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# Atrazine residues in flooded and nonflooded soil and effects on soybean

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**Research Article**

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## Abstract

Atrazine applied at planting is commonly used for weed control in corn. With global climate change causing an increase in river flooding in the United States over the past decade, producers need information to determine the best course of action in flooded fields treated with atrazine into which they wish to immediately plant soybean. Studies were designed to understand the effect of flooding on atrazine residual activity including atrazine concentration, soybean injury, and soybean yield. In 2012, soybean yield in flooded treatments was reduced by prior atrazine application. In 2014, soybean injury was <10% in all plots, and nonflooded, atrazine-treated soils had yields equal to the nontreated. Findings from this research indicated that it is possible for producers to consider replanting soybean after atrazine application, with appropriate changes to product labeling.

## Introduction

Atrazine is a commonly used herbicide providing PRE and POST weed control in corn, sorghum [*Sorghum bicolor* (L.) Moench], and sugarcane (*Saccharum officinarum* L.) (Mitchell 2014). The longevity of atrazine in soil is a primary attribute that allows residual weed control for producers. This persistence has led to concern of possible surface and groundwater contamination (Brecke et al. 1981; Burnside and Wicks 1980; Burnside et al. 1971; Hall et al. 1972; Kelly and Wilson 2000; Laroche et al. 1996; Richards et al. 1987, 1996; Toccalino et al. 2014).

Given the increased prevalence of climate shifts and the probability of flooding continuing to affect crop production, producers should aim to better understand available options when replanting a field to a different crop. From 2010 to 2019, several significant flooding events occurred in the soybean and corn production regions of the United States (Fournier et al. 2016; Martin et al. 2016; Vahedifard et al. 2016; Wang et al. 2016; van der Wiel et al. 2017). Flooding may destroy the corn crop, and growers would like to plant a different crop after the flood waters recede. Producers have questions about how to manage fields previously treated with atrazine. Late frosts, hail damage, wildlife damage, or other factors may also destroy the crop and force producers to consider replanting a field in soybean after an atrazine application has been made. Simply replanting corn will often result in reduced corn yield due to late planting (Benson 1990, Olson 2009). Specifically, in Tennessee corn yield loss ranged from 4% to 25% depending upon hybrid when planting is delayed from April to May (McClure 2011). Therefore, alternatives are needed.

One objective of this research was to examine the persistence of atrazine in flooded soils and to examine the effect of soil condition on later atrazine effects on soybean. Many papers have previously reported on atrazine behavior in soil (Brecke et al. 1981; Burnside et al. 1971; Gallaher and Mueller 1996; Krutz et al. 2009, 2010) with a wide range of half-lives reported (20 to >100 d). Looking at the effect of soil wetting and the resultant changes in redox potential, atrazine will be more persistent under anaerobic conditions than in the aerobic, more oxidizing environments that are normally found in surface agricultural soils (DeLaune et al. 1997). Seybold et al. (2001) indicated that atrazine can degrade under strongly reducing conditions, such as those found in wetland soils. Conversely, atrazine was equally degraded under aerobic and anaerobic conditions (Issa and Wood 2005) and was not affected by tight adsorption to soil.

No published research has examined the effects of atrazine on soybean replanted after a period of soil flooding. Although Pawlak et al. (1987) described soybean injury from carryover in no-till systems, no definitive answer can be given regarding the effect of flooding on atrazine carryover. These results strive to inform producers with the best course of action to replant soybean in atrazine-treated fields.

Our hypothesis was that atrazine in flooded soils could be moved off-site, or that atrazine degradation could be reduced or increased under anaerobic soil conditions. In the absence of flooding, atrazine persistence would be expected to prevent subsequent soybean planting as a result of crop injury. The objective was to record soybean injury symptoms for comparison with

**Figure 1.** Field image of main plots, nonflooded and flooded.

effect on overall soybean yield (Anderson 1970; Pawlak et al. 1987). Current use labels also forbid soybean replanting soon after atrazine treatment.

## Materials and Methods

### Flooding Plots

Experiments were carried out in the spring and summer of 2012 and 2014 in Knoxville, TN. Studies were conducted in Sequatchie silt loam soil with a pH of 6.2, cation exchange capacity of 10.4 mEq 100 $g^{-1}$, and organic matter content of 1.7%. Data from a 2013 field experiment was not valid because of heavy rainfall (~20 cm over 10 d) that resulted in the flooding of all plots.

