This is an Accepted Manuscript of an article published in the Journal of Environmental Management published in September 2021, available online:
https://doi.org/10.1016/j.jenvman.2021.112914

Nonpoint Source Water Quality Trading Outcomes: landscape-scale patterns and integration with watershed management priorities

Linnea Saby[a] *, Jacob D. Nelson[b], Lawrence E. Band[c] , Jonathan L. Goodall[d]

[a] * *Corresponding Author*. University of Virginia, Department of Engineering Systems and Environment. Olsson Hall, 151 Engineer's Way, Charlottesville, Virginia, USA, 22904. Email: ls3en@virginia.edu
[b]University of Virginia, Department of Engineering Systems and Environment. Olsson Hall, 151 Engineer's Way, Charlottesville, Virginia, USA, 22904. Email: jn8vc@virginia.edu
[c]University of Virginia, Department of Environmental Sciences. 291 McCormick Rd., Charlottesville, Virginia, USA, 22903. Email: lband@virginia.edu
[d]University of Virginia, Department of Engineering Systems and Environment. Olsson Hall, 151 Engineer's Way, Charlottesville, Virginia, USA, 22904. Email: goodall@virginia.edu

---

ABSTRACT: Nonpoint source (NPS) water quality trading (WQT) has been lauded as a way to reduce water pollution while mitigating costs, but NPS WQT programs often do not account for cumulative landscape-scale impacts to hydrological and ecological processes. In this work, we parameterize the landscape-scale patterns of an emerging NPS WQT market in Virginia (*n*= 606 transactions) and describe potential tradeoffs and synergies. We also examine program outcomes in the context of Virginia's spatially-explicit conservation and restoration priorities, and discuss ways in which NPS WQT integrates or fails to integrate with these state-level watershed management goals. These spatial and policy analyses present novel methods for evaluation of NPS WQT programs. Our results reveal how NPS WQT has influenced Virginia land management patterns in practice. Specifically, we show that this program has encouraged the transfer of water quality Best Management Practices (BMPs) from urban to rural areas. Impact sites are often far from mitigation sites, at an average of 164.6km apart measured along the stream network and most often migrated outside the 8-digit Hydrologic Unit Code watershed boundaries. We also find opportunity for improved integration with the state-level management priorities, including that an estimated 22% of the NPS WQT mitigation site area works against state priorities (for example by converting prime farmland to forest), 9% supports state priorities, and 69% neither negates nor supports state priorities. We suggest policy and management actions that can increase the integration of NPS WQT with statewide watershed management goals, and could ultimately improve environmental returns from this fast-growing program.

Keywords: watershed management; water quality trading; landscape-scale; land use prioritization; nonpoint source pollution

1. INTRODUCTION

Managing nonpoint source water pollution (NPS pollution) has been classified as a "wicked problem" in environmental management (Patterson et al., 2013). NPS pollutants, such as nutrients, sediment, and toxins, enter waterways from sources including agricultural runoff, urban stormwater, and atmospheric deposition, where they can severely degrade water resources. These sources are often challenging to quantify or directly attribute to polluters, which makes eliminating pollutants through regulations exceedingly challenging and costly. In the United States, significant amounts of NPS pollution from agriculture are subject to few environmental restrictions, as some claim regulations will stifle food production (Stubbs, 2014). As climate change increases the frequency of water quality emergencies resulting from NPS pollution including toxic algal blooms (Griffith and Gobler, 2020; Moore et al., 2008; Trainer et al., 2020), it becomes increasingly urgent that we utilize all policy tools available to effectively address the NPS problem.

Water Quality Trading (WQT) is a policy system that holds potential to enable more cost-effective mitigation of NPS pollution through cap-and-trade, without introducing new agricultural regulations (Fisher-Vanden and Olmstead, 2013). Under WQT, a regulated entity with a high cost of abatement is permitted to purchase pollutant load offsets, called credits, from an offsite entity which has abated pollution at a lower cost. Participants may be point sources (PS), such as wastewater treatment plants or industrial dischargers, or NPSs. WQT programs including NPSs can result in average pollution abatement cost savings ranging from 27% to 76% compared with command-and-control approaches (Corrales et al., 2014; 2017). WQT has been promoted by regulatory agencies in the United States for decades as a means of meeting water quality goals at minimal cost. In 2003, the U.S. Environmental Protection Agency (USEPA) issued strong support and guidance for WQT programs, including NPS trading (USEPA, 2003). By 2008, 33 statewide or local NPS trading programs had been established or were under development in the U.S. (Selman et al., 2009). In the most common form of NPS WQT markets, Waste Water Treatment Plants (WWTPs) regulated under the Clean Water Act purchase credits annually from agricultural producers, who voluntarily generate NPS credits each year through the application of approved Best Management Practices (BMPs).

