Spatial Variability of Best Management Practices Effectiveness on Water Quality within the Yazoo River Watershed

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Abstract: Best management practices (BMPs) are management operations that reduce pollution and improve water quality. This study assessed the spatial variability of BMPs effectiveness within the Yazoo River Watershed (YRW) using Soil and Water Assessment Tool (SWAT). Two field-scale watersheds, Merigold Watershed (MW) from the Delta and Skuna River Watershed (SRW) in the Bluff Hills, were selected within the YRW. The SWAT model was calibrated and validated for monthly streamflow, and daily total suspended solids (TSS), total nitrogen (TN), and total phosphorus (TP). Monthly evaluated streamflow Nash–Sutcliffe efficiency indices were in the range from 0.60 to 0.86; daily evaluated TSS indices were in the range from 0.11 to 0.15, TN from 0.11 to 0.12, and TP from 0.05 to 0.26 during model calibration and validation periods. BMPs were implemented in MW and SRW to analyze the spatial variability effect on water quality. Cover crops (CC), vegetative filter strips (VFS), and a combination of VFS and CC were applied as BMP scenarios. Overall, a larger reduction in streamflow was about 15%, sediment about 26%, and nutrient loads, which was about 39% (TN) and 50% (TP), was determined in the MW, whereas in the large watershed (YRW) the reductions in streamflow, sediment, TN, and TP loads were about 4%, 5%, 30%, and 24%, respectively. Therefore, the novelty of this research is to compare the efficiency of a BMP in pollutant reduction at two different geographic scales. The results from this study could help farmers, scientific researchers, precision management planning, and implementing agencies select appropriate BMP for field-scale water resources management in minimizing sediment and nutrient quantities in surface water.

Keywords: hydrology; water quality; BMP; watershed modeling; environment management SWAT

1. Introduction

Agricultural non-point source pollution has been a predominant factor for water quality impairment in the United States and throughout the world [1]. A total of 48% of the river miles in the US are classified as impaired waters. The major reason for that is agricultural runoff [2,3]. Sediment and nutrients transport from agricultural lands to surface water bodies, primarily rivers, and lakes, which leads to eutrophication, resulting in the reduction of viability for aquatic species [4]. YRW is the largest watershed in the state of Mississippi, spanning about 50,000 km², with heterogeneous land-use conditions, which include agriculture, forest, wetlands, and lakes. Therefore, the use of hydrologic models is preferred for water quality assessments in large catchments. SWAT [5] is a modeling tool capable of dividing a larger area into smaller sub-watersheds. The heterogeneity in land-use conditions varies for every sub-watershed, which modeling tools can maintain by adjusting specific parameters that affect the elevation, land-use, soil, etc., conditions. The implementation of BMPs resulted in reduced sediment and nutrient loads at the watershed scale. It is also important to understand the practices implemented at a large watershed scale [6] could have various simulated outcomes compared to simulated results when applied at the field scale [7]. Water quality assessments can be done at both field and watershed scales, as they vary based on numerous topographic, hydro-climatic, and land conditions.
use characteristics [7,8]. Several studies show that the use of SWAT contributed to a better water quality analysis and had been used across the world [9–13]. SWAT model was also applied in some of the previous studies for water quality and BMP assessments in the Mississippi Delta [14–17].

BMPs were efficient in decreasing streamflow, sediment, and nutrient loads [18–21]. The streamflow affects the sediment and nutrient load; these components reduce when the runoff generated in the field is reduced [22]. Risal and Parajuli (2022) applied BMPs in field- and watershed-scale models in the Big Sunflower River Watershed, which is located in the Mississippi Delta, to see the effect of applied practices at both scales, and found that the application of the same practices at the field and watershed scales had different reduction potential [23]. The study in Eagle creek, Ohio was conducted at the field scale of the Maumee River watershed to look at sediment and nutrient reduction to mitigate harmful algal blooms in Lake Eire because of those pollutants [19]. BMP effectiveness can fluctuate amongst spatial scales (field and watershed scales); consequently, it is essential to quantify the variation in reduction capabilities of a specific practice between spatial scales. The uniqueness of this study is that it provides a field- and watershed-scale analysis for streamflow, sediment, and nutrient load reductions when BMPs were implemented, since the quality of water in a watershed is influenced by various land-use factors and the sub-watersheds that are neighboring the outlets. It is crucial to assess the field scale of the watershed since it can impact the outputs based on the land-use conditions within the boundary of the field scale watershed [24]. As a result, this study’s uniqueness lies in comparing the effectiveness of a best management practice (BMP) in reducing pollutants on two distinct geographic scales. There is very limited research available in YRW, and there are no studies conducted focusing on field-scale assessments for YRW; thus, the results from this study could be a novel addition for the scientific community working towards environmental conservation.