In both years, the previous year the plots had been in soybean. There was no atrazine present in the plot area, as atrazine was prohibited to be used on this research farm. For this reason, soil samples prior to atrazine application were not collected.

The entire field area was tilled 40 d before study initiation to bury plant residue and allow for soil berm construction. Main plots were created by building soil berms around 12-m by 12-m plots containing three 9-m by 3-m subplots (Figure 1). Glyphosate was applied 14 d prior to research initiation at a rate of 870 g $ha^{-1}$ to all plots to control existing weeds. Atrazine (Aatrex 4L; Syngenta, Greensboro, NC) treatments of 0, 2.2, and 4.5 kg $ha^{-1}$ were applied within berms prior to flooding using a six-nozzle handheld boom at 276 kPa in 190 L $ha^{-1}$ of water carrier. Applications were made on May 18, 2012 and May 19, 2014. All plots received 20 mm of overhead irrigation at 0 d after treatment (DAT), and then nonflooded treatments were allowed to dry. Flooded treatments were applied immediately after surface irrigation (~ 1 h) on 0 DAT using large pipes to dispense water into the main plots, with care taken to minimize soil disturbance (Figure 2).

The location of this research is in the foothills of the Great Smoky Mountains (35.9773°N, 83.8524°W) and is situated at the confluence of the French Broad River and the Holston River, which then form the Tennessee River. Technically the water source for flooding treatments was the Holston River and lay approximately 200 m upriver from the start of the Tennessee River. This site was chosen in part because of access to water that would not be expected to contain atrazine. Atrazine is sometimes found in rivers in the United States, but the area of this research is predominantly forested, with only some residential areas and a few pastures and hayfields within the watershed. More widely, Knox County grows <270 ha of corn annually (Bowing and Smith 2019), all of which lies downriver from this site. The most recent sampling of the same area of the river showed no atrazine to be present, even when multiple analytical laboratories separately examined the water from this same location (Senseman et al. 2003). Based on these factors, these authors strongly assert that the water used in the flooding regimen contained no atrazine.

Depth of flood was ~5 to 15 cm and was maintained for 5 d. At that time, berms were opened and plots were allowed to dry. After drying for ~7 d, berms were leveled with tillage and all plots were no-till planted with commercial equipment at 2.5 cm depth and 76 cm row spacing. Seeding rate of Asgrow 4532 RR (Bayer Crop Sciences, St. Louis, MO) soybean was 50 kg $ha^{-1}$. Soybean was planted on May 31, 2012 and June 6, 2014. Plots were maintained weed free using glyphosate applied POST, as no glyphosate-resistant weeds were present at this location.

### Data Collection

In 2012 and 2014, soil samples from each individual plot were collected prior to planting. Three samples from each plot were mixed to form a single sample from that particular individual plot.

**Figure 2.** Water being added to main plots in flooded treatments.

Samples were collected from a depth of 0 to 8 cm using a turf cup cutter at 13 d in 2012 and 17 d in 2014 after flooding (0 d after planting, DAP). These soil samples were transported in coolers to the lab and stored at –20 C until extraction. Soil samples were later homogenized and extracted using methanol, shaking, and filtration, and analyzed via liquid chromatography–mass spectrometry (LC-MS) according to previous methods (Mueller et al. 2010). Peaks detected via LC-MS were converted to concentration in μg kg$^{-1}$ for later statistical analysis.

At 28 and 42 DAP, soybean injury was visually evaluated using a scale of 0% to 100%, with 0% being no injury and 100% representing complete plant necrosis. At ~120 DAP in both studies, two center rows of soybean were mechanically harvested and yield data were collected for analysis.

### Experimental Design and Data Analysis

A randomized complete block 2 × 3 factorial split-plot design was used with two levels of flooding (flooded and nonflooded) across three atrazine rates. Atrazine rates were used to examine both average and twice the normal use rates (Anonymous 2020). Each treatment was replicated four times, and the entire study was repeated in time in 2012 and 2014.

Data were subjected to ANOVA in SAS (v. 9.2, SAS® Institute Inc., Cary, NC) using PROC GLIMMIX to test for significance of atrazine rate and flooding treatment on atrazine concentration in soils, soybean injury, and yield. Year and replication were considered random effects, with flooding and atrazine rate being considered fixed effects. All visual evaluation data were transformed for statistical analysis using a square root transformation; true means are presented here. Means were separated using Fisher's protected LSD and considered significant if $P \leq 0.05$.