There are inherent challenges and uncertainties in assuring good environmental tradeoffs when NPSs are included in WQT programs (Abdalla et al., 2007; Faeth, 2000; Fisher-Vanden and Olmstead, 2013; Stephenson et al., 1998). These concerns center on the challenge of accurately evaluating transaction equivalency in annual pollutant loads using model estimates, which may have a wide range of error depending on the variability in hydrology, ecology, geology, and climate of a region. Equivalency concerns increase as the distance between credit purchaser and seller increases, and clusters of offset purchases increase the risk of local pollution hot-spots (BenDor et al., 2009).

Trading regulations are designed to mitigate equivalency concerns for individual transactions, but often do not sufficiently account for cumulative landscape-scale impacts to hydrological and ecological processes (Accatino et al., 2018). Indeed, other market-based environmental trading programs have been shown to have unintended consequences at the landscape scale. BenDor et al. (2009) analyzed transaction-level data for a stream and wetland mitigation trading program, and found significant inconsistencies with the restoration timing, trading proximity, and ecological value among market participants. They concluded that analyzing transaction outcomes on a case-by-case basis obscures substantial impacts seen at the landscape scale. In air emissions trading as well, individual trades can be equivalent but markets can result in concentration of poor air quality in pollution hot-spots (Boyd et al., 2003; Wang et al., 2007).

Another landscape-scale issue that arises with NPS WQT is the limited ability to target restoration areas in the landscape based on the expected water quality returns. Prioritizing areas in the landscape for restoration to maximize environmental benefits for people is an important tenet of watershed management, and has become common practice among state and local governments, consultants, land trusts, and others involved in land use planning (Crossman and Bryan, 2009; Giri et al., 2018; Lee et al., 2002; Yang and Best, 2015). Land use prioritization not only enables effective allocation of funds for land acquisition and restoration projects, but supports efficient arrangement of limited land resources for human use and environmental protection (Giri et al., 2018; Randhir et al., 2001). These programs may target riparian areas, sites along headwater streams, and other field-level planning within a watershed where simulations or direct measurement show higher-than-average impacts to water quality. By contrast, WQT policies often encourage market flexibility (Corrales et al., 2013), and may not include explicit impetus for water quality traders to establish restoration or conservation projects at priority sites, nor to avoid use of offsite mitigation in hydrologically sensitive areas. WQT can, therefore, risk working against existing land use management strategies by placing water quality BMPs in the landscape based on market forces, rather than ecological value. For example, wetland mitigation banking programs have been shown to result in landscape-scale "migrations" of wetland resources from urban to rural areas, in contravention to urban stormwater management efforts (BenDor and Brozović, 2007; King and Herbert, 1997; Ruhl and Salzman, 2006). Better integration of urban environmental policies could result in better environmental outcomes from policy interventions (Bernhardt et al., 2008).

Despite these landscape-scale risks, the landscape-scale outcomes of NPS WQT have rarely been evaluated in literature. In part, this is because traditional WWTP-agriculture NPS WQT markets have historically failed to generate significant credit supply, demand, or both (Abdalla et al., 2007; DeBoe and Stephenson, 2016; Hoag et al., 2017; Stephenson and Shabman, 2016, 2017). However, exceptions to this rule are emerging, and in 2018 and 2019 the U.S. Environmental Protection Agency (USEPA) released documents and guidelines to reaffirm strong support of NPS WQT as a method to reduce pollution, and encouraging development of innovative local and statewide WQT programs (USEPA, 2018, 2019a, 2019b). Innovative and flexible market designs including non-traditional participation have been proposed, and may help incentivize creation of new markets (Heberling et al., 2018). As strong support for NPS WQT among regulatory agencies continues, evaluation of operational non-traditional programs is important to mitigate landscape-scale risks.

