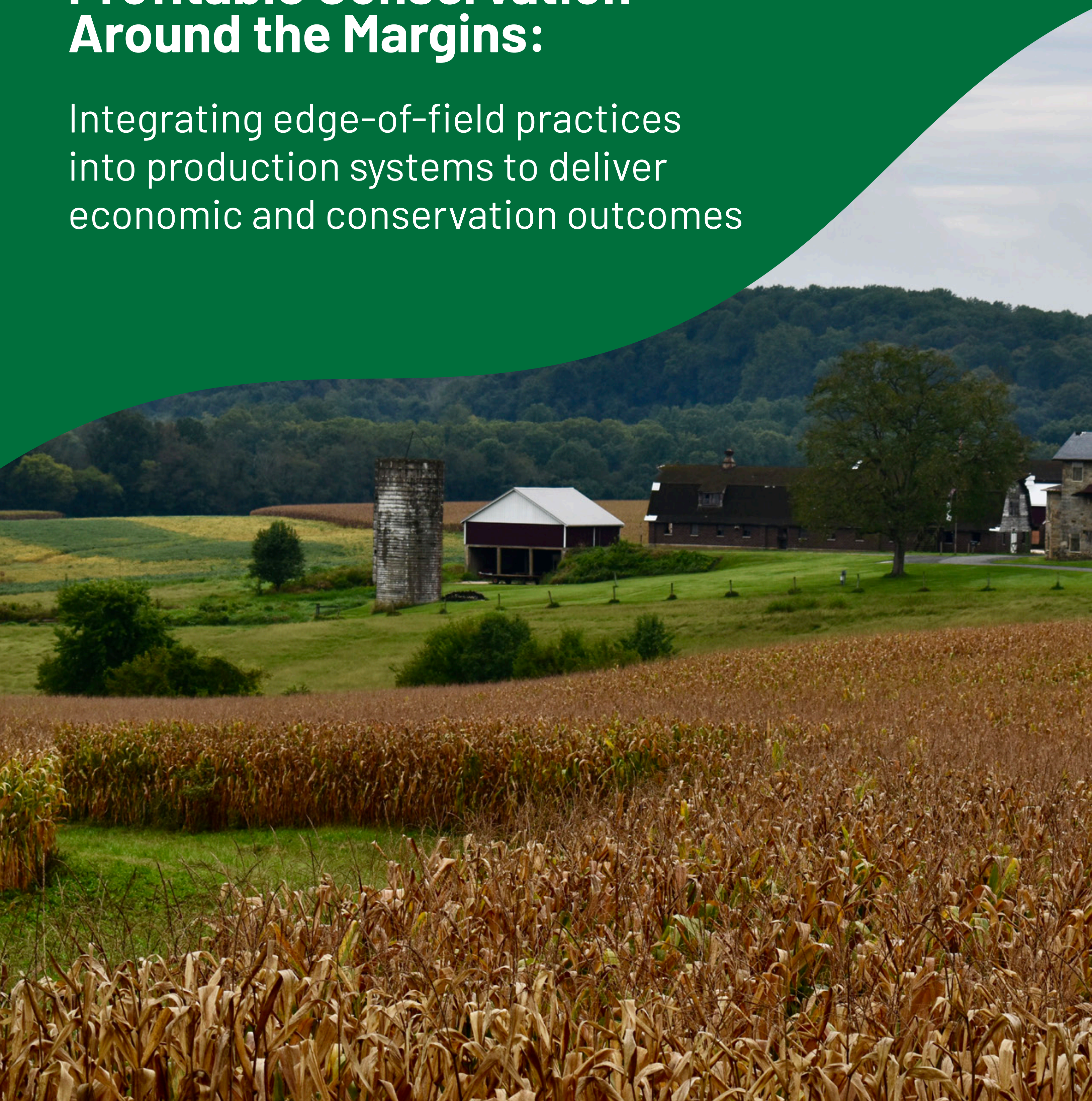
Profitable Conservation Around the Margins:

Integrating edge-of-field practices into production systems to deliver economic and conservation outcomes



EXECUTIVE SUMMARY

Edge of Field (EoF) practices are a suite of nature-based conservation practices such as vegetative buffers, wetlands, as well as engineered practices like saturated buffers (DeLong et al. 2021). The conversion of marginal cropland to EoF practices results in improved environmental quality, while also supporting farmers' economical management of agricultural inputs (Basso et al. 2019). Despite these benefits, EoF adoption rates still lag behind targeted goals for critical watersheds (Dahl 2014).

Our goal for this work was to advance knowledge needed to accelerate EoF practice implementation across key US agricultural geographies. We focused on the potential to develop a framework for an ecosystem-market payment scheme for EoF practices, related to carbon, water quality and biodiversity benefits. We set out to establish a robust understanding of EoF practices' ecological impacts, farmers' willingness to adopt EoF on marginal lands, and the potential scope of the EoF opportunity across our focal geographies, given ecological potential and farmer adoption preferences.

Our results suggest that opportunities to accelerate EoF use exist now and may be relatively achievable. Farmer interviews revealed that marginal lands—or lands farmers are most willing to take out of production—are defined primarily by profit loss, and also management inefficiencies, due to factors such as small field sizes or irregular shapes.

In considering these "marginal" characteristics in our spatial analysis, we find that for some practices, there are tens of thousands of acres of potentially ecologically restorable lands that are also marginal based on break-even revenues using estimated yields and field size/shape. These acres represent "low-hanging fruit" where potentially limited incentives could encourage more widespread EoF adoption.

At the same time, barriers remain to developing an ecosystem market-based payment scheme. While some EoF outcomes are more well established in the scientific literature—such as water quality benefits from riparian buffers and wetlands—significant knowledge gaps exist. Biodiversity and carbon benefits are understudied, and potential ecological "tradeoffs" from EoF implementation exist but are difficult to generalize and quantify.

There is a also a need for additional evaluation of incentive/ payment structures that address current barriers to participation. Notably, requested payment levels for ecosystem services varied across our study regions and even within regions (state by state). Interviewed farmers discussed payment needs that exceed existing ecosystem service credit values, though both interview and survey results suggest that relatively limited increases in payment levels could encourage a non-trivial proportion of farmers to adopt such practices. While our work was designed to focus on financial motivations, barriers beyond payment levels also exist to EoF practice implementation, including reduced management efficiency, limited use of precision-management technologies, along with other factors.

Based on our work, we make the following interrelated recommendations:

1. Efforts to identify marginal land should further incorporate economic and social factors into spatial analyses
2. Promote the adoption of precision-management to foster awareness of sub- field marginality
3. Integrate EoF practices into precision-management technologies to enable market-payments
4. Conduct additional research and farmer engagement to reveal the agronomic benefits of EoF practices
5. Strengthen public/ private partnerships to maximize conservation impacts
6. Conduct additional research to identify how ecological benefits from EoF practices can be incorporated into various types of crediting schemes

Cover image © Matt Kane/TNC

INTRODUCTION

Agriculture is positioned to play a key role in addressing contemporary environmental problems. Through shifts in management practices, agricultural systems across the United States (US) can reduce emissions from production, support species' habitat, and mitigate nutrient loss to waterways while enhancing farm profitability and supporting a global food system.

Marginal lands are a key site where these potential solutions can begin to be realized. In many regions across the US, a non-trivial portion of cropland acres are considered "marginal" (Tiwari et al. 2023). While the definition of marginal land varies, it is generally associated with low(er) production potential (Helliwell 2018). Marginal lands are typically sites of inefficient input management on farms, contributing to profit loss and environmental impact given low or variable yield potentials (Martinez-Feria and Basso 2020).

