 2017, 2019
Contexts where participant encouraged others to adopt pro-environmental personal behaviors	Reduction of plastic usage	2016, 2017, 2019
	Encourage sustainable environmental practices (picking up debris, avoid unnecessary buying, reusable water bottles, etc.)	2016, 2019
Communication about R/V *Lake Guardian* SSW with non-scientists or educators	Discussed with colleagues	2016, 2019
	Presented to other educators/school board/ conferences/etc.	2016, 2018
	New collaborations with other educators	2016, 2017
Personal or professional impacts or experiences	Wonderful, unique, memorable experience	2016, 2017, 2019
	Inspiring and motivating	2016, 2018, 2019
	Appreciation for networking opportunities	2016, 2018, 2019

to their classes' knowledge on these subjects and no longer presumed their students had a baseline knowledge simply from growing up in the Great Lakes region. Another reflected on the fact that the lessons presented gave her the ability to let her students have more autonomy over their learning and reminded her of what it was like to be a student herself.

Respondents also reported that they were inspired to become more involved in their communities. By participating in the R/V *Lake Guardian* SSW, some survey respondents reported that they were better able to educate others, both personally and professionally, about the work being done by scientists in the Great Lakes, and to use their knowledge to impact the next generation. Overall, respondents indicated positive and unique experiences for participating educators that left a lasting impact on their personal and professional philosophies about science education. In addition,

Table 3. Social network sociogram summary, R/V *Lake Guardian* Shipboard Science Workshops, 2016-2019.

Dimensions	2016	2017	2018	2019
# Educators	16	11	10	14
# Scientists	6	2	3	1
# CGLL staff	2	2	2	4
Total actors	24	15	15	19
Actor with highest betweenness centrality score	Educator #2	Educator #2	Educator #5	Educator #1
Actor(s) with highest closeness centrality score	Educator #15	Scientists #24 & #25	Scientist #26	Educator #15
Actor with highest degree centrality score	Educator #10	Educator #2	Educator #6	Educator #1
Actor with highest Eigenvector centrality score	Educator #10	Educator #2	Educator #6	Educator #1

the lessons learned aboard the R/V *Lake Guardian* assisted some in professional development. Participants expressed a greater understanding of Great Lakes literacy and for one, the knowledge gained assisted them in completing an educational certificate.

The SSW experience provided more real-world examples they could share with their classes, while others mentioned that they gained a much greater depth of understanding of Great Lakes issues, affecting their lesson planning as a result. Specifically, Great Lakes lessons such as place-based information, proper data collection techniques, information on water contaminants like perfluorooctane sulfonic acid (PFOS), and water quality principles were added to teachers' units and lessons. Exposure to scientific concepts and sampling techniques resulted in respondents expressing increased confidence using data collection equipment and utilizing some of the instrumentation within their classrooms, such as incorporating water and macroinvertebrate sampling or microscope usage into their lessons.

Several participants reported creating lessons around the impacts of coastal storms and the effects of climate change, water contamination, invasive species, and knowledge of water contaminant issues and the impacts of harmful algal blooms and microplastics (principles three, five, and six; CGLL 2023). Another respondent reported that they began including fish dissections in their classroom lessons following SSW participation, in order to incorporate a hands-on element to their lessons (principle seven; CGLL 2023). One individual reported borrowing a deployable freshwater sensor (e.g., Hydrolab) for their students to take water quality measurements around their community. As a result of SSW participation, teachers guided their students in collecting and analyzing real world data in their own communities, making the scientific processes learned during the SSW locally relatable (principle six; CGLL 2023). One participant also planned a field trip for their class to The Ohio State University's Stone Lab as a result of SSW participation. Another reached out to a local university to help fully immerse their students in their annual field trip to the beach to collect water samples by providing an excursion on Lake Michigan. Survey responses also indicated an increased awareness of Great Lakes stewardship and local water issues and a greater confidence in their ability to communicate those issues to their students, engaging students and fostering a greater sense of stewardship for both their local resources as well as those of the larger Great Lakes basin.

Information gained as part of the SSW extended beyond formal classroom lessons as well. One respondent described the development of a student-run education program focused on Great Lakes invasive species based on the Attack Pack, an aquatic invasive species education kit developed by Sea Grant CGLL they were introduced to during the SSW. Another respondent indicated one of their 8th grade students was so inspired by the knowledge that was shared in the classroom regarding macroinvertebrates they did their own research project on the health of their local rivers, making it into their science project for that year. In addition, resources such as videos of the shrinking cups activity from the SSW and U.S. EPA data records were incorporated in order to supplement classroom lessons. Another respondent reported they conducted a "microplastic sweep" of their schoolyard following their participation on the SSW, removing several pounds of "tiny plastics from their school-yard ecosystem."

Changes in Pro-environmental Behavioral Intentions and Behaviors, including Communication with Others

Overall, changes in pro-environmental behavioral intentions were related to invasive species. Respondents described a desire to adopt behaviors that would reduce the spread of invasive species as well as prioritizing the use of native plant species, stewardship, and increasing the awareness of the impacts of invasive species. Changes in personal behaviors fell into one of two categories: reduction of water contaminants and increased awareness. Specifically, changes in behaviors focused on reducing plastic waste and preventing environmental contamination, including reducing the use of single-use plastics and avoiding purchasing products with plastic microbeads. Respondents mentioned encouraging the use of reusable water bottles and leading by example by limiting plastic product usage in both personal and professional settings. Proper disposal of items harmful to water quality was also discussed, including both living (aquarium plants) and non-living (medications, harmful soaps and chemicals) items.

Other respondents brought their pro-environmental behaviors into their schools by producing public service announcement (PSA) style videos with their class on Great Lakes issues, encouraging their students to attend local environmental talks with their families for extra credit, encouraging the use of water quality nutrient issues for science fair projects, or by teaching their students the value of seeing the system as a whole, that all of these issues are interconnected and impact the greater environmental system (principles one and eight; CGLL 2023). A common theme was leading by example. By performing pro-environmental behaviors themselves (e.g., using reusable water bottles, using metal straws, picking up debris while outdoors) and then discussing them with their students, participants were able to open a dialogue about shared interests and environmental behaviors. There was also strong support of the Great Lakes and an awareness of Great Lakes issues, specifically at the policy level. One respondent indicated that they would be proactive, contacting their state leaders to ensure that Great Lakes issues remained forefront in budget discussions. Some took this conscientious behavior a step further, applying these changes to their school by introducing recycling programs or becoming involved in their local conservation programs. Another respondent reported the increased awareness of plastics in the Great Lakes as a result of the SSW which led to contributing to a local watershed group to support their activities. Being good environmental stewards by using chemicals like fertilizers responsibly was also mentioned.

Several respondents reported that they shared their experiences with other educators who did not participate in the SSW. These efforts included presentations, curriculum development, other workshops, sharing photos through social media, and sharing SSW resources through shared workspaces like Google Drive. Survey respondents reported sharing their knowledge with not only their students, but with fellow teachers, and utilized several of the activities they took part in aboard the SSW in order to do so, such as the shrunken cup activity demonstrated while on board. Responses indicated presenting as part of several major organizations and conferences such as the National Science Teachers Association, The Association for the Advancement of Sustainability in Higher Education conference, the Master Teachers program, and the Math and Science Workshop at the State University of New York Plattsburgh. Respondents also encouraged fellow educators to participate in the SSW by both collaborating on projects and sharing with individual departments.

At least one respondent participated in a future workshop as a result of these efforts, according to survey responses. Respondents described contacts and collaborations they initiated with water research and conservation groups and programs as a result of participating in the SSW. The contacts included staff at Grand Valley State University Annis Water Resources Institute, Michigan Technological University Great Lakes Science Center, Save the River – St. Lawrence, New York Department of Environmental Conservation, the University of Buffalo Great Lakes Program, and the Milwaukee Metropolitan Sewage District.

Post-SSW Communities of Practice

Individuals with educator roles were at the center of the sociograms as indicated by the betweenness centrality measures (Figure 1) and closeness centrality (Figure 2; Table 3). Therefore, they have the greatest opportunity to influence the entire network and all individuals within the network with the information they share. Similarly, individuals with educator roles also had the highest degree centrality scores (Figure 3; Table 3) meaning that they have close neighbor actors that they can influence. Except for 2019 (Figure 4d; Table 3), scientists were on the periphery of the network sociograms as indicated by closeness centrality, meaning that they have greater opportunity to directly influence others (i.e., SSW coordinators and educators) in the network. Individuals with an educator role had the highest eigenvector centrality scores (Figure 4), meaning that educators ranked highest of most network connections relative to other actors in the network. Much of the interaction described by respondents identified social media and other digital means of communication (e.g., Google Drive, email, etc.) as the primary method of connecting, communicating, and sharing resources. Facebook appeared to be the most prominent mechanism for educators; however, this may not be the most likely way scientists communicate with others.

Overall, SSW respondents shared positive comments about their experience. Individuals characterized the SSW as "memorable," "unique," and "wonderful" among others. Many gained motivation and inspiration for their teaching, giving them new perspectives or new tools to incorporate into classroom lessons. The opportunity to network with like-minded educators from around the state, as well as to connect with scientific professionals, was also noted highly. This experience was mentioned by several to have made a significant impact on them, both personally and professionally. They valued the friendships found in a group of like-minded teachers that shared some of the same interests. These sentiments were aptly summarized in the comment made by one respondent:

> *"Having the opportunity to participate as an educator in the* [R/V] *Lake Guardian Shipboard Science Workshop was one of the most memorable professional and personal experiences of my life. I absolutely loved being on board the ship and conducting research with other educators from around this part of the country. I formed many lasting friendships and gained many new ideas for how to make learning engaging and fun for my students. This experience will be something that I carry with me throughout the rest of my life!"*

Discussion

Overall, we believe the R/V *Lake Guardian* SSW was an effective professional learning opportunity, achieving its goals to (1) enhance understanding of scientific concepts, processes, or techniques; (2) influence changes in teaching practices, curriculum, or personal behaviors; (3) influence pro-environmental behavioral intentions and behaviors, including communication with others; and (4) establish communities of practice, including educators, scientists, and SSW coordinators. We believe educators increased their knowledge and application of Great Lakes literacy principles and the PBE framework for empowering youth to solve complex environmental problems today and for the future. The most salient outcomes are (1) the shift in educators viewing themselves from expert instructor to student-centered learning process facilitator (i.e., educator is learning guide on the side), (2) educators' efforts to connect their classrooms to community through projects and field trips, and (3) self-reflections on how the experience inspired their love of teaching.

Using the PBE framework (GLSI 2017), the SSW *set the focus (PBE pillar I)* through a vessel-based

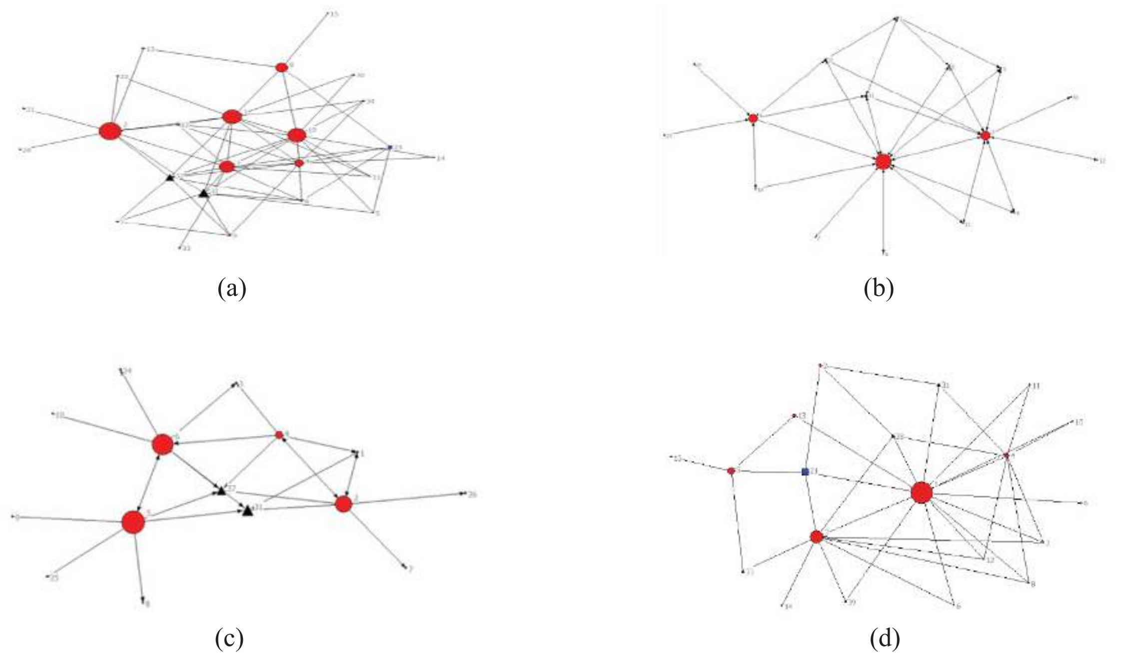

Figure 1. Community of practices network sociograms, all network actors: (a) 2016; (b) 2017; (c) 2018; (d) 2019. Red circles = educators; blue squares = scientists; black triangles = CGLL coordinators; size of node = betweenness centrality. R/V *Lake Guardian* Shipboard Science Workshops, 2016-2019.

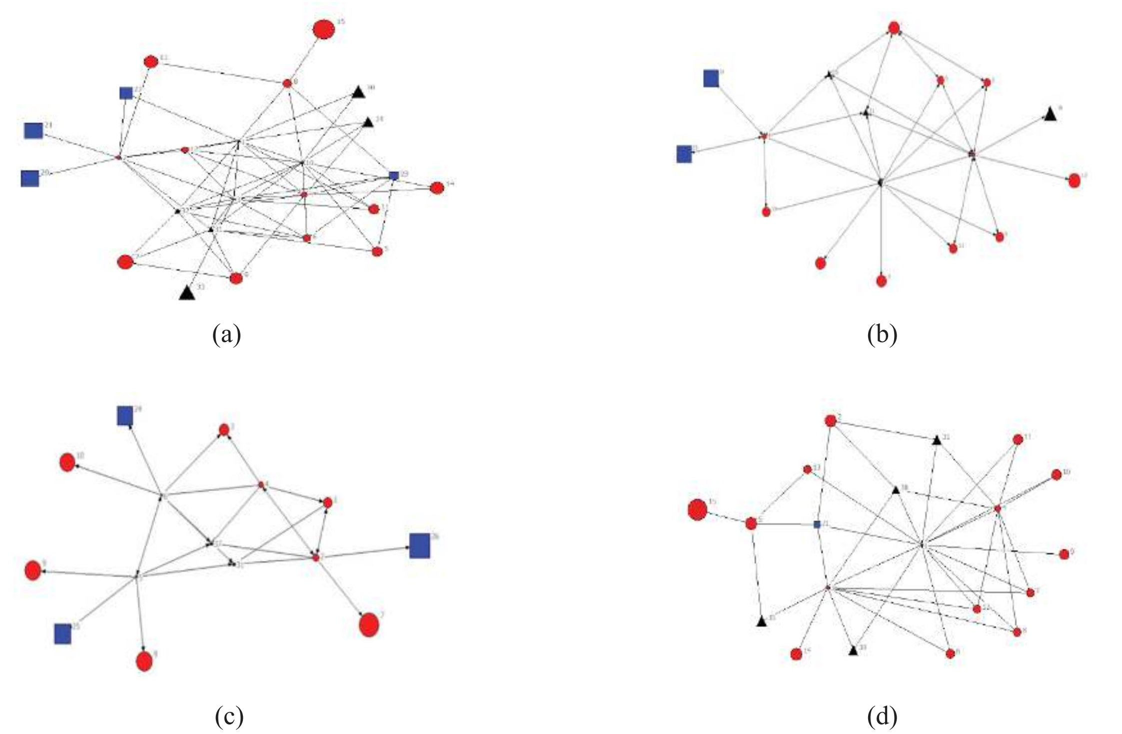

Figure 2. Community of practices network sociograms, all network actors: (a) 2016; (b) 2017; (c) 2018; (d) 2019. Red circles = educators; blue squares = scientists; black triangles = CGLL coordinators; size of node = closeness centrality. R/V *Lake Guardian* Shipboard Science Workshops, 2016-2019.

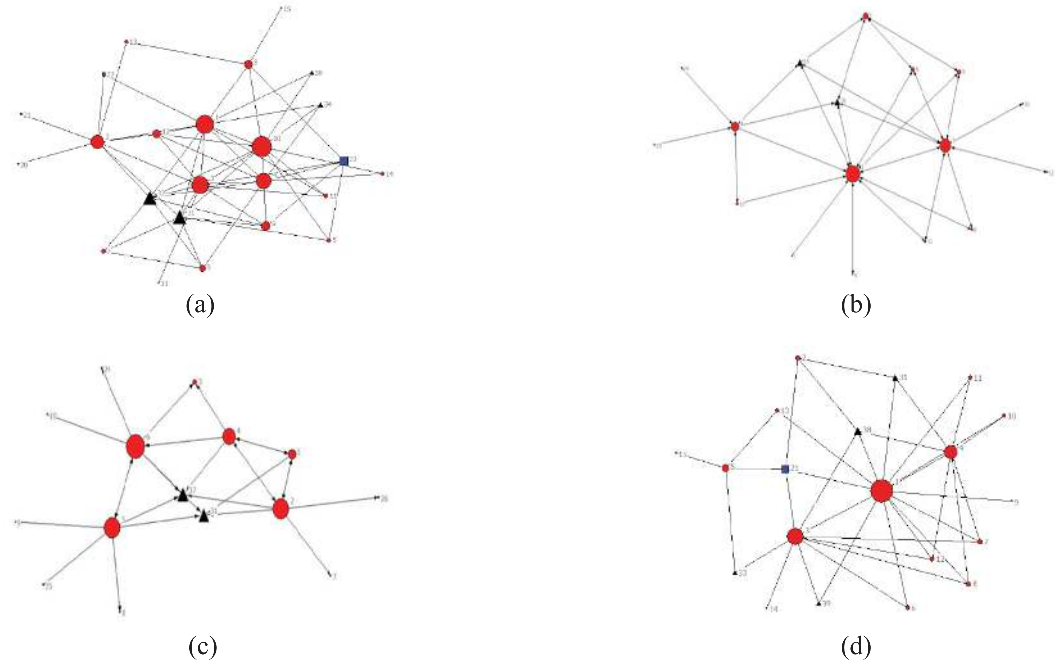

Figure 3. Community of practices network sociograms, all network actors: (a) 2016; (b) 2017; (c) 2018; (d) 2019. Red circles = educators; blue squares = scientists; black triangles = CGLL coordinators; size of node = degree centrality. R/V *Lake Guardian* Shipboard Science Workshops, 2016-2019.

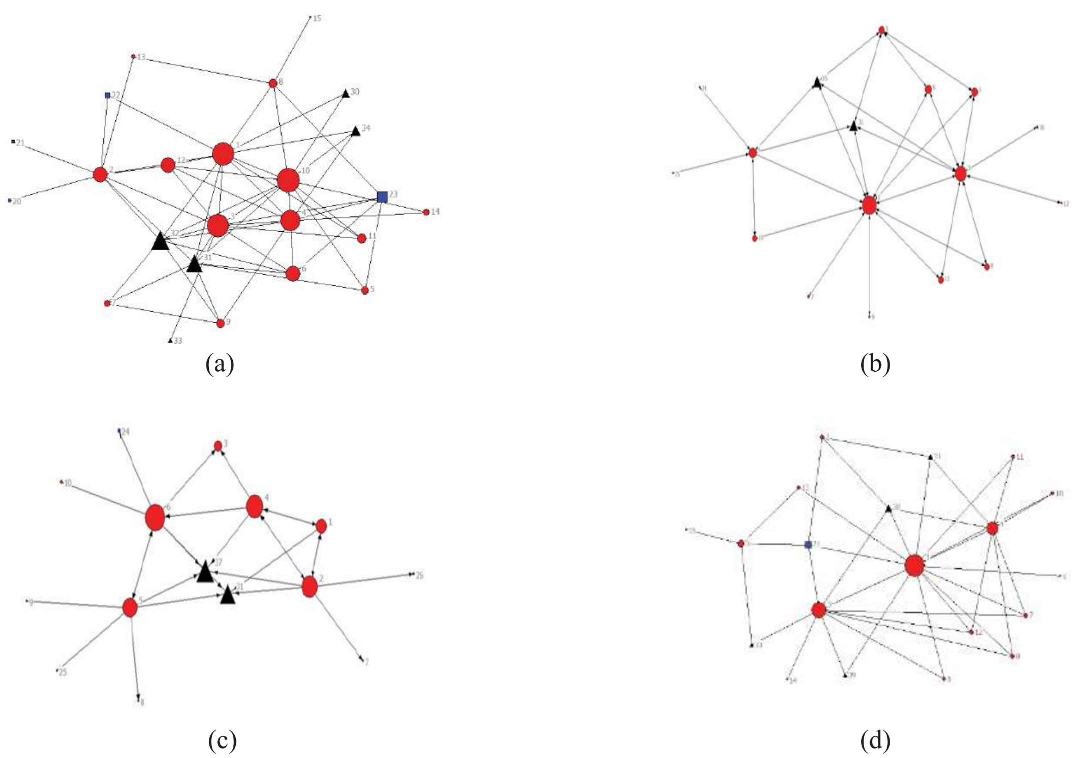

Figure 4. Community of practices network sociograms, all network actors: (a) 2016; (b) 2017; (c) 2018; (d) 2019. Red circles = educators; blue squares = scientists; black triangles = CGLL coordinators; size of node = eigenvector centrality. R/V *Lake Guardian* Shipboard Science Workshops, 2016-2019.

experience on the Great Lakes where participants learned about the context, including the Great Lakes literacy principles. This is also where they learned about scientific concepts, processes, or techniques, a key dimension of establishing a *foundation of PBE teaching and learning (PBE pillar II)*. While this evaluation demonstrates that overall, SSW participants learned scientific concepts, processes, and techniques, it did not examine progress toward specific Great Lakes Literacy principles or specific scientific dimensions. Future evaluation could address this research gap. Alternatively, future SSW planning could strategically evaluate which Great Lakes Literacy principles, as well as specific scientific concepts, processes, or techniques, are most transferable to teaching and learning settings, and therefore prioritize them in the SSW curriculum.

Educators are implementing curriculum enhancements that they made because of what was learned while participating in the SSW and their COPs. Most respondents shared that they incorporated much of the presented information into their lesson plans, including incorporating new scientific equipment usage or organizing field trips for their students like their own SSW experience. Frequent comments also indicated that the SSW experience solidified their commitment to the Great Lakes Literacy principles as well as inspiring them with renewed passion for their lessons.

Our 10-month follow-up survey reveals how SSW participants are *deepening impact (PBE pillar III)* through a variety of school-community partnerships, such as field trips to university laboratories or to visit a Great Lake. Consequently, educators' student-run Great Lakes education programs or specific environmental research topics are excellent examples of sustained inquiry into a local environmental issue. Similarly, respondents described students producing PSA-style videos on the Great Lakes and encouraging students to attend local environmental talks with their families, all examples of *PBE pillar IV (developing skills for participation in democratic practices)*. If specific pro-environmental behaviors are of interest (e.g., reduce single use plastics or reduce fertilizers), future SSW coordinators may want to incorporate specific examples into the learning experiences or provide tailored resources. Alternatively, highlighting examples of past participants, to provide relatable, real-world examples from those who have completed the SSW, may be an effective way to show participants how to implement the PBE approaches. Specifically, examples from student-led initiatives are now highlighted in a marine debris Great Lakes Literacy education exploration (Great Lakes Literacy education exploration 2023).

Finally, one of the tenets of SSW is to foster Great Lakes literacy by creating an engaged COP. Overall, our 10 months post-SSW evaluation reveals network connections among most participants, indicating an established COP. For the most part, educators serve in central roles, instead of SSW coordinators or scientists, indicating their ownership and potential influence on collective learning about the Great Lakes literacy principles and adoption of the PBE framework. Social media platforms such as Facebook or collaboration software such as Google are most often used by educators, therefore SSW coordinators may want to consider how to effectively use social media to connect with each other and to share educational resources. In contrast, scientists may not typically use Facebook or Google collaboration in their work. Therefore, SSW coordinators may need to be intentional about how they invite scientists to connect with or share resources with educators. In other words, post-SSW, educators appear to be off and running with self-organizing a COP, and SSW coordinators may need to check-in with them, see what needs or opportunities exist, and reach out or bridge to scientists and invite them to contribute to the COP as needed.

One research limitation was a somewhat low response rate (42%); additional efforts to reach participants may have been helpful at increasing the response rate. Alternatively, a study design that utilized participant interviews may have yielded a higher response rate. Another study limitation is that the questions were open-ended instead of including some Likert-type questions that invited participants to select response options that could be descriptively summarized or used in other analyses.