The difference between field- and watershed-scale assessments was the following: (i) the area considered during the watershed-scale evaluation is greater compared to the field scale; (ii) the watershed-scale assessment focuses on the entire drainage area of a river, whereas field-scale evaluation focuses on a small region that is part of the larger watershed; and (iii) a more detailed analysis such as site-specific practice can be computed for field-scales. Therefore, two field-scale watersheds, Merigold Watershed (MW) and Skuna River Watershed (SRW), were selected for this study, based on land use in corresponding regions. Default model-generated threshold values were used while delineating field-scale watersheds. MW was cropland dominated, whereas SRW had more forest land with less than 15% of agricultural land. The field-scale watershed selection criterion was to have varied land-use conditions between the regions. Therefore, in the case of MW, agricultural land use was predominant, whereas, in the case of SRW, it was forested land use. The key objectives of this study were to: (i) develop two field-scale models using SWAT; calibrate and validate hydrologic and water quality parameters of the models; and (ii) evaluate the BMP effect at different spatial scales on water quality and hydrology in YRW.

2. Materials and Methods

2.1. Study Area

YRW is about 5 million hectares, it is the largest watershed in the state of Mississippi which is about 47% agricultural land, about 49% forested land, and the rest (4%) wetlands, urban, lakes, and reservoirs. The soil type found in YRW was silty loam which has less infiltration and high erosion potential. This had been determined through watershed delineation in the SWAT model with the help of the Soil Survey Geographic (SSURGO) database, obtained from NRCS—Web Soil Survey [25]. These soils are highly erodible, have lower water holding capacity, and lower percolation. The resolution of the soil layer applied to the model was 30 m × 30 m, similar to other data inputs of the model, which is preferred for field and watershed analysis.
MW was in the Delta region of YRW with a drainage area of about 162,000 ha, agricultural land close to 77%, about 16% of wetlands both forested and non-forested, 5% residential, and 2% water. Dowling, Dundee, Alligator, Forestdale, Tunica, and Sharkey are predominant soils in the watershed. These soil groups belong to Hydrologic Soil groups C and D with less infiltration and higher erosivity. SRW is located in the Bluff hills region of YRW with an area of about 97,000 ha. Land use in SRW was predominantly forested, covering about 60%, agricultural land covering about 21%, and the rest (19%) of pastureland, residential, lakes, and ponds. Major soil types in SRW are Mayhew, Urbo, Falkner, Tippah, Falaya, and Cuthbert. These belong to hydrologic soil groups C and D, which are similar to MW. Each field-scale watershed has one US Geological Survey (USGS) monitoring station and weather stations located at multiple locations. Locations of MW and SRW concerning YRW are shown in Figure 1.

Figure 1. Study area with field (right) and large (left) scale watersheds including sub-watershed numbers, weather stations, and USGS monitoring stations; Yazoo River Watershed (upper left), field-scale watersheds: Merigold Watershed (top right), and Skuna River Watershed (bottom right).

2.2. Model Description and Data Inputs

The Soil and Water Assessment Tool (SWAT) is a daily time-step model that can continuously simulate hydrologic and water quality outputs for longer periods. SWAT is efficient in delineating large watersheds into smaller sub-watersheds and further into hydrologic response units (HRUs). HRU is the smallest scale of all and is essential in applying management operations specific to the region. Simulated results can also be viewed annually, daily, and monthly at watershed, sub-watershed, and HRU levels. SWAT is an ArcGIS extension developed by the US Department of Agriculture-Agriculture Research Service (USDA-ARS); model outputs could be used to determine a specific management practice for the region.
Watershed delineation was based on elevation points from a digital elevation model (DEM) of 30 m × 30 m resolution [26]. Land-use classification with the help of the LULC data layer was obtained from the USDA—National Agricultural Statistical Service (NASS) [27]. Soils layer was obtained from the SSURGO database [25]. Precipitation and temperature data were primary inputs to the model, obtained from the National Oceanographic and Atmospheric Administration (NOAA) [28]. Agricultural practices such as planting, irrigation scheduling, fertilizer, and pesticide inputs were obtained from the Mississippi Agricultural and Forestry Experiment Station (MAFES) variety trials [29]. Appropriate manure inputs were collected and applied as per American Society for Agricultural and Biological Engineers (ASABE) standards [30].