As such, "marginal" lands present a key opportunity where "edge of field" (EoF) practices can be implemented. EoF practices are a suite of nature-based conservation practices such as vegetative buffers, wetlands, as well as engineered practices like saturated buffers (DeLong et al. 2021). The conversion of marginal crop land to EoF practices results in improved environmental quality, while also supporting farmers' economical management of agricultural inputs (Basso et al. 2019). While federal and state-funded programs exist to encourage farmer use of EoF practices on marginal land, the *adoption rates still lag behind targeted goals for critical watersheds* (Dahl 2014).

Given this scenario, we see a critical opportunity to achieve agricultural conservation goals by directly valuing the ecosystem services EoF restored habitats can provide on marginal land. Private sector "ecosystem market" incentives, especially if strategically paired with precision management tools that facilitate marginal land identification and professional advising services, may be a means to accelerate widespread adoption of EoF practices on marginal lands, thereby promoting reduced carbon emissions, nutrient loss to waterways, and biodiversity benefits.

The primary goal of this project was to develop the foundational knowledge needed to accelerate the adoption of EoF practices, specifically considering the potential opportunity for and structure of a market-based payment scheme. We focused on addressing three interrelated research needs toward this end:

1. Identifying the water quality, biodiversity, and carbon benefits associated with EoF practices
2. Understanding how farmers define or what leads them to view land as "marginal", and the economic payments needed to encourage adoption of EoF practices
3. And, based in part on farmers' views of marginal land, mapping EoF practice opportunities across two priority landscapes

We address these three needs using a variety of methodological approaches in two priority agricultural landscapes in the US: Indiana and the Chesapeake Bay Region (VA, MD, PA) (Figure 1). Identifying this foundational information is key to supporting effective implementation and accelerating adoption. Our baseline information can shed light on the scope of opportunity and what developments must happen for interested parties to leverage this opportunity. Below we review our key findings from each activity. We follow these reviews with a synthetic discussion of overall recommendations for future efforts.

Figure 1: Study areas: Indiana (within the Mississippi River basin) and the Chesapeake Bay watershed

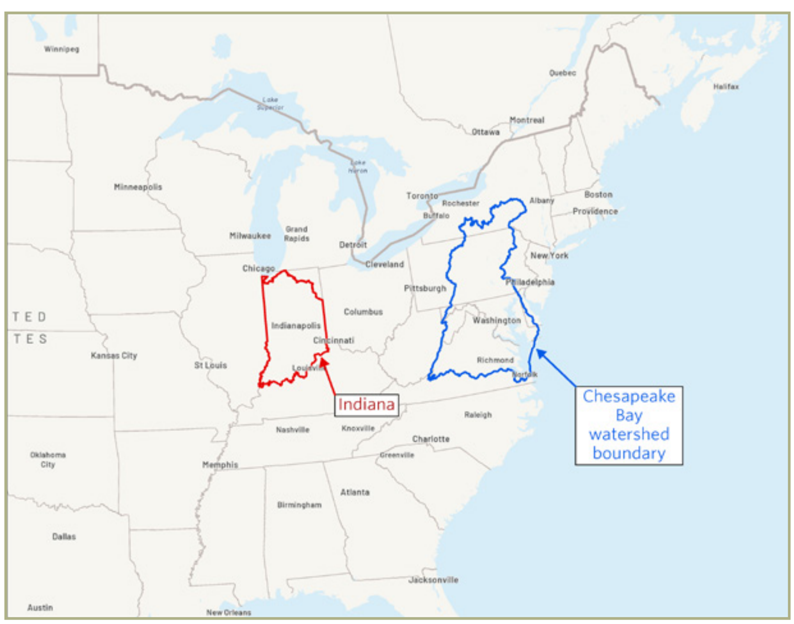


Figure 2: Focal Edge of Field Practices

A **vegetated riparian buffer** provides a transition zone between the crop field and a water feature. Vegetation growing in the buffer slows surface runoff, filters out pollutants, and reduces bank erosion.

© USDA Natural Resources Conservation Service

A **grassed waterway** is an erosion control practice that provides a stabilized flow path for water through a farm field.

© Jason Johnson/Iowa USDA-NRCS

A **contour buffer strip** is a narrow strip of permanent, herbaceous vegetative cover established around the hill slope, and alternated down the slope with wider cropped strips that are farmed on the contour.

© Jason Johnson/Iowa NRCS

A **restored wetland** recreates, to the extent possible, the hydrology, topography, native vegetation, processes, and functions of a historically occurring wetland.

© Don Poggensee

A **saturated buffer** resembles a traditional buffer, but it is designed to capture and treat water from underground tile drains. As water seeps slowly through the buffer, high organic matter in the soil promotes denitrification.

© Lynn Betts/NRCS/SWCS

BENEFITS OF EDGE OF FIELD PRACTICES

SECTION HIGHLIGHTS:

- There is overwhelming evidence for water quality benefits from EoF practices, particularly for riparian buffers and wetlands, and relatively robust evidence for biodiversity benefits. Quantifying carbon benefits from EoF practices is harder given tradeoffs between sequestration benefits vs. emissions for several practices.
- Synergies and ecological tradeoffs between practices exist but are very context dependent, meaning they vary temporally, spatially, and based on the practice design itself. This variability makes the development of a generic EoF practice "credit" difficult.
- Few peer reviewed publications focus on EoF adoption economics because they depend on regionally driven costs like land rental rates and contractor/construction costs.

In the context of this larger project, the objectives of this activity were three-fold:

1. Quantify co-benefits from select EoF practices on water quality, biodiversity and carbon based on peer-reviewed literature.
2. Identify factors and spatial attributes that influence the effectiveness of practices that could inform future prioritization exercises.
3. Identify gaps in the literature that if addressed, could advance the development of an economic valuation of benefits.

Our focal EoF practices are ones with suitability criteria analyzable at a landscape scale in support of mapping opportunities (see section 4) and have higher potential environmental co-benefits toward identifying strong payment for ecosystem service potential (LATE 2021, Table 1). They include: (i) Vegetated Riparian Buffers (ii) Saturated Buffers (iii) Restored Wetlands (iv) Contour Buffer Strips and (v) Grassed Waterways (Figure 2). A comprehensive, systematic literature review was conducted to identify studies relevant to these practices and the outcomes of interest and the full text of 378 publications were reviewed, detailed in our methodology in Appendix A. The key findings are presented below.

Prairie strips © NRCS/SWCS photo by Lynn Betts

Figure 3: Percentage Reduction in nitrate-N and total phosphorus-TP from received flow to the practice (median, minimum and maximum).