The Virginia NPS WQT program provides a strong example of an emerging non-traditional market with unassessed landscape-scale outcomes. Over 250 NPS WQT mitigation sites and thousands of transactions have occurred across the state since 2014 (USACE, 2020), but spatial data for these transactions has not been curated before this study. Virginia's program incorporates several concepts from literature proposed to increase market activity, including permitting participation from non-traditional market participants (proposed by Heberling et al., 2018), employing simplistic transaction rules to facilitate implementation (USEPA, 2019a), subtracting baseline trading requirements at the time of credit awarding to reduce up-front costs (Ghosh et al., 2011), permitting large and flexible trading areas (Hoag et al., 2017), and generally devising a low-risk market for both credit buyers and sellers. The market activity observed in Virginia, therefore, provides validation that it is possible to generate NPS WQT transactions, and increases the need to evaluate the environmental efficacy of the program in meeting water quality goals.

Given the recent renewed interest in creative NPS WQT programs, as well as the marked success of the non-traditional Virginia program in garnering participation, non-traditional WQT markets may be a coming frontier in NPS pollution management. Considering this, along with landscape-scale risks of market-based environmental trading shown in other trading programs, it is critical that we analyze the outcomes of existing NPS WQT programs. Armed with knowledge of market characteristics, environmental tradeoffs and potential externalities can be evaluated and corrected, and policy improvements woven into newly forming WQT programs.

In this work, we curate data from several publicly available sources to demonstrate landscape-scale outcomes of Virginia's NPS WQT program for the first time. This work addresses two primary research questions. First, how is this emerging NPS WQT program impacting land use patterns across Virginia? Second, does this program effectively forward state-level environmental and land use management goals? To answer the first question, we use transaction-level spatial data (n= 606 transactions) to determine clustering patterns and migration of water quality offsets along stream networks and within watersheds. We discuss the hydrologic and ecologic implications of these patterns, to provide new insight into how NPS WQT impacts water quality in practice. To answer the second question, we assess the spatial integration of Virginia's NPS WQT program with state-level watershed management goals, and propose methods to improve this integration using existing state resources. This represents a novel policy analysis method to evaluate the effectiveness of NPS WQT in targeting high-impact areas in the landscape.

As regulatory agencies continue to seek methods for implementing NPS WQT programs across the country, this research provides a leading example of outcomes of a non-traditional NPS WQT program and delivers policy guidance to increase the utility of WQT to address targeted NPS pollution. We conclude by discussing the need for future research, and describing the ethical implications of NPS WQT policies based on our results.

2. VIRGINIA NONPOINT SOURCE WATER QUALITY TRADING (NPS WQT) BACKGROUND

Virginia's NPS WQT market is designed to reduce the cost and increase flexibility for achieving the nitrogen, phosphorus, and sediment Total Maximum Daily Loads (TMDLs) for the Chesapeake Bay. One NPS credit is equivalent to one pound of pollutant per year removed from edge-of-tide loads (i.e., prevented from entering the Chesapeake Bay). These credits are calculated using a lookup table of average outputs generated with the Chesapeake Bay Model version 6 (the Chesapeake Assessment Scenario Tool, CAST), and sold one time rather than being sold each year at a lower price (Branosky et al., 2011).

Though credits for these pollutants can be generated through a wide array of mitigation actions, NPS credits have been most frequently awarded to landowners for the permanent conversion of agricultural land to forest (personal correspondence with Sara Felker, VADEQ Environmental Specialist, 09/17/2020). These one-time credits are known as "perpetual" credits, with cost ranging from $10,430 to $20,000 per phosphorus credit (Nobles et al., 2017), a price intended to account for abatement for perpetuity. Credit generating sites are known as banks. In addition to the predominant agricultural conversion banks, there are also a small number of banks created through the conversion of golf courses to forest, one bank created through the establishment of a bioretention pond (Cranston's Mill Pond bank), and two banks created through stream restoration that have sold NPS WQT credits (personal correspondence with Sara Felker, VADEQ Environmental Specialist, 09/17/2020).

Forests established as credit banks may be timbered periodically (see Virginia Code 9VAC25-900-120C) to maximize long-term profit from the land. All conversions are credited based on a minimum stem count of 450 native tree seedlings per acre (VADEQ, 2008). Pine seedlings are the least expensive seedling for sale by the U.S. Forest Service and provide profitable lumber so are frequently planted, though native volunteers around the periphery may also be included in the stem count (personal correspondence with Sara Felker, VADEQ Environmental Specialist, 01/05/2021). Credit banks are inspected to ensure this stem count, but in-stream monitoring is not a part of this NPS WQT program. Other NPS WQT program do include stream- and field-level water quality monitoring, for example in Ohio (Kieser and McCarthy, 2015).