2.3. Calibration and Validation

Streamflow, sediment, total nitrogen (TN), and total phosphorus (TP) were the parameters that were adjusted during the calibration and validation processes. Two statistical indices, the coefficient of determination (R²) and Nash–Sutcliffe efficiency index (NSE) [31,32], were mainly used in model accuracy assessment. The previous literature in a similar field to watershed modeling used R² and NSE for model accuracy assessment [15,33–39]. Streamflow was calibrated and validated with the help of an auto-calibration tool called SWAT-Calibration Uncertainty Procedure (SWAT-CUP). SWAT-CUP uses the Sequential Uncertainty Fitting—2 (SUFI-2) algorithm that helps change multiple parameters within an acceptable range at once during the calibration and validation process [40]. Both field- and watershed-scale models were simulated from 2002 to 2019. YRW was calibrated from 2008 to 2011 and validated from 2012 to 2015 using the observed streamflow data for 8 USGS monitoring stations. Model accuracy assessment through calibration and validation for streamflow was performed in MW and SRW from 2008 to 2011 and validated from 2012 to 2015 using the observed streamflow data for 8 USGS monitoring stations. Monthly observed USGS streamflow data from Merigold (Gage: 7,288,280) and Skuna River at Bruce (Gage: 7,283,000) were used for model calibration and validation. Concentrations (mg/L) of total suspended sediment, TN, and TP were obtained at the Merigold USGS monitoring station in the Big Sunflower River. These concentrations were then attributed to sediment and nutrient loads (tons/day) by correlating with streamflow. The auto-calibration tool was not successful for sediment and nutrient loads. Therefore, sediment load, TN load, and TP load were manually calibrated from 2013 to 2014 and validated from 2015 to 2016. Calibration and validation parameters were adopted from the previous literature [41–46]. The parameters used while the calibration and validation procedure were listed and detailed in the study conducted by Venishetty and Parajuli in 2022 [47].

2.4. Management Scenarios

BMP implementation could help in mitigating water pollution. Although numerous reported BMPs are effective, this study assessed practices such as vegetative filter strip (VFS), cover crop (CC), and the combination of CC and VFS (Table 1). The selection and design of these BMPs such as CC scheduling, CC type, the width of VFS, location, etc., were as per farming practices in the YRW.

2.4.1. Vegetative Filter Strips (VFS)

Vegetative areas with known widths are those grown naturally or planted alongside surface water sources that are in the path of water drained from an agricultural field. VFSs are usually small grasses and bushes that help trap sediment and nutrients from runoff generated during a precipitation event [48]. In the previous study [47], a VFS width of 20 m was a result of the highest reduction in sediment and nutrient loads; therefore, a 20 m width was considered for this study.
2.4.2. Cover Crops (CC)

CCs provide vegetative cover to the ground by dissipating the energy of a raindrop and avoiding splash-generated erosion. CCs also utilize residual nutrients such as nitrogen and phosphorus that were applied during a crop growing season. They also improve soil porosity, increasing soil infiltration potential [49]. CCs’ schedule was planned in such a way that they were planted post-harvest of the main crop and killed by tilling at the beginning of the next crop [50]. CCs such as ryegrass, winter wheat (WWheat), and winter barley (WBarley) were considered for this study since they were commonly used in the region. The combination scenarios include VFS + CC, and CCs chosen in combination scenarios were the same as individual CC scenarios. All BMP scenarios are listed in Table 1 below:

Table 1. List of BMPs applied in this study.