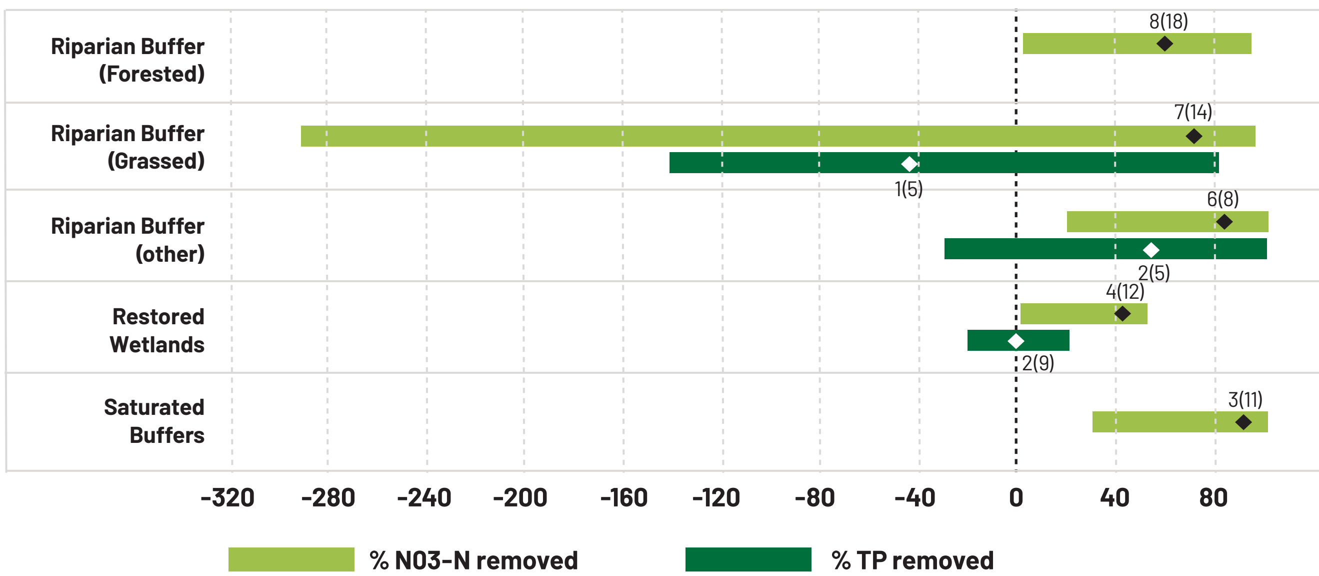


Figure 3: Review includes a subset of practices chosen for quantitative data extraction based on availability of sufficient data to calculate nutrient removal efficiencies (>5 studies or data-years) and those that had also been evaluated for carbon and biodiversity benefits. Number on top of median datapoint indicates the number of studies, number in parenthesis indicates total number of datapoints (data-years) from the studies included for the calculation of the median.

Negative reduction indicates increase in release from the buffer. For grassed buffers, the increase in N (1 study) was due to very low inflow concentration and can be considered an outlier in the intensive agriculture context. TP removals and increases in semi-natural systems like riparian buffers and restored wetlands are related to sediment settling and sorption dynamics and appeared to be more variable across studies reviewed. Other EoF practices designed specifically for phosphorus removal were not reviewed.

Ecological benefits

The body of literature quantifying outcomes through EoF practices suggest they can be designed to effectively target outcomes (nutrient removal through denitrification, sedimentation and assimilation, GHG reductions, biodiversity, etc.) at varying spatial scales. We found *overwhelming evidence of water quality benefits from the EoF practices, with the vast majority of quantitative data available for riparian buffers and wetlands.* The effectiveness of these practices is summarized in Figure 3.

Although there is a significant body of evidence for biodiversity benefits from buffers and wetlands in particular, because of a lack of a singular measurement unit, driven by the context of the studies we reviewed, *we cannot generalize or quantify the biodiversity impacts from these practices* (See Appendix A for a list of studies, biodiversity metrics and findings).

Some aspects of greenhouse gas dynamics have been explored but there is *little field research on the full suite of greenhouse gas fluxes* occurring to conclusively generalize comprehensive carbon outcomes – more of this exists for wetlands, but it remains complex and depends on multiple environmental and situational factors. For example, we expect large carbon sequestration benefits from vegetation in riparian buffers, particularly forested buffers, but sequestration through biomass production depends on the size, age and type of tree planted. Studies also indicate that nitrous oxide emissions from forested buffers are significantly higher than grassed buffers (Hefting et al. 2003), reducing the overall sequestration benefit that is expected. Due to the large quantity of biomass sequestered by trees, there could still be a net benefit, but mature trees have lower carbon capture potential than growing trees (Jiang et al. 2020), which also adds complexity to quantifying the overall benefits from this practice over time, especially when buffers continue to receive large seasonal nitrogen loads from adjacent cropland.

In general, there is evidence to show that emissions from grassland tends to be lower than that of row crops due to both lower cropland nitrous oxide emissions and upstream GHG savings from reduced fertilizer application (Stehfest and Bowman, 2006; Eagle et al. 2011). This is a critical point to consider when discussing climate benefits from implementing EOF practices on marginal cropland.

Potential ecological tradeoffs

There is some literature on potential synergies and tradeoffs between outcomes, particularly on "pollution swapping" between water quality and air quality. Most notably, denitrification is the primary mechanism of nitrogen removal for water quality improvement in the practices we studied. Incomplete denitrification can result in nitrous oxide emissions, meaning that some practice installations will reduce nitrogen loss to waterways while increasing nitrogen emissions to the atmosphere. However, these emissions are highly uncertain and vary significantly spatially and temporally.

More research on the factors driving the key processes of nutrient removal or habitat provision could improve context-based decisions on where and which practices will be most beneficial given these potential trade-offs. Very few studies explicitly study tradeoffs and synergies between outcomes and practices though – a gap for future research**.** We highlight a few studies that adopt this lens in Appendix A.

EoF Adoption Economics

Finally, we found few peer-reviewed publications (13) on the economics of edge of field adoption*. Of the limited studies, the focus was on the cost of installing and maintaining an EoF practice or the cost effectiveness of EoF practices*, i.e. $/lb of nitrogen/sediment/phosphorus removed (See Appendix A). EoF practice adoption costs are driven by capital/establishment costs, maintenance costs that vary based on the lifetime over which the practice is effective and the opportunity cost of retiring "productive land". Establishment costs are driven by design and construction costs that vary between regions. Opportunity cost is often calculated based on rental rates of agricultural land in the region, that also results in significant regional differences. Valuation of benefits literature was not explicitly reviewed in this study.

© Lauren Peeler Brice

Farmer Perspectives On Marginal Lands: Definitions And Payment Needs

SECTION HIGHLIGHTS:

- Farmers generally define land as marginal based largely on absolute, economic profitability at the field scale, though they considered sub-field characteristics such as soil or topography, as contributors.
- There were multiple factors that contributed to "marginality," or profit loss, including excess water, wildlife intrusion, tree borders, poor soils and management inefficiencies (i.e. irregular field shape, electrical lines, trees).
- Likeliness of incorporating edge of field practices on marginal land shifted based on type of practice and available money per acre. Vegetative grassed buffers had the lowest willingness to accept payment (approximately $95/acre more than existing federal/state payments).

Understanding Farmers' Views

In support of the spatial opportunity and ecological benefit analyses, we conducted a social science study to understand farmer views and decision-making related to EoF practice adoption. We address two central questions related to EoF decision-making:

1. How do farmers define marginal land?
2. Can an additional monetary incentive—such as would be provided by an ecosystem-market—encourage more widespread EoF practice adoption?

To address these questions, we draw on farmer interviews in Indiana (IN) and the Chesapeake Bay Region (Maryland (MD) and Virginia (VA)), as well as a larger mail-survey directed specifically at VA and Pennsylvania (PA) agricultural landowners. See Appendix B for a full description of our methodological approach.

What is Marginal Land?