## Results and Discussion

### Atrazine Concentration

The expected initial atrazine concentration on 0 DAT would have been ~2,000 and ~4,000 μg kg$^{-1}$ in the 2.2- and 4.5-kg ha$^{-1}$ treatments, respectively, based upon previous research on this soil and with the same sampling procedure (Gallaher and Mueller 1996). In 2012, atrazine concentration within a given atrazine rate was similar in both flooded and nonflooded soils (Table 1). Atrazine concentration was greatest in soils treated with the higher rate of atrazine, with about 35% less atrazine recovered in soils treated with the lower rate. Low atrazine concentrations in control plots suggest that atrazine movement in surface water was minimal but may have occurred. Atrazine would not be expected to be in the soil from previous years, as soybean had been grown, and no atrazine use is allowed on this research farm. In 2014, atrazine concentrations were much higher in nonflooded soils compared with flooded soils (Table 2). Atrazine degradation may be occurring in the moist, flooded soils because of an increase in the population of microbes capable of metabolizing atrazine (Mueller et al. 2010; Shaner and Henry 2007; Shaner et al. 2007). Nonflooded soils may have lacked the moisture required to support microbial populations capable of metabolizing atrazine within surface soils in the time interval after soybean planting (Table 3). However, the readers are reminded that the atrazine was incorporated with 20 mm of rainfall on the day of application.

### Soybean Injury

In 2012 at both 28 and 42 DAP, soybean injury within the nonflooded treatments was similar to the nontreated plots, regardless of atrazine use rate (Table 1). There were large differences of

**Table 1.** Atrazine dose, concentration, soybean yield, and soybean injury from a field site in Knoxville, TN, in 2012.[a]

| | | Soybean injury | | | Atrazine concentration |
|---|---|---|---|---|---|
| | Atrazine dose | 28 DAP[b,c] | 42 DAP | Soybean yield | 0 DAP |
| Flooded | kg ha$^{-1}$ | % | | kg ha$^{-1}$ | µg kg$^{-1}$ |
| Yes | 0 | 7 b | 4 b | 3,600 a | 91 cd |
| Yes | 2.2 | 70 a | 75 a | 2,400 c | 503 bc |
| Yes | 4.5 | 74 a | 46 a | 2,400 c | 870 ab |
| No | 0 | 4 b | 2 b | 3,200 ab | 15 d |
| No | 2.2 | 6 b | 4 b | 2,700 bc | 700 ab |
| No | 4.5 | 13 b | 9 b | 2,800 bc | 1,040 a |
| LSD | | 12.6 | 14.1 | 770 | 420 |

[a]A two-way interaction of flooding and atrazine rate was significant ($P < 0.05$).
[b]Abbreviations: DAP, days after planting.
[c]Means sharing a letter within columns are not different according to Fisher's protected LSD (0.05).

**Table 2.** Atrazine dose, concentration, soybean yield, and soybean injury from a field site in Knoxville, TN, in 2014.[a]

| | | Soybean injury | | | Atrazine concentration |
|---|---|---|---|---|---|
| | Atrazine dose | 28 DAP[b,c] | 42 DAP | Soybean yield | 0 DAP |
| Flooded | kg ha$^{-1}$ | % | | kg ha$^{-1}$ | µg kg$^{-1}$ |
| Yes | 0 | 0 d | 0 c | 3,600 a | 98 c |
| Yes | 2.2 | 7 b | 4 b | 3,500 a | 249 c |
| Yes | 4.5 | 8 b | 6 b | 3,600 a | 346 c |
| No | 0 | 0 d | 0 c | 3,500 a | 4 c |
| No | 2.2 | 5 c | 4 b | 3,400 a | 1,300 b |
| No | 4.5 | 10 a | 7 a | 3,300 a | 3,990 a |
| LSD | | 1.4 | 2.2 | NS | 605 |

[a]A two-way interaction of flooding and atrazine rate was significant ($P < 0.05$).
[b]Abbreviations: DAP, days after planting.
[c]Means sharing a letter within columns are not different according to Fisher's protected LSD (0.05).

soybean injury in 2012 in flooded soils, with substantial response at both atrazine rates. In 2014, soybean injury from atrazine was much lower (<10%) (Table 2). All atrazine treatments caused injury compared with the nontreated, but the maximum observed was 10%.

## Soybean Yield

In 2012, flooded plots treated with atrazine had lower soybean yields (Table 1). These lower yields were consistent with the visual injury previously noted in those plots. Plots in 2012 that were not flooded showed no yield difference from atrazine application. Within flooded atrazine soils, yield was reduced at both 2.2 and 4.5 kg ha$^{-1}$ from over 3,600 kg ha$^{-1}$ to under 2,400 kg ha$^{-1}$, respectively.