<table>
<thead>
<tr>
<th>S. No.</th>
<th>BMP Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>VFS Vegetative Filter Strip (20 m applied)</td>
</tr>
<tr>
<td>2</td>
<td>Cover Crop ryegrass</td>
</tr>
<tr>
<td>3</td>
<td>Cover Crop winter wheat (WWheat)</td>
</tr>
<tr>
<td>4</td>
<td>Cover Crop winter barley (WBarley)</td>
</tr>
<tr>
<td>5</td>
<td>VFS + CC_ryegrass</td>
</tr>
<tr>
<td>6</td>
<td>VFS + CC_WWheat</td>
</tr>
<tr>
<td>7</td>
<td>VFS + CC_WBarley</td>
</tr>
</tbody>
</table>

3. Results

3.1. Calibration and Validation

The calibrated and validated model for YRW on the watershed scale was used to delineate the field scale MW and SRW. The calibration and validation period for streamflow was from 2008 to 2015. Using the parameters applied for the watershed-scale model, streamflow, and water quality parameters for the MW and SRW were calibrated and validated. \( R^2 \) and NSE for monthly streamflow in MW were 0.62 and 0.60 during calibration and 0.69 and 0.62 for validation, respectively. Similarly, \( R^2 \) and NSE for SRW were 0.86 and 0.86 during calibration and 0.77 and 0.76 for validation, respectively. Streamflow calibration and validation results are graphically depicted in Figures 2 and 3 for MW and SRW field-scale watersheds. Sediment and nutrient calibration and validation parameters were applied from the watershed-scale study for YRW detailed in Venishetty and Parajuli 2022. After obtaining a satisfied statistics, sediment, TN, and TP parameters were calibrated and validated using similar parameters as the watershed scale. Calibration and validation for TN and TP were performed from 2013 to 2014 and 2015 to 2016, respectively. With the limited observed data, the highest NSE for TN was 0.12 and 0.26 for TP. Despite the extreme weather events in the region and the high observed values of sediment, TN, and TP samples [51], model calibration and validation performances showed satisfactory results and they were in the range of the previous studies conducted in watersheds of Mississippi, Texas, Indiana, Wisconsin, and European countries [37,52–56]. Moriasi in 2007 stated that NSE values between 0.00 and 1.00 can be considered an acceptable level of performance [57]. The study conducted by Mahdian et al., 2023 [58] in the Anzali wetland watershed of Iran indicated that monthly time-scale calibration of sediment load resulted in satisfactory to good model performance. Abbaspour et al., 2015 [56] applied the SWAT model in the major rivers across Eurasia, where model calibration for monthly time-scale nutrient loads resulted in satisfactory to poor model performance [56]. In this study, model accuracy assessments for sediment and nutrient loads were performed for the daily time scale. Calibration and validation results of sediment and nutrient load in this study are mentioned in Table 2.
Calibration $R^2 = 0.86$  
NSE = 0.86
Validation $R^2 = 0.77$  
NSE = 0.76

Figure 2. Streamflow calibration and validation for the Merigold Watershed.

Calibration $R^2 = 0.62$  
NSE = 0.60
Validation $R^2 = 0.69$  
NSE = 0.62

Figure 3. Streamflow calibration and validation Skuna River watershed.

### Table 2. Calibration and validation results for sediment and nutrient loads.

<table>
<thead>
<tr>
<th></th>
<th>Sediment</th>
<th></th>
<th>TN</th>
<th></th>
<th>TP</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$R^2$</td>
<td>NSE</td>
<td>$R^2$</td>
<td>NSE</td>
<td>$R^2$</td>
<td>NSE</td>
</tr>
<tr>
<td>Calibration</td>
<td>Big Sunflower at</td>
<td>0.15</td>
<td>0.15</td>
<td>0.12</td>
<td>0.11</td>
<td>0.30</td>
</tr>
<tr>
<td>Validation</td>
<td>Merigold</td>
<td>0.27</td>
<td>0.11</td>
<td>0.33</td>
<td>0.12</td>
<td>0.82</td>
</tr>
</tbody>
</table>