Finally, SSW program coordinators could redesign the SSW learning objectives by selecting grade-level(s) to focus the NGSS instruction of practices, crosscutting concepts, and core scientific ideas covered and aligning to the CGLL principles and PBE pillars. If this occurs, future research could examine the extent to which educators implement NGSS and PBE approaches in their classrooms. Within the context of the CGLL principles (2023), PBE (GSLI 2017), and MWEE (NOAA BWET 2023) frameworks, effective incorporation of NGSS into classroom learning empowers students to act locally today, as well as continue a trajectory of developing human capacity to be part of a global twenty-first century. Future efficacy evaluation could document the student-led outputs and impacts and relate it to evaluation results from other PBE initiatives.

Conclusion

Our study reveals SSW is effective at enhancing understanding of scientific concepts, processes, or techniques, and had an impact on Great Lakes teaching and learning activities. Additionally, educators are implementing modifications to teaching and curriculum using the PBE approach through student-led, sustained inquiry and youth-community partnerships to empower students with voice and choice. Although SSW has many requirements, participation refreshes and inspires educators' love of teaching and capabilities for empowering youth to solve Great Lakes issues today and in the future. While not every educator can participate in this type of professional learning opportunity, through the resulting COPs, place-based networks and capabilities can grow locally.

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Author Bios and Contact Information

Jennifer Hunnell was a professional assistant for Michigan Sea Grant with Michigan State University (MSU) Extension. She has a B.S. in fisheries and wildlife and a M.A. in strategic communication, both from Michigan State University. In her capacity as a professional assistant, she was responsible for meeting and workshop planning, data analysis and technical writing, and other administrative tasks. She is now Communications Coordinator for Michigan State University, W.J. Beal Botanical Garden and may be contacted at hunnellj@msu.edu or by mail at Olds Hall, 408 W. Circle Dr., Room 207, East Lansing, MI 48824.

Heather A. Triezenberg (corresponding author) is Associate Director and Extension Program Leader for

Michigan Sea Grant with Michigan State University Extension. She provides leadership and operations support for Michigan Sea Grant's outreach program through MSU Extension's Community, Food, and Environment Institute, and is jointly appointed with the Fisheries and Wildlife Department and affiliated with the MSU Institute of Water Research. Her research focuses on Extension-based needs assessments, evaluation, and public perceptions using community-engaged approaches. She may be contacted at vanden64@msu.edu or by mail at 446 W. Circle Drive, Justin S. Morrill Hall of Agriculture, Room 73, East Lansing, MI 48824.

Brandon C. Schroeder is a Senior Extension Educator with Michigan Sea Grant serving the coastal communities of Northeast Michigan to bring science-based knowledge to address Great Lakes and northern Lake Huron issues. Brandon's efforts include fisheries leadership, coastal community development, biodiversity conservation, and Great Lakes education and stewardship. Brandon is co-chair of the regional Center for Great Lakes literacy team, serves on the statewide Great Lakes Stewardship Initiative's Board of Directors, and supports place-based stewardship education in Northeast Michigan. He may be contacted at schroe45@msu.edu or by mail at 603 South 11th Avenue, Alpena, MI 49707.

Meaghan J. Gass is an Extension Educator with Michigan Sea Grant serving the coastal communities surrounding Saginaw Bay, Lake Huron to apply science-based knowledge to address Great Lakes issues locally. Beginning in 2018, her Sea Grant Extension efforts involve biodiversity conservation, community resilience, and Great Lakes education and stewardship. Meaghan is co-chair of the regional Center for Great Lakes Literacy team, serves on the Michigan Alliance for Environmental and Outdoor Education's Board of Directors, and supports place-based stewardship education regionally in the Saginaw Bay Watershed. She may be contacted at gassmeag@msu.edu or by mail at 515 Center Avenue, Suite G-102, Bay City, MI 48708.

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Appendix A. Sea Grant – Center for Great Lakes Literacy Lake Guardian Shipboard Science Workshops Evaluation Survey, 2016 – 2019

1. What is your name? *(Please type name in box below.)*
2. Please describe one major concept (e.g., aquatic invasive species, harmful algal blooms, lake stratification) you learned about or increased your previous knowledge about while participating in the Lake Guardian Shipboard Science Workshop. Tell us about one or two teaching and learning situations in which you effectively conveyed this to students, other teachers, school administrators, or others (e.g., family, friends, neighbors, or community partners). *(Please type one paragraph or less in box below.)*
3. Please name and describe one scientific process or technique (e.g., use of specific equipment, specific sampling technique, online data analysis program) you learned while participating in the Lake Guardian Shipboard Science Workshop. Tell us about any teaching and learning situations in which you effectively conveyed this to students, other teachers, school administrators, or others (e.g., family, friends, neighbors, or community partners). *(Please type one paragraph or less in box below.)*
4. Please describe any changes in teaching practices or curriculum enhancements you have adopted since participating in the Lake Guardian Shipboard Science Workshop (e.g., increased use of scientific inquiry, adding new Great Lakes-related units or stewardship projects) to support Great Lakes literacy. *(Please type one paragraph or less in box below.)*
5. Please describe any changes in personal behaviors you have adopted (e.g., limiting purchases of bottled water, limiting single-use plastic products, taking precautions to reduce spread of aquatic invasive species, reducing overuse of fertilizers) as a result of participating in the Lake Guardian Shipboard Science Workshop. *(Please type one paragraph or less in box below.)*

6. Please describe any contexts in which you have encouraged others to adopt personal behaviors (e.g., reducing overuse of fertilizers, limiting purchases of bottled water, limiting single-use plastic products, taking precautions to reduce spread of aquatic invasive species) that reduce impacts on the environment as a result of participating in the Lake Guardian Shipboard Science Workshop. *(Please type one paragraph or less in box below.)*
7. Please identify up to 10 educators who participated in the Lake Guardian Shipboard Science Workshop that you have contacted since your experience. Type each educator's name below and describe the type of interaction or request made of that educator (e.g., following on social media, sharing ideas or resources, collaborating on class projects or stewardship projects). *(Please type educators' names below.)*
   a. Educator 1 (name and describe interaction):
   b. Educator 2 (name and describe interaction):
   c. Educator 3 (name and describe interaction):
   d. Educator 4 (name and describe interaction):
   e. Educator 5 (name and describe interaction):
   f. Educator 6 (name and describe interaction):
   g. Educator 7 (name and describe interaction):
   h. Educator 8 (name and describe interaction):
   i. Educator 9 (name and describe interaction):
   j. Educator 10 (name and describe interaction):
8. Please identify up to 3 scientists (e.g., Lake Guardian scientists, scientists from shoreside partners) you have contacted since your participation in the Lake Guardian Shipboard Science Workshop. Type each scientist's name below and describe the type of interaction or requests made of that scientist (e.g., request for resources to share with students, clarification on a concept, virtual or actual classroom visit.)
   a. Scientist 1 (name and describe interaction):
   b. Scientist 2 (name and describe interaction):
   c. Scientist 3 (name and describe interaction):
9. Please identify up to 3 Center for Great Lakes Literacy staff you have contacted since your participation in the Lake Guardian Shipboard Science Workshop. Type each staff member's name below and describe the type of interaction or requests made of that person (e.g., request for resources to share with students, clarification on a concept, virtual or actual classroom visit).
   a. CGLL Staff 1 (name and describe interaction):
   b. CGLL Staff 2 (name and describe interaction):
   c. CGLL Staff 3 (name and describe interaction):
10. Please describe any communication about workshop content that you have had with scientists or educators who were NOT part of the Lake Guardian Shipboard Science Workshop. *(Please type in box below.)*
11. Please share any other comments you have about personal or professional impacts or experiences stemming from your participation in the Lake Guardian Shipboard Science Workshop. *(Please type in box below.)*

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Case Study Article

Western Water Network: A Case Study in Water Network Formation

Travis Warziniak[1], Robert Heinse[2], Alexander Fernald[3], Michael Gaffney[4], *Kristiana Hansen[5], Bret Hess[6], Lyla Houglum[7], Ginger Paige[8], and Qin Zhang[9]

[1]Rocky Mountain Research Station, USDA Forest Service; [2]Department of Soil and Water Systems, University of Idaho; [3]New Mexico Water Resources Research Institute, NM State University; [4]Washington State University Extension, Washington State University; [5]Department of Agricultural and Applied Economics, University of Wyoming; [6]Western Association of Agricultural Experiment Station Directors, University of Nevada; [7]Western Extension Directors Association, Oregon State University; [8]Department of Ecosystem Science and Management, University of Wyoming; [9]Department of Biological Systems Engineering, Washington State University
**Corresponding Author*

Abstract: Increased water scarcity and drought frequency are creating water management challenges for many communities in the western U.S. In response, the Western Association of Agricultural Experiment Station Directors sponsored a virtual summit in August 2020 to develop a framework for identifying and addressing the most pressing water issues in the western United States (the West). Summit attendees were research scientists, university extension specialists and professionals, and federal/state agency representatives with knowledge and expertise of water management in the West. The summit elicited opinions from 54 experts on pressing water issues and possible methods for addressing them. A follow-on survey of 49 individuals increased the depth and breadth of perspectives collected. Summit and survey results show that water scarcity is a growing concern among water scientists and other experts. Increased water scarcity is leading to overallocated river basins, depleted aquifers, and elevated tensions between water use sectors. Summit and survey participants emphasized the need for increased integration—across research, extension, and education efforts; across the social and physical sciences; across uses (including ecological); and across surface and groundwater systems. These results serve as a sensing of what many of our colleagues believe to be the major western water issues over the next 30 years and, in some cases, possible solutions for addressing them. The expert opinions elicited through the summit and survey informed the creation of the Western Water Network, whose mission is to advance collaborative, proactive, science-based water decision-making that supports dynamic human and natural systems in the West.

Keywords: *water management, water scarcity, water quality, water resilience, water security, expert survey*

Climate change is increasing average temperatures, water supply variability, and the frequency of long-term drought in the western United States (Aliyari et al. 2021; Heidari et al. 2021; Zhang et al. 2021). These changes have significant implications for water management in all sectors of the economy. In its recent Adaptation Plan for Climate Adaptation and Resilience, the U.S. Department of Agriculture (USDA) identified threats to water quantity and quality as a major vulnerability and called for increased support for science and broader outreach and education efforts (USDA 2021). This paper describes efforts responsive to that call and to the needs of water managers faced with growing challenges, sometimes without an existing road map.

In August 2020, the Western Association of Agricultural Experiment Station Directors (WAAESD) hosted a virtual summit on water security to develop a framework for identifying and addressing the most pressing water issues in the western United States (the West). The summit

Research Implications

- Research scientists and extension specialists with expertise in water management are well-positioned to identify water challenges in the western U.S. and to provide input on improving climate adaptation, resolving water conflicts, and increasing resilience to water scarcity and variability.
- Surveyed water experts in the western U.S. emphasized the need for increased integration—across research, extension, and education efforts; across the social and physical sciences; across uses (including ecological); and across surface and groundwater systems, to solve water challenges.
- As droughts in the western U.S. become more frequent and competition for water increases, the need to address problems and opportunities at a basin scale (rather than within a state) becomes more acute. A research- and extension-focused network that transcends state boundaries, such as the Western Water Network, may improve coordination and collaboration between states.

provided a venue for research scientists, university extension specialists and professionals, and federal/state agency representatives to discuss climate adaptation, water conflict resolution, and resilience to water scarcity and variability. The summit was focused on themes outlined in the USDA Science Blueprint: sustainable intensification, environment and climate adaptation, and science policy leadership. Summit participants identified the need for continued dialogue regarding how to most effectively organize and undertake research and outreach activities. Thus, WAAESD leadership convened a subset of summit participants (this article's coauthors, the Leadership Team) to continue the discussion initiated at the summit. The Leadership Team has been meeting regularly since August 2020 to build a network of researchers, extension specialists, and the stakeholders with whom they work that can help water managers and decision-makers adapt to climate change and increase resiliency.

The Leadership Team conducted an online survey of research scientists, university extension specialists and professionals, and federal/state agency representatives in the winter of 2021 to increase the depth and breadth of perspectives collected during the summit. Respondents were asked to identify the most important existent and emerging issues related to water security in the West.

This paper summarizes the results of the summit and survey. The survey was not meant to be rigorous and comprehensive, but rather a sensing of what researchers and extension specialists believe to be the major water issues in the West over the next 30 years and, in some cases, possible solutions for addressing them. Highlights from the summit include the need for innovative funding solutions and original ideas for extension and outreach, themes that would arise in the survey as well. The survey gave further details on pressing water issues in the West and offered topics for continued dialogue on potential solutions. Survey results also informed the creation of the Western Water Network (WWN), whose mission is to advance collaborative, proactive, science-based water decision-making that supports dynamic human and natural systems in the West.

Methods

Information was gathered through a virtual summit on water security and an online survey administered by the Leadership Team. The virtual water summit was primarily attended by representatives of organizations that would eventually be surveyed. The summit and survey are described here.

Virtual Summit on Water Security in the Western U.S.

WAAESD received funding for the *Mini-Summit on Water Security in the Western U.S.* (referred to here as "summit") from USDA-NIFA (Proposal No. 2020-04914) to convene leaders of water-related multistate research projects, directors of Water Resource Research Institutes in the West, leaders of the western USDA Climate Hubs, and select members of the First Americans Land-Grant Consortium (FALCON). The focus of the summit was to develop a framework for identifying, then addressing, either through extension or research, the most pressing water issues in the West. Originally planned for an in-person meeting in Boise, Idaho, the summit was held virtually due to the COVID-19 pandemic on August 8, 2020. Fifty-four people attended the summit.

The summit consisted of plenary sessions and breakout sessions. One of the plenary session speakers, then Deputy Under Secretary for USDA's Research, Education, and Economics mission area, Scott Hutchins, introduced the USDA Science Blueprint themes, which informed topics for breakout sessions later in the day: Sustainable Agriculture Intensification, Agriculture Climate Adaptation, Food and Nutrition Translation, Value-Added Innovations, and Agricultural Science Policy Leadership. Hutchins emphasized the need for sound science to guide agricultural policy and innovative agricultural methods to cope with climate change.

Of the 54 participants, 30 self-selected into breakout groups on environment and climate adaptation; 12 selected into a breakout group on science policy leadership; and 12 selected into a breakout group on sustainable intensification. The environment and climate adaptation topic was divided into two groups to facilitate more active discussion; the other two topics had one breakout group each. Each breakout group addressed three questions: 1) Who are the target audiences we need to influence?; 2) Where do we want to move the target audiences?; and 3) What method to move the target audiences should be considered in an "audacious proposal" that would ensure the attainment of ample water with sufficient quality to meet future demands of the Western Region? The term "audacious" was used to encourage "outside-the-box" thinking in imagining how to solve big water challenges in the western U.S.

Each group had a facilitator and a reporter/note-taker. Notes were compiled via shared online documents, viewable by group participants and developed in real-time with group feedback. Following the breakout sessions, participants re-convened in the full group, where each group shared the main themes discussed in the breakout sessions. The summit concluded by asking for volunteers to continue the work via regular meetings coordinated by WAAESD. Those volunteers formed the Leadership Team.

Expert Survey on Water Security in the West

In Spring 2021, the Leadership Team conducted an online survey to identify water security issues existent or emerging in the West. The survey was conducted through Padlet (padlet.com) and included the following seed question: *What are the significant, region-wide issues you see coming our way over the next 30 years that will affect freshwater security in the West?* The survey was, in essence, an online brainstorming activity. Participants responded to the question on digital cards that were visible to other respondents, who were then able to comment on other participants' responses. Responses were thus not anonymous. The ability to comment on other cards contributed a conversational tone to the survey and was intended to spark creative interactions among colleagues.

The survey was sent to summit participants and an expanded group of stakeholders and experts identified by experiment station and Extension directors, including members of the water-related multistate committees represented in the summit, directors of Water Resource Research Institutes in the West, leaders of the western Climate Hubs, and representatives of the 1994 land-grant colleges and universities. The survey was eventually sent to over 500 people.

Two weeks before the survey was administered, an email was sent telling participants to expect a survey with a short description of the survey topic. One week later, another email told participants that the survey itself would consist of a single question, asking respondents to identify the issues that a WWN should tackle. Finally, the actual survey was sent to participants and was open for two weeks. A reminder to complete the survey was distributed one week before the survey closed. In some cases, leaders representing the groups surveyed also encouraged their members to participate in the survey. There was no financial incentive for participation.

Responses were analyzed using the key phrase extraction prebuilt model in Microsoft Power Automate to identify topic-based clustering in participant responses. Prior to key-word extraction, common phrases without semantic content (stop words) were removed.

Results

Summit on Water Security in the Western U.S.

Results from the virtual summit mainly consisted of breakout session notes and chat transcripts. Each group addressed three main questions: 1) Who are the target audiences we need to influence?; 2) Where do we want to move the target audiences?; and 3) What method to move the target audiences should be considered in an audacious proposal? Results for each question are summarized below.

1) Who are the target audiences we need to influence? The unifying theme among groups was that the target audience and range of stakeholders for water-related issues is broad and inclusive. Target audiences spanned types of users (urban, agricultural, industrial, households) and roles in providing water (technical service providers, conservation districts, government agencies, and political leaders). While all groups recognized that the list of traditional audiences is broad, some also highlighted the need to target communities that are often left out of the discussion (for example, low-income communities, tribes, minority groups). In recognizing water's broad role, it was suggested that care needs to be taken to ensure everyone has a voice at the table. Part of this discussion involved outreach to children through schools and programs like 4H.

All groups expressed concern about increasing conflict between target audiences, particularly between urban consumers and farmers. Participants predicted that pressure to transfer water from agriculture to municipal uses will increase, particularly in times of drought, further increasing conflict between these target audiences. All groups acknowledged this tension and expressed concern over the disconnect between urban resident perceptions of agriculture and agricultural production needs. Most participants had ties to agriculture either through research or extension and stressed the importance of agriculture in local and regional economies. To this end, groups also identified economic development agencies and authorities as target audiences and the need to consider water resources in strategies for sustainable economic growth.

Funding was seen as an impediment to sustainable water use in the West, both for research and for carrying out water conservation programs. Innovative funding sources might include connecting with green investors and venture capitalists. Members of the environmental community, tribes, water managers, agencies, and lawmakers were all identified as target audiences.

2) Where do we want to move them? When thinking about where to move target audiences, all groups mentioned legal and regulatory barriers that can make efficient use of water difficult. Participants mentioned legal barriers imposed by the doctrine of prior appropriation, which largely governs water allocation in the western U.S. They also mentioned that variation in water law between states can hinder water management at the scale needed for real change (e.g., at the basin scale, or joint management of ground and surface water). A key point brought up was what one group called the different "colors of water" and the costs of changing water from one use to another. Given these costs, participants thought sustainability would require sacrifice by all parties, for example, by removing irrigated lawns, which was mentioned as a way to reduce pressure placed on the agricultural system from urban growth. They felt that education and increasing people's respect for the land and passion for natural resources would increase awareness of water issues and impacts of individual actions on regional, if not global, resources.

All groups talked about the need to move audiences and water users (presumably the same in many cases) from a competitive approach to water use to one of collaboration. Education and more holistic views of water and aquatic systems were seen as the keys to this movement. Educating the public about the role water plays in urban areas, agricultural systems, and industry, and how those uses interact with and are affected by environmental outcomes were seen as important steps to reducing conflict over water. Participants mentioned management case studies of win-win situations and thought learning from those case studies and spreading their message are important.

3) What method to move them should be considered in an "audacious proposal?" Participants of the summit struggled with the concept of an audacious proposal. Participants wanted more clarification on what such a proposal would be, whether there already was or would be funding for such a proposal, and who would implement the proposal. One key takeaway from the exercise is that more targeted goals should be articulated by summit leaders. In spite of the challenges associated with thinking outside of familiar boxes, all groups eventually engaged in brainstorming parts of an audacious proposal.

One group member suggested "redefining state boundaries according to watersheds," and while members of the full group did not seem to take this suggestion seriously, it did spark conversation and the need to expand boundaries of water management to areas of common use. Some groups mentioned that the "method to move" the target audiences would need integration of science, education, and policy; others noted that data by itself is not enough. Decisions are based on deep-seated beliefs about water and social values. To this end, there is a need to integrate social sciences with hydrology and agronomy studies. Similarly, revising economic incentives to better align with social goals, more efficient water use, and the One Water approach proposed by Howe and Mukheibir (2015) were mentioned by all groups.[1]

Participants thought the key to accomplishing something audacious in the realm of western U.S. water challenges was to break the problem down into manageable parts. Real change requires research, policy change, social acceptance, and education. The most consistent theme in answering this question, much like the other questions, was the need to make meaningful connections between the people in different user groups. Participants thought case studies, demonstration sites for xeriscaping, creation of roundtables and interstate forums, and more savvy use of marketing and social media would benefit the water community. Overall, participants emphasized the need to address the human dimensions of water use. As several groups stated, inspiration and a clear vision of the future are critical to the success of any endeavor, audacious or otherwise.

Online Survey on Freshwater Security in the West

The survey consisted of the following seed question: *What are the significant, region-wide issues you see coming our way over the next 30 years that will affect freshwater security in the West?* Forty-nine people posted initial comments on the Padlet survey cards, i.e., entered their opinions as a discreet, stand-alone narrative in the survey tool. Participants commented on those cards, thereby creating over 100 total comments. Fifty-one issues were raised in the online survey that the key phrase extraction model in Microsoft Power Automate grouped into six categories: research, extension, and education needs; water quantity, water quality, and water equity; spatial scale (global, regional, local); groundwater, surface water, and coupled surface-groundwater systems; water uses (agricultural, municipal, industrial, and ecological); and data and science synthesis, communication, and implementation (Figure 1). Responses in each category are summarized below.

Research, Extension, and Education Needs. Of the survey responses, 41 addressed research, extension, and education needs. The majority of survey responses (73%) indicated greater need for research, 12% indicated a greater need for extension, and 15% indicated a greater need for education. Themes that emerged were frequently centered around coupled water systems, indicating that research needs to better integrate policy and social preferences in water planning and management. There was agreement that both research and engagement are needed at basin-scales, recognizing the large regional impacts of water-related decisions.

Other research directions included studies on more efficient water allocation and improvements in water use efficiency. Several respondents suggested rethinking the doctrine of prior appropriation, which was mentioned throughout this project as an impediment to real change in water management in the West. Others thought the best way to address future water scarcity would be to increase water storage, both with human-built infrastructure and by increasing soil health so it

[1]The One Water approach, "considers the urban water cycle as a single integrated system, in which all urban water flows are recognized as potential resources, and the interconnectedness of water supply, groundwater, stormwater, and wastewater is optimized, and their combined impact on flooding, water quality, wetlands, watercourses, estuaries, and coastal waters is recognized (Howe and Mukheibir 2015, 3)."

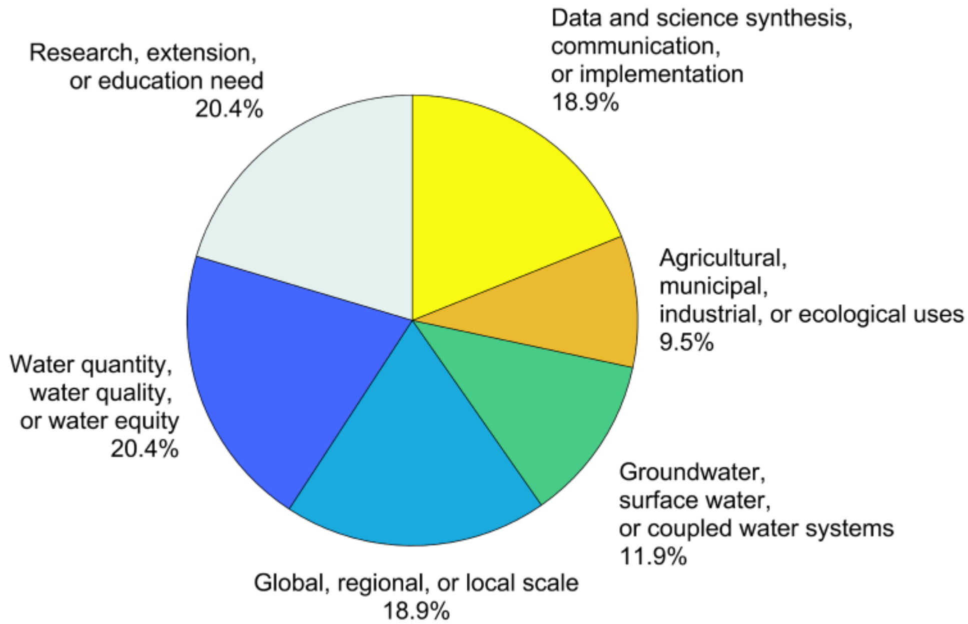

Figure 1. Survey response categories for water issues affecting freshwater security in the West.

could better retain water (i.e., green water). Some responses emphasized the need to improve water-use efficiency with technology, support tools, and smart water systems; other respondents cautioned that overreliance on efficiency reduces resilience and increases susceptibility to drought.

Summit and survey participants repeatedly mentioned the three land-grant pillars of research, extension, and education and the importance of connections between communities of water users, managers, researchers, and decision-makers. Respondents noted that successful water-smart communities rely on effective networks of researchers, extension educators/ specialists, and managers. As droughts become more frequent and competition for water increases, the need to address problems and opportunities at a larger scale becomes more acute. Networks of researchers, extension educators/specialists, and managers based on state boundary lines are often not adequate to address water management issues when rivers and watersheds cross state boundaries.

