Published February 1, 2019

Agricultural & Environmental Letters

Research Letters

Saturated Buffers: What Is Their Potential Impact across the US Midwest?

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Core Ideas

- Saturated buffers can help achieve regional water quality goals.
- Roughly 75,520 km of US Midwest stream banks could host a saturated buffer.
- 248,000 to 360,000 saturated buffers could be implemented across the Midwest.
- Saturated buffers could potentially treat 3.85 million ha of Midwest drained land.
- Wide implementation could result in a 5–10% overall tile drainage N load reduction.

Abstract: Because saturated buffers are a new conservation practice, there has been no large-scale assessment of their potential to aid in meeting water quality goals. Publicly available data were used in a stepwise fashion within a geographic information system to estimate the total stream length suitable for saturated buffer implementation across the US Midwest region and the resulting potential nitrate loading reduction from widespread saturated buffer implementation. Approximately 37,760 km of streams (or 75,520 km of stream bank) was deemed suitable to host a saturated buffer, and 3.85 million ha of drained land has the potential to drain to a saturated buffer. These results suggest that implementing saturated buffers widely could result in a 5 to 10% reduction of the estimated N load from midwestern tile-drained land. Saturated buffers can be an important component of plans to achieve water quality goals.

Subsurface tile drainage systems are a transformative landscape feature to improve agricultural productivity in the US Midwest, but this infrastructure has been linked to chronic nitrate-nitrogen (N) pollution. A saturated buffer is a relatively new edge-of-field conservation practice to reduce nitrate loads from tile-drained areas, where, rather than drainage water flowing directly to the stream or ditch through the outlet pipe, the drainage water is diverted to flow as shallow groundwater through a vegetated buffer's soil. A water level control structure and perforated diversion pipe are used to reroute the drainage water into the buffer subsurface, essentially reconnecting the stream buffer's hydrology (Jaynes and Isenhart, 2014). Nitrate removal in a saturated buffer occurs through plant uptake, microbial immobilization, and denitrification (Jaynes and Isenhart, 2014, 2018; Davis et al., 2018). During large drainage events, a portion of the drainage water will overtop the control structure's stop logs and flow directly to the stream, thus limiting drainage backup in the field (Jaynes and Isenhart, 2014).

Potential saturated buffers (i) are located in tile-drained areas; (ii) do not need to be existing vegetated buffers, although well-established perennial vegetation aids in nitrate removal (Jaynes and Isenhart, 2018); (iii) have soils containing at least 1.2% soil organic matter (SOM) in the top 76 cm so the soil is carbon-sufficient to fuel denitrification; and (iv) do not have high conductivity subsoil layers (e.g., no sand lenses or gravel layers) so the buffer can remain saturated to promote anoxic conditions required for denitrification (USDA–NRCS, 2016). Utt et al. (2015) documented that 15 saturated buffers across the Midwest had nitrate N load reductions averaging 23 ± 28% (range: 0–85%; n = 23 site-years). Several of these initial sites were monitored over an additional 6-mo period (September 2016–February 2017), during which a 61% reduction in nitrate loading was observed (Brooks and Jaynes, 2017). A more recent report by Jaynes and Isenhart (2018) of nearly 20 saturated buffer site-years

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Agric. Environ. Lett. 4:180059 (2019)
doi:10.2134/ael2018.11.0059

Received 14 Nov. 2018.
Accepted 22 Dec. 2018.
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Abbreviations: CDL, Cropland Data layer; MANAGE, Measured Annual Nutrient loads from AGricultural Environments database; NHD+, National Hydrography Dataset Plus; SOM, soil organic matter; SSURGO, Soil Survey Geographic Database.

indicated an average of approximately 50% of the annual drainage volume was treated within the buffers and nearly all the nitrate N within that water was removed (mean: 83%); taken together, this resulted in an average N removal of 44 ± 26% at the edge of the field. This work also calculated a cost efficiency of \$2.94 kg^{-1} N removed which is similar to other cost-effective edge-of-field practices (e.g., \$2.10 and \$2.90 kg^{-1} N for denitrifying bioreactors and constructed wetlands, respectively; Christianson et al., 2013).

Because saturated buffers are a new practice, many questions remain about their potential. Objectives here were to use a simple GIS approach (i) to identify the extent of conditions suitable for saturated buffer implementation across the US Midwest and (ii) to estimate the total impact on N loading if all potential saturated buffers were installed across this region. While more advanced GIS platforms are available for this sort of modeling (e.g., the Agricultural Conservation Planning Framework [ACPF]; Tomer et al., 2013), these approaches require more intensive datasets, which may not be available for the entire Midwest (e.g., Light Detection and Ranging [LiDAR]–derived digital elevation models) and are more suitable for watershed-specific planning. A variety of conservation practices will be required to achieve regional goals to reduce the size of the Gulf of Mexico hypoxic zone, and this first large-scale assessment of the potential contribution of saturated buffers will help better inform conservation programming efforts.