In 2014, there were no differences in yield across all treatment factors (Table 2). That yields were similar was consistent, with all soybean response being <10% at 28 and 42 DAP.

So how could much higher atrazine soil concentrations in 2014 result in lower soybean injury? One possible reason is that the soil conditions soon after planting in 2012 were drier, with weeks 1, 2, and 3 after soybean planting receiving only 7.6, 3.6, and 0.5 mm of rain each week, respectively. The rainfall soon after planting (33 mm in week 1) allowed for adequate atrazine uptake, as atrazine is a xylem-mobile herbicide and must be transported into leaves for activity. This would be consistent with those results reported by Gallaher and Mueller (1996). The plots during the first 4 wk of 2014 received >5 mm of rainfall each week, and this possibly allowed the soybean to compensate for the atrazine presence and show less than 10% soybean injury.

Another possibility is that different mechanisms were at work in the flooded and nonflooded plots in 2014. The flooded plots may have shown less soybean injury because the atrazine applied had largely been degraded, as adequate soil moisture resulted in the presence of <400 µg kg$^{-1}$ atrazine in 0 to 8 cm soil (Table 2). The nonflooded plots had much higher atrazine concentrations (1,300 and 3,990 µg kg$^{-1}$), but possibly this herbicide was concentrated near the soil surface and was not as fully available for plant root uptake by the soybean plants. Rainfall during week 2 was <5 mm, and perhaps during this critical time interval the atrazine remained on the soil surface and was not as fully moved into the soybean plants. It is also possible that once rainfall began in 2014 (after planting), the atrazine degraded rapidly. Soil moisture during the interval prior to planting was dry, and the nonflooded plots received only 4.6 mm of rainfall during those 2 wk (Table 3).

These data indicate that it was possible to plant soybean after flooding into atrazine-treated fields with no yield loss in one of two years in this research. These data also indicate that planting soybean after atrazine may be possible in nonflooded soils as well. Situations other than flooding, including late freezes, hail damage, and herbicide drift scenarios, may lead producers to plant soybean or a different crop. Although some soybean injury may occur, it will be similar to the injury thresholds that producers experience when utilizing protoporphyrinogen oxidase–inhibiting herbicides such as fomesafen in soybean (Cieslik et al. 2014). The observed injury also did not affect overall soybean yields in nonflooded plots.

**Table 3.** Rainfall and irrigation data for studies in 2012 and 2014.

| 2012 | | | 2014 | | |
|---|---|---|---|---|---|
| WAP[a] | Mean air temperature | Total rainfall | WAP | Mean air temperature | Total rainfall |
| wk | C | mm | wk | C | mm |
| −2 | 21.2 | 29.1 | −2 | 21.5 | 23.6 |
| −1 | 24.2 | 0.0 | −1 | 23.8 | 1.0 |
| 0 | 20.6 | 32.8 | 0 | 22.8 | 20.6 |
| 1 | 22.1 | 7.6 | 1 | 23.7 | 10.2 |
| 2 | 24.2 | 3.6 | 2 | 25.5 | 4.6 |
| 3 | 25.8 | 0.5 | 3 | 25.7 | 27.4 |
| 4 | 27.9 | 20.3 | 4 | 23.5 | 30.0 |
| 5 | 27.6 | 79.5 | 5 | 24.0 | 5.8 |
| 6 | 25.0 | 33.8 | 6 | 23.7 | 85.6 |
| 7 | 26.5 | 71.1 | 7 | 22.5 | 62.0 |
| 8 | 26.4 | 13.2 | 8 | 23.3 | 3.8 |
| 9 | 26.4 | 29.0 | 9 | 23.9 | 42.7 |
| 10 | 23.0 | 120.9 | 10 | 23.3 | 49.5 |
| 11 | 22.2 | 3.0 | 11 | 25.2 | 2.8 |
| 12 | 23.9 | 0.5 | 12 | 25.4 | 32.8 |
| 13 | 26.2 | 26.4 | 13 | 24.9 | 26.7 |
| 14 | 22.2 | 13.2 | 14 | 21.1 | 2.8 |
| 15 | 21.1 | 172.7 | 15 | 19.2 | 6.9 |
| 16 | 17.7 | 0.0 | 16 | 20.9 | 0.0 |
| 17 | 20.6 | 3.6 | 17 | 14.7 | 8.1 |
| | | 631.7 | | | 422.1 |

[a]Abbreviation: WAP, weeks after planting.