Water Quantity, Water Quality, and Water Equity. Many of the respondents directly addressed water quantity, water quality, and more equitable distribution of water. Forty-one responses were included in this category, of which the majority (56%) addressed water quantity as the main issue likely to affect the West, noting increased frequency of drought and projections that indicate a drier future with larger populations for much of the region. Twelve percent of responses addressed water quality, and 32% mentioned that water quantity and water quality were highly coupled. This category includes threats to water resources, of which the following were listed: wildfire; erosion, infiltration, and forest management; spread of pests in water-stressed environments; adaptation to less snow and more rain; nonpoint source water contamination; water reuse; drinking water safety; and alternative water storage.

Equitable distribution of water was raised as a concern. Respondents noted disparity in infrastructure improvements among communities and that many groups, such as tribes, have been left out of regional management and planning efforts. And while conflict seems to be the norm in water-related issues, managing by conflict avoidance was also raised as a concern.

Spatial Scale (Global, Regional, and Local). Thirty-eight responses mentioned that different water issues span global, regional, and local scales and noted the importance of getting the spatial scale of water management right. Global climate change was indicated as a driver for many of the research needs, but most responses (66%) indicated that water issues are predominantly regional in scale. (Local issues were indicated by 29% of responses.) Thus, stressors to water systems might come from outside the region (e.g., the impacts of climate change), but solutions must ultimately come from within the region. The survey did not define local vs. regional, and some respondents questioned what 'regional' means with respect to water resources. Hypoxic zones, for example, are caused by stressors at multiple spatial scales, from global to hyper-local, and connect communities throughout a river basin or aquifer. In that vein, respondents thought governance should recognize linkages between surface water and groundwater systems, both geologically and economically. Coupled ground and surface water systems arose both with regard to spatial scales of management and with regard for better science of coupled systems, discussed below.

Water Uses (Agricultural, Municipal, Industrial, and Ecological). There were 19 survey responses in this category.[2] Responses primarily addressed measurement of use, more efficient use, and overallocation. One of the issues most frequently raised by summit and survey participants was increased levels of conflict between water users. Conflict, it seems, is a defining feature of water in the West. The nature of the conflict often stems from a mismatch in scale; water decisions are local but conflicts are regional, or vice versa. Summit and survey participants also emphasized the need for increased integration—across research, extension, and education efforts; across the social and physical sciences; across uses (including ecological); and across surface and groundwater systems.

Responses recognized that agriculture is the biggest water user (74% of responses were about agricultural systems) and emphasized the need for more resilient agriculture and more efficient irrigation methods. Other solutions included crop breeding for more efficient water use, planting crops that use less water, and implementing best practices for groundwater and irrigation systems. In overallocated river systems, participants called out the need to reserve instream flows for ecological values and expressed concern over constraints (political, social, scientific uncertainty) that often hinder this aspiration. Policy suggestions to address overallocation and conflict between uses included more holistic management of water resources at the watershed and ecosystem levels and wider use of scarcity pricing.

Groundwater, Surface Water, and Coupled Surface-Groundwater Systems. Twenty-four respondents focused on water source, whether groundwater, surface water, or coupled systems. The majority of responses in this category (67%) were about coupled systems rather than just groundwater or surface water in isolation. Participants stated the need to address surface and groundwater as coupled systems in research, management, and policy. Key groundwater issues included improving recharge and soil water holding capacity. Reponses in this category focused heavily on the role of groundwater sources in meeting current needs, but they also indicated concern about sustainable groundwater use.

Data and Science Synthesis, Communication, and Implementation. Forty-eight responses fell under this category and were approximately evenly split between the three subcategories, though the largest group of responses addressed data needs and synthesis science. Respondents wanted to see more science addressing social and human behavior, culture, values, beliefs, norms, ideas, decision-making biases, and buying behavior. Needs identified ranged from better understanding and synthesis to better implementation and communication. No response indicated a need for more data, but several voiced the need for wider adoption of data-driven support tools and for guidance to help users distinguish between good and bad data.

Discussion and Conclusion

The objective of this case study has been to document the development of a water network in the western U.S., from initial problem identification to formal network creation. The Padlet survey was critical to network formation, in that key observations made by summit participants and survey respondents have guided

[2]Survey responses related more to extension and education – engaging communities to reduce conflict – are included in the section above.

development of the network. First, competition for water, exacerbated by climate change, is altering patterns of water availability in the West. Second, agriculture and rural extension will be critical in addressing the challenges water users face in the region, because the agricultural sector uses more water in the western U.S. than any other (Dieter et al. 2018). Third, the three land-grant pillars of research, extension, and education build more connected communities – of water users, managers, researchers, and decision-makers.

The survey was exploratory in nature and designed to elicit the maximum number of responses possible from acknowledged water researchers and other experts. It was an early step in an iterative process of determining whether support existed for the idea of a network. Study limitations should thus be noted. The survey methods were designed to elicit the maximum number of responses possible from acknowledged water researchers and other experts. Future iterations of the network formation process need to be more intentional about identifying and incorporating feedback and membership from representatives of marginalized and under-represented communities.[3]

In response to summit and survey participant feedback, the Leadership Team moved forward to develop the WWN, whose mission is to advance collaborative, proactive, science-based water decision-making that supports dynamic human and natural systems in the West. The WWN held a workshop in June 2023 in conjunction with the Universities Council on Water Resources annual meeting in Fort Collins, Colorado, to establish priorities and to chart a vision for land-grant focused research and engagement to address western U.S. water challenges for the next ten years.

The keystone of the WWN is the research (Agricultural Experiment Station) and engagement (Extension) pillars of the land-grant university, along with the stakeholders/groups with whom land-grant researchers and Extension professionals regularly collaborate and serve. The WWN is thus a "network of networks" that aims to connect the broad, West-wide community of stakeholders, researchers, educators, Extension professionals, service providers, and policymakers tasked with confronting the most pressing water issues in the West. The WWN has created a new USDA National Institute of Food and Agriculture (NIFA) project intended to unite the many water-related multistate projects and convene a regular congress on water in the West, focused on collaborative fact-finding and cooperative solutions.

In an important sense, then, the audacious proposal originally sought by WAAESD leadership during the 2020 summit is the formation of the WWN itself—the creation of a framework that facilitates collaboration and coordination across state boundaries, across academic disciplines, and between researchers and practitioners, for those working on transboundary water issues. Moving forward, the WWN seeks to support the next wave of innovations for water resiliency; explore the feasibility of innovative water management practices, policies, and institutions; characterize, in collaboration with the USDA climate hubs, the patterns of water availability expressed as water budgets in the West; and build teams of stakeholders and professionals to support decision-making and policy formulation for a secure water future in the West.

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[3]This is already occurring. For example, the Fort Collins Workshop referenced below included a thematic area on Diversity, Equity, and Inclusion. There was also a broadly shared understanding among Fort Collins Workshop participants that research and engagement activities directed toward increasing water security in the western U.S. must include diverse voices and approaches to be effective.

Author Bios and Contact Information

Dr. Travis Warziniack is a research economist with the USFS Rocky Mountain Research Station. His work focuses on valuation of ecosystem services, with an emphasis on watershed health, climate impacts to water resources, and nature's role in regional economies. He serves as the water specialist for the Resource Planning Act (RPA) Assessment, which looks at the status and trends of the nation's renewable natural resources, and leads the development of the U.S. natural capital accounts for forests. He may be contacted at travis.w.warziniack@usda.gov or 240 W. Prospect Rd, Fort Collins, CO 80526.

Dr. Robert Heinse is an Associate Professor of Soil and Environmental Physics in the Soil and Water Systems Department at the University of Idaho. His research interests revolve around water in the soil environment and characterization using geophysical methods. He is a past director of the interdisciplinary water resources program. Above all, however, he has a growing appreciation for the complexities of human and ecosystem interactions with the physical world. Dr. Heinse completed a Ph.D. in Soil Science at Utah State University. He may be contacted at rheinse@uidaho.edu or 875 Perimeter Drive, Moscow, ID 83843-2339.

Dr. Alexander "Sam" G. Fernald was appointed Director of the New Mexico Water Resources Research Institute (NM WRRI) in July 2013 after having served as interim director since January 2011. His research interests include coupled human and hydrologic systems; water quality hydrology; land use effects on infiltration, runoff, sediment yield, and nonpoint source pollution; and effects of surface water/groundwater exchange on water availability and water quality. Dr. Fernald has a Ph.D. in watershed science from Colorado State University. He may be contacted at afernald@nmsu.edu or PO Box 30001, Las Cruces, NM 88003-8001.

Michael J. Gaffney is the Assistant Director of WSU Extension and Director of Extension's Community and Economic Development Program Unit. He has conducted research and published on a number of topics, including Social Capital, Community-Oriented Policing, Regional Planning, Economic Development, Citizen/Government Relationships, Natural Resource Stewardship, Biased Policing, Project and Program Evaluation, Disaster Response, and Community Resilience. Mike previously served as the Director of the WSU Division of Governmental Studies and Services – an applied public policy research unit. Mike can be contacted at: mjgaffney@wsu.edu or 411E Hulbert Hall, Washington State University, Pullman, WA 99164.

Dr. Kristiana Hansen (corresponding author) is an Associate Professor and Extension Water Resource Economist in the Department of Agricultural & Applied Economics at the University of Wyoming. Dr. Hansen's current research is in water resource economics and community adaptation and response to changes in weather and climate variability. Her extension programs seek to inform and improve regional decision-making in water allocation. Several current research/extension projects focus on informing Colorado River Basin water management challenges, through analysis of economic impacts, conservation program design, and collaborative decision-making. Dr. Hansen completed a Ph.D. in Agricultural and Resource Economics from the University of California, Davis. She may be contacted at kristi.hansen@uwyo.edu or 1000 E. University Ave Dept 3354, Laramie, WY 82070.

Dr. Bret Hess serves as the Executive Director for the Western Association of Agricultural Experiment Station Directors. He provides leadership and manages the western region's portfolio of multistate projects which are funded through the multistate research fund, including development of integrated multistate projects involving research, extension, and academic programs. Additionally, he provides leadership for national activities through the Experiment Station Committee on Organization and Policy. Dr. Hess completed a Ph.D. in Animal Science from the University of Missouri-Columbia. He may be contacted at bhess@unr.edu or 5890 Brittania Drive, Reno, NV 89523.

Dr. Lyla E. Houglum, Oregon State University Professor Emeritus, served as Executive Director of the Western Extension Directors Association from 2005-2021. Dr. Houglum previously served as Dean and Director of the Oregon State University Extension Service helping design and implement the concept of "Scholarship Unbound" resulting in an organizational model at OSU that allows Extension to work University wide, creating partnerships with 9 of OSU's 11 Colleges. Houglum served on numerous national, regional, and state boards and committees, including Chairing the Extension Committee on Organization and Policy (ECOP – the national Board of Directors for Extension).

Dr. Ginger Paige is a Professor and Water Resource Extension Specialist in the Department of Ecosystem Science and Management at the University of Wyoming. Dr. Paige's current research focuses on the measurement and modeling of watershed hydrologic processes in the snow-rain transition zone of the intermountain West. Her extension programs include the development of hydrologic decision support tools for water resource management from field to basin scale. Dr. Paige has a Ph.D. in Watershed Management from the University of Arizona. She may be contacted at gpaige@uwyo.edu or 1000 E. University Ave., Dept 3354, Laramie, WY 82071.

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Perspective Piece

The Relevance of Water Education in Children: Perspectives from the Americas

*Pablo A. Garcia-Chevesich[1,2], Rafael Val[3], Gisella Martínez[4], Adriana Álvarez[5], Oscar Luna[3], Paloma Maya[3], Roberto Pizarro[6], Maite Pizarro-Granada[7], and John E. McCray[1]

*[1]Colorado School of Mines, Department of Civil and Environmental Engineering, [2]UNESCO, Intergovernmental Hydrological Programme, [3]Government of México, [4]National University of Saint Augustine, Arequipa, Peru, [5]University of Colorado Denver, [6]University of Talca, Chile, [7]University of Barcelona, Spain, *Corresponding author*

Water-related challenges and environmental issues persist globally, including in Latin America, the Caribbean, and United States. An imperative step to improve the water management issues faced by many countries is to educate children on this important topic. Even though water conservation is not found in the basic (formal) education curricula of most the Americas (including the United States), the topic has been present in many parts of this region, and the efforts made are worthy of admiration, with decades of hard work. Moreover, the regional experience (which was recently documented in the book "*Water education in children: the experience from 11 countries in Latin America and the Caribbean*") indicates that, to reach an acceptable level of efficiency, children's education programs focused on water must be flexible, according to the reality of the region and the socioeconomic level of the students, and should not include solutions that do not involve children, for example, water supply infrastructure. Similarly, methods that are not recommended when trying to educate children about water conservation are those based on negative emotions (e.g. "if we don't save water, we'll face a catastrophe"); so techniques based on positive emotions work better. Another common mistake is to use material that a certain age group will not be able to process because their brains haven't yet developed, for example, their *scientific reasoning* (e.g. getting them involved in water quality projects during early ages); in fact, neuroscience is a crucial part of an effective water education program. Finally, a regional pattern is the lack of indicators or evaluations on the effects of the different educational methods applied on family water consumption, even in the United States (the most advanced country on the subject).

Government entities have played an important role in children's education applied to this important topic in the region (e.g. "*USGS water science school*" in the United States). Furthermore, what has given better results is intra- and inter-institutional collaboration, such as ministries of education, culture, water resources, and the environment, etc., collaborating with NGOs, municipalities, universities, and schools, without excluding the private sector. In other words, joint work to care for water can contribute to citizen involvement beyond the school's classroom.

Another important fact is that children's education programs on water care should have continuity and promote a protagonist role of children in solving the problem (e.g. *Children defenders of water* in Colombia, *Little plumber teams* in Cuba, *The super inspector of water in Mexico*, *Water watchers* in Peru). Similarly, it is also important to train teachers, who are the ones directly in charge of educating children on different environmental issues, including water care, a topic in which Chile has taken the lead.

Most of the countries in the region focus more on the care of water as a consumer (quantity), ignoring the quality of the resource (pollution, except for examples on river clean-up campaigns in Bolivia and the United States), most likely because the main visible problem is the scarcity of the vital element in the countries involved. Among the most used educational methods in the region are multi-institutional programs, classroom planning, after school activities, workshops/projects, sporting events, family fairs, annual events, exhibitions in museums, songs, storybooks and poems, guides for teachers, fictional characters that represent a drop of water, videos, drawing contests, photographs and scientific projects, water care campaigns, river clean-up and/or monitoring campaigns, marches for water, cooperative games, and didactic games, among others. Remarkable examples of the above are represented by projects *Drinking water gives you life, becoming aware gives you water* in Bolivia and *Let's take care of water today to live tomorrow* in Peru, among other projects that seek to make children understand how crucial water is for their own future, while having fun. Similarly, annual events such as the *World Water Day* is celebrated in almost all countries of the region, but Argentina also celebrates its *National water and education week*, increasing even more the relevance of water in children, as the event includes games. Moreover, the Chilean storybook *Water for everyone* represented important material for preschool educators to show young children how important water is and to discuss how they can save it at home. Impressive material was also generated through the *Zero water waste photography contest* in Cuba or the *Rain on wet photography contest* in Mexico. The list is endless, and the regional efforts to make children save water are admirable.

In conclusion (besides the protagonist role), the *game* has been the methodology that encourages, challenges, and mobilizes children to develop actions towards the conservation and care of water, i.e. the more entertaining the material (or activity), the more they learn and the more they apply it in their daily lives. Similarly, successful results have also been obtained through the participation of older children in data collection (e.g. daily precipitation, as is the case of the "*Network of voluntary rain observers*" in Cuba) for real scientific studies, where minors acquire participatory interest and, as a consequence, value the resource.

Additionally, successful methodologies have been based on the use of cell phones, the internet, and social networks (especially during the recent pandemic, a situation that has been addressed quite well in countries such as Costa Rica), through free platforms. Many government agencies offer water stewardship education platforms, which teachers rely on to educate children in schools.

Finally, our most important message is that the ultimate goal of educating children is to create a new generation that cares for water, without forgetting that children bring the "water culture" to their homes, transmitting it to their parents (adults). Countries in the Americas have set a clear example to be followed not only by the rest of the region, but by the entire planet. As climate change and overconsumption reduce the water storage of a significant portion of the world's continental territory, the valuation and care of the resource is crucial for a sustainable future, because without water, there is no life.

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Author Bio and Contact Information

Dr. Pablo A. Garcia-Chevesich (corresponding author) is a Professor and Hydrologist at Colorado School of Mines (Department of Civil and Environmental Engineering) and member of the Intergovernmental Hydrological Programme of UNESCO. His research focus is on watershed hydrology, for a better environment. He may be contacted at pablogarcia@mines.edu.

Dr. Rafael Val is a water educator at Sistema de Aguas de la Ciudad de México (Government of México). He may be contacted at rafael.val.segura@gmail.com.

Gisella Martínez is a Professor at Universidad Nacional de San Agustín de Arequipa (Facultad de Geología y Minas). She may be contacted at omartinez@unsa.edu.pe.

Dr. Adriana Álvarez is a Professor at University of Colorado Denver (Culturally and Linguistically Diverse Education. School of Education and Human Development). She may be contacted at adriana.alvarez@ucdenver.edu.

Oscar Luna is a water educator at Sistema de Aguas de la Ciudad de México (Government of México). He may be contacted at oscar.luna.sacmex@gmail.com.

Paloma Maya is a water educator at Sistema de Aguas de la Ciudad de México (Government of México). She may be contacted at paloma.maya.sacmex@gmail.com.

Dr. Roberto Pizarro is a Professor and Hydrologist at University of Talca (Faculty of Forest Engineering) and University Chile (Faculty of Forest Sciences and Nature Conservancy). He is the Director of the Unesco Chair on Surface Hydrology (Universidad de Talca), and member of CENAMAD (Centro de Excelencia para la Industria de la Madera, Pontificia Universidad Católica de Chile). He may be contacted at rpizarro@utalca.cl.

Maite Pizarro-Granada is associated with the University of Barcelona and Somos Libros Press (Barcelona, Spain). She may be contacted at mmpizarr@uc.cl.

Dr. John E. McCray is a Professor at Colorado School of Mines (Department of Civil and Environmental Engineering) and campus PI for the NSF Engineering Research Center on Urban Water (ReNUWIt). His research focus is on chemical transport and treatment in urban and natural watersheds using a combination of field, laboratory, and modeling techniques. He may be contacted at jmccray@mines.edu.

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Producer Perceptions on the Value and Availability of Water for Irrigation in the Mississippi Delta

*Gurpreet Kaur[1], Nicolas E. Quintana Ashwell[2], Gurbir Singh[1], Drew Gholson[2], Martin A. Locke[3], L.J. Krutz[4], and Trey Cooke[5]

[1]Northern Missouri Research, Extension, and Education Center, University of Missouri, Novelty, Missouri, USA
[2]National Center for Alluvial Aquifer Research, Mississippi State University, Stoneville, Mississippi, USA
[3]National Sedimentation Laboratory, USDA Agricultural Research Service, Oxford, Mississippi, USA
[4]Water Resources Research Institute, Mississippi State University, Mississippi State, Mississippi, USA
[5]Mississippi River Basin Program, The Nature Conservancy, Cleveland, Mississippi, USA
**Corresponding Author*

Abstract: The agricultural production in the Mississippi Delta is threatened by the water level declines in the Mississippi River Valley Alluvial Aquifer (MRVAA). This study assesses the growers' perceptions of the value and availability of water for irrigation based on data collected in a survey in 2012 in the Delta region of Mississippi, USA. The total cooperation rate for this survey was 79.3%. The results showed that 97.39% (448 out of 460) of respondents believed that water is important for farming in the Delta region of the MRVAA. Fifty-two percent of the survey respondents agreed that the major cause of groundwater depletion is agricultural irrigation water use. More than 50% of the survey respondents believed there is sufficient water in the Delta region, but it is not managed properly. The value of water for irrigation ranged from $463 to $690 per ha for corn (*Zea mays* L.), $399 to $615 per ha for soybean (*Glycine max* L.), and $223 to $336 per ha for cotton (*Gossypium hirsutum* L.). The majority of the respondents considered that there is a need for regulation of water use to protect the aquifer and ensure water availability in the future.

Keywords: *water crisis, water shortage, groundwater depletion, regulations*

Agriculture is the leading industry in Mississippi. Major crops grown in Mississippi are soybean, corn, cotton, rice *(Oryza sativa L.),* sweet potatoes *(Ipomoea batatas),* peanuts *(Arachis hypogaea)*, wheat *(Triticum aestivum* L.*),* and grain sorghum (*Sorghum bicolor*). About 80% of row crop production in Mississippi occurs in the north-western portion of the state known as the Delta region. The Delta region occupies more than 1.6 million ha and is one of the most productive agricultural areas in the United States (Snipes et al. 2005; Kebede et al. 2014). The Mississippi Delta region has 220 to 260 frost-free days per year and has deep alluvial soils developed over time through deposition from seasonal flooding of the Mississippi River and its tributaries (Snipes et al. 2005). The Delta soils vary widely in texture, ranging from a coarser sandy texture to finer clayey textured soils which swell when wet and shrink when dry (locally referred to as gumbo or buckshot) (Snipes et al. 2005). The soils are low in organic matter and most of the coarse-textured soils (sandy loam, silty loam) are compacted due to heavy equipment traffic, resulting in poor water infiltration and more water runoff. Drainage and proper soil management are critical for optimum crop production in the Delta region.

The Mississippi Delta receives an annual average rainfall of about 1143 mm in the northern Delta to about 1524 mm in the southern Delta (Snipes et al. 2005). About 70% of the annual rainfall in the Mississippi Delta is received during the off-season from September to April (Snipes et al. 2005; Kebede et al. 2014), making the agricultural fields more prone to erosion losses during the winter and

Research Implications

- Water withdrawals at unsustainable rates result in declining groundwater levels in the Mississippi River Valley Alluvial Aquifer.
- Irrigation is important for agriculture in the Mississippi Delta region, but most respondents anticipate future water shortage in the central Delta region.
- Water availability for irrigation in the future might be ensured by regulations on water pumping.

early spring months. The remaining 30% of rainfall is received from May to August, resulting in brief in-season periods of drought that can negatively impact crop production and farm profitability. Therefore, the producers in the Mississippi Delta rely heavily on irrigation to achieve profitable yields due to the uncertainty of rainfall during the summer months when crops are at their peak water demand (Snipes et al. 2005; Kebede et al. 2014).

The main source of irrigation water supply in this region is the Mississippi River Valley Alluvial Aquifer (MRVAA) (Wax et al. 2008). The MRVAA covers an area of 82,879 km^2 and irrigates over 700,000 hectares of row crops in the Mississippi Delta region (Wax et al. 2008; Massey 2010). Higher volume of water pumping for irrigation than the rate of recharge has resulted in a water level decline in the MRVAA (Wax et al. 2008; Marston et al. 2015). Ongoing water-level declines in the MRVAA and the current inefficient and unsustainable crop production and irrigation management practices in the Mississippi Delta jeopardize the long-term water availability from the MRVAA for fulfilling the demand for irrigation. Therefore, there is an urgent need for the development and adoption of improved crop and water management practices to conserve water and contribute to aquifer recharge. However, the adoption of management practices depends upon farmers' perceptions and knowledge about their water issues. In Mississippi, all wells drilled with a casing diameter of six inches or greater are required by law to have a permit which is valid for five years (YMD 2013). The permitting process was started in 1985 by the Department of Environmental Quality. Beginning in 1993, all new agricultural permits in the Mississippi Delta were processed by the Yazoo Mississippi Delta Joint Water Management District. About 80% of the water use permits are in the Delta region in Mississippi.

The first step in solving a problem is to recognize that the problem exists. Therefore, it is important to assess the perceptions of producers on irrigation water availability and its value in the Mississippi Delta. The objective of this paper is to determine the value of water and the perceptions of the farmers on water-related issues in the Mississippi Delta region based on unpublished data from the 2012 Mississippi Irrigation survey (Mississippi State University's Survey Research laboratory). Documenting historic perceptions regarding the value and availability of groundwater for irrigation would facilitate an understanding of the current status and anticipate future groundwater management challenges.

Materials and Methods

A survey was conducted by the Mississippi State University's Survey Research laboratory from November to December 2012 to assess the Mississippi Delta producers' perceptions of the value and availability of irrigation water. For this survey, the target population included all the permit holders, landowners, and operators (producers) who withdraw water (surface and groundwater) for agricultural irrigation in the Yazoo-Mississippi Delta region. The Permit Database from the Office of Land and Water at the Mississippi Department of Environmental Quality was used as the survey contact list. About 1,877 individuals were identified from these records who were thought to hold permits for irrigation water withdrawals in the Yazoo-Mississippi Delta. Out of these 1,877, only 1,789 farmland owners and operators were used for the survey; the remaining 88 were excluded due to duplicate entries or missing telephone numbers. The Survey Research laboratory personnel called the valid phone numbers, and only 460 respondents completed the survey out of the total 1,789 cases. Out of 1,789 cases, 120 respondents refused to complete the survey, 14 were out of town at the time of the survey, 314 did not answer the call, 26 had communication or language problems, 68 were either deceased or were unable to talk due to personal health issues, and 606 had their telephone number disconnected. About 133 respondents no longer held a permit for agricultural irrigation wells and were therefore not included in this survey. In summary, the total cooperation rate for this survey was 79.3%. The cooperation rate was calculated as a ratio of completed surveys (460) to the sum of completed responses plus refusals which was 580 (460 completed surveys + 120 refusals).