Materials and Methods

Publicly available data sources commonly used for conservation decision making (Soil Survey Geographic Database [SSURGO; USDA–NRCS, 2018]; National Hydrography Dataset [NHD+; USEPA, 2018]; Cropland Data Layer [CDL; USDA–NASS, 2018]) were used in a stepwise fashion within a GIS (ArcGIS version 10.5; North American Albers Equal Area Conic projection) to eliminate areas not suitable for saturated buffer implementation across the US Midwest region (Fig. 1). The first GIS decision point identified the perennial river/stream network using the NHD+ dataset (USEPA, 2018). This excluded both major rivers and intermittent streams from the analysis to provide conservative estimates of suitable stream reaches. Intermittent streams in particular were removed to avoid potential overestimation as a result of ditches and artificial waterways being included. A 100 m wide zone along this isolated stream network was identified to represent the soil surrounding the stream, as these areas would be where saturated buffers would be installed. This 100 m zone also helped overcome discrepancies between the NHD+ representation of the stream location and the "real" stream location with bends and meanders. The second decision point involved limiting this 100 m area to only that with SOM content of greater than 2.5%. The USDA Natural Resources Conservation Service practice standard recommends saturated buffers be located in soils with at least 1.2% SOM in the top 76 cm (USDA–NRCS, 2016), but the SSURGO soils information was only described at 0 to 2.5% SOM or >2.5% SOM. Thus, the latter was used to provide conservative estimates based on the limitations of this readily available dataset.

The third decision point was to isolate a new 300-m-wide zone associated with the remaining stream network, which was used to identify potentially drained crop production areas within proximity to the stream. The initial 100-m zone helped assess if a given area adjacent to a stream would have suitable soils to host a saturated buffer; this second 300-m zone was to assess if there was likely tile drainage that could contribute to a saturated buffer in that location (i.e., proximity to tile-drained crop land). Soils classified as "somewhat poorly drained," "poorly drained," and "very poorly drained" that fell within the 300-m zone were selected. These soils tend to be artificially drained in the US Midwest if they are predominantly used for the production of corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.]. Since the soils in the entire 300-m zone needed to meet these soil drainage conditions, it was assumed this would eliminate the need to separately remove any areas of high soil conductivity (e.g., sand lenses per USDA–NRCS (2016)) occurring within the

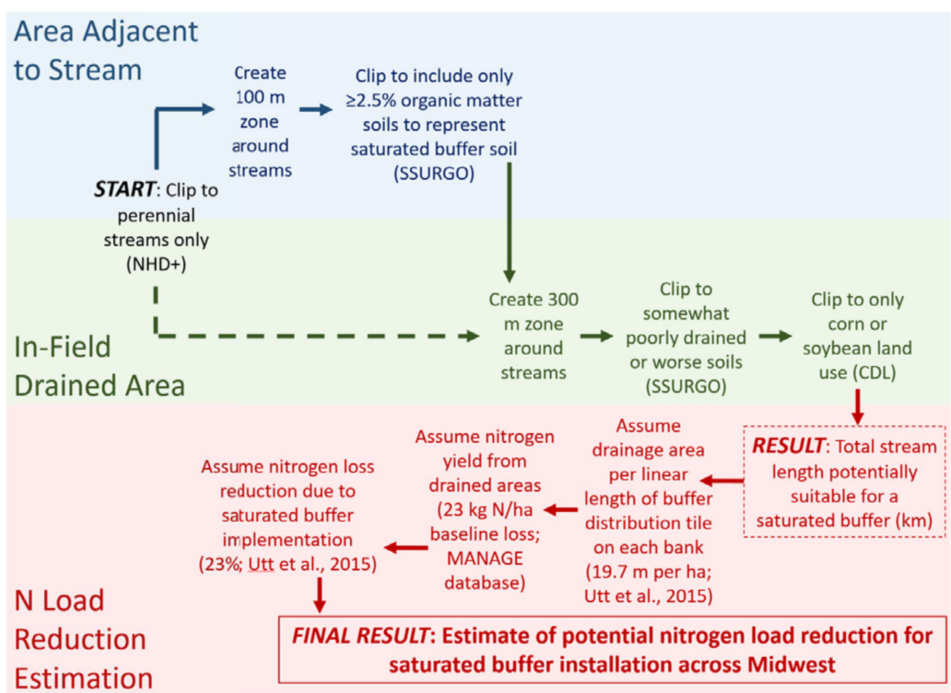

Fig. 1. Stepwise decision point flow chart for estimating total stream length suitable for saturated buffers, associated area that is potentially tile-drained, and the resulting N loading reduction due to potential saturated buffer implementation. SSURGO, Soil Survey Geographic Database; NHD+, National Hydrography Dataset Plus; CDL, Cropland Data layer; MANAGE, Measured Annual Nutrient loads from AGricultural Environments.