EoF practices are often framed as a solution for the challenge of "marginal" acres on farms (Haddad et al. 2023), but little is known regarding how farmers view or "define" marginality on-farm. During interviews, farmers were asked how they define "marginal land" or the land they were most willing to take out of production. We also asked each farmer to identify marginal land on their operation using a digital map and to describe why they selected these lands. Across these responses, a key common theme emerged. *Most interviewed farmers directly defined marginality based on economic performance, i.e. loss of profitability (8/15 interviewees)***.** These farmers emphasized the role of poor yields, especially relative to input costs. The remaining farmers still primarily defined marginality based on economic performance, but did so indirectly, by discussing the specific factors contributing to lack of profitability. *Notably, farmers' comments suggest that absolute profit loss (i.e. negative returns) at the field-scale or sub-field scale, rather than relative profit loss (i.e. lower than other areas) is the criterion for seeing land as marginal.* As one of these farmers simply put it, land is marginal "[…] when yield doesn't cover cost" (IND01).

Figure 4: Field identified as marginal given its shape.

Factors contributing to marginality included: excess moisture, poor soils, topography, wildlife intrusion, tree borders, nearby electrical lines, and irregular field shapes. See table 3 in Appendix B for more detail. These factors primarily contributed directly to reduced yield and thereby profitability. However, several factors (trees, field shape, electrical lines, small fields) were also discussed as contributing to management inefficiencies, meaning farmers had to dedicate more time within a field for basic management (see figure 4 for an example of an irregular field). Increasing management efficiency was emphasized as a particularly important factor shaping farmers' land management decisions.

While most farmers perceived at least some of their ground to be marginal, about a fifth (20%) of our participants felt they did not have any marginal ground on their operation. These farmers defined marginality based on absolute profit, like other farmers, but generally felt that they had corrected the issues that contributed to poor performance.

EoF Ecosystem Market Payments

While farmers may be motivated to use EoF practices given stewardship ethics or their capacity to address emergent environmental challenges (Farmer et al. 2011), well established barriers discourage or limit farmers' adoption of EoF practices on these marginal lands. EoF practices can increase perceived time spent in fields managing the practices themselves (e.g., herbicide treatments) or operating equipment around practices and thereby decreasing management efficiency (Houser et al. 2024). Farmers, additionally, remain hesitant to take land "out of production" given normative pressures to continue to farm every acre (Houser, unpublished data). Farmers also primarily manage inputs at a farm or field level (Houser 2022), with the majority not using precision data technologies to assess sub-field zone use or loss (Thompson et al. 2019), and even less using variable rate application technologies (Schimmelpfennig 2016). The lack of adoption of these technologies may discourage sub-field EoF management efforts, as many farmers remain unaware of these inefficiencies.

At the same time, payment levels for EoF practices matter (Luther et al. 2021, Farmer et al. 2015). Farmers emphasize that payment rates from traditional federal and state programs are important, but often insufficient to motivate adoption given construction costs, lost revenue potential from cropping, among the other barriers noted above (Houser et al. 2024). Can ecosystem market payments help overcome these challenges?

For this study, we examine the potential of stacking an ecosystem market payment on top of current federally funded restoration programs. Our figures, therefore, represent payment levels needed in addition to current EoF programs. During interviews, we presented farmers with a hypothetical, but realistic state-incentive program for each practice. We asked about our focal EoF practices, though we condensed these practices into three "categories": restored wetlands, vegetative buffer with only grass and vegetative buffer with trees. This reduction was done to simplify the interview process. The hypothetical program was based on the Conservation Reserve Enhancement Program (CREP) in each state, a program that is a joint federal and state funded restoration incentive program. The program covered implementation cost up to 100%, and provided a 1-time adoption incentive payment in addition to an annual rental payment. Farmers were presented with a series of standard "ecosystem market" payment levels above this program payment, and asked iteratively if they would participate or not for this additional value. If farmers said no to all of the values, they had an open-ended opportunity to tell us how much it would take.

Our sample (80%) was most likely to implement grassed buffers if they had to choose one. While every interviewed farmer felt more EoF practices should be implemented in their region, we found that farmers were very hesitant to remove land from crop production.

Farmers tended to emphasize that additional payments above existing program rates would be critical. The average additional incentive requested across our sample varied by practice type, at $95.73/acre/year (vegetative grassed buffer only), and $116.80/acre/year (wetlands) $143.13/acre/year (vegetative buffer with trees) as an additional annual payment to current CREP payments. See Appendix B, Table 4 for the breakdown of payments by farm size, state, and portion of rented land. W*e also found that past EoF practice use reduced requested payment levels***.** For instance, farmers who already had a wetland installed on their property requested $104 per acre payment, compared to approximately $127 on average for non-adopters. Similarly, buffer payments also varied by adopters and non-adopters, $53 per acre compared to $108 per acre, respectively. *This suggests that adopters see tangible benefits from EoF practices once they experience them, meaning non-adopters may not fully perceive the agronomic efficacy of these practices.*

Survey results:

In support of our interview work, we built on initial findings by conducting a more generalizable survey. This survey focused on understanding agricultural landowners' willingness to adopt EoF practices. For the survey, we focused only on wetlands given space considerations.

All respondents were identified as owning land that has restoration opportunities. Our approach to identify a desired ecosystem market payment rate for restorable wetlands mirrored that of our interview approach. We developed a realistic federal-state funded program (15-year contract length, 100% cost share, and a one-time incentive payment). Respondents were asked how much above these payments they would like to receive from an ecosystem market program. Given the spatial variability of the survey, we did not give out a hypothetical rental rate, but instead baselined our ecosystem market payment at slightly below average CREP rental rates in each state. Consequently, survey payment rates indicate the total annual incentive acceptable to farmers. An experimental treatment of four variable potential payments was used to ground-participant responses (each respondent was exposed to one payment level). Across the surveys we achieved an approximately

	Payment treatment	% Yes
PA	$75/ac	27%
	$125/ac	29%
	$175/ac	15%
	$225/ac	45%
VA	$30/ac	40%
	$80/ac	44%
	$130/ac	63%
	$180/ac	65%

Table 1: PA and VA Survey Program Payment Results

Percentages are not cumulative. Respondents were only given one of the four price options. Percentages therefore represent the proportion of unique respondents who said "yes" to each payment level.

19% response rate, with 1,255 respondents across VA (600) and PA (655). For the purposes of this report, we focus only on respondents who farm the land themselves or whose immediate family farms their land (VA = 104 respondents; PA = 152).

We found that across payment treatments, approximately 28% of PA respondents accepted the hypothetical wetland ecosystem market program. Another 13% of PA farmer respondents were willing to enroll, but only at a higher payment than was offered (average of $460/ac requested). In VA, 55% accepted, with only another 6% saying "yes" at a higher than offered payment ($292/ace). Statistical modeling suggests that for PA respondents, only the highest payment level ($225/acre/year) produces a significant increase in likelihood of participation when compared to all other treatments. In VA, a linear trend emerging where higher payment rates increase the likelihood of enrollment. While higher payment mattered for adoption, a non-trivial proportion of farmers in both PA (27%) and VA (40%) said "yes" to the restoration program even at the lowest level of payment, suggesting that enrollment payments are not the key barrier to all farmers in the region.

Reflecting other studies, farmer responses in both states suggest the importance of non-monetary barriers to EoF use. Few farmers expressed motivation to remove marginal land from production (6% in both VA and PA saying it is "very motivating"). Reflecting management efficiency challenges, most VA farmers (56%) somewhat or strongly agreed that the introduction of wetlands makes farming harder, with 71% of PA farmers saying the same.