The questionnaire for the survey was developed by a team of scientists at Mississippi State University and Delta Farmers Advocating Resource Management (Delta F.A.R.M.). Delta F.A.R.M. is an association of growers and landowners that work on the conservation, restoration, and enhancement of the environment in northwest Mississippi (https://deltafarm.org/). The questionnaire included a total of 13 questions, out of which many had sub-parts. In this article, only part of the survey questionnaire related to the value and availability of water for irrigation is included. The full questionnaire is presented in Appendix 1. The frequency of specific answers to each question was determined and presented in the results section.

Results

Out of the 460 respondents to the survey, 37.8% were landowners only, 51.5% were both landowners and operators, and about 10.7% were operators only. When asked about the crop(s) they grow, only 286 of the 460 replied either yes or no, and the remaining 174 either did not know or did not reply to the survey. The percentages of respondents planting corn, cotton, soybean, and rice were 78.7, 19.1, 59.6, and 22.4%, respectively (Figure 1). About 16.3% of respondents said they plant crops other than corn, soybean, cotton, and rice. The other crops or commodities included assorted grains and peas, catfish, vegetables, peanuts, turfgrass, fruits, wheat, sorghum, sunflower (*Helianthus annuus* L.), and millets (*Panicum miliaceum*).

Value of Water

To assess the farmers' perceptions on water status and importance for irrigation in the Delta, they were asked if it would be difficult to farm without irrigation water using a five-point Likert scale: *strongly disagree, disagree, neither disagree nor agree, agree, strongly agree*, with two additional response options, *do not know*, and *refused to answer* as mentioned in Appendix 1. Although 97.39% (448 out of 460 respondents) believed that water is important for farming, 1.5% disagreed, and 0.9% of respondents neither agreed nor disagreed.

Another survey question asked for a ranking of the following water issues in order of priority: (a) flooding, (b) aquifer depletion, (c) lack of alternative surface water supplies, (d) wasting irrigation water, and (e) lack of streamflow (Figure 2). About 366 respondents provided a valid response to this question, and of those valid responses, 52.2% believed that the depletion of groundwater aquifers was the most important water issue, whereas only 5.7% thought it was the least important issue (Figure 2). Based on the survey responses, 52% (239 respondents out of a total of 460) considered the major cause of groundwater depletion to be agricultural irrigation water use. However, 30.7% of respondents thought agricultural irrigation was not the major cause of groundwater depletion, and 17.4% of respondents were undecided, refused to answer, or did not know.

Respondents were asked about groundwater availability in the Delta region. Out of 460 respondents, only 28.5% agreed that there was not enough groundwater in the Delta to supply all irrigation water needs, whereas the majority of the respondents (48.2%) disagreed. About 8% neither disagreed nor agreed, whereas 15.9% of respondents either refused to provide a reply or did not know about the water status for irrigation needs in the Delta. At the same time, when respondents were asked about their opinion concerning whether "there is enough water in the Delta, but it is not managed properly," a slight majority, 54.6%, of the respondents agreed, whereas 27.2% disagreed.

To better understand the economic value of irrigation water, the survey also included a question on the value of irrigation water in terms of dollars per acre to produce a crop (corn, soybean, or cotton) on their farm (Figure 3). Out of 460 respondents, 204 provided a dollar value for the irrigation water to produce corn on their farm. Among those 204 respondents, 41.2% said the value of irrigation

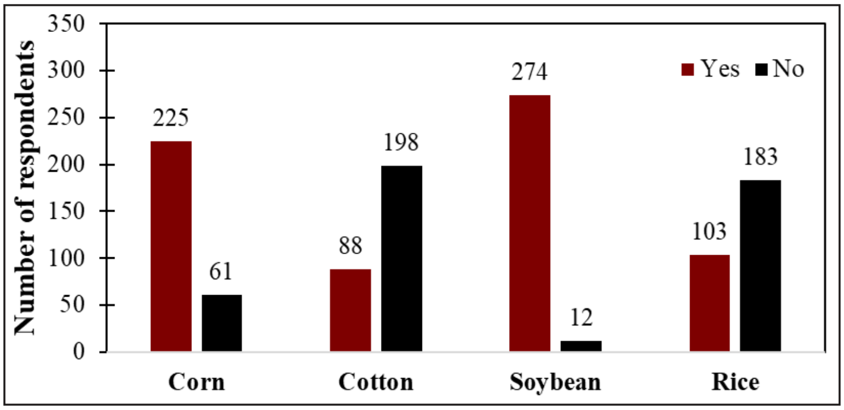

Figure 1. Number of responses to the question whether the respondents grow and irrigate crops including corn, cotton, soybean, and rice. (Valid responses: 286 out of 460 respondents.)

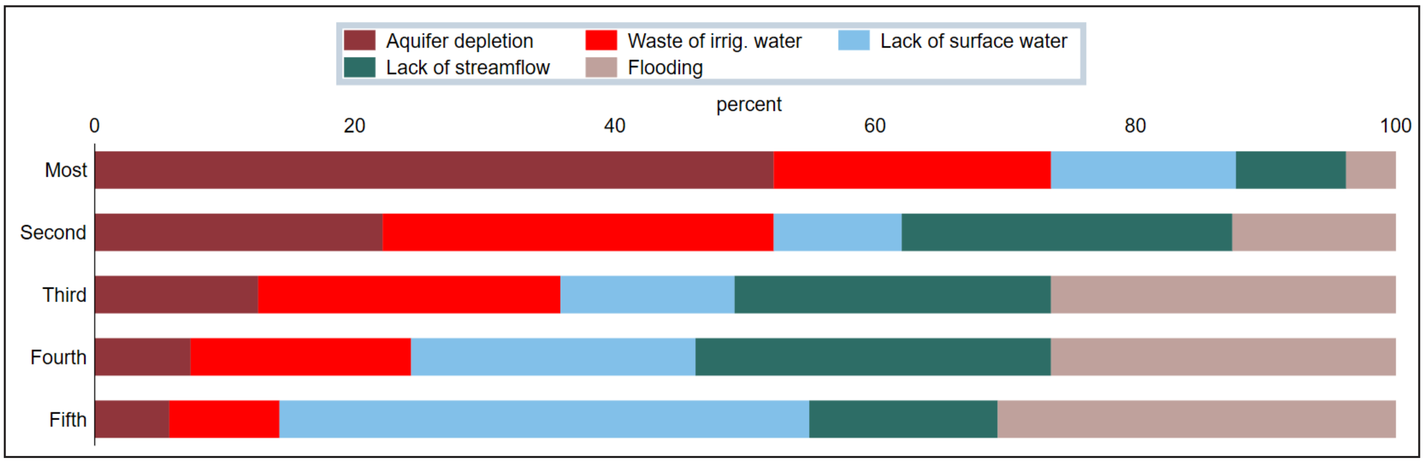

Figure 2. Percent responses to the survey question about the most important, second most important, third most important, fourth most important, and least important water-related issues in the Delta.

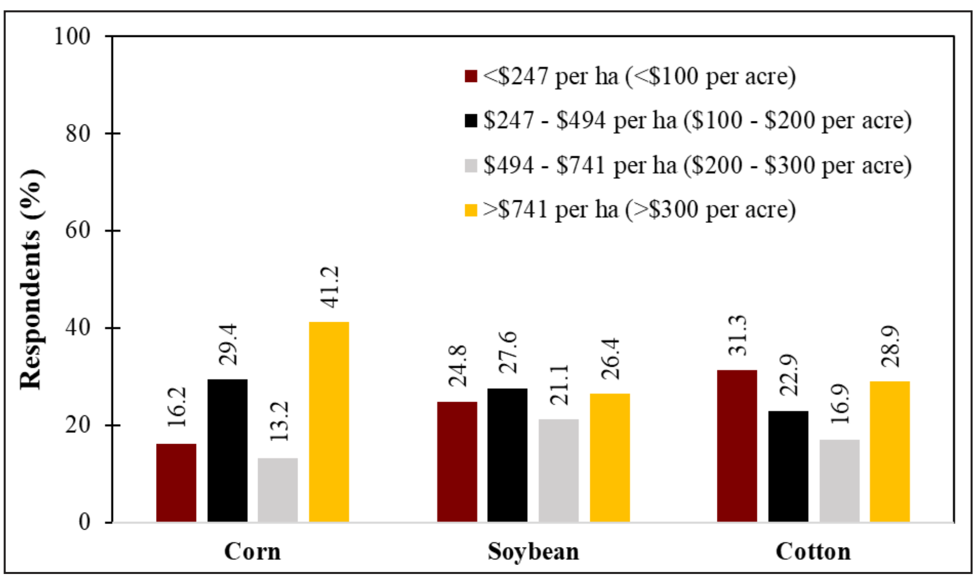

Figure 3. Percent responses to the value of the irrigation water in terms of dollars per ha for producing corn, soybean, and cotton.

water was more than $741 per ha, whereas 29.4% said the value was between $247-$494. About 13.2% of the respondents answered that the irrigation value was between $494-$741 per ha on their farm, whereas 16.2% of respondents thought it was less than $247 per ha. Similarly, for soybean, 246 respondents provided the value of irrigation water in terms of dollars. The percentages were 24.8, 27.6, 21.1, and 26.4% for less than $247 per ha, $247-$494 per ha, $494-$741 per ha, and more than $741 per ha, respectively. For cotton, 31.3% of the respondents believed that the value of irrigation water was less than $247 per ha out of the 83 total respondents who grew cotton.

Because the survey captured the valuation responses in a range of values rather than an amount, it is difficult to produce a point estimate of the value of irrigation water. Therefore, we summarized a weighted average for each crop in Table 1. The lower bound was calculated using the lowest number for each value range category, the upper bound was the highest number in each value range, and the mid-point fell between the high and low values (e.g., for the $247-$494, the three levels are $247, $371, and $494 per ha). Then, each number is multiplied by the percentage under each crop category to provide a range and mid-point of valuation estimate for each type of crop grown. The value of water in corn irrigation ranged from $463 to $690 per ha with a mid-point of $577 per ha. For soybean production, the value ranged from $399 to almost $615 per ha with a mid-point of $507 per ha. In cotton production, water for irrigation was valued at $223 to $336 per ha with a mid-point of $280 per ha. These amounts were produced directly from responses to the 2012 survey so they are assumed to reflect the values of the dollar at the end of the year 2012, which, considering the Producer Price Index, indicate the conversion factor to bring these values to current prices would be 1.15, or about 15% higher than reported in 2012. Of course, the base valuation may have changed since 2012.

Table 1. The weighted average valuation of irrigation water in dollars per ha by crop grown.

	Value of Irrigation Water ($ per ha)		
Crop	**Lower Bound**	**Mid Point**	**Upper Bound**
Corn	463	577	690
Soybean	399	507	615
Cotton	223	280	336

All respondents, regardless of their locations, were asked about the status of water in different regions of the Mississippi Delta (Tables 2 and 3). Among the respondents who only owned land in the Delta region, 73% believed that water was available in abundance, whereas 12.6% thought there was a water shortage (Table 2). Of the respondents who both rented and owned land in the Delta region, about 2% thought there was a water crisis. Among respondents who only rented land in the Delta region, 46.5% believed that there was abundant water available, whereas 11.1% thought there was a shortage. Overall, 24.1% of the respondents thought that there was a water shortage Delta-wide, and 3.5% responded there was a water crisis Delta-wide. About 7.2% of respondents thought there was a water crisis in the central Delta, whereas only about 2 to 2.4% of respondents thought it was true for the north and south Delta regions as well. Similarly, 29.6% of the respondents believed that there was a water shortage in the central Delta, whereas only 15 and 12.4% of respondents thought there was a water shortage in the north and south Delta, respectively. About 32.2, 46.7, and 29.8% of respondents replied that there will be a water shortage in the future in the north Delta, central Delta, and south Delta, respectively (Table 3), while 40.2% of the respondents said "yes" to anticipated Delta-wide future water shortages.

Regulations on Water

Since the MRVAA water levels are declining, the survey also included questions on the regulation of water to protect the aquifer. About 28.3% of respondents from the 460 disagreed that regulations are needed to protect the MRVAA. About 56.3% of the respondents agreed that water use regulations are needed to protect the aquifer and ensure water availability in the future. However, only 6.1% of respondents either refused to reply or said they did not know, and about 9.3% of respondents neither agreed nor disagreed about the regulations on water use. In addition, the respondents were also asked if

Table 2. Percent responses to the current water situation (water crisis, water shortage, water abundance) at different locations.

Location	Water crisis	Water shortage	Water abundance	Don't know	Refused	Does not apply
	----------	----------	----------	%	----------	----------
Land you own	2.4	12.6	73.0	4.3	1.1	6.5
Land you rent	2.0	11.1	46.5	2.8	1.1	36.5
North Delta	2.4	15.0	39.6	40.0	1.1	2.0
Central Delta	7.2	29.6	35.2	25.4	1.3	1.3
South Delta	2.0	12.4	39.8	42.4	1.1	2.4
Delta-wide	3.5	24.1	42.8	28	1.1	0.4

Table 3. Percent responses to the question: "Do you anticipate a future water shortage?"

Location	Yes	No	Don't know	Refused	Does not apply
	----------	----------	%	----------	----------
Land you own	29.3	54.1	12.0	0.4	4.1
Land you rent	23.9	39.8	8.5	0.4	27.4
North Delta	32.2	35.9	29.3	0.7	2.0
Central Delta	46.7	30.4	21.3	0.9	0.7
South Delta	29.8	36.7	30.7	0.7	2.2
Delta-wide	40.2	33.9	24.3	0.7	0.9

"self-regulation by farmers can protect the aquifer from overuse and ensure water availability in the future" and if "regulations on water use will hurt agriculture." About 83.4% of respondents believed that self-regulation by farmers can help in reducing declining water tables in the MRVAA, however, 4.5% neither agreed nor disagreed. About 9.6% of respondents disagreed that self-regulation by farmers will help with aquifer overuse. Sixty-eight percent of respondents also thought that regulation of water use will hurt agriculture in the Delta, whereas only 18.3% disagreed. About 7.4% were undecided, and 6.7% either refused to answer or answered that they did not know.

Discussion

The survey conducted by Mississippi State University found that respondents believed that water is important for farming in the Delta, and water withdrawals for irrigation are the primary reason for water-level declines in the MRVAA. In the midsouth U.S., there was a 71% increase in irrigated farmland from 1988 to 2008 (Vories and Evett 2014), and increases in irrigated areas in Mississippi and Arkansas were 92 and 71%, respectively, during this period. The irrigated land increased in the lower Mississippi River Valley at an annual average rate of 2% between 2002 and 2012 (Massey et al. 2017). About 60% of the agricultural land is irrigated, either using furrow or center pivot irrigation systems in the Mississippi Delta (Kebede et al. 2014). Water withdrawals from the MRVAA have increased since the early 1900s and about 96% of the water removal is attributed to irrigation use for agriculture (Reba et al. 2014). Seventy-five percent of the irrigated area is under furrow irrigation. The furrow irrigation method is less efficient in terms of water savings as it results in deep percolation losses and tail-water runoff, which further elevates the water depletion issue in the Delta region. Based on our survey results, producers in the Mississippi Delta acknowledged that there is a water depletion issue in the Delta. Depletion of the aquifer groundwater is the most important water-related issue in the Delta followed by the wasting of irrigation water. The third most important water-related issue is the lack of alternative water supplies. This indicates that producers are interested in exploring and using alternative options for meeting irrigation water needs. However, a small percentage (28.5%) of the respondents acknowledged that there is not enough groundwater in the Delta. Most of the respondents believe that water is not managed properly, but there is enough water in the Delta. The survey conducted in 2012 helped in understanding the perception about value and availability of water by the farmers. The survey results indicate the need to develop and adopt better crop and water management strategies that will conserve water and increase irrigation water use efficiency. Currently, farmers have multiple technologies for better irrigation water management, such as computer-hole-selection (CHS), surge valve flow irrigation (SURGE), tailwater recovery systems, on-farm water storage, sprinkler irrigation systems, and sensor-based irrigation scheduling.The CHS technology computes the flow and pressures along the length of lay-flat polyethylene tubing and selects optimal hole sizes to improve down-row uniformity across the irrigation set regardless of furrow length (Bryant et al. 2017; Spencer et al. 2019). Sensor thresholds for irrigation scheduling for soybean (*Glycine max* L.), corn (Zea mays L.), cotton (*Gossypium hirsutum* L.), and peanuts (*Arachis hypogaea*) have been developed by the researchers at the Mississippi State University (Williams et al. 2018; Leininger et al. 2019).

Survey respondents provided an economic value of irrigation water in dollars for producing corn, soybean, and cotton. However, more respondents (41%) indicated that the value of irrigation water for corn was greater than $741 per ha ($300 per acre) than they did for cotton (28.9%) or soybean (26.4%). This is possibly due to greater water requirements for corn than for other crops. A study by Massey et al. (2017), over a period of 12-years (2002-2013), reported that the irrigation rates were greater for corn (3100 m^3 ha^{-1}), followed by soybean (2800 m^3 ha^{-1}), and cotton (1800 m^3 ha^{-1}) in the Mississippi Delta. The same study reported no change in irrigation rates for cotton over time, but increases were observed for corn and soybean irrigation rates over time by approximately 200 m^3 ha^{-1} yr^{-1}. The largest share of cotton producers (31.3%) reported that the economic value of irrigation water for cotton production is less than $247 per ha ($100 per acre). For soybean, the economic value of irrigation water varied widely with similar shares across the available category responses.

Survey responses indicated that the severity of water-related issues varied across the Delta. More respondents thought that there was a water shortage in the central Delta than believed that there was a shortage of water in the north and south Delta. Similarly, more respondents expect to see future water shortages in the central Delta than in the north and south Delta regions. This might be due to higher rice production in the counties in the central Delta region, as the water requirement of rice is greater than other crops including corn, soybean, and cotton. Massey et al. (2017) reported that the irrigation rate for rice was 9200 m^3 ha^{-1}, whereas the rates were 3100, 2800, and 1800 m^3 ha^{-1} for corn, soybean, and cotton, respectively, averaged over 12 years in the Mississippi Delta region. Smith et al. (2007) reported irrigation water use was 721 and 895 mm in rice production systems in Arkansas and Mississippi, respectively, when data was averaged over two years (2003-2004). The higher rate of alluvial aquifer decline was associated with areas of intensive aquaculture and rice production with approximately 268 mm yr^{-1} in Mississippi (Pennington 2005; Young and Sweeny 2005). These survey results indicate that farmers in the central Delta may benefit from increased emphasis on education and extension programs concerning water conservation practices and improved irrigation practices. To save water, a majority of farmers agreed that regulations are needed for water use in the Delta, however, such regulations were expected to negatively impact agriculture production in the Delta region. Regulation of irrigation water use could limit the amount of water that farmers can pump from the MRVAA and, consequently, reduce crop yields. Cotton was the predominant crop in the Mississippi Delta with 53,000 ha in 2000; however, cotton production has been declining in recent years with only 18,000 ha of land under cotton in 2021 (USDA-NASS 2021) due to lower economic returns and introduction of irrigated corn and soybean crops. However, any regulation on irrigation water use in the future might result in reversing this trend as corn and soybean have higher water requirements than cotton. To date, no volumetric or pecuniary regulations have been imposed on groundwater users. Regulation on water use for irrigation might include restrictions on the amount of water withdrawals from wells for irrigation. Imposition of regulatory controls would encourage producers to use alternatives such as tailwater recovery systems, on-farm water storage, and surface water bodies as water sources, adopt more efficient irrigation systems, or use crop management practices that will conserve water, e.g., improve water infiltration into the soil and increase soil water holding capacity and reduce surface runoff losses.

Conclusion

The survey results presented in this article evaluated the perceptions of crop producers about irrigation water availability and its value. The majority of survey respondents in the Mississippi Delta recognized that irrigation is necessary for farming in this region. Irrigation was also considered as the main cause of water declines in the MRVAA. Water level declines might result in a water shortage for irrigation in the future if proper conservation measures are not implemented. This survey provided important information to the scientists at the Mississippi State University and the USDA which will be used to develop programs for water conservation in the Mississippi Delta for sustainable water management. However, the target population included all permit holders, landowners, and operators (producers) who withdraw water (surface and groundwater) for agricultural irrigation in the Yazoo-Mississippi Delta region. One of the limitations of this survey is that only 26% of the sample population used in the study completed the survey. Therefore, future surveys in the area should pay attention to the selection of the population sample for the survey and include more numbers of producers to get opinions about the value for water in the Delta region of Mississippi.

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Author Bio and Contact Information

Dr. Gurpreet Kaur (corresponding author) is an Assistant Professor at the University of Missouri Northern Missouri Research, Extension, and Education Center in Novelty, MO. Dr. Kaur received her Ph.D. degree in Natural Resources from the University of Missouri in 2016. Dr. Kaur can be contacted at gk478@missouri.edu or by mail at Lee Greenley Jr. Memorial Research Farm, 64399 Greenley Place, Novelty, MO 63460.

Dr. Nicolas E. Quintana Ashwell is an Assistant Professor and Natural Resource Economist at the National Center for Alluvial Aquifer Research, Mississippi State University. Dr. Quintana received his Ph.D. degree from Kansas State University. Dr. Quintana's research is focused on improving academic and stakeholder understanding of the economic factors that drive the decline of an aquifer in an area with abundant precipitation and surface water sources. Dr. Quintana can be contacted at n.quintana@msstate.edu or by mail at National Center for Alluvial Aquifer Research, 4006 Old Leland Road, Leland, MS 38756.

Dr. Gurbir Singh is an Assistant Professor at the University of Missouri Northern Missouri Research, Extension, and Education Center. Dr. Singh received his Ph.D. degree in Agricultural Sciences from Southern Illinois University in 2018 and M.S. degree in Soil, Environmental, and Atmospheric Sciences from the University of Missouri in 2013. Dr. Singh can be contacted at singhgu@missouri.edu or by mail at Lee Greenley Jr. Memorial Research Farm, 64399 Greenley Place, Novelty, MO 63460.

Dr. Drew Gholson is an Extension Irrigation Specialist at the Delta Research and Extension Center, Mississippi State University and Coordinator for the National Center for Alluvial Aquifer Research. Dr. Gholson received his Ph.D. from Texas A&M University. Dr. Gholson can be contacted at drew.gholson@msstate.edu or by mail at Delta Research and Extension Center, 82 Stoneville Road, Stoneville, MS 38756.

Dr. Martin A. Locke is the director of the USDA-ARS National Sedimentation laboratory, Oxford, MS. Dr. Locke received his Ph.D. degree in Soil Science from Texas A&M University and M.S. degree from the University of Missouri. Dr. Locke's research is focused on assessing the impact and value of conservation management practices and their influence on environmental quality. Dr. Locke can be contacted at martin.locke@usda.gov or by mail at National Sedimentation Laboratory, 598 McElroy Drive, Oxford, MS 38655.

Dr. L.J. Krutz is the director of the Mississippi Water Resources Research Institute, Mississippi State University. Dr. Krutz received his Ph.D. from Texas A&M University. Dr. Krutz can be contacted at ljk81@msstate.edu or by mail at MS Water Resources Research Institute, 207 Ballew Hall, Mississippi State, MS 39762.

Trey Cooke works for The Nature Conservancy, Cleveland, MS. Mr. Cooke can be contacted at trey.cooke@tnc.org.

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Appendix 1. Survey questions and their respective answer choices.

Question	Response
Are you a:	a) Landowner only b) Landowner & operator c) Operator only d) Other e) Don't know/not sure f) Refused
Please tell me whether you grow and irrigate each of the following crops: corn, cotton, soybeans, rice, other crops	a) Yes b) No c) Don't know/not sure d) Refused
What other crops do you grow and irrigate?	a) None b) Don't know/not sure c) Refused
Please tell me whether you strongly disagree, disagree, neither disagree nor agree, agree, or strongly agree with the following statement: • It would be difficult to farm without irrigation water	a) Strongly disagree b) Disagree c) Neither disagree nor agree d) Agree e) Strongly agree f) Don't know g) Refused
Please rank the following water issues in order of priority. Which one you would rank as the most important, second most important, third most important and so on?	• Flooding • Depletion of the groundwater aquifer • Lack of alternative surface water supplies • Wasting irrigation water • Lack of stream flow • Don't know/not sure • Refused

Appendix 1 Continued.