These results show that current atrazine replanting restrictions may be excessive on these soil types and climate (Anonymous 2020).

Several factors affected our results, including environmental conditions. Soil temperatures were warmer than would be the case in more northern climates; thus, decreased soil temperature would most likely result in slower atrazine degradation and therefore a higher atrazine concentration at the time of soybean planting (Brecke et al 1981; Burnside and Wicks 1980). Cooler temperatures may also result in less vigorous plant growth, and thus soybean present may be less able to detoxify the atrazine. Soil pH and texture may also have affected our results. Other locations that grow both corn and soybean will have soils that will be less conducive to atrazine degradation, and thus possibly more prone to soybean injury.

One aspect of herbicide use in the United States is the adherence to published labels. Failure to follow labels is inappropriate, and producers are required to read and follow all label instructions. The publication of these data does not expressly encourage the off-label use of planting various crops prior to the stated re-cropping interval.

The atrazine soils data indicated some movement from treated to nontreated plots in the flooded areas. Atrazine concentration in the flooded, nontreated plot was approximately 90 $\mu g\ kg^{-1}$ each year, compared to 4 to 15 $\mu g\ kg^{-1}$ in the nonflooded, nontreated plots. This research was conducted in a "closed system," and the atrazine was contained within each whole-plot berm; thus, the atrazine present in the water was not diluted. Water volumes in flooded-field scenarios would probably dilute the atrazine concentration to much lower levels and potentially reduce soybean responses.

The shortened atrazine persistence in the 2014 study in the flooded plots provides credence to a re-examination of atrazine labels based on these data and other findings (Mueller et al. 2017). Shorter allowable re-crop intervals for cover crops, wheat, and other desirable crops would allow more flexibility for producers. One challenge for the primary registrant to change labels is that the Environmental Protection Agency insists that all atrazine field studies utilize locations with no previous atrazine use history. This does not match the current reality of atrazine use in agriculture in the United States, where atrazine is used in fields repeatedly over several years, and enhanced degradation may alter atrazine persistence (Mitchell 2014; Mueller et al. 2017).

Future research should target the effects of enhanced atrazine degradation on plant-back intervals of atrazine-sensitive crops. More research should also address the impact of rainfall amount, tillage system, and other pesticide use on the success of replanted corn and soybean after a flooding event.

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## References

Anderson R (1970) Influence of soybean seed size on response to atrazine. Weed Sci 18:162–164

Anonymous (2020) AAtrex® 4L Product Label. Syngenta Crop Protection, LLC P.O. Box 18300, Greensboro, NC 27419-8300: Syngenta Crop Protection, LLC Publication SCP 497A-L38TT 1112 4021678. 24 p

Benson GO (1990) Corn replant decisions: a review. J Prod Agric 3:180–184

Bowing B, Smith A (2019) 2019 Planted acres for corn, cotton, soybean, grain sorghum and wheat in Tennessee by county. Extension Pub W442. UT Extension Institute of Agriculture. https://extension.tennessee.edu/publications/Documents/W442.pdf. Accessed: November 15, 2020

Brecke BJ, Currey WL, Teem DH (1981) Atrazine persistence in a corn–soybean doublecropping system. Agron J 73:534–537

Burnside OC, Fenster CR, Wicks GA (1971) Soil persistence of repeated annual applications of atrazine. Weed Sci 19:290–293

Burnside OC, Wicks GA (1980) Atrazine carryover in soil in a reduced tillage crop production system. Weed Sci 28:661–666

Cieslik LF, Vidal RA, Trezzi MM (2014) Fomesafen toxicity to bean plants as a function of the time of application and herbicide dose. Acta Sci Agron 36:329–334

DeLaune RD, Devai I, Mulban C, Crozien C, Lindan CW (1997) The influence of soil redox conditions on atrazine degradation in wetlands. Agric Ecosyst Environ 66:41–46

Fournier S, Reager JT, Lee T, Vazquez-Cuervo J, David CH, Gierach MM (2016) SMAP observes flooding from land to sea: The Texas event of 2015. Geophys Res Lett 43:338–346

Gallaher K, Mueller TC (1996) Effect of crop presence on persistence of atrazine, metribuzin and clomazone in surface soil. Weed Sci 44:698–703

Hall JK, Pawlus M, Higgins ER (1972) Losses of atrazine in runoff water and soil sediment. J Environ Qual 1:172–176

Issa S, Wood M (2005) Degradation of atrazine and isoproturon in surface and sub-surface soil materials undergoing different moisture and aeration conditions. Pest Manag Sci 61:126–132