Additionally, 70% of VA farmers and 79% of PA farmers perceive that wetlands increase pest and mosquitoes' presence. This result may indicate that farmers see EoF practices as potentially a threat to nearby crop production, increasing pest-induced harm.

Prairie strips © NRCS/SWCS photo by Lynn Betts

Mapping Edge Of Field Opportunities And Marginal Lands

SECTION HIGHLIGHTS:

- There is significant opportunity to implement EoF practices in both study areas (Indiana and Chesapeake Bay) ranging from more than 1 million acres potentially restorable to wetland in Indiana to approximately 2,700 acres suitable for saturated buffer implementation in Chesapeake Bay. Ecological opportunities vary considerably across focal study areas and by EoF practice.
- Assessing EoF opportunity within the scope of marginal lands, identified 4-40% of the ecological opportunity across both focal areas occurred on marginal lands depending on the definition of marginal lands used. Restorable wetlands and contour buffer strips featured most prominently in both geographies.

Spatial modeling

We identified the total potential opportunity for implementation of the five focal EoF practices across our study areas (IN and the Chesapeake Bay watershed). This analysis was limited to cultivated cropland as identified by the Multi-Resolution Land Characteristics Consortium's National Land Cover Dataset for 2019. We address the following questions in this activity:

1. What is the total opportunity based on hydrogeomorphic landscape parameters for each EoF practice across two priority landscapes?
2. How does limiting implementation of EOF to marginal lands impact EoF practice opportunity?

Using GIS spatial analysis, we incorporated a stepwise analysis approach where we first set out to identify the potential for EoF practice implementation based on hydrogeomorphic criteria alone, followed by more restrictive analyses incorporating marginal lands that build upon our initial model (Figure 5).

For the hydrogeomorphic analysis, wetlands had the greatest number of opportunity acres (over 1 million acres) in Indiana, followed by contour buffer strips (over 550,000 acres). In the Chesapeake, contour buffer strips had the greatest acres (over 200,000), followed by vegetated riparian buffers (nearly 95,000). (See "hydrogeomorphic opportunity for implementation" in Tables 2 and 3 for findings for the five practices).

Subsequent spatial analysis accounted for farmers' views of marginal land, or the land they were most willing to take out of production. Based on farmer interviews, we considered two interrelated, but distinct, factors (see above): (1) the management efficiency of the fields, defined by small field sizes and irregularly shaped fields and (2) the profitability of the land, defined based on 250-meter resolution yield model to contain any areas where corn or soy yields were below the economic breakeven yield for the study area (i.e. were likely to result in absolute loss for the farmer), based on extension crop budgets between 2018-2023. See Appendix C for detailed methods.

Saturated buffer © NRCS/SWCS photo by Lynn Betts

Figure 5: An illustration of our stepwise approach to identifying opportunity areas for EoF practices.

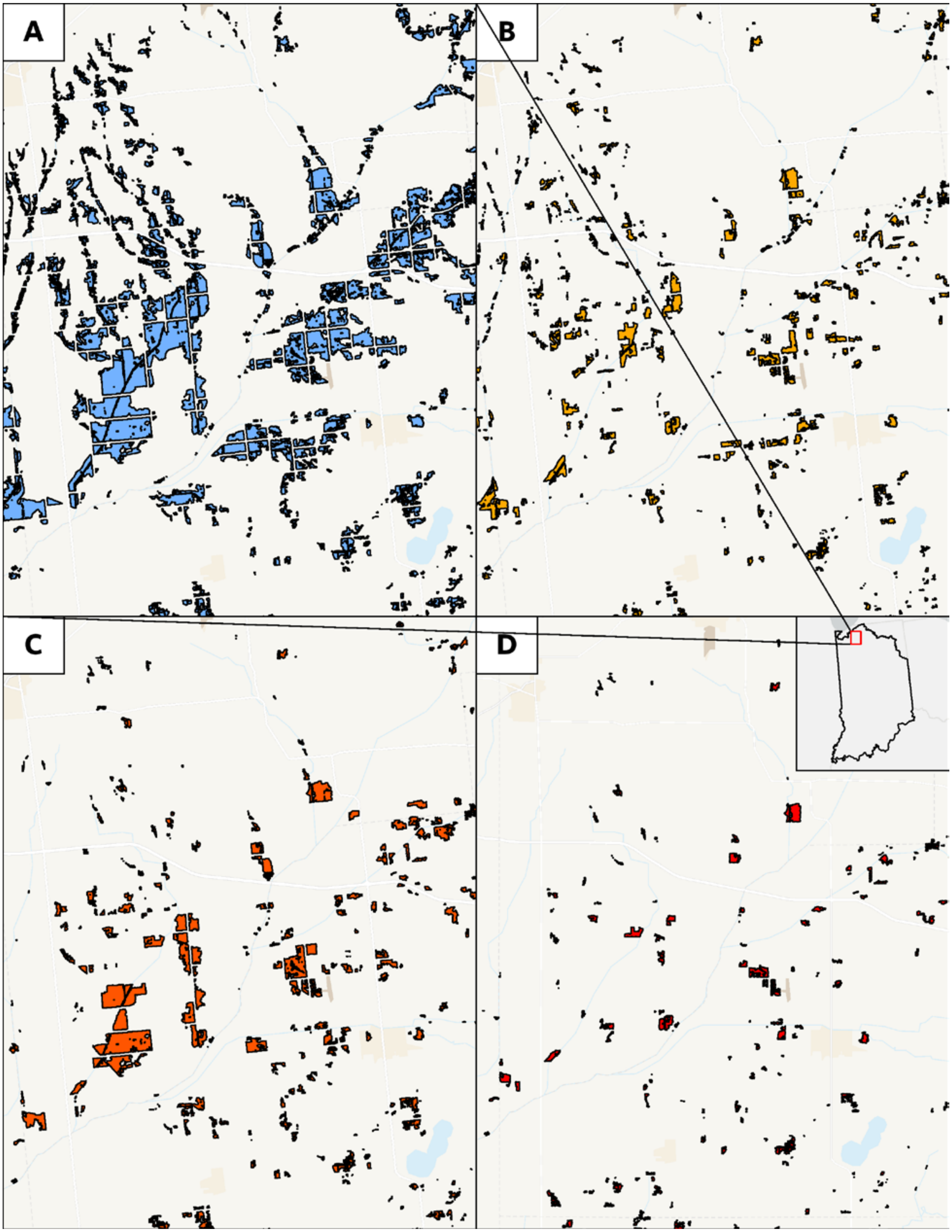


Figure 5 Caption: Opportunity areas for patches with potential for wetland restoration are shown for: a). All areas where hydrogeomorphic criteria alone are met; b). The footprint in "a" subset to only those patches that are marginal based on a definition of wholly or partly on small or irregularly shaped fields; c). The footprint in "a" subset to only those patches that are marginal based on a definition of wholly or partly on fields containing any area where corn or soy yields are estimated to be below the economic break-even yield; d). The footprint in "a" subset in the manner described for "b" and "c" simultaneously.

These results are intended to identify the lands where hydrogeomorphic opportunity for EoF practices exist and where farmers are most likely to be willing to implement EoF practices (based on farmer definitions of marginality). We expect, in general, that the most restrictive analysis (profitability + management efficiency) represents the "lowest hanging fruit" in terms of EoF potential acres. These acres are significantly lower than the total hydrogeomorphic opportunity (see column "Opportunity on marginal lands (both criteria)" in Tables 2 and 3). Yet, significant potential for EoF siting remains in both geographies.