Question	Response
What is the value of irrigation water in terms of dollars per acre in producing following crops on your farm? Would you say? • Corn • Soybean • Cotton	a) Less than $100 per acre b) $100 to $200 per acre c) $200 to $300 per acre d) More than $300 per acre e) Don't know/Not sure f) Refused g) Doesn't apply (doesn't grow)
Next, I am going to read some statements about water conservation, for each one please tell me if you strongly disagree, disagree, neither disagree nor agree, agree, or strongly agree. • Regulations on water use are needed to protect the aquifer and ensure water will be available in the future • Self-regulation by farmers can protect the aquifer from overuse and ensure water will be available in the future • There is not enough groundwater in the Delta to satisfy all the irrigation needs • Regulations on water use will hurt agriculture • There is currently sufficient water in the Delta, but we aren't managing it properly • Agricultural irrigation water use is the primary cause of the groundwater depletion	a) Strongly disagree b) Disagree c) Neither disagree nor agree d) Agree e) Strongly agree f) Don't know g) Refused
For the following locations, please tell if you would describe the current water situations as having a water crisis, water shortage, or water abundance? • The land you own • The land you rent • North Delta • Central Delta • South Delta • Delta-wide	a) Water crisis b) Water shortage c) Water abundance d) Don't know e) Refused f) Does not apply
For which of these same locations, do you anticipate a future water shortage: • The land you own • The land you rent • North Delta • Central Delta • South Delta • Delta-wide	a) Yes b) No c) Don't know d) Refused e) Does not apply

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Single and Multispecies Cover Crop Effects on Corn Production and Economic Returns

Bhupinder Singh[1], Gurpreet Kaur[2], *Gurbir Singh[2], Jagmandeep S. Dhillon[3], and Nicolas Quintana Ashwell[4]

[1]*Texas A&M Agrilife Research and Extension Center, Vernon, TX*
[2]*Northern Missouri Research, Extension, & Education Center, University of Missouri, Novelty, MO*
[3]*Department of Plant and Soil Sciences, Mississippi State University, Mississippi State, MS*
[4]*National Center for Alluvial Aquifer Research, Mississippi State University, Stoneville, MS*
**Corresponding Author*

Abstract: The adoption of cover crops (CCs) has gained popularity in the continuous corn (*Zea mays* L.) production system due to their multiple benefits including scavenging or fixing nitrogen (N) in the soil. However, a CC's ability to develop early cover, scavenge N, and provide N to the following cash crop is species-dependent and affected by environment. A field study was conducted in three diverse environments to determine growth characteristics of nine CC treatments (i.e., monocultures or mixes of grasses, legumes, and brassica), and their effect on the following corn crop was compared to no cover crop treatment (noCC). Cover crops significantly differed for above-ground biomass, plant tissue carbon (C) and N concentrations, carbon to nitrogen ratio (C/N), and total N uptake (TNU). Among monocultures, grasses had the highest biomass and C/N ratio, and legumes had the highest N concentrations and TNU. Corn grain yield was highest following radish, whereas lowest corn yield was found following cereal rye + crimson clover mix in environment 1. Cover crops varied for C/N ratios in all three environments, but only affected corn plant height (PH) and grain yield in one environment. Cover crops belonging to the same species also exhibit different responses for characteristics measured, depending upon the environment. The expected returns were also variable, especially in CC mixes. The study provides valuable information on the species-specific functionality of CCs in continuous corn under variable environmental conditions. The information will benefit future studies to explore a high diversity mixture of CCs that may outperform across all three environments.

Keywords: *cereal rye, wheat, crimson clover, hairy vetch, radish, turnip*

Corn was ranked as the second main crop in Mississippi (MS) after soybean (*Glycine max* L.), with its economic value to the state estimated at $665 M in 2021 (USDA NASS 2021a). Corn was planted on 0.3 million ha in MS with total production of 3.2 million metric tons in 2021 (USDA NASS 2021a). Corn yields vary across MS because of crop and irrigation management practices. The non-irrigated corn yield in 2021 averaged 11.9 Mg ha^{-1} across MS. Irrigated corn is predominantly produced in the Delta region of the state with an average yield of 14.6 Mg ha^{-1} in 2021 (MSU 2021). Despite variable yield, the net returns across the state varied within ± $30, with the highest of $366 ha^{-1} and lowest of $336 ha^{-1} for irrigated and non-irrigated corn, respectively (Gregory 2020).

Research Implications

- Cover crops provide multiple benefits and help with soil and water conservation.
- Cover crop mixes showed no improvement in the corn yield over the cover crop monocultures.
- Benefits of cover crops on corn production depend upon the environment.

Farmers of the U.S. Mid-South made a quick shift from cotton to corn production with the introduction of the Farm Bill in 1995 (Sanchez

2016). Initially, the shift was from a continuous cotton production system to a continuous corn production system, until 2007. Corn production was increased from 121,000 ha in previous years to 376,000 ha in MS in 2007 with a 50% reduction in cotton acreage (USDA NASS 2021b). Corn yield was greatly increased primarily due to improved genetic and management practices (Duvick 2005). After 2007, biennial rotation of soybean and corn gained interest due to ease of management when compared to cotton. Cotton requires intensive efforts to manage foliage growth continuing even after it creates a seed, due to its indeterminate perennial growth habit. However, many corn farmers skip rotation and engage in corn monocropping, especially when the market returns for corn are higher (Wang and Ortiz-Bobea 2019).

Continuous corn production has a risk of yield drag due to cooler and wetter soils, nitrogen (N) immobilization, increased disease pressure, and allelopathy (Gentry et al. 2013). Past studies have reported a yield reduction ranging from 2 to 29% in continuous corn compared to corn following soybean (S-C) (Peterson and Varvel 1989; Porter et al. 1997; Wilhelm and Wortmann 2004). Among various factors, N immobilization plays a dominant role in yield penalty in continuous corn production compared to S-C rotation (Stanger and Lauer 2008). Long-term research in Iowa showed corn yields averaged only about 3.7 Mg ha^{-1} for continuous corn compared to 7.2 Mg ha^{-1} for S-C, when corn was not fertilized with N (Sawyer and Randall 2008). Therefore, cover crops (CCs) in a continuous corn production system can act as a rotational crop and may provide benefits like a two-year S-C rotation (Torbert et al. 1996; Dapaah and Vyn 1998; Gentry et al. 2013). Cover crops can substantially enhance N availability to subsequent corn in both till and no-till systems, however, their benefits are species-dependent. The species-specific N credits from legume and non-legume to corn were mainly quantified in terms of growth, biomass production, and yields in the past. For instance, Dapaah and Vyn (1998) reported that corn planted following ryegrass *(Lolium multiflorum* L.) was shorter in height with fewer leaves and less biomass compared to corn following red clover *(Trifolium pratense* L.). They also reported that corn yielded highest following red clover compared to ryegrass, oilseed radish *(Raphanus sativus* L.), and no cover crop (noCC). Torbert et al. (1996) reported a 7 to 22% increase in corn yield at the highest fertilizer N application level following crimson clover, compared with noCC. In addition, CCs help reduce nutrient losses from agricultural fields, improve water quality, and increase N supply for succeeding crops (Sanchez 2016). Martinez-Feria et al. (2016) reported that planting cereal rye reduced 26% nitrate-nitrogen (NO_3-N) losses without consistently reducing corn yields. Cover crops can be extremely beneficial in MS since its rainfall is greatest during the non-cash crop growing season from October to April (Tang et al. 2018), which can increase soil erosion, runoff losses, and nutrient leaching.

Cover crops used in the U.S. can generally be categorized into three groups: grasses, legumes, and brassica. Grasses produce a large volume of root biomass, are good in scavenging soil N, and fit well in a no-till system. However, they have a high carbon to nitrogen ratio (C/N) in their residues (Kaye et al. 2019). On the other hand, residues of legumes and brassica decompose more rapidly in the spring, due to a low C/N ratio compared with grasses (Kaye et al. 2019). Additionally, legumes are valued for their ability to fix N, which can benefit the succeeding crop. Multispecies CCs can have superior performance over monoculture CCs. For instance, a mix of grasses and legumes could allow quick soil cover and N scavenging by grasses, and N additions and quick residue break down by the legume. Hence, investigating region-specific selection, integration, and management of CCs in a continuous corn production system is crucial to determine the full potential of corn yield based on past advancements.

Cover crop benefits are long-term while the costs are upfront. Early CC performance is an important determinant in whether a farmer adopts the practice permanently or is discouraged by early results and prematurely drop the practice. These early results provide important information for conservation agencies sponsoring CC programs. Only about 30% of MS farmers have opted to implement CCs, according to a recent survey of irrigators in MS (Quintana-Ashwell et al. 2020). The overall objective of this study was to determine the effect of monocultures and multispecies overseeded CCs on the growth, yield, and quality of the following corn crop, and to estimate the production cost and expected returns from CC monocultures and multispecies mixes under diverse growing conditions. We hypothesized that CCs' performance and their effect on corn growth and development depend on the type of CCs.

Materials and Methods

Site Description and Experimental Layout

The experiment was conducted at two research sites for three years: Stoneville, MS (33°25'42.6"N, -90°57'13.5"W) in 2019-2020 and 2020-2021; and Starkville, MS in 2020-2021 (33°28'40.1"N, -88°47'13.2"W) (Table 1). The combinations of experimental site and year for the duration of CC or corn were referred to as environments. From this point in the article, environment 1 refers to Stoneville during 2019-2020, environment 2 refers to Stoneville during 2020-2021, and environment 3 refers to Starkville during 2020-2021 (Table 1). The dominant soil series at the Stoneville site was classified as Bosket very fine sandy loam (Fine-loamy, mixed, active, thermic Mollic Hapludalfs). Bosket very fine sandy loam is well-drained soil with moderately high saturated hydrologic conductivity and moderate permeability. The dominant soil series at the Starkville site was classified as Leeper silt clay loam (Fine, smectitic, nonacid, thermic Vertic Epiaquepts). Leeper silt clay loam is a somewhat poorly drained soil with very slow saturated hydraulic conductivity that occasionally causes flooding. The weather data for research sites were obtained from Mississippi State University's North Farm Starkville station and Stoneville West station of The Delta Agricultural Weather Center (MSU 2016). The data included average monthly temperatures, mean monthly solar radiations, and monthly total precipitation for three environments (Figure 1). The 30-year average annual minimum and maximum temperatures were 12.1°C and 23.6°C, respectively. The 30-year average annual precipitation received at the research site was 1406 mm.

The experimental layout was a randomized complete block design, with four replications of ten CC treatments randomly planted in each environment. The ten treatments included in this study were: noCC, cereal rye (*Secale cereale* L.), wheat (*Triticum aestivum* L.), crimson clover (*Trifolium incarnatum* L.), hairy vetch (*Vicia villosa* L.), radish (*Raphanus sativus* L.), cereal rye + crimson clover, wheat + crimson clover, hairy vetch + radish, and wheat + radish + turnip (*Brassica rapa* subsp. rapa L.). The seeding rates for cereal rye, wheat, crimson clover, hairy vetch,

Table 1. Dates for field operations and data collection during the experimental period.

Environments	Year	Location	Crop	Tillage	Planting	N-Fertilizer Split Application		Biomass Collection	Cover Crop Termination or Corn Harvest
						1st	2nd		
1	2019	Stoneville	Cover crops	3 Oct. 2019	03 Oct. 2019	‡	‡	28 Feb. 2020	28 Feb. 2020
2	2020	Stoneville	Cover crops	3 Oct. 2020	07 Oct. 2020	‡	‡	10 Mar. 2021	11 Mar. 2021
3	2020	Starkville	Cover crops	1 Sep. 2021	16 Sep. 2021	‡	‡	10 Mar. 2021	24 Apr. 2021
1	2020	Stoneville	Corn	‡	03 Apr. 2020	29 Apr. 2020	05 May 2020	‡	03 Sep. 2020
2	2021	Stoneville	Corn	‡	16 Mar. 2021	05 Apr. 2021	14 May 2021	‡	17 Aug. 2021
3	2021	Starkville	Corn	‡	07 May 2021	28 May 2021	18 June 2021	‡	14 Sep. 2021

‡No data.

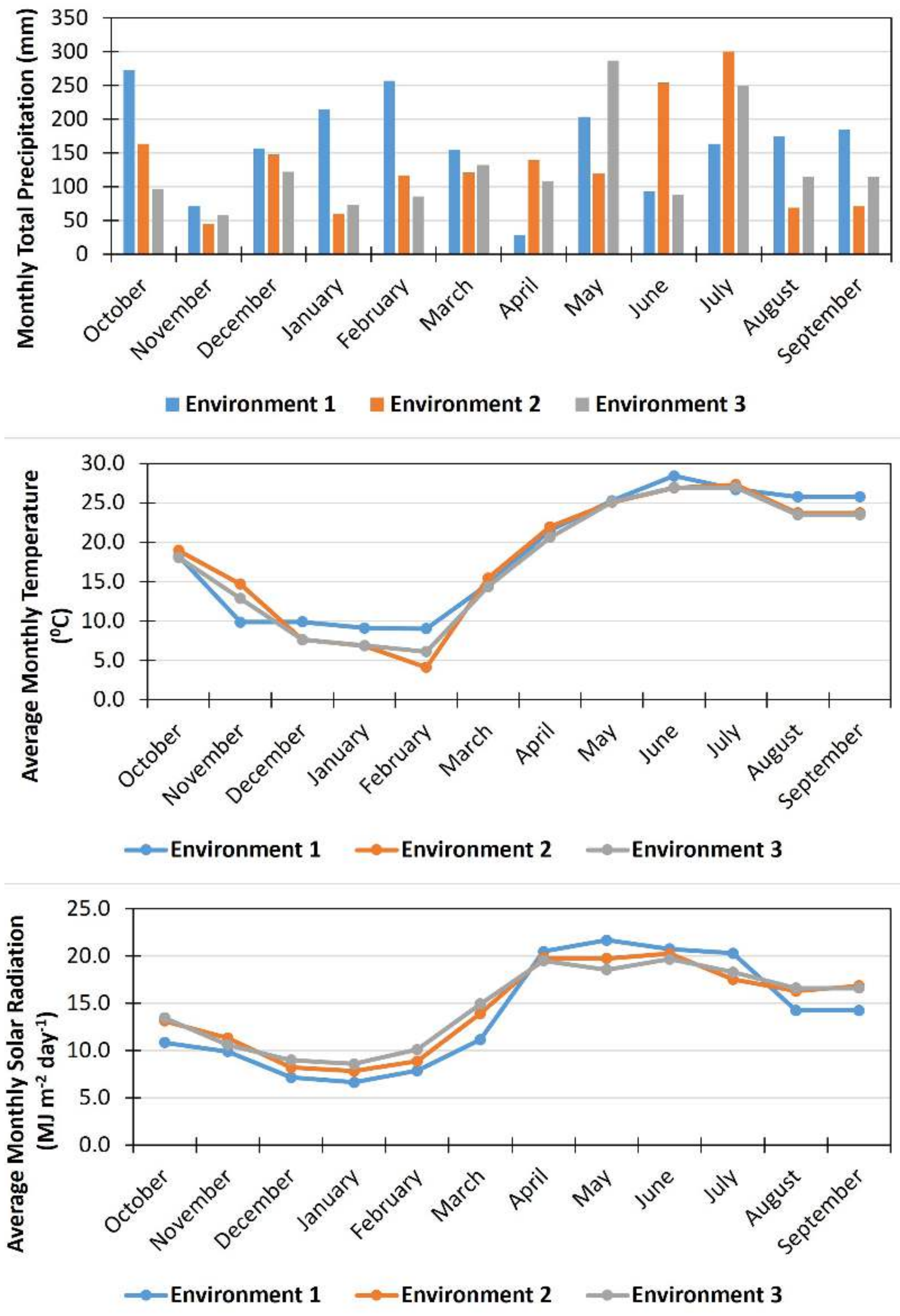

Figure 1. Monthly total precipitation, average monthly air temperature, and monthly solar radiation data recorded across three environments.

radish, hairy vetch + radish, and wheat + radish + turnip were 67.25, 67.25, 8.97, 22.47, 8.97, 11.21 + 4.48, and 44.83 + 4.48 + 2.24 kg ha^{-1}, respectively. Cereal rye + crimson clover and wheat + crimson clover CCs were planted at a seeding rate of 33.63 + 4.48 kg ha^{-1}. Each treatment plot was four rows wide with an inter-row spacing of 1.016 m in environments 1 and 2, and 0.965 m in environment 3. The plot size for every treatment was 4.06 m x 9.14 m in environments 1 and 2, and 3.86 m x 9.14 m for environment 3.

Field and Crop Management

The CCs were planted as monoculture or multispecies in fall 2019 and 2020 at Stoneville, and in fall 2020 at Starkville. The details of field and crop management at the three environments are given in Table 1. Tillage was performed in the experimental fields in the fall before aerial seeding or overseeding of CCs. The experiment fields were tilled using one pass of a stalk shredder, followed by at least two passes of disking, one pass of a field cultivator, and then finally hipped using a bedder roller. The CCs were overseeded on the ground after the tillage operations using a hand spreader. The CCs selected belonged to one of three groups based on species: grasses (cereal rye and wheat), legumes (hairy vetch and crimson clover), or brassica (radish and turnip). Cover crops in all three environments were terminated using Roundup Weathermax [glyphosate, N-(phosphonomethyl) glycine] at 1.89 kg a.e. ha^{-1}, 2,4-D (2,4-dichlorophenoxyacetic acid) at 0.80 kg a.e. ha^{-1}, and Scanner 0.25 v/v in the spring before planting corn.

Soil samples were collected from 0 to 30 cm depth in the fall before planting CCs, to analyse for physical and chemical soil properties of the field sites. The soil analysis results are reported in Table S1. Following the termination of CCs in the springs of 2020 and 2021 at the three environments, the corn cultivar Dekalb DK 70-27 (*DEKALB*®) was planted using a John Deere 1710 Maxemerge XP eight row seed drill. Fertilization, tillage, and weed management for corn were conducted according to Mississippi State University Extension Service recommendations. Nitrogen fertilizer was applied as preemergence and as a split application around V4-5 corn growth stage, while the phosphorus (P) and potassium (K) fertilizers were applied as a single application before tillage operations in the fall. Corn planted in environment 1 received NPK fertilizers at a rate of 278 kg N ha^{-1} as 32% urea ammonium nitrate (UAN), 20 kg P ha^{-1} as triple superphosphate (TSP), and 40 kg K ha^{-1} as Muriate of Potash (MOP). Environments 2 and 3 received a total of 263 kg N ha^{-1} as 32% UAN, 56 kg P ha^{-1} as TSP, and 112 kg K ha^{-1} as MOP. The biomass data were collected from both CCs and corn for all three environments (Table 1). The field sites received preemergence herbicide application of Lexar EZ [(S-Metolachlor, 2-chloro-N-(2-ethyl-6-methylphenyl)-N-(1-methoxypropan-2-yl) acetamid + Mesotrion, 2-[4-(Methylsulfonyl)-2-nitrobenzoyl]cyclohexane-1,3-dione + Atrazine, 6-Chloro-N^2-ethyl-N^4-(propan-2-yl)-1,3,5-triazine-2,4-diamine)] at 3.11 kg a.i. ha^{-1} plus scanner 0.25 v/v and a postemergence application of Halex GT [(S-Metolachlor, 2-chloro-N-(2-ethyl-6-methylphenyl)-N-(1-methoxypropan-2-yl) acetamid + Glyphosate, N-(phosphonomethyl) glycine + Mesotrione, 2-[4-(Methylsulfonyl)-2-nitrobenzoyl]cyclohexane-1,3-dione + Atrazine, 6-Chloro-N^2-ethyl-N^4-(propan-2-yl)-1,3,5-triazine-2,4-diamine)] at 2.21 kg a.i. ha^{-1} plus scanner 0.25 v/v for weed management.

Data Collection and Analysis

Above-ground biomass samples of CCs and winter weeds (noCC) were collected from a 0.19 m^2 area before CC termination by clipping all plant biomass above the ground (Table 1). The samples collected were dried at 60°C until the constant dry weight was achieved. Dried samples were weighed, ground using a Wiley Mill (Thermo Scientific), and sifted using a 0.5 mm sieve. Sieved subsamples were analysed for C and N concentrations using dry combustion followed by gas chromatography (Flash 2000, organic elemental analyser, Thermo Scientific). The total N uptake (TNU) was then calculated by multiplying the N concentration with dry weight. The C/N ratio was also determined by dividing C concentration by the N concentration of the sample.

At physiological maturity, the mean plant height (PH) of corn was recorded from 1-m row length from each plot at all three environments. A FieldScout CM 1000 Chlorophyll Meter was used for measuring the chlorophyll index, a measure of relative greenness, of the ear leaf. Corn yield, test weight, and moisture were determined by harvesting the middle two rows along the entire plot length using a plot combine (Kincaid 8xp; Haven, KS) equipped with a harvest master H_2 yield monitor (Juniper Systems; Logan, UT). The grain yield obtained was adjusted to 15.5% grain moisture before data analysis. Grain samples of 500 to 600 g were collected at the time of harvesting from each plot to analyse for grain quality, including oil, protein, and starch content with Near-infrared (NIR) spectroscopy using the Foss Infratec 1241 grain analyzer (Hilleroed, Denmark). After analysing grain quality, the grain samples were also used to measure seed index (SI) by measuring the weight of 100 grains.

Statistical and Economic Analysis

Data collected during the season were analysed using the GLIMMIX procedure in SAS 9.4 (SAS Institute, Cary, NC). The CC and environment were considered as fixed effects and replication as random effects. The environmental effect was significant for all the traits but protein (Table 2). Therefore, data were reanalysed to determine the influence of CCs on corn growth and development for each environment separately (Tables 3 and 4). Post hoc differences were determined using Fisher's Least Significant Difference ($\alpha = 0.05$). The expected farm revenue was calculated by multiplying the yields under each treatment by the average (average of two years, 2020 and 2021) bid price for corn reported by the U.S. Department of Agriculture (USDA) Economics, Statistics and Market Information System (ESMIS) for county elevators in Greenville, MS, at \$221.65 Mg^{-1}. Partial budget analyses were performed to compare the profitability implications of different CC treatments to the returns and variability associated with the noCC system. The production cost estimates were obtained from the 2022 crop planning budgets published by the Mississippi State University's Department of Agricultural Economics (MSU 2022), which employed prices for the year 2021. Since the corn planning budgets for corn are only generated for production on 76.2 and 95.5 cm row spacing, a space factor was created, and the budget was adjusted to account for 101.6 cm row spacing. The relationship between risk and returns exploited the variability reported for the yields to calculate the variability in returns.

Results

Weather Data

The highest average monthly temperature was in July for Environments 2 and 3, whereas it was in June for environment 1. The lowest average monthly temperature was in February for all three environments (Figure 1). The average monthly temperature in June was 1.5^{o}C higher in environment 1 than environments 2 and 3. The average monthly temperature in December and January was 2.2^{o}C higher in environment 1 than the other two environments. Similarly, the monthly temperature in February was also 4.9 and 2.9^{o}C higher in environment 1 than the environments 2 and 3, respectively.

Average monthly solar radiation was lower for environment 1 than the other environments from October to March (Figure 1). However, solar radiation was higher in environment 1 than the other two environments in May and July. The total monthly precipitation from October to September was 367 and 445 mm greater for environment 1 (1,978 mm) than environments 2 (1,611 mm) and 3 (1,533 mm), respectively (Figure 1). The monthly total precipitation received during the CC growing season from October to March was 473 and 559 mm higher in environment 1 (1,129 mm) than environments 2 (656 mm) and 3 (569 mm), respectively. January and February accumulated at least 100 mm more precipitation in environment 1 than the other two environments. The highest environmental variation in monthly total precipitation occurred in January, February, June, and July.

Cover Crop Biomass, Plant Tissue Nitrogen, Carbon, and C/N Ratios

Environments 1 and 3 had significant variation in CC biomass, N, C, and C/N ratio, but environment 2 exhibited only variation for C/N ratio (Table 3).

Biomass. In environment 1, all CC monocultures and mixtures had 2092 to 4830 kg ha^{-1} greater biomass production than noCC, except crimson

Table 2. P-values from statistical analysis showing the effects of cover crops and environments on data collected during the studies conducted in Mississippi.

Source of Variation	Cover Crop					Corn								
	Biomass	C†	N	C/N	TNU	PH	CI	GM	TW	SI	Yield	Oil	Protein	Starch
E	0.0082	<0.0001	<0.0001	<0.0001	0.0017	<0.0001	0.0013	<0.0001	<0.0001	<0.0001	0.0002	<0.0001	0.7844	<0.0001
CC	0.0900	<0.0001	<0.0001	<0.0001	0.0203	0.0178	0.2345	0.3970	0.9500	0.4400	0.5542	0.5300	0.4809	0.7100
E × CC	0.3748	<0.0001	<0.0001	0.0964	0.2235	0.6014	0.7007	0.5432	0.9700	0.0900	0.0485	0.6100	0.4933	0.9000

E, environment; CC, cover crop; C, carbon concentration; N, nitrogen concentration; C/N, carbon to nitrogen ratio; TNU, total nitrogen uptake in biomass; PH, plant height; CI, Chlorophyll index; GM, grain moisture; TW, test weight; SI, 100 seed weight. P-values showing significant differences have been underlined and where interaction is significant, only interaction p-values have been underlined.

clover, hairy vetch, and wheat + crimson clover mix (Table 4). No differences in biomass were observed among wheat, cereal rye, and radish, and on average they were 82% higher in biomass production than the crimson clover and hairy vetch legume CCs (Table 4). Growing hairy vetch in a mix with radish resulted in greater biomass production than the hairy vetch monoculture whereas growing wheat in a mix with crimson clover had lower biomass (1259 kg ha^{-1}) compared to growing wheat as monoculture (2405 kg ha^{-1}). No differences were observed in between cereal rye and radish biomass when planted as monocultures or as a mix.