3.2. Impact Due to BMP Implementation at Field and Watershed Scales

A total of 7 BMP scenarios were evaluated, with 4 of them being individual applications and 3 combination scenarios. The results for each BMP and a comparative analysis are discussed further. The implementation of VFS as BMP had minimal impact on the flow but there was a significant reduction in sediment and nutrient loads. CC and Combination VFS + CC scenarios showed significant streamflow, sediment, and nutrient load reductions.
3.2.1. Vegetative Filter Strips (VFS)

VFS had a significant impact on reducing sediment and nutrient loads in the agriculture-dominant MW, but the minimum impact on SRW since the percentage of land in the field-scale watershed used for agriculture was comparatively less than that of forested land area. Therefore, a change in percentage reductions has been observed between YRW, MW, and SRW. Since a VFS width of 20 m showed maximum reduction, other simulations were disregarded for this study. The difference in sediment and nutrient loads for field- and watershed-scale models can be observed in Tables 3–5.

Table 3. Percentage reductions when different BMPs were implemented in YRW.

<table>
<thead>
<tr>
<th>BMP</th>
<th>Percent Decrease</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Streamflow</td>
</tr>
<tr>
<td>VFS + Ryegrass</td>
<td>5.40</td>
</tr>
<tr>
<td>VFS + WB</td>
<td></td>
</tr>
<tr>
<td>VFS + W</td>
<td></td>
</tr>
<tr>
<td>VFS + WWheat</td>
<td>3.30</td>
</tr>
</tbody>
</table>

Table 4. Percentage reductions when different BMPs were implemented in MW.

<table>
<thead>
<tr>
<th>BMP</th>
<th>Percent Decrease</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Streamflow</td>
</tr>
<tr>
<td>VFS 20 m</td>
<td>0.00</td>
</tr>
<tr>
<td>CC_Ryegrass</td>
<td>19.01</td>
</tr>
<tr>
<td>CC_WBarley</td>
<td>17.77</td>
</tr>
<tr>
<td>CC_WWheat</td>
<td>15.05</td>
</tr>
<tr>
<td>VFS + CC_Ryegrass</td>
<td>19.01</td>
</tr>
<tr>
<td>VFS + CC_WBarley</td>
<td>17.77</td>
</tr>
<tr>
<td>VFS + CC_WWheat</td>
<td>15.05</td>
</tr>
</tbody>
</table>

Table 5. Percentage reductions when different BMPs were implemented in SRW.

<table>
<thead>
<tr>
<th>BMP</th>
<th>Percent Decrease</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Streamflow</td>
</tr>
<tr>
<td>VFS 20 m</td>
<td>0.00</td>
</tr>
<tr>
<td>CC_Ryegrass</td>
<td>2.67</td>
</tr>
<tr>
<td>CC_WBarley</td>
<td>2.52</td>
</tr>
<tr>
<td>CC_WWheat</td>
<td>2.01</td>
</tr>
<tr>
<td>VFS + Ryegrass</td>
<td>2.68</td>
</tr>
<tr>
<td>VFS + WB</td>
<td></td>
</tr>
<tr>
<td>VFS + WWheat</td>
<td>2.01</td>
</tr>
</tbody>
</table>

3.2.2. Cover Crops (CC)

CCs Ryegrass, WWheat, and WBBarley showed significant reductions in streamflow, sediment, and nutrient loads. Ryegrass had the highest reduction in streamflow, sediment, and TP load. WWheat had the highest reduction in TN load for MW, whereas in SRW, Ryegrass showed the highest reduction for all parameters. Combination scenarios were assigned with a VFS width of 20 m plus a CC. The change caused by the implementation was detailed in Tables 3–5. Figures 4 and 5 graphically display a comparative assessment in percentage reduction between each scenario for YRW, MW, and SRW. CC scenarios for YRW had no impact on sediment load reduction, but a 5.30% reduction in flow was seen when Ryegrass was applied, and a 10.60% decrease in TP loads was also observed. Maximum reduction in TN loads was observed when winter wheat was applied as CC with 25.40% [47].
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Percentage reductions in hydrologic and water quality outputs at different spatial scales

Figure 4. Comparative analysis of percentage reductions in streamflow, sediment, TN, and TP loads between field- and watershed-scale models when BMPs were implemented.

Comparative analysis of average overall percentage change among YRW, MW and SRW

Figure 5. Overall average comparative assessment in percentage reductions for YRW, MS, SRW.