Table 2. Indiana: Opportunity area (acres) of EoF practices on cropland based on hydrogeomorphic characteristics and overlap with marginal lands based on two definitions (% in parentheses indicates percentage of hydrogeomorphic opportunity for implementation)

Practice	Hydro-geomorphic opportunity for implementation	% of total cropland within study region and in opportunity zone	Opportunity on marginal lands (field shape/size)	Opportunity on marginal lands (economics)	Opportunity on marginal lands (both criteria)
Restorable wetlands	1,038,224	9.14%	253,397 (24.41%)	150,637 (14.51%)	50,742 (4.89%)
Vegetated riparian buffers	241,505	2.13%	60,349 (24.99%)	37,166 (15.39%)	13,570 (5.62%)
Saturated buffers	14,513	0.13%	3,222 (22.20%)	1,243 (8.57%)	451.49 (3.11%)
Grassed waterways	13,010	0.11%	3,189 (24.51%)	1,636 (12.58%)	578.10 (4.44%)
Contour buffer strips	554,308	4.88%	140,844 (25.41%)	70,745 (12.76%)	24,482 (4.42%)

Results for spatial opportunity of practices should not be seen as cumulative potential across practice types. Practice opportunities are overlapping; some areas could be identified as opportunities for multiple practices; & we did not prioritize which would be the best practice to deliver an ecosystem benefit.

Table 3. Chesapeake Bay: Opportunity area (acres) of EoF practices on cropland based on hydrogeomorphic characteristics and overlap with marginal lands based on two definitions (% in parentheses indicates percentage of hydrogeomorphic opportunity for implementation)

Practice	Hydro-geomorphic opportunity for implementation	% of total cropland within study region and in opportunity zone	Opportunity on marginal lands (field shape/size)	Opportunity on marginal lands (economics)	Opportunity on marginal lands (both criteria)
Restorable wetlands	67,993	1.63%	21,698 (31.91%)	20,271 (29.81%)	8,174.8 (12.02%)
Vegetated riparian buffers	94,941	2.27%	24,220 (25.51%)	17,194 (18.11%)	7,749.1 (8.16%)
Saturated buffers	2,722.2	0.07%	565.03 (20.76%)	209.20 (7.68%)	108.83 (4.00%)
Grassed waterways	22,573	0.54%	6,956 (30.82%)	3,109 (13.77%)	1,506.9 (6.68%)
Contour buffer strips	211,972	5.07%	83,270 (39.28%)	46,540 (21.96%)	23,487 (11.08%)

Results for spatial opportunity of practices should not be seen as cumulative potential across practice types. Practice opportunities are overlapping; some areas could be identified as opportunities for multiple practices; & we did not prioritize which would be the best practice to deliver an ecosystem benefit.

Tables 4 and 5 show the potential for EoF practices to achieve nitrogen (N) reduction, given their implementation at various scales. Differences in the potential for EoF practices across regions may reflect certain assumptions in our models. For example, differences in the nitrogen reduction benefits of buffers in Chesapeake and Indiana are primarily driven by the decision to use different resolutions of the National Hydrography Network (NHD) across the two study areas (see Tables 4 and 5). Higher-resolution data used in the Chesapeake likely led to reduced estimates of potential N reductions from buffer installation, relative to the medium-resolution data used in Indiana, which may over-represent N reduction potential.[1]

For wetlands, the nitrogen reduction differences across study areas are driven by the relative sparseness—compared to Indiana—of two spatial criteria in the Chesapeake: poorly drained soils and cropland presence. These features are widely present only in the Bay's Outer Coastal Plain (i.e., the Delmarva Peninsula). As a result, in the Chesapeake, there are areas producing significant nitrogen loads from non-agricultural sources that have limited predicted wetland opportunity. Notably, when wetland opportunity and subsequent nitrogen reductions were compared between Indiana and the Delmarva Peninsula region of the Chesapeake Bay—two regions that are much more comparable in their distribution of these criteria—the results were similar.

Using SPARROW modeling parameters, we assessed the relative importance of EoF management strategies in achieving established N reduction goals in each region, in relation to the impact of in-field management practices.[2] According to our estimates, adopting cover crops and recommended precision fertilizer management practices (split application, subsurface placement, stabilized N formulas, and appropriate N rates [Robertson et al. 2013]) on 50% of all corn-soy row-crop acres achieves an 18% N loss reduction in Indiana (60.99 million pounds of N) and a 19% reduction in the Chesapeake (19.7 million pounds of N). While these impacts are significant, in neither region do cover crops and precision fertilizer management alone achieve the total established N reduction goals—even considering the relatively optimistic adoption rate (45% total reduction in the Mississippi River Basin and 30% in the Chesapeake Bay).

EoF practices can help close this achievement gap and are quite efficient in terms of their impact. For instance, based on the parameters established in this study, if wetlands were restored on Indiana corn-soy fields that are marginal based on field shape/size—2.17% of total cropland acres—you could treat or "capture" N loss from nearly 20–40 times the size of the wetlands restored, resulting in an N loss decrease of up to 14% (60.1 million pounds of N). In the Chesapeake Bay, restoring 0.52% acres (based on field shape/size) would reduce N by 1.5% (3.7 million pounds of N).

The relatively limited impact of wetland restoration in the Chesapeake our analysis may be an effect of our model parameters. Other modeling efforts have found that land retirement, such as that achieved through the implementation of EoF practices, is necessary to meet water quality goals in the Chesapeake, given factors such as future increases in crop yields and nutrient demands (Gomez et al. 2024). As this suggests, our estimates for the potential impact of EoF practices are likely conservative, especially in the Chesapeake. Beyond absolute impact, the efficiency of wetland's impact is notable. Applying cover crops to the same acreage as noted above (0.52% of marginal corn in the Chesapeake) would reduce nitrogen by only 0.006%—orders of magnitude less efficient than wetlands.

Footnotes:

1. The proportion of nitrogen-bearing runoff in a given catchment that encounters buffers on its way to the stream is assumed to be equivalent to the proportion of the riparian zone (defined as all area within 30 m of a stream) that contains buffers. Therefore, a catchment could have less N removal either by having less buffer opportunity or by having a larger riparian zone, so the available opportunity makes up a smaller portion of this zone. Because high-resolution NHD delineates more streams—and thus more riparian zone—than medium-resolution NHD, the larger riparian zones lead to a lowered estimate of how much N encounters the buffer.

2. Model parameters are based on Conservation Effects Assessment Project (CEAP) and SPARROW data. Our estimates assume a total loading of 332.6 million pounds of N from agriculture in Indiana and 103.7 million pounds from agriculture in the Chesapeake Bay watershed.

Table 4. Indiana: Estimates of N reduction (lbs/yr) associated with opportunity areas.

Practice	Hydro-geomorphic opportunity for implementation	Opportunity on marginal lands (field shape/size)	Opportunity on marginal lands (economics)	Opportunity on marginal lands (both criteria)
Restorable wetlands	96,586,573 13,630,430 – 127,975,384	60,141,712 8,454,584 – 79,699,004	28,061,066 3,939,954 – 37,187,974	12,126,979 1,699,237 – 16,072,611
Vegetated riparian buffers	116,714,067 51,611,048 – 193,395,174	28,401,960 12,555,709 – 47,066,348	13,921,903 6,189,843 – 23,029,053	5,012,958 2,227,524 – 8,293,761
Saturated buffers	6,623,795 2,829,508 – 7,197,033	1,404,822 602,008 – 1,526,110	539,290 231,051 – 585,859	191,900 82,125 – 208,485

Results for spatial opportunity of practices should not be seen as cumulative potential across practice types. Practice opportunities are overlapping; some areas could be identified as opportunities for multiple practices; & we did not prioritize which would be the best practice to deliver an ecosystem benefit. Top number in each cell represents the median lbs of N reduction per year. Bottom numbers represent the estimated range.