Except monoculture hairy vetch and crimson clover, all other CCs planted whether as monoculture or mix had greater biomass production than noCCs in environment 3 (Table 4). The biomass of legume monoculture CCs (crimson clover and hairy vetch) was 62% less than the average biomass of wheat, cereal rye, and radish monocultures. Among CC mixes, crimson clover legume when planted with cereal rye showed a 64% increase in biomass than monoculture crimson clover (Table 4). Cereal rye + crimson clover had the highest biomass production in environment 3, however, it was not significantly different from the wheat + radish + turnip mix and wheat, radish, and cereal rye monocultures CCs. Further, no differences were observed in biomass when grasses and brassica were planted as mix or as single species in all three environments (Table 4). In contrast, wheat showed a 33% decline in biomass when mixed with crimson clover than its monoculture although the difference was not significant.

Plant Tissue Nitrogen Concentration and Uptake. Significant differences in N concentrations among CCs were observed in environments 1 and 3 (Table 3). The lowest plant tissue N concentration was obtained for weeds in noCC treatment. In the case of CC monoculture, radish consistently maintained higher N in both environments 1 and 3 (Table 4). In environment 1, radish planted as monoculture had 49, 57, 70, and 77% higher N concentrations than cereal rye, wheat, crimson clover, and hairy vetch monocultures, respectively (Table 4). Crimson clover, hairy vetch, and noCC showed the lowest N, averaging 9 g kg^{-1} for environment 1. In environment 3, radish and hairy vetch had

Table 3. P-values from statistical analysis showing the cover crop effects on the data collected during the experiment and separated for each environment.

Data Collected	Environment 1	Environment 2	Environment 3
Cover Crop			
Biomass	<0.0001	0.3731	<0.0001
Carbon (C) Concentration	<0.0001	0.5402	<0.0001
Nitrogen (N) Concentration	<0.0001	0.2715	<0.0001
Carbon / Nitrogen Ratio	<0.0001	0.0108	0.0003
Total Nitrogen Uptake	<0.0001	0.1209	<0.0001
Corn			
Plant Height	0.0163	0.6855	‡
Chlorophyll Index	0.1272	0.3556	‡
Grain Moisture	0.6249	0.9206	0.4200
Yield	0.0232	0.4292	0.2674
Test Weight	0.6230	0.0195	0.9700
Seed Index	0.1181	0.8221	0.0226
Oil	0.5131	0.5763	0.3200
Protein	0.8321	0.6280	0.3528
Starch	0.8167	0.0311	0.7700

P-values showing significant differences have been underlined.
‡No data collected.

an average of 20% greater N concentrations than crimson clover, wheat, and cereal rye (Table 4). A CC mix of hairy vetch + radish showed no change for N concentration from radish monoculture in environment 1, while the N concentration of this mix declined by 21% compared to the hairy vetch and radish monocultures in environment 3. The N concentration of cereal rye + crimson clover mix was greater than monocultures of cereal rye and crimson clover in environments 1 and 3. The three-way mix of wheat + radish + turnip had a slight improvement in N concentration compared to monoculture wheat in environment 1. No differences were observed for N concentration among CC monocultures, mixtures, and noCC in environment 2 and they averaged 24.1 g kg^{-1} across all treatments (Table 4).

Like biomass, CCs showed a significant difference for TNU in environments 1 and 3 (Table 3). In both environments, the decreasing order of TNU in the CC monocultures was in the order of: brassica > grasses > legumes. Among CC monocultures, radish (172.8 kg ha^{-1}) and cereal rye (63.3 kg ha^{-1}) had higher TNU followed by wheat (34.8 kg ha^{-1}) in environment 1, whereas significantly lower TNU was found in hairy vetch, crimson clover, and noCC (Table 4). Total nitrogen uptake was similar among all mixes except for wheat + crimson clover, which had 122 and 145 kg ha^{-1} lower TNU than the wheat + radish + turnip and hairy vetch + radish mixes, respectively in environment 1 (Table 4). In environment 3, the highest TNU was obtained in the CC mix of cereal rye + crimson clover (200.24 kg ha^{-1}), while the lowest was obtained in noCC (32.36 kg ha^{-1}) (Table 4). The combination of cereal rye + crimson clover outperformed for TNU among all treatments, except wheat + radish + turnip and radish (Table 4). All other CC mixes showed no improvement in TNU over CC monocultures. Among CC mixes in environment 3, the lowest TNU accumulated was in the wheat + crimson clover mix. The trend of low TNU for wheat + crimson clover mix was similar to that of environment 1 (Table 2).

Carbon to Nitrogen Ratio (C/N). Cover crops significantly differed for C/N ratios in all three environments, with the highest being in grasses and the lowest in single-planted or mix of hairy vetch

Table 4. Cover crops biomass production, C and N concentration, C/N ratio, and total nitrogen uptake as affected by the cover crop treatments in three environments.

Treatment	Biomass kg ha^{-1}	C g kg^{-1}	N g kg^{-1}	C/N ratio	TNU kg ha^{-1}
			Environment 1		
No Cover Crop	313±101c†	98.7±80b	9.3±7d	7.78±1f†	3.64±1c
Cereal Rye	3,584±1,600a	256.8±50a	18.0±3c	14.07±1ab	63.26±23ab
Wheat	2,405±660a	249.8±13a	15.6±8cd	15.72±1a	34.81±17b
Crimson Clover	765±634bc	123.5±40b	10.5±3d	11.77±1bcd	7.92±1c
Hairy Vetch	489±295bc	88.7±20b	8.0±2d	10.18±1def	4.71±4c
Radish	4,831±1,194a	321.1±10a	35.0±2a	8.96±1def	172.82±41a
Cereal Rye + Crimson Clover	4,247±382a	288.3±40a	21.8±4b	13.34±1abc	91.98±16ab
Wheat + Crimson Clover	1,259±750b	268.1±50a	18.8±4c	14.44±1ab	23±16b
Hairy Vetch + Radish	4,764±1,611a	311.0±10a	35.0±4a	8.77±1ef	168.35±52a
Wheat + Radish + Turnip	5,143±3369a	278.9±20a	26.0±5b	10.79±1cde	144.63±19a
			Environment 2		
No Cover Crop	1,423±1,074	268.2±10.2	21.9±1.1	12.89±2.14abcd	32.85±35.45
Cereal Rye	2,035±731	349.7±2.0	24.6±0.5	14.60±2.41ab	52.77±32.32
Wheat	1,940±822	267.3±3.9	17.5±0.2	15.26±1.37a	34.57±17.59
Crimson Clover	1,809±255	256.1±6.0	19.0±0.6	14.08±2.45abc	33.56±9.99
Hairy Vetch	2,415±280	306.9±5.2	27.9±3	10.92±1.37d	67.73±12.52
Radish	1,733±751	299.4±6.0	25.0±0.3	11.67±1.28cd	45.37±22.23
Cereal Rye + Crimson Clover	2,521±1,085	312.9±5.1	24.0±0.7	13.11±2.35abcd	57.81±11.51
Wheat + Crimson Clover	1,352±444	293.2±9.5	2.6±0.9	13.29±1.41abcd	29.10±11.01
Hairy Vetch + Radish	2,583±1,240	308.5±3.3	28.0±0.3	10.94±0.47d	70.25±30.36
Wheat + Radish + Turnip	2,590±1,342	310.5±2.8	24.6±0.3	12.64±0.73bcd	65.15±35.11
			Environment 3		
No Cover Crop	1,744±1,242f	327.0±3.4e	17.0±0d	18.78±0.1a	32.36±28.00e
Cereal Rye	5,617±861abc	395.0±0.8a	24.8±0c	16.09±0.2abc	140.89±36.05bc
Wheat	5,807±1,705abc	399.4±1.3a	24.0±5c	17.34±0.4ab	134.60±34.56bc
Crimson Clover	2,498±637ef	366.0±1.1cd	24.2±5c	15.68±0.3bc	62.85±29.26ed
Hairy Vetch	3,452±934def	384.0±1.9abc	29.2±3ab	13.31±0.2cd	103.68±36.57cd
Radish	5,442±1,569abc	369.9±0.8bcd	31.5±3a	11.80±0.1d	171.15±50.18ab
Cereal Rye + Crimson Clover	6,940±1,539a	391.9±0.9ab	32.0±7a	14.89±0.5bc	200.24±73.93a
Wheat + Crimson Clover	3,879±1,943cde	393.2±0.6a	28.0±1abc	15.53±0.1bc	101.31±57.30cd
Hairy Vetch + Radish	4,463±1,260bcd	358.6±1.9d	24.0±1c	11.14±0.1d	143.34±39.31bc
Wheat + Radish + Turnip	5,737±564abc	365.1±0.7cd	26.0±3bc	13.78±0.1cd	154.66±30.75abc

†The same letter within a column indicates no significant difference for a given factor or combination of factors ($\alpha = 0.05$). Note: C, carbon concentration; N, nitrogen concentration; C/N, carbon to nitrogen ratio; TNU, total nitrogen uptake in cover crop biomass. The values are means ± standard deviation.

and radish (Tables 3 and 4). The average C/N ratio of grasses was 33% higher than the average C/N ratio obtained in the mix of hairy vetch + radish across all environments (Table 4). The comparison of noCC plots with treatments was highly variable for C/N ratios among environments. For instance, noCC had the lowest C/N ratio in environment 1, whereas environments 2 and 3 had comparable C/N ratios between noCC and CCs. Overall, the CC mixtures did not exhibit any improvement over CC monocultures for C/N ratio.

Corn Growth, Grain Yield, and Quality

Plant Height. In environment 1, corn PH was 8% higher following radish than grasses (wheat and cereal rye) (Table 5). Corn following radish showed a 6% increase in PH compared to corn following crimson clover. No differences in PH were observed between corn following legumes or grasses. The cereal rye + crimson clover CC mixture produced stunted corn plants compared to other CC monocultures and mixtures. In environment 1, corn following CC showed a wide range of PH, varying from 217.4 to 242.3 cm. Also, the noCC had a comparable effect on PH (228.6 cm). Corn height in environment 2 had a narrow range (10.1 cm) of variation among CC treatments.

Grain Yield. Like PH, yield differences among treatments were only significant in environment 1 (Table 3). Cereal rye + crimson clover reduced corn grain yield by 24% compared to the noCC. Corn yields differed by 25.7% among CCs, with the highest following radish (11,520 kg ha^{-1}) and the lowest following the cereal rye + crimson clover mixture (8,561 kg ha^{-1}) (Table 5). The CC mixes over the CC monocultures showed no improvement in the yield.

Grain Quality. Cover crops affected grain quality in environments 2 (test weight (TW) and starch concentration (SI)) and 3 (Table 3). In environment 2, the starch concentration was lowest in the cereal rye + crimson clover CC mix, which was not significantly different from wheat, crimson clover, and wheat + radish + turnip (Table 5). Overall, the average starch concentration among all three environments was within ± 10 of 700 g kg^{-1}, which is close to the standard for grain quality analysis (U.S. Grain Council 2021). In environment 1, no differences were observed in corn TW following grass, legume, and brassica species. However, hairy vetch + radish increased TW by 1.6% than monoculture radish (Table 5). Also, TW was significantly increased (1.6%) by crimson clover + wheat mixture compared to their monoculture stands. Hairy vetch + radish mix showed higher TW than other CC mixes except for crimson clover + wheat mix. Overall, environments 1 and 2 had higher TW in all treatments, including noCC, than the standard set for corn grain quality (72.08 kg hL^{-1}). Environment 3 showed lower TW than the set standard averaging 61.59 kg hL^{-1}. In environment 3, corn following cereal rye or hairy vetch showed lower SI (35.7g) than other single-species CC treatments (38.1 g). Further, the study did not show any improvements in SI with planting multispecies CCs. Unlike TW, corn in environment 1 had the lowest SI of 30.5 g compared to a ~37 g average for the other two environments (Table 5).

Risk and Profit Analysis

The estimated production costs and profits for each treatment in each environment are summarized in Table 6. Table 7 shows the profitability ranking of each treatment in each environment, while table 8 summarizes the overall risk-return combinations for each treatment. The noCC showed the highest level of expected profits overall ($649.50 ha^{-1}), although it was most profitable only under environment 2 ($746.89 ha^{-1}), while it showed the third-highest expected profits under environments 1 ($769.68 ha^{-1}) and 3 ($531.99 ha^{-1}). Crimson clover CC showed the second highest overall returns at $502.94 ha^{-1}, ranking second highest for environment 1 ($785.77 ha^{-1}), fifth for environment 2 ($477.88 ha^{-1}), and fourth for environment 3 ($347.11 ha^{-1}).

Radish monoculture showed the third overall highest returns at $398.07 ha^{-1}, ranking highest in environment 1 with $810.16 ha^{-1}, fourth in environment 2 with $563.73 ha^{-1}, and eighth in environment 3 with an expected loss of $222.03 ha^{-1}. Fourth overall was hairy vetch with $368.18 ha^{-1} followed by cereal rye with $352.41 ha^{-1}. The least profitable overall, in descending order, were wheat with $329.88 ha^{-1}, hairy vetch + radish mix with $320.38 ha^{-1}, wheat + radish + turnip mix with $316.99 ha^{-1}, cereal rye + crimson clover mix

Table 5. Corn production as affected by the cover crop monoculture and mixtures in three environments.

Treatments	Plant Height cm	Chlorophyll Index	Grain Moisture g kg^{-1}	Grain Yield kg ha^{-1}	Test Weight kg hl^{-1}	Seed Index g	Oil g kg^{-1}	Starch g kg^{-1}	Protein g kg^{-1}
Environment 1									
No Cover Crop	229±7abc[†]	369.08±36.55	176.3±6.7	11,230±781ab	73.33±1.20	30.27±0.89	44.8±4.9	702±1	89.0±3.5
Cereal Rye	226±5bc	3.1667.17±9.16	179.0±5.7	9,838±692bc	72.50±0.60	30.51±2.06	40.5±8.8	705±17	88.0±1.2
Wheat	217±20cd	316.50±27.57	172.5±3.6	10,311±1,682ab	72.88±0.73	30.20±2.02	40.3±4.1	705±12	88.8±4.1
Crimson Clover	227±4bc	351.67±29.14	175.3±9.5	11,427±517ab	73.33±0.32	32.18±1.59	38.0±6.6	710±12	85.8±1.7
Hairy Vetch	229±10abc	350.50±40.51	170.3±16.0	11,100±853ab	72.50±1.67	30.61±2.20	35.5±4.6	716±7	88.0±3.9
Radish	242±7a	360.75±31.37	176.3±3.5	11,520±1,761a	73.43±0.82	32.18±1.48	43.5±8.5	701±15	89.3±3.3
Cereal Rye + Crimson Clover	212±6d	307.00±34.77	173.8±3.4	8,561±1,258c	72.85±0.80	28.46±0.92	38.3±3.8	711±11	92.0±1.4
Wheat + Crimson Clover	229±10abc	357.42±32.78	175.3±6.8	10,390±940ab	73.33±0.68	30.34±2.61	40.0±5.3	703±10	89.5±1.9
Hairy Vetch + Radish	232±12ab	363.67±24.66	181.8±6.7	10,661±950ab	73.36±0.98	32.19±2.92	41.3±3.4	705±8	89.8±1.2
Wheat + Radish + Turnip	223±6bcd	379.92±84.26	171.0±8.1	9,911±1.101abc	73.56±0.54	29.01±1.62	37.0±5.7	703±16	89.0±1.6
Environment 2									
No Cover Crop	212±6	478.33±89.63	203.3±2.9	11,602±465	74.68±0.73abc	36.95±2.81	37.8±0.5	698±1ab	94.0±7.1
Cereal Rye	205±6	365.08±110.91	205.0±3.5	9,514±1,285	73.68±1.80bcd	36.96±1.63	37.8±0.9	697±2abc	97.0±3.4
Wheat	211±11	363.50±39.11	201.0±9.0	9,899±1,013	73.49±0.36d	36.99±1.69	38.3±0.5	695±2bcd	101.2±5.2
Crimson Clover	202±8	420.92±59.56	201.5±11.8	10,466±1,194	73.58±0.54cd	35.30±3.96	38.3±0.5	695±2bcd	99.3±2.1
Hairy Vetch	213±5	352.58±118.69	205.3±4.9	10,586±951	74.58±0.22abcd	37.73±0.36	38.8±0.5	696±2abc	99.8±3.4
Radish	215±18	424.50±114.62	200.3±9.5	10,852±2,301	74.36±1.17bcd	37.45±1.97	38.5±1.0	697±3abc	98.5±4.3
Cereal Rye + Crimson Clover	203±7	395.75±70.58	206.8±5.5	9,847±1,441	73.91±0.73bcd	38.44±0.89	38.0±0.8	693±1d	14.3±4.2
Wheat + Crimson Clover	208±12	377.25±29.08	203.3±3.3	11,143±1,825	74.74±0.66ab	36.81±1.55	38.0±0.8	697±2abc	99.8±4.0
Hairy Vetch + Radish	211±14	399.08±41.18	201.0±5.2	11,506±1,159	75.58±0.68a	37.22±2.14	38.5±0.5	699±2a	96.3±5.2
Wheat + Radish + Turnip	206±12	409.67±49.40	200.3±9.7	10,577±1,267	73.87±1.09bcd	37.35±2.27	38.0±0.8	695±2cd	101.0±4.2
Environment 3									
No Cover Crop	.	.	187.0±9.4	10,599±2,280	63.55±3.64	38.02±1.24a	37.0±1.1	705±2	98.5±6.4
Cereal Rye	.	.	183.5±7.7	10,946±513	56.53±11.92	36.2±1.70bc	35.5±0.5	707±6	98.5±4.9
Wheat	.	.	184.5±8.3	9,672±3,225	64.12±9.48	38.1±0.63a	37.3±1.8	708±4	100.3±7.3
Crimson Clover	.	.	190.5±6.2	9,859±3,133	65.35±6.69	37.98±2.22a	37.0±1.1	708±5	97.0±5.1
Hairy Vetch	.	.	187.0±12.2	9,629±2,684	63.48±5.20	35.25±1.59c	35.8±1.2	711±5	96.8±8.0
Radish	.	.	178.0±12.6	7,105±3,140	51.484±18.26	37.33±3.07a	37.5±1.0	703±5	99.8±4.5
Cereal Rye + Crimson Clover	.	.	212.0±5.3	11,438±1,421	65.55±7.40	37.75±0.46ab	37.3±1.5	709±2	97.3±3.2
Wheat + Crimson Clover	.	.	190.5±11.9	6,421±4,408	63.80±9.94	35.86±1.30bc	36.5±0.5	709±8	99.3±5.7
Hairy Vetch + Radish	.	.	188.0±4.5	7,238±3,140	54.76±13.98	37.41±0.30abc	36.0±0.0	709±4	99.0±4.6
Wheat + Radish + Turnip	.	.	192.3±4.9	9,115±3,422	67.27±12.15	37.49±1.71ab	37.0±1.0	706±4	99.0±8.5

[†]The same letter within a column indicates no significant difference for a given factor or combination of factors ($\alpha = 0.05$). The values are means ± standard deviation.

Table 6. The estimated production costs and profits for the cover crop monoculture and mixture treatments in three environments.

Cover Crop Treatments	Grain Revenue	Production Cost	Expected Profit	Profit Standard Deviation
	$ ha^{-1}			
		Environment 1		
No Cover Crop	2,489.21	1,719.53	769.68	173.11
Cereal Rye	2,180.73	1,778.24	402.49	153.38
Wheat	2,285.43	1,787.66	497.77	372.82
Crimson Clover	2,532.90	1,747.13	785.77	114.59
Hairy Vetch	2,460.40	1,850.92	609.48	189.07
Radish	2,553.54	1,743.38	810.16	390.33
Cereal Rye + Crimson Clover	1,897.56	1,769.84	127.72	278.84
Wheat + Crimson Clover	2,302.91	1,775.77	527.14	208.35
Hairy Vetch + Radish	2,363.05	1,812.94	550.11	210.57
Wheat + Radish + Turnip	2,196.77	1,795.32	401.45	244.04
		Environment 2		
No Cover Crop	2,571.56	1,824.67	746.89	103.07
Cereal Rye	2,108.71	1,864.46	244.25	284.82
Wheat	2,194.15	1,877.38	316.77	224.54
Crimson Clover	2,319.87	1,841.99	477.88	264.65
Hairy Vetch	2,346.51	1,946.87	399.65	210.79
Radish	2,405.45	1,841.72	563.73	510.02
Cereal Rye + Crimson Clover	2,182.67	1,859.09	323.57	319.40
Wheat + Crimson Clover	2,469.84	1,876.76	593.08	404.52
Hairy Vetch + Radish	2,550.43	1,917.21	633.22	256.90
Wheat + Radish + Turnip	2,344.45	1,891.17	453.28	280.84
		Environment 3		
No Cover Crop	2,347.57	1,815.58	531.99	505.10
Cereal Rye	2,424.43	1,857.78	566.64	113.70
Wheat	2,142.28	1,875.30	266.97	714.29
Crimson Clover	2,183.60	1,836.48	347.11	694.13
Hairy Vetch	2,132.61	1,938.17	194.45	594.54
Radish	1,573.56	1,795.59	-222.03	321.41
Cereal Rye + Crimson Clover	2,533.29	1,847.58	685.71	314.75
Wheat + Crimson Clover	1,422.16	1,833.96	-411.80	976.41
Hairy Vetch + Radish	1,603.15	1,867.42	-264.27	695.67
Wheat + Radish + Turnip	2,018.89	1,857.27	161.63	757.97

Table 7. The profitability ranking of the cover crop monoculture and mixture treatments in three environments with 1 as the most profitable and 10 as the least profitable.

Cover Crop Treatments	Profitabilty Ranking			
	Environment 1	*Environment 2*	*Environment 3*	*Overall*
No Cover Crop	3	1	3	1
Cereal Rye	8	10	2	5
Wheat	7	9	5	6
Crimson Clover	2	5	4	2
Hairy Vetch	4	7	6	4
Radish	1	4	8	3
Cereal Rye + Crimson Clover	10	8	1	9
Wheat + Crimson Clover	6	3	10	10
Hairy Vetch + Radish	5	2	9	7
Wheat + Radish + Turnip	9	6	7	8

Table 8. The overall risk-return combinations for cover crop monoculture and mixture treatments.

Cover Crop Treatments	Average Profit	Profit difference‡	Risk-return equivalent††	Risk-adjusted Compensation†
	$ ha^{-1}			
No Cover Crop	649.50	-	649.50	-
Cereal Rye	352.41	-297.09	495.47	143.06
Wheat	329.88	-319.62	955.85	625.97
Crimson Clover	502.94	-146.56	910.20	407.26
Hairy Vetch	368.18	-281.32	805.56	437.38
Radish	398.07	-251.44	1,239.29	841.22
Cereal Rye + Crimson Clover	316.35	-333.16	820.48	504.14
Wheat + Crimson Clover	205.10	-444.41	1,601.43	1,396.33
Hairy Vetch + Radish	320.38	-329.12	1,177.42	857.04
Wheat + Radish +Turnip	316.99	-332.51	905.04	588.05
All Cover Crops	345.82	-303.68	1,010.56	664.74
Cover Crop Monocultures	390.82	-258.69	890.77	499.96
Cover Crop Mixtures	287.82	-361.68	1,143.84	856.01

‡Profit difference = (Average profit from cover crop treatment) - (Average profit from no cover crop treatment).
†Risk-adjusted compensation = risk-return equivalent - average profit.
††Risk-return equivalent indicates the returns that a cover crop treatment needs to show to be equivalent to the no cover crop treatment which offers the best risk-return ratio.

at \$316.35 ha^{-1}, and wheat + crimson clover mix at \$205.10 ha^{-1}.

The results were highly variable depending on the agro-climatic conditions of the site. This fact indicated that a "one size fits all" approach is inadequate to make CC decisions and expected returns should not be the only factor to be considered to make the optimal choice of CC species or mix of species. The variability of expected returns, which provides a measure of risk, should also be considered in the decision.

Table 6 and Figure 2 show the implicit trade-offs between expected returns and their variability. This is an important insight to consider when crafting incentives for farmers to adopt CCs and any associated policies. As a group, single-species treatments produced higher returns and lower return variability than mixed species treatments. This implies that incentive programs aiming at encouraging multi-species CCs should provide larger payments than those for single-species programs. Indeed, the Environmental Quality Incentives Program (EQIP) in MS (program code 340) offers a larger incentive for multi-species CCs (\$157.70 ha^{-1}) than single-species CCs (\$128.92 ha^{-1}), with contracts that can extend up to five years. However, our estimates show that these incentives cover less than half the expected losses with respect to the noCC scenario—and even a lower proportion of the risk-return equivalents.