4. Discussion

The model performance during calibration and validation was good for streamflow. In the case of sediment, TN, and TP, the performance was satisfactory and in the suggested range from the previous literature [37,51–55]. This was mainly due to the limited availability of observed data and the unfavorable climatic conditions in the region [56]. BMP scenarios selected in this study were according to the farm practices in the region. Therefore, the results provide an understanding of the reduction in different parameters when these practices were implemented.

With VFS width set to 20 m, TN and TP load reduction for YRW were 34.60% and 33.40%, respectively, with a decrease in sediment load by 8%, whereas, in MW at field scale, the decrease in TN and TP loads contributed by the implementation of VFS were 65.33% and 65.61%, respectively, with sediment load reduced by 14.91%. This was a significant
increase in reduction when applied to the same practice at field scale MW. Similarly, when VFS was applied in agricultural land [59] in SRW there was no change in sediment loads. However, in the case of SRW percentage of land occupied by forests was significantly higher than agricultural land. A decrease in TN and TP was observed and accounted for 33.47% and 33.52%, respectively. Validation of the results of this study was performed by comparing the results from the studies conducted in watersheds of the Upper Midwest United States, such as Alger Creek in Michigan [60], the Delta region of Mississippi in Big Sunflower Watershed [38], paired watershed studies in central Iowa [61], and sediment yield reduction studies of Upper Wakarusa watershed in Kansas [62].

CC and a combination of VFS and CC scenarios were able to reduce sediment and nutrient loads along with streamflow. For YRW, CC implementation resulted in significant reductions for nutrient loads and with minor reduction for streamflow; similarly, in field-scale watersheds, significant reductions were observed for streamflow, sediment, and nutrient loads. The highest flow, sediment, and TP reductions with 19.01%, 25.97, and 35.45%, respectively, were seen when ryegrass was applied as CC in MW; similar results were seen in SRW, as well as with ryegrass as CC, as detailed in Tables 3 and 4. Maximum reduction in TN for MW was seen for winter wheat at 12.01%. The trends of this study were similar to other studies conducted in various watersheds located in the Choptank River Watershed in Maryland and Delaware [63]; the German Branch Watershed of the Choptank River Watershed [64]; the Tuckahoe Creek Watershed and Greensboro Watershed of Choptank River Watershed [65]; the Mississippi Delta [66]; Walnut Creek Watershed in Iowa [67]; and the coastal watersheds of Mississippi [68].

5. Conclusions

The results of this study suggested that there was a significant difference in percentage reductions when BMPs were applied at field and watershed scales. The SWAT model performance was evaluated for monthly streamflow with the NSE from 0.60 to 0.86, daily TSS with the NSE range from 0.11 to 0.15, TN from 0.11 to 0.12, and TP from 0.05 to 0.26 during model calibration and validation periods. Seven BMP scenarios were applied for both field- and watershed-scale models. Although the percentage reduction in streamflow was lower than the reduction in sediment and nutrient loads for CC practice, the combination of VFS and CC resulted in a significant decrease in streamflow. Combination scenarios VFS + CC had the highest average reductions when applied for YRW with the highest flow, sediment, TN and TP reductions with about 5%, 8%, 41% and 34%, respectively. In the case of MW, VFS + ryegrass had the highest reduction for stream flow at about 19%, sediment about 33%, and TP loads about 64%. VFS + WWheat had the highest reduction of TN load close to 54%. In the case of SRW, TP load reduction when VFS + CC was about 35% which was higher when compared to the YRW. The combination of scenarios had the highest reduction compared to the individual application; the investigations of this study also indicated that the smaller field-scale assessments were more detailed than the watershed-scale evaluations. Therefore, the methods could be correlated and applied in watersheds across the world. It was evident that BMP implementation had different reduction potentials between field and watershed-scale models and the implementation at the field scale had more benefits compared to the watershed scale. The results of this study could provide an insight into selecting appropriate management practices based on the location and severity of pollution to farmers and multiple institutions in decision making and implementing conservation practices for environmental benefits by improving water quality.

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Conflicts of Interest: The authors declare no conflict of interest.

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NRCS United States Department of Agriculture—Natural Resources Conservation Service (USDA-NRCS)—Cover Crop | NRCS.


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