100-m-width potential saturated buffer zone. The final decision point was to use the CDL for 2017 (USDA–NASS, 2018) to trim the 300-m zone with poorly drained soils to areas where corn and soybean production occupied at least 50% of the 300-m width. The 50% criteria ensured large contiguous blocks of the specified row crop agriculture were being evaluated. The remaining stream network (total kilometers) was considered to be potentially suitable to host a saturated buffer.

Once the total suitable stream length (and stream bank length, which was double the stream length to account for both banks) was calculated, the associated tile drainage area was estimated. Across 15 saturated buffer sites reported by Utt et al. (2015), the median drainage area was 15.5 ha and the median buffer distribution tile length was 305 m, which yielded a ratio of 19.7 m of distribution tile (or stream bank length) per hectare drained. This meant, for example, given a 10-ha drainage area, a resulting saturated buffer distribution tile would be 197 m long. This ratio was applied to the suitable stream length calculated above, to both sides of the stream, for each state to calculate a state-based drainage area associated with these potential saturated buffer sites. This simple approach of using a drained area/distribution tile length ratio necessarily included some variability, which could be refined as design procedures are improved and there are more saturated buffer sites on which to base this information.

The Measured Annual Nutrient loads from AGricultural Environments (MANAGE) database (Christianson and Harmel, 2015; Harmel et al., 2017) was used to develop a baseline N yield for midwestern drained land of 23 kg N ha^{-1} (median value from n = 718 site-years). This value was applied to the drainage areas calculated above to estimate N loss entering the potential saturated buffer areas. The total reduction in N load due to the implementation of saturated buffers was estimated by applying a 23% reduction, which was the average N loss reduction across 23 saturated buffer site-years reported by Utt et al. (2015). This early study by Utt et al. (2015) included some sites with poor suitability that contributed to this relatively low average compared with more recent work (e.g., Jaynes and Isenhart, 2018); a 23% reduction was nevertheless used to provide a conservative estimate as site selection procedures continue to be refined.

Results and Discussion

The cumulative US Midwest stream length suitable for saturated buffer implementation was 37,760 km (or, 75,520 km of stream bank; Table 1), with the greatest potential in Iowa, Illinois, and Ohio (10,720, 10,590, and 6520 km of stream, respectively). Each decision point reduced the total suitable stream length with the most significant restriction being the inclusion of only perennial streams (i.e., Step 1 reduced total length by 84% from 3551,790 to 568,970 km; Table 1) followed by the necessity for the stream to be adjacent to high organic matter soils (66% reduction from 568,970 to 193,220). While this process isolated the perennial stream network as an initial step, there could be

Table 1. Stepwise calculation by state (and US Midwest total) of stream length suitable for saturated buffers, associated area that is potentially tile-drained, associated N load for that area, and the resulting N loading reduction due to potential saturated buffer implementation along those stream lengths.

State	Sequential decision point	1: NHD+† perennial streams only	2. SSURGO† soils with >2.5% OM‡	3. SSURGO drainage class of at least somewhat poorly drained soil	4. CDL† land use	5. Nitrogen reduction estimates		
	Total length of rivers and streams	Perennial streams/ rivers	Perennial streams/ rivers near high OM soils	Perennial streams/ rivers near poorly drained soils	Perennial streams/ rivers near crop land	Total associated potentially drained area (using 19.7 m ha^{-1})	Estimated N loading entering saturated buffer (MANAGE:† 23 kg N lost ha^{-1})	Estimated N loading reduction assuming 23% reduction (Utt et al., 2015)
	km of stream (double for km of stream bank)					ha	t N yr^{-1}	
Illinois	348,640	56,760	18,000	12,100	10,590 (21,180)	1,079,780	24,830	5,710
Indiana	497,710	37,750	6,870	3,260	2,430 (4,860)	248,150	5,710	1,310
Iowa	293,990	61,390	38,530	16,360	10,720 (21,440)	1,093,470	25,150	5,780
Michigan	246,370	65,900	24,680	16,930	1,450 (2,900)	147,540	3,390	780
Minnesota	288,460	73,550	23,130	10,110	2,970 (5,940)	302,620	6,960	1,600
Missouri	426,020	61,740	17,530	8,250	2,010 (4,020)	205,010	4,720	1,080
Nebraska	346,570	32,710	12,340	1,410	310 (620)	31,490	720	170
North Dakota	261,270	23,790	7,120	700	260 (520)	26,510	610	140
Ohio	251,280	61,160	21,350	15,600	6,520 (13,040)	664,620	15,290	3,520
South Dakota	389,520	31,950	11,360	950	270 (540)	27,700	640	150
Wisconsin	201,970	62,270	12,300	7,070	240 (480)	24,350	560	130
Total	3,551,790	568,970	193,220	92,730	37,760 (75,520)	3,851,230	88,580	20,370