Discussion

The study supported the hypothesis that CC performance and consequent benefits on corn growth, yield, and quality were highly regulated by environmental factors such as precipitation and temperature. The average monthly temperatures, solar radiations, and total precipitation recorded during the study period followed the annual patterns of long-term historical data (1989-2018) recorded by the National Weather Services for MS (https://www.weather.gov/wrh/Climate?wfo=jan). Yang et al. (2020) reported ~60% of annual precipitation accumulated during the offseason (October to April) for 80 consecutive years (1938-2017) in MS, while a lower proportion of the annual rainfall accumulated during the cash crop season, similar with the yearly trends for precipitation reported in the present study. Yang et al. (2020) also classified the historical 80-year rainfall pattern accumulated in the CC growth period (October to April) into three groups, dry (mean = 540 mm), normal (mean = 771 mm), and wet (mean = 1,029 mm). Likewise, the rainfall accumulated during the CC period in the present study was highly

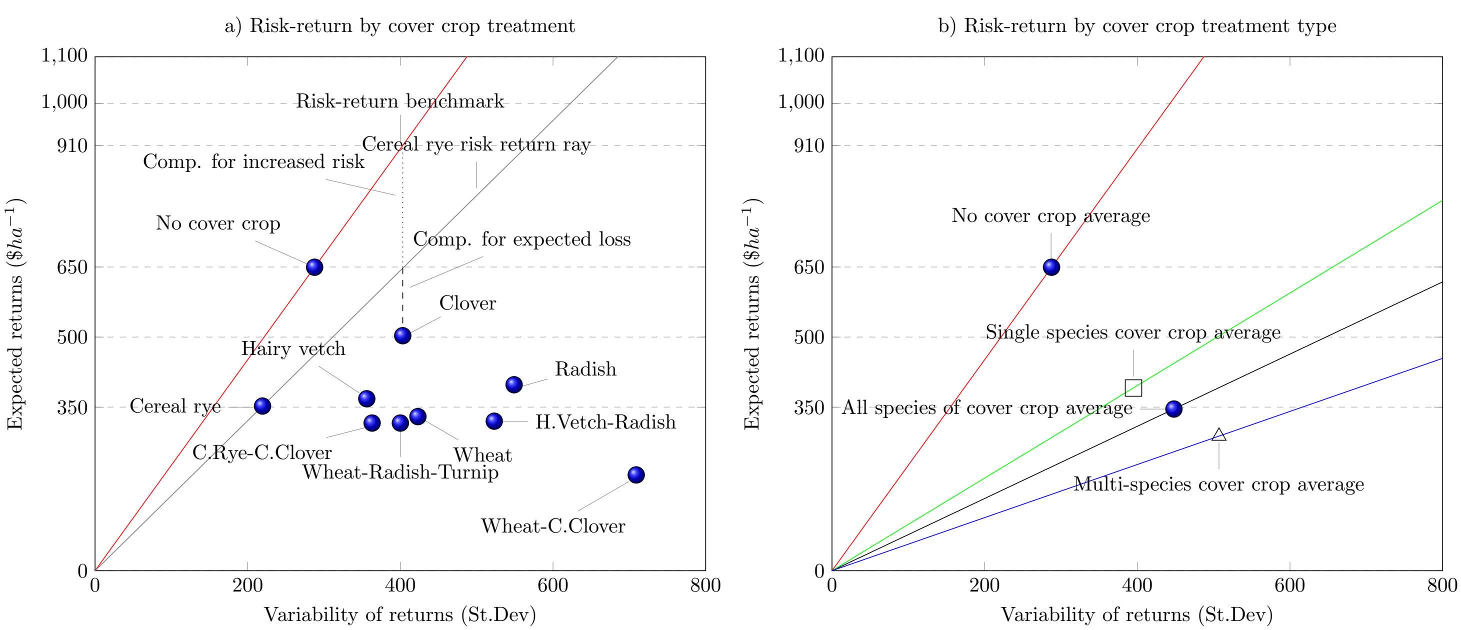

Figure 2. Illustration of farm profits compared to their variability across cover crop monocultures and mixture treatments. Notice: Cereal rye-crimson clover mixture is risk-reducing when compared to the no-cover crop treatment.

variable across the three environments compared to temperature and solar radiation. The CCs season from October to April accumulated 1,157 mm, 795 mm, and 677 mm rainfall in environments 1, 2, and 3, respectively. Cover crops are considered a potential tool for improving soil water dynamics by reducing runoff and subsequently improving soil water storage, thus mitigating the impact of rainfall variability on following crop yield (Yang et al. 2020). However, Yang et al. (2020) concluded that coefficient of variation in corn yields substantially decreases from dry to wet CC periods. Significant improvement in corn yields by CC than noCC treatment was observed only in the dry group that accumulated mean rainfall ≤ 540 mm (Yang et al. 2020). In the present study, rainfall accumulation during the CC period in all three environments was > 540 mm. Hence, the low coefficient of variation in corn yields under high rainfall conditions during the CC seasons in the present study might have attributed to no difference in corn yield between noCC and CC treatments in all three environments. Similarly, other studies have correlated the rainfall amount and CC efficiency in water conservation to improve subsequent cash crop yield (Qi et al. 2011; Martinez-Feria et al. 2016). However, previous studies have mostly simulated the impact of CCs on soil nutrients, water dynamics, and subsequent cash crop productivity using only one type of CC species (Qi et al. 2011; Martinez-Feria et al. 2016; Yang et al. 2020). The present study is unique in that it quantified the impact of different CC species on subsequent cash crops across different rainfall patterns. This study has also recognized the degrees of phenotypic plasticity among CC species to changing weather patterns. In the present study, differential rainfall accumulation during CC season (October to April) among the three environments might have contributed to variable biomass, C and N concentration, C/N ratio, and Total N among treatments. High rainfall during CC season in environment 1 resulted in lower biomass production (hairy vetch and crimson clover) in legumes possibly due to poor stand establishment and root growth, and consequently, lower N and TN which were not statistically different from noCC. Legumes under low rainfall scenarios in environment 3 had significantly higher N and TN than noCC. A controlled environment study conducted by Munyon et al. (2021) reported that specie-specific changes in CC performance to environmental challenges like temperature and drought are likely associated with changes in biochemical and physiological processes. The present study proposes future studies to intensively investigate phenotypic plasticity of CCs in relation to dynamic weather patterns to determine site-specific suitability of CC species.

Drought and excessive rainfall are the second most influential cause of loss in corn production in the U.S., however, the impact can vary with the time of their occurrence relative to the corn growth stage (Li et al. 2019). Rainfall received during the cropping season (May to September) was not different (± 40 mm) among the three environments (averaging 830 mm) but the high variability in monthly total precipitation recorded in corn cropping season, especially July, might have played a significant role in the differential response of corn to CCs among the three environments. The rainfall received in July was lowest in environment 1 (164 mm) and highest in environment 2 (300 mm), although average air temperature was not very different (< 1^{o}C). Environment 2 received greater rainfall during the peak growing period in July, when the corn is usually at tasselling and silking stages (R1 growth stage), than the other two environments, which might have resulted in higher corn yield in environment 2 (averaging 10,599 kg ha^{-1}). Consistent with the present study, the effects of mean precipitation in July positively impacted corn yield across several locations in the U.S. (Thomson 1969; Asghari and Hanson 1984). According to the model developed from 25 years of historical data by USDA's Economic Research Service (ERS), a decline in corn yield below the 25-year average with reductions in July precipitation exceeded yield gain above averages from equal magnitudes of increase in July precipitation (Westcott and Jewison 2013). The average high precipitation in July can also alleviate the determinant effect of high temperatures on corn yield (Hendrick and Scholl 1943; Gilmore and Rogers 1958), perhaps primarily because of the higher water use efficiency of corn in wet summers compared to normal or dry summers (Yang et al. 2020). The recommended rate of N application may not be economically significant to increase grain yield under rainfall deficit conditions in July (Pattey et al. 2001). Corn grain quality parameters had differential sensitivity to weather patterns in the present study. Like previous studies, this study proposes a weather component inclusion in process-based models to accurately access CC benefits and subsequent growth of corn (Pattey et al. 2001; Munyon et al. 2021).

The present study also recognized the innate differences among CCs based on their growth characteristics and benefits to the following corn crop. Consistent with past studies, our study found greater biomass and C/N ratios with monoculture of grasses (wheat or cereal rye) compared to the monoculture of legumes (crimson clover or hairy vetch) (Kaye et al. 2019; Munyon et al. 2021). Also, radish planted as a monoculture CC exhibited higher biomass but a lower C/N ratio than legume monoculture in two out of the three environments. Overall, radish outperformed among CCs and benefits corn yield in a monoculture stand. A CC mix could be more beneficial than single-species CCs in balancing early cover and N scavenging along with fast decomposition of residues and N availability to cash crop (Finney et al. 2016; White et al. 2017). The present study also recognized the weather influence on functionality of different CCs within same groups, rarely studied in the past. For instance, hairy vetch had a ~20% greater N concentration than crimson clover in environment 3, while no significant difference was found between them in the other two environments. The addition of turnip to a mixture of wheat and radish did not significantly improve the parameters measured. Therefore, future studies should explore the significance of CC mixes consisting of different species as high-diversity mixtures are used more often by farmers (Hamilton 2016).

Economic analysis at this early stage indicates that farmers looking to adopt CC practices should expect both financial losses and increased risks in almost every case. Although the long-term benefits of CCs are well documented (Qi et al. 2011; Martinez-Feria et al. 2016; Sanchez 2016), the outcomes of the first few years can strongly encourage or discourage farmers to continue their programs. Consequently, our data suggest that existing incentive programs compensate for approximately half of the expected losses during the earlier stages of adoption. Furthermore, our estimates provide a range of incentive values that could induce adoption of CCs at a faster rate by minimizing farmer concerns about expected losses and increased risks.

Conclusion

The present study provided information on the benefits of growing winter CCs during a fallow period in MS's continuous corn production system. The CC species had innate differences in growth characteristics (biomass, C/N ratios, total N) and subsequently affected corn growth, yield, and quality. However, the functionality of CC treatments was highly influenced by weather patterns among the three environments. Mixed CC treatments exhibited balanced N scavenging and N credits but less stable returns than single-species treatments. The information will be helpful to farmers for the selection of species in a CC mix to balance biomass, N scavenging, and N availability to the following corn crop under variable rainfall patterns. The study also proposes future studies to explore resilience in the functionality of a high-diversity mixture under diverse weather conditions.

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Author Bios and Contact Information

Dr. Bhupinder Singh is a Postdoctoral Research Associate at the Texas A&M AgriLife Research and Extension Center, Texas A&M University, Vernon, Texas. Dr. Singh received his Ph.D. degree from Mississippi State University in 2020. Dr. Singh can be contacted via email at Bhupinder.singh@ag.tamu.edu.

Dr. Gurpreet Kaur is an Assistant Professor at the University of Missouri Northern Missouri Research, Extension, and Education Center in Novelty, MO. Dr.

Kaur received her Ph.D. degree in Natural Resources from the University of Missouri in 2016. Dr. Kaur can be contacted at gk478@missouri.edu or by mail at: Lee Greenley Jr. Memorial Research Farm, 64399 Greenley Place, Novelty, Missouri 63460.

Dr. Gurbir Singh (corresponding author) is an Assistant Professor at the University of Missouri Northern Missouri Research, Extension, and Education Center. Dr. Singh received his Ph.D. degree in Agricultural Sciences from Southern Illinois University in 2018 and M.S. degree in Soil, Environmental, and Atmospheric Sciences from University of Missouri in 2013. Dr. Singh can be contacted at singhgu@missouri.edu or by mail at: Lee Greenley Jr. Memorial Research Farm, 64399 Greenley Place, Novelty, Missouri 63460.

Dr. Jagmandeep Dhillon is an Assistant Professor in the Department of Plant and Soil Sciences, Mississippi State University. Dr. Dhillon received his M.S. and Ph.D. degrees in Agronomy from Oklahoma State University in 2019. Dr. Dhillon can be contacted at jsd369@msstate.edu or by mail at: 470 Dorman Hall, Mississippi State University, Mississippi State, MS 39762.

Dr. Nicolas E. Quintana Ashwell is an Assistant Professor and Natural Resource Economist at the National Center for Alluvial Aquifer Research, Mississippi State University. Dr. Quintana received his Ph.D. degree from the Kansas State University. Dr. Quintana's research is focused on improving academic and stakeholder understanding of the economic factors that drive the decline of an aquifer in an area with abundant precipitation and surface water sources. Dr. Quintana can be contacted at n.quintana@msstate.edu or by mail at: National Center for Alluvial Aquifer Research, 4006 Old Leland Road, Leland, MS 38756.

Disclosure Statement

No conflict of interest was reported by the authors.

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Supplementary Data

Table S1. Soil properties at the three sites used in this study.

Soil Properties	Units	Environment 1 Stoneville Fall 2019	Environment 2 Stoneville Fall 2020	Environment 3 Starkville Fall 2020
Cation Exchange Capacity	cmol (+) kg^{-1}	9.13	7.76	7.79
pH_s		6.57	6.23	6.25
Organic Matter	g kg^{-1}	8.6	9.3	7.7
Bulk Density	g cm^{-3}	1.38	1.37	1.46
Nitrogen Release	kg ha^{-1}	37.26	40.35	35.02
NH_4-N	mg kg^{-1}	5.2875	5.5875	5.475
NO_3-N	mg kg^{-1}	<0.5	1.37	1.4
Bray I Phosphorus	mg kg^{-1}	16.375	18.625	61.25
Phosphorus*	mg kg^{-1}	17.13	20.88	40.5
Potassium*	mg kg^{-1}	106.38	102.75	143.38
Calcium*	mg kg^{-1}	1166.88	971	928
Magnesium*	mg kg^{-1}	222.5	158.13	169.5
Sulphur*	mg kg^{-1}	9.125	4.25	4.25
Boron*	mg kg^{-1}	0.25	0.23	<0.2
Sodium*	mg kg^{-1}	37.5	17.13	10.88
Aluminium*	mg kg^{-1}	322.75	311.63	298.75
Iron*	mg kg^{-1}	145.5	155.13	208.75
Manganese*	mg kg^{-1}	23	23.13	27.13
Copper*	mg kg^{-1}	1.27	0.96	0.94
Zinc*	mg kg^{-1}	1.53	1.06	1.18

*Mehlich III extractable

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Opinions on Irrigation Water Management Tools and Alternative Irrigation Sources by Farmers from the Delta Region of Mississippi

*Gurbir Singh[1], Nicolas E. Quintana Ashwell[2], Gurpreet Kaur[1], Drew Gholson[2], Martin A. Locke[3], L.J. Krutz[4], and Trey Cooke[5]

[1]*Northern Missouri Research, Extension, and Education Center, University of Missouri, Novelty, Missouri, USA*
[2]*National Center for Alluvial Aquifer Research, Mississippi State University, Stoneville, Mississippi, USA*
[3]*National Sedimentation Laboratory, USDA Agricultural Research Service, Oxford, Mississippi, USA*
[4]*Water Resources Research Institute, Mississippi State University, Mississippi State, Mississippi, USA*
[5]*Mississippi River Basin Program, The Nature Conservancy, Cleveland, Mississippi, USA*
**Corresponding Author*

Abstract: Water withdrawals for irrigation at an unsustainable rate resulted in a decline in the groundwater levels in the Mississippi River Valley Alluvial Aquifer (MRVAA) in the central southern USA. This drawdown of groundwater threatens agricultural production in the Mississippi Delta, an important agricultural region in the state of Mississippi, USA. Effective and efficient use of available resources is important to sustain and enhance agricultural productivity in this area. This study assessed the opinions of farmers on water conservation management practices and technologies that improve irrigation management and save water in the Mississippi Delta region based on data collected in an irrigation survey conducted in 2012. Most landowners believed that water conservation practices were effective in reducing irrigation water use without reducing maximum crop yields and have a positive return on investment. Land forming, tailwater recovery system, on-farm storage, instream weirs to pond surface water, computerized hole selection for furrow irrigation, short irrigation runs, and irrigation scheduling were considered efficient water conservation technologies by landowners. Perceptions about use of different practices also depend upon the crops produced by the respondents. About 20 to 24% and 14.9 to 86% of survey respondents thought that on-farm storage and center pivot, respectively, were inefficient water conservation practices for irrigating crops in the Mississippi Delta. The adoption of these practices may be increased if the landowners know the economic returns of implementing them.

Keywords: *computerized hole selection, center pivot, irrigation scheduling, land forming, on-farm water storage, tailwater recovery, water meters*

Groundwater is critically important for human society, as it provides an estimated 42% of agricultural water use globally (Konikov and Kendy 2005; Döll 2009; Döll et al. 2012) and in the United States (USGS 2015). The demand for water supply for agriculture is expected to increase by approximately 20% by 2050 to meet the increasing demand for food production (Vörösmarty et al. 2000; Konikow and Kendy 2005). In Mississippi, the main source of water for agricultural irrigation is groundwater extracted from the Mississippi River Valley Alluvial Aquifer (MRVAA). The MRVAA underlies 82,879 km^2 of the states Kentucky, Missouri, Tennessee, Louisiana, Arkansas, and Mississippi in the USA. These states had more than 3.9 million hectares (ha) of irrigated land in 2017 (USDA NASS Cropland Data Layer 2017). The MRVAA supplies approximately 370 million cubic meters of water per year and irrigates over 700,000 ha of row crops in the Mississippi Delta region (Wax et al. 2008; Massey 2010). Irrigated cropland has increased by 92% in 20 years from 1988 (306,000 ha) to 2008 (588,000 ha) in Mississippi (Vories and Evett

Research Implications

- Groundwater levels are declining in the Mississippi River Valley Alluvial Aquifer.
- Survey results showed a need for better farmer/landowner understanding of available water conservation practices as a means to reduce irrigation water use.
- Adoption of water conservation practices depends upon the economic returns from their implementation.

2014). Groundwater from the MRVAA contributes to over 90% of the irrigation water applied, whereas only 6 to 7% of the irrigation water is provided from surface water (Reba and Massey 2020). There has been a decline in water levels in the MRVAA due to withdrawals for irrigation that exceed its recharge rate (Wax et al. 2008). This aquifer has been reported to be declining at rates of 0.15 to more than 0.45 m per year in western Mississippi and eastern Arkansas (YMD 2013). Water withdrawals from the MRVAA are comparatively higher during the summer season, a period of high-water requirement by plants due to high evapotranspiration losses, high heat index, and low precipitation (Wax et al. 2008; Massey 2010; Kebede et al. 2014). The precipitation occurring during the remainder of the year is insufficient to recharge the aquifer and offset withdrawals (Wax et al. 2008), resulting in net declining water levels in the MRVAA. Therefore, it is important to implement better irrigation methods and technologies and agronomic management practices in this region that will increase water application and use efficiencies and reverse the current trend of declining water levels in the MRVAA.

Multiple technologies are available to farmers for better water management and higher irrigation water-use efficiency, such as computerized hole selection (CHS) (e.g., PHAUCET: Pipe Hole and Universal Crown Elevation Tool or Pipe Planner), surge valve flow irrigation (SURGE), tailwater recovery systems (TWS), on-farm water storage, sprinkler irrigation systems, and sensor-based irrigation scheduling. Computerized hole selection technology computes the flow and pressures along the length of lay-flat polyethylene tubing and selects optimal hole sizes to improve down-row uniformity across the irrigation set regardless of furrow length (Bryant et al. 2017; Spencer et al. 2019). Sensor thresholds for irrigation scheduling for soybean (*Glycine max* L.), cotton (*Gossypium hirsutum* L.), corn (*Zea mays* L.), and peanuts (*Arachis hypogaea*) have been developed by Mississippi State University researchers (Williams et al. 2018; Leininger et al. 2019). In the Mississippi Delta region, irrigation water management (IWM) practices, including those mentioned previously, reduced soybean irrigation water use and increased irrigation water use efficiency by 21 and 36%, respectively, compared to a conventional continuous-flow delivery system that utilized lay-flat polyethylene tubing attached to the well or riser head and then laid perpendicular to the furrows at the upper end of the field (Bryant et al. 2017). Integrated systems of CHS, SURGE, and sensor-based technologies improved on-farm profitability by as much as $198 per ha (Bryant et al. 2017; Spencer et al. 2019). Despite these available technologies, furrow irrigation practice has low application efficiency. Approximately 80% of the irrigated land in Mississippi is furrow irrigated, and the remaining 20% is under sprinkler or other irrigation systems. Irrigation application efficiency can be increased with the use of sprinkler systems compared to furrow irrigation methods (Sammis 1980; Cetin and Bilgel 2002). Additionally, TWS and on-farm water storage can help to conserve groundwater by facilitating the capture and re-use of precipitation and irrigation runoff (Omer et al. 2018).

Although conservation technologies exist for improved IWM, and water conservation and water quality education and extension programs are available for producers, adoption rates for IWM practices are low (Adams et al. 2013; Reba and Massey 2020). However, the impact of education programs depends on water user's attitudes, perceptions, and behavior (Adams et al. 2013). Therefore, it is important to know and understand the perceptions of farmers toward water-related issues and irrigation management practices. Surveys are one of the tools that can be used for generating information about farmers' perceptions on irrigation management practices. The objective of this paper was to assess the opinions of farmers on water conservation management practices and technologies for better irrigation management and water savings in the Mississippi Delta region, based on unpublished data from the 2012 Mississippi Irrigation Survey. Results from this study can be used for designing and implementing future research and extension programs in the state of Mississippi for better conservation of water resources for irrigation.

Materials and Methods

Mississippi State University's Survey Research laboratory conducted a survey in 2012 to evaluate farmers' opinions on IWM tools and alternative irrigation sources in the Mississippi Delta. The survey focused on all permit holders, landowners, and operators (producers) who withdraw water (surface and groundwater) for agricultural irrigation in the Yazoo-Mississippi Delta region, a region formed between the Mississippi and Yazoo Rivers in western Mississippi (Massey et al. 2017). The survey contact list was obtained from the Permit Database at the Office of Land and Water, Mississippi Department of Environmental Quality. Potential respondents identified from the Permit Database records, believed to own or hold permits for irrigation water withdrawals in the Yazoo-Mississippi Delta, totaled 1877, but only 1789 of the 1877 farmland owners and operators were used for the survey. Excluded respondents (88) were not selected because of duplicate entries or missing contact information. The survey was conducted by calling valid phone numbers. The survey was completed by 460 of the 1789 respondents, but 120 refused to complete the survey, 14 were not available at the time of the survey, 314 did not answer the phone call, 26 had issues with communication or language, 68 were either deceased or unable to speak due to health problems, and 606 had disconnected telephone numbers. Because they no longer held a permit for an agricultural irrigation well, 133 potential respondents were not included in the survey. The percentage of completed surveys based on the sum of completed responses and refusals was 79.3%.

The survey questionnaire was developed by the Mississippi State University's scientists and members of the Delta Farmers Advocating Resource Management (Delta F.A.R.M.). The Delta F.A.R.M. is an association of the growers and landowners working to conserve and restore the environment of Northwest Mississippi (https://Deltafarm.org/). The survey consisted of 13 overarching questions, most of which included additional follow-up questions. The portion of the survey questionnaire related to water conservation management is discussed in this article (Appendix 1).

Results

Importance and Opinions on Water Conservation Practices

Of the survey respondents, 52% thought the primary cause of groundwater depletion was agricultural irrigation water use, whereas 30.7% of respondents disagreed or strongly disagreed. To understand farmers' opinions on water management and conservation practices, survey respondents were asked if: a) water conservation practices are effective in reducing irrigation water use, and b) water conservation practices can reduce maximum crop yields. Respondents were given the following options to choose from: strongly disagree, disagree, neither disagree nor agree, agree, or strongly agree. Out of 460 respondents, 420 respondents (91.3%) believed that water conservation practices are effective in reducing irrigation water use, whereas only 17 respondents disagreed or strongly disagreed with the statement. About 211 respondents (45.8%) disagreed or strongly disagreed that water conservation practices can reduce maximum crop yields, whereas 186 respondents (40.5%) agreed or strongly agreed that crop yields will be reduced if water conservation practices are adopted. A total of 423 out of 460 respondents (91.9%) believed that using water conservation practices saves money, whereas only 7.4% disagreed with the statement (Figure 1). Over 47% of the respondents believed that adopting conservation practices alone could take care of the water problems in the Mississippi Delta, but 41.5% of them disagreed, and 7.2% were undecided. Respondents were asked to comment on the statement: "you can implement water conservation practices and not effectively manage water." To which 70% of respondents agreed, and 21.5% did not agree. Based on 230 valid responses, 15.2% thought it is important to

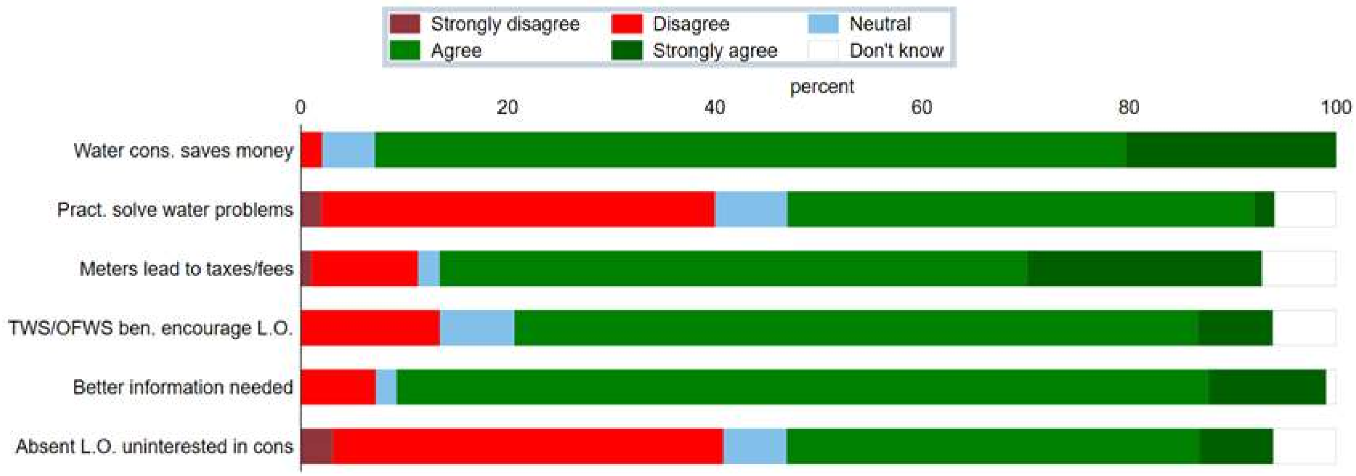

Figure 1. Survey responses to questions related to the water conservation practices in the Mississippi Delta. (Abbreviations: Pract., practices; TWS, tailwater recovery systems; OFWS, on-farm water storage systems; ben., benefits; L.O., landowners; cons., conservation practices).

have better estimates of water use efficiencies for different water conservation practices.