Only practices with sufficient evidence are included.

Table 5, Chesapeake Bay: Estimates of N reduction (lbs/yr) associated with opportunity areas

Practice	Hydro-geomorphic opportunity for implementation	Opportunity on marginal lands (field shape/size)	Opportunity on marginal lands (economics)	Opportunity on marginal lands (both criteria)
Restorable wetlands	9,020,826 1,265,497 – 11,955,275	3,723,471 521,687 – 4,934,957	2,920,756 409,653 – 3,870,904	1,364,172 190,993 – 1,808,078
Vegetated riparian buffers	16,309,948 7,728,522 – 26,417,516	4,057,542 1,927,997 – 6,565,811	2,032,631 984,153 – 3,267,574	920,983 444,655 – 1,482,023
Saturated buffers	89,606 68,456 – 92,802	16,364 12,613 – 16,931	4,250 3,157 – 4,415	2,159 1,626 – 2,239

Results for spatial opportunity of practices should not be seen as cumulative potential across practice types. Practice opportunities are overlapping; some areas could be identified as opportunities for multiple practices; & we did not prioritize which would be the best practice to deliver an ecosystem benefit. Top number in each cell represents the median lbs of N reduction per year. Bottom numbers represent the estimated range.

Only practices with sufficient evidence are included.

Recommendations

Our goal for this project was to advance the knowledge needed to accelerate the implementation of EoF practices across key US agricultural geographies. We focused on the potential to develop a framework for an ecosystem-market payment scheme for EoF practices, related to water quality, carbon, and biodiversity benefits. Our findings have implications for traditional EoF farmer engagement and are suggestive of broader needs toward developing EoF-related ecosystem markets. Based on our work, we make the following interrelated recommendations.

Recommendation 1: Efforts to Identify Marginal Land Should Further Incorporate Economic and Social Factors into Spatial Analyses

EoF practices are often framed as a solution for the challenge of "marginal" acres on farms (Haddad et al. 2023). Past spatial analyses have identified large tracts of "marginal" ground across key agricultural regions in the US suitable for EoF practices (Martinez-Feria & Basso 2020). These studies often define marginality based on physical characteristics, such as soil quality and production (Helliwell 2018). Few studies have considered marginality as related to economic performance, with only recent spatial research including the economics and environmental impacts of land management as qualities of marginal land (Khanna et al. 2021; Tiang et al. 2021). While this work offers key insights, rarely have farmers' own criteria for marginality been examined (Helliwell 2018). This oversight may be critical, given that farmers are key decision-makers for the ultimate adoption of EoF practices.

Our social findings, which draw on farmers' definitions of marginality, affirm the importance of considering economic factors as driving "marginality, but also show that less explored factors matter too, such as field-shape and size, along with overall management efficiency. Bringing these farmer-revealed drivers of marginality into our spatial analysis increases its practical value for future engagement and prioritization efforts. Ultimately, our social analysis is preliminary and could be enhanced by further research.

Recommendation 2: Promote the Adoption of Precision-Management to Foster Awareness of Sub-Field Marginality

Our work did not explicitly cover the use of precision-management data. However, it is well established that most farmers are not widely managing inputs at the sub-field level (see above) and which is a likely barrier to further EoF adoption. Greater use of precision-management data may be a critical first step in supporting the identification of sub-field marginality "problems." Precision data tools exist and are widely available to support farmers' understanding and management of sub-field zones based on critical agronomic factors. These tools can show where yields are consistently low and where management changes should be considered.

A larger portion of farmers must become aware and concerned about sub-field zones if EoF practices are to be more widely adopted. Engagement and incentive programs that further promote the adoption of precision data tools and enable farmers to collect the necessary data to populate these tools are likely a key step toward EoF practice use. Further, promoting precision farm data management has the co-benefit of facilitating the use of variable rate technologies, a suite of practices that can also support farmer profitability and improved environmental outcomes.

Recommendation 3: Integrate EoF Practices into Precision-Management Technologies to Enable Market-Payments

Our literature review confirmed that EoF practices can produce positive water quality and biodiversity outcomes, and in select EoF practices, potential greenhouse gas benefits as well. The processes that drive the effectiveness of these practices are complex, and absolute benefits depend on the local context and existing climatic conditions. Therefore, their ecological impact will vary based on the siting location and management. While the additional generalized research into the ecological function of these practices is important, there is an opportunity to collect the data needed to assess local outcomes (e.g., N loading, vegetation species and biomass) with precision-management technology that would reduce the uncertainty with estimating environmental outcomes.

While underutilized (see Recommendation 2), precision data is being collected on millions of agricultural acres that includes subfield management data on fertilizer applications, planting dates, etc. Developing a mechanism to leverage this data for EoF practice siting and impact assessment could dramatically increase the attraction of these practices for farmers and market players. This precision-management data provides an opportunity to assess pre-EoF implementation conditions and therefore to generate a reliable site-specific estimate of the ecological benefits derived from the adoption of an EoF practice. Integrating precision-management data with EoF implementation creates the circumstances necessary to facilitate verified market-based payments by helping to overcome the barrier our literature review identified of significant spatial variability in practices' environmental impacts.

Recommendation 4: Conduct Additional Research and Farmer Engagement to Reveal the Agronomic Benefits of EoF Practices

Our results also may indicate that EoF practices, particularly wetlands, are perceived to increase pest pressure and challenges. While our data cannot clearly show that farmers expect reduced agronomic performance as a result, it does imply the need to consider and potentially mitigate the potential challenge moving forward. Toward making EoF practices "productive", we feel that beyond ecosystem market payments, farmers must also come to understand the significance of the agronomic benefits that EoF practices may provide to primary commodity crops. For instance, EoF practices are already promoted as aspects of integrated pest management approaches. More research into these agronomic benefits may be needed, but also on-farm demonstrations could support farmers' belief in these benefits, a key aspect of eventual adoption (Wilson et al. 2018).

Recommendation 5: Strengthen Public/ Private Partnerships to Maximize Conservation Impacts

Our approach to determining the price and potential for a market-based incentive to encourage EoF practices was based on a critical assumption: that federal and state conservation programs and staff would provide implementation costs, technical assistance, and additional monetary incentives, including annual rental payments. The potential "ecosystem market" payments our work discovered were relatively modest, but we fully expect that these payment rates would need to dramatically increase if public services and financing were not available or diminished. This suggests that private sector actors interested in achieving environmental goals through EoF practice adoption benefit significantly from a robust system of government-supported conservation programs across the country.

In addition to advocating for support of USDA and state-based conservation programs including the needed capacity to deliver projects, we also recommend that explicit efforts be taken to form public-private partnerships related to EoF practice adoption. Based on our findings, private sector actors could potentially greatly increase the acres of EoF practices by providing relatively modest additional incentives if they coupled these payments with government programs and technical support. For those organizations looking to generate ecological benefits, we see this as a relatively cost-efficient model that leads to persistent benefits given EoF practices' durability once installed. Specific efforts to design programs that leverage these existing funds and technical support staff should be pursued.