† NHD+, National Hydrography Dataset Plus; SSURGO, Soil Survey Geographic Database; CDL, Cropland Data layer; MANAGE, Measured Annual Nutrient loads from AGricultural Environments database.
‡ OM, organic matter.

potential for saturated buffer implementation on intermittent and ephemeral streams, which would increase applicability estimates, though a more rigorous or site-specific approach would be needed. The 193,220 km of stream length mentioned above was further reduced by 52% and then again by 59% for the consideration of proximity to likely tile-drained land and proximity to cropland, respectively (i.e., reduced to 92,730 then to 37,760 km stream length; Table 1).

Assuming average saturated buffer distribution tile lengths ranging from approximately 210 m (Jaynes and Isenhart, 2014) to 305 m (Utt et al., 2015) and that implementation could happen on both sides of the stream would result in approximately 248,000 to 360,000 total saturated buffers across the Midwest to cover this 75,520 km of cumulative stream bank. Iowa and Illinois, the two most intensively tile-drained states, which are also generally the top nitrate loading contributors to the Mississippi River, could each host approximately 70,000 to 100,000 saturated buffers. There are few other similar estimates for context, but Jaynes (2014) estimated 20% of the 62,850 km of riparian areas already in perennial vegetation in Iowa would be suitable to host a saturated buffer (12,570 km). This was less than the value here of 21,440 km of stream bank for Iowa, likely due to the inclusion of only areas already in perennial vegetation in the 2014 estimate. A more recent assessment using an online saturated buffer estimation tool indicated 23,190 km of stream banks in Iowa were suitable to host a saturated buffer, which is within 10% of the estimate here (USDA–ARS, 2017).

Approximately 3.9 million ha across the US Midwest, or approximately 22% of the Midwest's 17.8 million tile-drained hectares (USDA–NASS, 2012), has the potential to drain to a saturated buffer based on this methodology (Table 1). The conservatively assumed saturated buffer N loss reduction effectiveness value of 23% would result in a total edge-of-field N load reduction of 20,370 t (Table 1), which equated to a 5% reduction of the estimated N load from all tile-drained land in these 11 states (i.e., 23 kg N ha^{-1} × 17.8 million ha = 408,500 t N baseline). In other words, with saturated buffers (i) placed on approximately 22% of all tile-drained land considered suitable in the Midwest and (ii) operating at 23% N loss reduction effectiveness, N loading from tile-drained areas in these 11 states would decrease by 5%. Using a higher N loss reduction value for saturated buffers of 44% calculated from the more recent report by Jaynes and Isenhart (2018) would result in a 10% N loading reduction from midwestern tile-drained acres if applied in the same way (39,000 t N reduced). For context, the N load delivered to the Gulf of Mexico between 2012 and 2016 ranged from 0.80 to 1.7 million t of total N annually (USGS, 2016).

Conclusions

This simple GIS-based approach using publicly available data showed approximately 37,760 km of streams (75,520 km of stream banks) across the US Midwest, equating to 3.85 million ha of tile-drained land, is suitable to host a saturated buffer. The intensively drained states of Illinois, Iowa, and Ohio have significant potential to host this conservation practice, and total N loading reduction to the Mississippi River could be on the order of 5 to 10% if this practice was widely implemented. These estimates are conservative due to limitations of readily available datasets (e.g., SSURGO SOM categories) and because we considered only perennial streams. There is substantial opportunity to implement this important practice across the Midwest with 248,000 to 360,000 saturated buffers regionally at full implementation. This illustrates saturated buffers can be an important component of plans to achieve water quality goals.

Acknowledgments

This work was funded through the USDA FSA contract number AG-3151-P-17-0164. Partial funding was also provided through the Illinois Nutrient Research and Education Council (NREC).

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