Respondents were also asked if it is important to know the amount of water used by each crop for effective irrigation practices. Out of 460 respondents, 75.3% agreed or strongly agreed that is the case, whereas 13.1% disagreed. When asked about the need for better information on the effectiveness of water conservation practices, 406 (88.2%) thought that there is such a need. Over 89% of respondents agreed that they were doing everything they could to conserve water. At the same time, 76.3% of respondents believed that more water supplies are needed in the Delta to sustain agriculture, whereas 11.1% disagreed. One of the reasons for the low level of adoption of the water conservation management practices might be less financial support by absentee landowners. Out of 460 respondents, 214 (46.5%) believed that absentee landowners are not interested in paying for water conservation on their land, whereas 40.7% disagreed.

Water Conservation Practices

Water Meters. About 52.4% of respondents believed that installing water meters is the best way to measure irrigation water use, but 28% did not agree. Respondents were also asked if meters will save water and whether installing meters on wells will lead to taxes or fees on water use (Figure 1). Nearly 47% of respondents believed that using meters as irrigation practices can save water, but 78.3% (360) of respondents thought that installing meters on wells will ultimately lead to taxes or fees on water use. Related to this, respondents were also asked about who should pay for the purchase and installation of the water meters. Approximately one-third or 151 respondents thought the federal government should shoulder the cost, while 15.4% of respondents thought the state government should do so. Out of 460, only 62 respondents thought farmers or producers should pay for the water meters.

Land Forming. Out of 455 respondents, 94.4% responded that land forming is an effective water conservation practice for all crops (Figure 2). Respondents were also asked about the efficiency of the different water conservation practices for irrigating corn, soybean, cotton, and rice (Table 1). They were provided the following responses to choose from: highly efficient, efficient, inefficient, don't know/not sure, and refused. Out of the valid responses (highly efficient, efficient, inefficient) from 460 respondents, 99.6% of the respondents believed that land forming is an efficient or highly efficient practice for corn and soybean (Table 1). For cotton, only 1.4% of respondents thought it was not efficient. For rice, 375 respondents provided a valid response to the question concerning the efficacy of zero grade land forming as an effective water conservation practice, and 66.5% agreed or strongly agreed that it is effective, while 11.8%

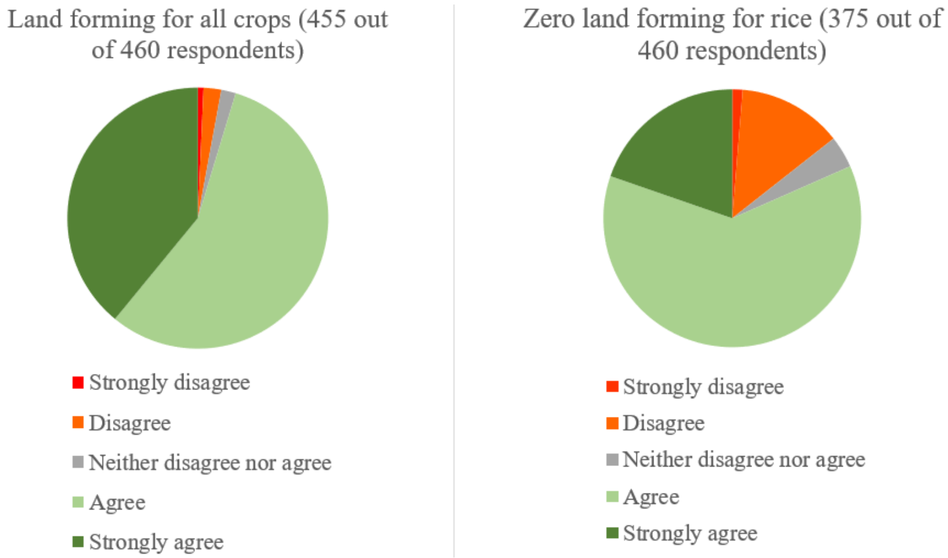

Figure 2. Survey responses to questions related to the effectiveness of the land forming in the Mississippi Delta.

disagreed (Figure 2). About 8.6% respondents thought it an inefficient practice.

Tailwater Recovery Systems. Valid responses received for TWS efficiency for irrigating corn, soybean, and cotton were 234, 256, and 133, respectively, out of the 460 respondents (Table 1). From the valid responses, only 11.1, 10.9, and 12.8% of the respondents believed it an inefficient practice for irrigating corn, soybean, and cotton, respectively.

On-farm Storage. Valid responses received for on-farm water storage systems efficiency for irrigating corn, soybean, and cotton were 227, 248, and 127, respectively, out of the 460 respondents (Table 1). Based on valid responses, 79.7, 79, and 75.6% of the respondents believed that on-farm water storage is an efficient or highly efficient practice for irrigating corn, soybean, and cotton, respectively. For this practice, more than 20% of the respondents thought it an efficient practice.

Instream Weirs to Pond Surface Water. Based on valid responses (highly efficient, efficient, inefficient), 85.5, 88.5, and 81.9% of respondents thought that instream weirs are an efficient or highly efficient practice for irrigating corn, soybean, and cotton, respectively (Table 1).

Center Pivot Irrigation. More than 20% of the valid responses to the survey questions believed that center pivot is not an efficient practice for water conservation in corn and soybean, whereas only 15% of the respondents provided the same response for irrigating cotton. About 238, 262, and 134 respondents out of 460 provided a valid response to this question for irrigating corn, soybean, and cotton, respectively. For corn, 74.7% of the respondents agreed that center pivot is efficient or highly efficient, whereas 78.6 and 85% of the respondents responded that it is an efficient practice for soybean and cotton, respectively (Table 1). Eighty-six percent of the 143 valid responses believed that center pivot irrigation is an inefficient practice for irrigating rice.

Short Irrigation Runs. An irrigation run is defined as moving water from one end of the field to the other end. Irrigation runs that are too long can result in water loss due to deep percolation at the upper end of the field prior to the lower end receiving adequate irrigation. Only 10, 11.3, and 11.6% of the 231, 257, and 129 respondents believed that short irrigation runs are an inefficient practice for irrigating corn, soybean, and cotton, respectively, while the majority of the respondents believed that they are an efficient water conservation practice (Table 1).

Irrigation Scheduling. Irrigation scheduling determines the right amount and timing to apply water to the crop (Taghvaeian et al. 2020). Irrigation scheduling is important in this region to avoid yield losses from flash droughts that occur during the summer due to insufficient

Table 1. Survey responses to the efficiency of different water management practices and tools in the Mississippi Delta.

Water Conservation Practices	Respondents that provided valid responses (out of 460 respondents)	Highly Efficient (%)	Efficient (%)	Inefficient (%)
CORN				
Land forming	254	48	51.6	0.4
Tailwater recovery system	234	33.3	55.6	11.1
On-farm storage	227	26	53.7	20.3
Instream weirs to store surface water	206	23.8	61.7	14.6
Center pivot irrigation	238	17.6	57.1	25.2
PHAUCET program for sizing holes for furrow irrigation	210	29.5	64.3	6.2
Short irrigation runs	231	20.8	69.3	10
Irrigation scheduling	241	18.3	69.7	12
SOYBEAN				
Land forming	276	52.5	47.1	0.4
Tailwater recovery system	256	30.1	59	10.9
On-farm storage	248	25.4	53.6	21.0
Instream weirs to pond surface water	226	19.9	68.6	11.5
Center pivot irrigation	262	18.3	60.3	21.4
PHAUCET program for sizing holes for furrow irrigation	231	27.3	64.1	8.7
Short irrigation runs	257	24.1	64.6	11.3
Irrigation scheduling	268	21.6	67.5	10.8
COTTON				
Land forming	139	46.0	52.5	1.4
Tailwater recovery system	133	31.6	55.6	12.8
On-farm storage	127	30.7	44.9	24.4
Instream weirs to pond surface water	116	25.9	56.0	18.1
Center pivot irrigation	134	24.6	60.4	14.9
PHAUCET program for sizing holes for furrow irrigation	118	28.8	61.9	9.3
Short irrigation runs	129	26.4	62.0	11.6
Irrigation scheduling	131	26.0	58.8	15.3
RICE				
Zero grade land forming	162	58.0	33.3	8.6
Side-inlets	150	34.0	62.0	4.0
Center pivot irrigation	143	2.8	11.2	86.0
Irrigation scheduling	151	17.9	58.3	23.8

rainfall events. Irrigation scheduling saves water and energy and helps to improve crop yields and quality. For corn and soybean, 241 and 268 respondents, respectively, provided valid responses by indicating that the practice is highly efficient, efficient, or inefficient (Table 1). Only 131 and 151 respondents provided valid responses for the cotton and rice, respectively, when asked about irrigation scheduling (Table 1). About 88, 89, 85, and 76% of the respondents thought irrigation scheduling is an efficient or highly efficient water conservation practice for irrigating corn, soybean, cotton, and rice, respectively, in the Delta region.

PHAUCET Program for Sizing Holes for Furrow Irrigation. Respondents were asked if the PHAUCET program should be used for every furrow irrigation system. Out of 460 respondents, 241 provided a valid answer by choosing from options including strongly disagree, disagree, neither disagree or agree, agree, strongly agree: with 113 respondents in agreement. Respondents were also asked about the efficiency of this water conservation practice for irrigating corn, soybean, and cotton. Out of the valid responses received, 93.8, 91.4, and 90.7% respondents believed that PHAUCET is an efficient or highly efficient practice for water conservation for irrigating corn, soybean, and cotton, respectively (Table 1).

Future of Irrigation and Economic Constraints

When asked about the future of irrigation management technologies in the Delta region, 270 out of 460 respondents provided a valid response (strongly disagree, disagree, neither disagree nor agree, agree, strongly agree). Of the valid responses, 68.1% agreed and 7% strongly agreed that automated irrigation metering, soil moisture probes, rain gauges, and other technology are the future of irrigation in the Delta region. However, 15.9% of the respondents disagreed whereas 1.5% strongly disagreed.

Respondents were also asked questions relating to the economic benefits of the management practices and how they might impact adoption in the Delta. About 32% of respondents thought it was important to have estimates of dollar savings associated with different conservation practices. A total of 430 valid responses were recorded for the question: "documenting the economic benefits of the tailwater recovery and on-farm storage systems would encourage more landowners to implement these practices." Of the valid responses, 76.8% thought that landowners would adopt the tailwater recovery and on-farm storage systems if they knew their economic benefits.

Similarly, the respondents were asked if they would consider implementing one or more different water conservation practices if these saved them money. Out of 254 valid responses, 30.3% of respondents said that they would implement new or different water conservation practices if it would save them \$124-\$247 per ha (\$50-\$100 per acre). For the same questions, 27.2 and 22.8% of the respondents mentioned that they would adopt the practices if their savings were in the range of \$62-\$124 per ha (\$25-\$50 per acre) and more than \$247 per ha (>\$100 per acre), respectively. About 19.7% of respondents agreed to implement new or different water conservation practices even if the savings are less than \$62 per ha (<\$25 per acre).

Respondents were also asked about who should be paying for alternative water supplies, including inter-basin transfers, or well fields near the levees. Out of 355 valid responses, 64.2% preferred that the federal government pay, whereas only 16.1% said that the state government should pay for these water supplies. Producers (7.6%) and landowners (12.1%) are the least preferred agents responsible for the payment of alternative water supplies.

Discussion

Based on the survey conducted in 2012, most of the landowners in Mississippi believed that water conservation practices are effective in reducing irrigation water use without reducing maximum crop yields, and, in return, help to save money. In agreement with the survey results, research studies conducted after year 2012 on the agronomic and water conservation practices in the Mississippi Delta have shown positive results in terms of water savings, economic returns, and yield production (Henry and Krutz 2016; Bryant et al. 2017; Wood et al. 2017; Spencer et al. 2019). Research conducted in the Mid-South USA has shown a 502 kg ha^{-1} improvement in corn yield and a 40% reduction in applied water with the implementation of water and agronomic management practices such as irrigation scheduling, surge valves, PHAUCET program for furrow irrigation, hybrid selection, population, and planting times (Henry and Krutz 2016). Depending on crop prices and actual pumping depths, the combined benefits could easily exceed \$148 per ha. However, farmers and landowners have been slow to adopt these practices (Quintana-Ashwell et al. 2020), possibly because the benefits and economic returns of the practices occur over time, whereas producers must pay the cost of implementation of practices upfront at the time of adoption (Quintana-Ashwell et al. 2020). Possibly, the positive results obtained at plot-level research are not well known to farmers or not easily replicated at farm scale. Other reasons for the low adoption of water conservation practices may be the lack of interest and financial support for their implementation by absentee landowners, and limited access/understanding of information on the effectiveness of available water conservation practices. According to the survey results, most respondents indicated the need for better information on the effectiveness of conservation practices and irrigation water demands for different crops grown in the Delta region.

The survey also included questions about the farmers' opinions on the efficiency of the conservation practices. Most landowners believed that land forming, TWS, on-farm storage, in-stream weirs to store pond surface water, PHAUCET program for sizing holes for furrow irrigation, short irrigation runs, and irrigation scheduling are efficient water conservation technologies. Land grade leveling creates a uniform slope that improves drainage, decreases soil erosion, facilitates furrow irrigation, and enables crop management (Massey et al. 2017). Irrigation water use by zero grade land forming for rice is 46% less than the ungraded crooked levees in Mississippi and Arkansas (Reba and Massey 2020). In Mississippi and Arkansas, combined use of CHS, soil moisture sensors for irrigation scheduling, and surge flow irrigation in soybean production fields reduced seasonal irrigation applications by an average of 21% and increased irrigation water use efficiency by 36%, compared to conventional furrow irrigation controls (Bryant et al. 2017). More than 2 million ha of cropland in the lower Mississippi River Basin is irrigated using poly-tubing and could benefit greatly from use of the PHAUCET program to improve irrigation water use efficiency (Reba et al. 2014). The on-farm water storage systems for irrigation can completely replace groundwater pumping in some years, depending upon the growing season climatic conditions, storage capacity, and farmed area (Quintana-Ashwell et al. 2020). Reba et al. (2014) mentioned that the construction of on-farm reservoirs is motivated by the depth to groundwater for a well, as observed for an increasing number of deep wells in areas such as Arkansas and Mississippi where significant groundwater declines have occurred. Adopting irrigation technologies is dependent upon the attributes of the technologies, including cost, ease of use, durability, data interpretation, and whether the technology is based on scientific research (Taghvaeian et al. 2020). In agreement, the survey results indicate that adoption of water conservation practices depends upon the economic benefits or dollar savings from the use of different conservation practices.

About 25.2, 21.4, 14.9, and 86% of the survey respondents thought center pivot systems were not an efficient water conservation practice for corn, soybean, cotton, and rice, respectively. Furrow irrigation is the predominant irrigation method in the Mississippi Delta region as it is relatively simple and comparatively inexpensive. In addition, the landscape in the Mississippi Delta is flat, with slopes ranging from 0.1 to 0.2% (Reba and Massey 2020) which enables the furrow irrigation as the preferred choice of irrigation (Henry and Krutz 2016). However, pivot irrigation systems have lower application rates compared to furrow irrigation in row crop production and can save water (Massey et al. 2017). A 12-year study by Massey et al. (2017) in Mississippi reported that irrigation applications by corn producers through center pivot sprinklers and furrow irrigation averaged around 160 ± 90 and 330 ± 200 mm, respectively. In the Mississippi Delta, most of the center pivots were installed in the 1980s, predominantly for irrigating cotton (Coblentz 2014). About 32% of the cropland was irrigated by overhead sprinklers in Mississippi, whereas 69% was under furrow irrigation in 1998 (Reba and Massey 2020). Previously installed pivot systems for cotton were not designed to meet the irrigation water demands of corn and soybean crops. Therefore, producers in the Mississippi Delta have been migrating away from the center pivot systems. A major consideration is the high cost for repairs or installation of new pivot systems in contrast to using poly pipe in furrow irrigation of row crops (Quintana-Ashwell et al. 2020). Precision land grading of the cropland has increased in the Delta region, which has also contributed to reduction in over-head sprinkler irrigation systems (Reba and Massey 2020). Other issues associated with the operation of the center pivot in the Delta region include wheels getting stuck in heavy clay soils and clogging of nozzles due to the poor quality of groundwater used for irrigation (Quintana-Ashwell et al. 2020).

Most respondents believed that installing meters on the wells is the best way to measure groundwater use, and that this practice can save water. These results are from a survey conducted in 2012; however, there have been changes in the area since then. Irrigated area has increased over time and the number of wells drilled has doubled since 1998 in Mississippi (Reba and Massey 2020). There were 14,000 wells in Mississippi drawing groundwater for irrigation needs in 2017 (Reba and Massey 2020). Flowmeters installed on these wells to measure the quantity of water pumped can facilitate tracking groundwater usage from the wells. The use of flowmeters was higher in Mississippi due to the requirement that at least 10% of the agricultural groundwater wells per county should be equipped with flowmeters by the end of 2015 (MSDEQ 2015). However, the survey respondents in 2012 thought that installing meters would result in some taxes or fees on water use, and that this might negatively impact agricultural production in the Delta.

In this 2012 survey, about 75% of the respondents agreed that there would be increasing future use of various technologies such as automation, irrigation metering, soil moisture probes, and rain gauges. This indicates that producers were concerned about depleting groundwater levels in the aquifer and would prefer to use irrigation technologies for saving water. Use of automation in irrigation scheduling has increased over the last ten years, possibly due to advances in soil moisture sensor and telemetry technologies, increased farm size, shortage of labor, and increased research and outreach efforts for increasing awareness about water conservation and best utilization (Reba et al. 2014). Survey responses in 2012 showed that producers would implement water conservation practices on their farms if it saved them money and would use alternative water supplies if the federal government helped to pay for it.

The survey conducted in 2012 was the first survey to gather information about perceptions of the agricultural producers in the Mississippi Delta region about the status of water resources and conservation practices. The 2012 survey can be used as a baseline and can help in future follow-up surveys about water resources and management practices. A future follow-up survey in the Delta region of Mississippi can be focused on changes in opinions and perceptions of producers about water resources and conservation practices over time (from 2012 to the present), and adoption of water conservation practices.

Conclusion

Available water resources should be used efficiently and effectively to sustain agricultural productivity. The survey results discussed in this article provided important information to the scientists at the Mississippi State University, Delta F.A.R.M., United States Department of Agriculture (USDA), and other organizations concerning the opinions of producers on water conservation practices. The results from this survey provide valuable insights into farmers' thoughts on water and water conservation practices in the Mississippi Delta. These insights will help with developing research and education programs that, in turn, will help inform policymakers and other stakeholders interested in improving the adoption of water conservation practices in the Mississippi Delta.

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Author Bio and Contact Information

Dr. Gurbir Singh (corresponding author) is an Assistant Professor at the University of Missouri Northern Missouri Research, Extension, and Education Center. Dr. Singh received his Ph.D. degree in Agricultural Sciences from Southern Illinois University in 2018 and M.S. degree in Soil, Environmental, and Atmospheric Sciences from the University of Missouri in 2013. Dr. Singh can be contacted at singhgu@missouri.edu or by mail at Lee Greenley Jr. Memorial Research Farm, 64399 Greenley Place, Novelty, MO 63460.

Dr. Nicolas E. Quintana Ashwell is an Assistant Professor and Natural Resource Economist at the National Center for Alluvial Aquifer Research, Mississippi State University. Dr. Quintana received his Ph.D. degree from Kansas State University. Dr. Quintana's research is focused on improving academic and stakeholder understanding of the economic factors that drive the decline of an aquifer in an area with abundant precipitation and surface water sources. Dr. Quintana can be contacted at n.quintana@msstate.edu or by mail at National Center for Alluvial Aquifer Research, 4006 Old Leland Road, Leland, MS 38756.

Dr. Gurpreet Kaur is an Assistant Professor at the University of Missouri Northern Missouri Research, Extension, and Education Center in Novelty, MO. Dr. Kaur received her Ph.D. degree in Natural Resources from the University of Missouri in 2016. Dr. Kaur can be contacted at gk478@missouri.edu or by mail at Lee Greenley Jr. Memorial Research Farm, 64399 Greenley Place, Novelty, MO, 63460.

Dr. Drew Gholson is an Extension Irrigation Specialist at the Delta Research and Extension Center, Mississippi State University and Coordinator for the National Center for Alluvial Aquifer Research. Dr. Gholson received his Ph.D. from Texas A&M University. Dr. Gholson can be contacted at drew.gholson@msstate.edu or by mail at Delta Research and Extension Center, 82 Stoneville Road, Stoneville, MS 38756.

Dr. Martin A. Locke is the director of the USDA-ARS National Sedimentation laboratory, Oxford, MS. Dr. Locke received his Ph.D. degree in Soil Science from Texas A&M University and M.S. degree from the University of Missouri. Dr. Locke's research is focused on assessing the impact and value of conservation management practices and their influence on environmental quality. Dr. Locke can be contacted at martin.locke@usda.gov or by mail at National Sedimentation Laboratory, 598 McElroy Drive, Oxford, MS 38655.

Dr. L.J. Krutz is the director of the Mississippi Water Resources Research Institute, Mississippi State University. Dr. Krutz received his Ph.D. from Texas A&M University. Dr. Krutz can be contacted at ljk81@msstate.edu or by mail at MS Water Resources Research Institute, 207 Ballew Hall, Mississippi State, MS 39762.

Trey Cooke works for The Nature Conservancy, Cleveland, MS. Mr. Cooke can be contacted at trey.cooke@tnc.org.

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Appendix 1. Survey questions and their respective answer choices.

Question	Response
Are you a:	a) Landowner only b) Landowner & operator c) Operator only d) Other e) Don’t know/not sure f) Refused
Please tell me whether you grow and irrigate each of the following crops: corn, cotton, soybeans, rice, other crops	a) Yes b) No c) Don’t know/not sure d) Refused
What other crops do you grow and irrigate?	a) None b) Don’t know/not sure c) Refused
Please tell me whether you strongly disagree, disagree, neither disagree nor agree, agree, or strongly agree with the following statement: • Water conservation practices are effective in reducing irrigation water use • Water conservation practices can reduce maximum crop yields • Effective irrigation practices rely on knowing how much water is used for each crop • Water meters are the best way of measuring water use	a) Strongly disagree b) Disagree c) Neither disagree nor agree d) Agree e) Strongly agree f) Don’t know g) Refused
Next, I am going to read some statements about water conservation, for each one please tell me if you strongly disagree, disagree, neither disagree nor agree, agree, or strongly agree. • Land forming is an effective water conservation practice for all crops • Zero grade land forming is an effective water conservation practice for rice • I am currently doing everything I can to conserve water • Water conservation practices save money • Using meters as part of irrigation practices can conserve water and maximize profits • You can implement water conservation practices, and not effectively manage water • Conservation practices alone can take care of water problems in the Delta	a) Strongly disagree b) Disagree c) Neither disagree nor agree d) Agree e) Strongly agree f) Don’t know g) Refused

Appendix 1 Continued.

Question	Response
Please tell me whether you consider each of the following water conservation practices as highly efficient, efficient, or inefficient for irrigating corn, soybean, and cotton: • Land forming • Tailwater recovery system • On-farm storage • Instream weirs to pond surface water • Center pivot irrigation • PHAUCET program for sizing holes for furrow irrigation • Short irrigation runs • Irrigation scheduling	a) Highly efficient b) Efficient c) Inefficient d) Don't know/not sure e) Refused
Please tell me whether you consider each of the following water conservation practices as highly efficient, efficient, or inefficient for irrigating rice: • Zero grade land forming • Side-inlets • Center pivot irrigation • Irrigation scheduling	a) Highly efficient b) Efficient c) Inefficient d) Don't know/not sure e) Refused

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Mail Code 4526
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