At the same time, our results suggest that a non-trivial portion of producers may be willing to adopt EoF practices without receiving additional incentives (assuming government conservation funding is provided). This could suggest that funding is a barrier for programs that are over-subscribed. Alternatively, it may be that targeted outreach is currently insufficient and is artificially reducing demand for the available program funding. While many non-governmental organizations are already conducting landowner outreach to support EoF practice use, outreach capacity is often a critical barrier (Houser et al. 2022). In the immediate term, private sector actors can rapidly support increased adoption through additional funding to outreach-focused organizations.

Recommendation 6: Conduct Additional Research to Identify How Ecological Benefits from EoF Practices can be Incorporated into Various Types of Crediting Schemes

Additional payments for EoF practices, based on our work, would likely increase adoption. However, to ensure funder/buyer trust and scalability, those payments need to be a) robustly and reliably tied to positive ecological outcomes and b) aligned with credible demand pathways. The potential for carbon markets to incentivize select EoF practices has not yet been fully realized, and demand signals for water quality and biodiversity markets for outcomes from agriculture practices are unclear and underdeveloped.

Unlike carbon, biodiversity and water are hyperlocal – contributions in one ecoregion or basin cannot compensate for impacts in another. Additionally, in the case of biodiversity credits, metrics to measure outcomes are also driven by the local context, and therefore need sufficient safeguards and nationally administered programs, as necessary prerequisites to ensure effective and appropriate use, aligned with local programs and priorities (TNC 2024). It is also unclear what role EoF practices will play in regulated schemes contributing to jurisdictional and national objectives, which likely have stronger demand and assurance drivers than voluntary, unregulated markets. Research to identify programs that meet these standards across a range of nature market segments could strengthen the economic case for EoF practice adoption (Task Force on Nature Markets 2022).

References:

Basso, B., Shuai, G., Zhang, J., & Robertson, G. P. (2019). Yield stability analysis reveals sources of large-scale nitrogen loss from the US Midwest. *Scientific Reports*, *9*(1), 5774.

Dahl, T. E. (2014). *Status and trends of prairie wetlands in the United States 1997 to 2009* (p. 67). Washington, DC: US Fish and Wildlife Service.

DeLong, C., Lindahl, C., & Johnson, K. (2021). Leading at the edge: A roadmap to advance edge of field practices in agriculture. *Journal of Soil and Water Conservation*, *76*(2), 41A-43A.

Eagle, A. J., Henry, L. R., Olander, L. P., Haugen-Kozyra, K. H., Millar, N., & Robertson, G. P. (2011). *Greenhouse gas mitigation potential of agricultural land management in the United States: A synthesis of the literature* (2nd ed.). Nicholas Institute for Environmental Policy Solutions

Farmer, J. R., Meretsky, V., Knapp, D., Chancellor, C., & Fischer, B. C. (2015). Why agree to a conservation easement? Understanding the decision of conservation easement granting. *Landscape and Urban Planning*, *138*, 11-19.

Farmer, J. R., Knapp, D., Meretsky, V. J., Chancellor, C., & Fischer, B. C. (2011). Motivations influencing the adoption of conservation easements. *Conservation Biology*, *25*(4), 827-834.

Gomez, M., Grady, C., Wainger, L., Cibin, R., Abler, D., Bosch, D., & Kaye, J. (2024). Impacts of future scenarios on the nitrogen loss from agricultural supply chains in the Chesapeake Bay. *Environmental Research Letters,* 19(8), 084039.

Hefting, M. M., Bobbink, R., & de Caluwe, H. (2003). Nitrous oxide emission and denitrification in chronically nitrate loaded riparian buffer zones. *Journal of Environmental Quality*, 32(4), 1194–1203

Houser, M., A. Jacobs, C. Colmorgen, M. Dryden, D. Lawson, D. Martin, M. Canick, C. McLean, R. Mason (September, 2022). Meeting the Bay's Wetland Goals: Insights from the Delmarva Wetland Partnership. *The Nature Conservancy*. Available at: https://www.conservationgateway.org/Documents/Delmarva-Wetland-Partnership-Report_Final.pdf

Houser, M., Campbell, B., Jacobs, A., Fanok, S., & Johnson, S. E. (2024). Farmers' participation in incentivized conservation programs: Exploring barriers and opportunities for innovative designs. *Journal of Soil and Water Conservation*, *79*(1), 20-30.

Houser, M. (2022). Farmer motivations for excess nitrogen use in the US Corn Belt. *Case Studies in the Environment*, 6(1), 1688823.

Jiang, M., Medlyn, B. E., Drake, J. E., Duursma, R. A., Anderson, I. C., Barton, C. V., Boer, M. M., Carrillo, Y., Castañeda-Gómez, L., Collins, L., & Crous, K. Y. (2020). The fate of carbon in a mature forest under carbon dioxide enrichment. *Nature, 580*(7802), 227-231

[LATE] Leading at the Edge: A Roadmap to Advance Edge of Field Practices in Agriculture (2021). The Nature Conservancy. Available at: https://www.nature.org/content/dam/tnc/nature/en/documents/EOF_Report_LORES_SPREADS.pdf

Luther, Z. R., Swinton, S. M., & Van Deynze, B. (2022). Potential supply of Midwest cropland for conversion to in-field prairie strips. *Land Economics*, *98*(2), 274-291.

[TNC] The Nature Conservancy (2024). The Role of Biodiversity Credits in Promoting Conservation Outcomes. The Nature Conservancy. Available at: https://www.nature.org/en-us/what-we-do/our-insights/biodiversity/biodiversity-credits/

Schimmelpfennig, D. (2016). Farm profits and adoption of precision agriculture.

Stehfest, E., & Bouwman, L. (2006). N2O and NO emission from agricultural fields and soils under natural vegetation: Summarizing available measurement data and modeling of global annual emissions. *Nutrient Cycling in Agroecosystems,74*(3), 207–228.

Thompson, N. M., Bir, C., Widmar, D. A., & Mintert, J. R. (2019). Farmer perceptions of precision agriculture technology benefits. *Journal of Agricultural and Applied Economics*, *51*(1), 142-163. https://doi.org/10.1017/aae.2018.27

Tiwari, P., Poudel, K. P., Yang, J., Silva, B., Yang, Y., & McConnell, M. (2023). Marginal agricultural land identification in the Lower Mississippi Alluvial Valley based on remote sensing and machine learning model. *International Journal of Applied Earth Observation and Geoinformation*, *125*, 103568.

Wilson, R. S., Schlea, D. A., Boles, C. M., & Redder, T. M. (2018). Using models of farmer behavior to inform eutrophication policy in the Great Lakes. Water research, 139, 38-46. Task force on Nature Markets (2022). Global Nature Markets Landscaping Study. *Nature Finance.* Available at: https://www.naturemarkets.net/publications/global-nature-markets-landscaping-study

Final Report
Submitted by The Nature Conservancy

Matthew Houser, PhD
Shamitha Keerthi, PhD
Lyndsey Dowell
Eugene Yacobson
Amy Jacobs
Rachel King
Nadia Alsadi
Seth Harden
Lowell George
Holly McLaughlin

Date: November 7, 2025

Funding and essential data for this report were provided by Corteva, enabling the research, analysis, and report development contained herein.

Recommended Citation: Houser, M., Keerthi, S., Dowell, L., Yacobson, E., Jacobs, A., King, R., Harden, S., Alsadi, N., George, L., McLaughlin, H., (2025). Profitable Conservation Around the Margins: A Program to Restore Marginal Farmland to Deliver Greenhouse Gas and Habitat Benefits. The Nature Conservancy. Available at:

nature.org/EdgeofField