Kelly WR, Wilson SD (2000) Movement of bromide, nitrogen-15, and atrazine through flooded soils. J Environ Qual 29:1085–1094

Krutz LJ, Burke IC, Reddy KN, Zablotowicz RM, Price AJ (2009) Enhanced atrazine degradation: evidence for reduced residual weed control and a method for identifying adapted soils and predicting herbicide persistence. Weed Sci 57:427–434

Krutz LJ, Shaner DL, Zablotowicz RM (2010) Enhanced degradation and soil depth effects on the fate of atrazine and major metabolites in Colorado and Mississippi soils. J Environ Qual 39:1369–1377

Laroche AM, Gallichand J, Lagacé R, Pesant A (1996) Simulating atrazine transport with HSPF in an agricultural watershed. J Environ Eng 122:622–630

Martin NC, Felton JW, Cole DA (2016) Predictors of youths' posttraumatic stress symptoms following a natural disaster: the 2010 Nashville, Tennessee, flood. J Clin Child Adolesc Psychol 45:335–347

McClure AM (2011) Corn RM and planting late. Utcrops Ext Blog. https://news.utcrops.com/2011/05/corn-rm-and-planting-late/. Accessed: June 20, 2020

Mitchell PD (2014) Market-level assessment of the economic benefits of atrazine in the United States. Pest Manage Sci 70:1684–1696

Mueller TC, Parker ET, Steckel LE, Clay SA, Owen MD, Curran WS, Currie R, Scott R, Sprague C, Stephenson D, Miller D, Prostko E, Grichar J, Martin J, Krutz LJ, Bradley K, Bernards M, Dotray P, Knezevic S, Davis VM, Klein R (2017) Enhanced atrazine degradation is widespread across the United States. Pest Manag Sci 73:1953–1961

Mueller TC, Steckel LE, Radosevich M (2010) Effect of soil pH and previous atrazine use history on atrazine degradation in a Tennessee field soil. Weed Sci 58:478–483

Olson K (2009) Impacts of 2008 flooding on agricultural lands in Illinois, Missouri, and Indiana. J Soil Water Conserv 64:167–171

Pawlak J, Kells J, Barrett M, Meggitt W(1987) Effect of atrazine residue on soybean growth under three tillage systems and various herbicides. Weed Technol 1:140–144

Richards RP, Baker DB, Creamer NL, Kramer JW, Ewing DE, Merryfield BJ, Wallrabenstein LK (1996) Well water quality, well vulnerability, and agricultural contamination in the Midwestern United States. J Environ Qual 25: 389–402

Richards RP, Kramer JW, Baker DB, Krieger KA (1987) Pesticides in rainwater in the northeastern United States. Nature 327:129–131

Senseman SA, Mueller TC, Riley MB, Wauchope RD, Clegg C, Young RW, Southwick LM, Moye HA, Dumas JA, Mersie W, Mattice JD, Leidy RB (2003) Interlaboratory comparison of extraction efficiency of pesticides from surface and laboratory water using solid-phase extraction disks. J Agric Food Chem 51:3748–3752

Seybold CA, Mersie W, McNamee C (2001) Anaerobic degradation of atrazine and metolachlor and metabolite formation in wetland soil and water microcosms. J Environ Qual 30:1271–1277

Shaner DL, Henry WB (2007) Field history and dissipation of atrazine and metolachlor in Colorado. J Environ Qual 36:1–5

Shaner DL, Henry WB, Krutz LJ, Hanson B (2007) Rapid assay for detecting enhanced atrazine degradation in soil. Weed Sci 55:528–535

Toccalino PL, Gilliom RJ, Lindsey BD, Rupert MG (2014) Pesticides in groundwater of the United States: decadal-scale changes, 1993–2011. Groundwater 52:112–125

Vahedifard F, AghaKouchak A, Jafari NH (2016) Compound hazards yield Louisiana flood. Science 353:1374–1374

Wang S-YS, Zhao L, Gillies RR (2016) Synoptic and quantitative attributions of the extreme precipitation leading to the August 2016 Louisiana flood. Geophys Res Lett 43:11,805–11,814

van der Wiel K, Kapnick SB, Jan van Oldenborgh G, Whan K, Philip S, Vecchi GA, Singh RK, Arrighi J, Cullen H (2017) Rapid attribution of the August 2016 flood-inducing extreme precipitation in south Louisiana to climate change. Hydrol Earth Syst Sci 21:897–921