Phosphorus is treated as a "keystone pollutant" in Virginia, meaning that actions permitted to reduce phosphorous (P) are also assumed to reduce nitrogen (N) and sediment according to ratios calculated with the Chesapeake Bay Model (Commonwealth of Virginia, Office of the Governor, 2019). Phosphorus credits are most commonly sold, and the associated ratios of nitrogen and sediment are then removed from the market or "retired" (USACE, 2020). For this reason, we use the term "credit" to refer to a perpetual NPS Phosphorus credit in this work. Baseline pollution reduction requirements for agricultural conversion banks, including a 35-foot buffer zone required around riparian and agricultural areas, are subtracted from the expected total load reduction before credits are awarded. Once the land use conversion has been established, little additional effort or expense is required of the landowner to secure credit certification. All of these factors, along with periodic profit from timbering operations, make water quality credit generation in Virginia more profitable, lower-maintenance, and lower-risk to landowners compared with other NPS WQT programs.

Credits from agricultural conversion have overwhelmingly been purchased by Construction General Permit (CGP) holders (USACE, 2020), who are regulated under the Virginia Stormwater Management Program (VSMP). Since 2012, these entities have been permitted to use credits to offset some or all of the required P mitigation actions for land disturbance activities, often with significant cost savings over constructing permanent onsite controls (Nobles et al., 2017). The P mitigation requirements are calculated using the Virginia Runoff Reduction Method (VRRM), which calculates loads and requirements according to proposed land use change and soil type, but not based on position within the watershed (calculation spreadsheets available at https://swbmp.vwrrc.vt.edu/vrrm/, accessed 11/12/2020). All water quantity requirements must be met onsite. Onsite extended detention basins are water quality BMPs that are frequently forgone when offsite credits are purchased (Nobles et al., 2017). Credits may be purchased from banks within a hydrologically-defined region, either up or downstream from the impact site (Virginia Code §62.1-44.15:35). Credits are sold at a 1:1 trading ratio, meaning that there is an expected net zero impact for transactions at the outlet to the Chesapeake Bay, calculated conservatively (VADEQ, 2008).

3. DATA AND METHODS

3.1 NPS WQT data

We obtained all available NPS WQT buyer and bank information from publicly available data sources. Coordinate data are available for all NPS WQT banks, but are not available for all individual transactions. In this subsection we describe the NPS WQT data that is available and its limitations.

WQT banks are permitted by NPS Nutrient Credit Certification specialists at the Virginia Department of Environmental Quality (VADEQ). Beginning in 2020, all point data for all banks and credit availability are published on the Regulatory In-lieu fee Banking Information System (RIBITS) maintained by the U.S. Army Corps of Engineers (USACE) in collaboration with VADEQ. Banks submit the net number of credits sold to RIBITS administrators at regular intervals, including the Hydrologic Unit Code (HUC)-8 level spatial information. Transaction records are also uploaded to RIBITS, which makes some buyer information available, including address. However, complete transaction information is not yet available for most banks. We downloaded the bank centroid coordinate data for all NPS WQT banks from RIBITS on May 20th, 2020, with a total of 266 banks.

WQT purchasing data was obtained from stormwater CGP specialists at the VADEQ VSMP office, who are responsible for approving purchases as a part of construction permitting. Credits are generally purchased early in the permitting process, before the land use disturbance activity has occurred. The intent to purchase credits is submitted on the permit Registration Statement at the beginning of the project. When the project land disturbance has been completed and the permit terminated, the name of the water quality credit bank and number of credits purchased are reported to VADEQ on the Notice of Termination form (personal correspondence with Holly Sepety, VADEQ Environmental Specialist, 01/12/2021). This means that complete transaction information (i.e., paired credit buyer and seller data) are only available for terminated CGP permits, after the impact has actually occurred and the permit is terminated. CGP permit cycles occur every five years (2009, 2014, and 2019), so WQT credit transaction information may not be available from VADEQ for multiple years after the date of purchase.

We obtained coordinates of all nutrient credit purchase sites with terminated CGP permits from VADEQ as of March, 2020. This includes 606 transactions, though several thousand transactions in total are estimated to have occurred through the program and do not yet have transaction information available from VADEQ. The purchasing data we obtained from VADEQ include the name of the bank from which credits were purchased, which was matched with NPS WQT banks by name using a text sorting algorithm we created in R version 3.6 (R core team, 2017), and making manual corrections as needed to account for typos. This resulted in a final database with coordinates of both credit buyers and sellers for 606 transactions between 2012 and present, including the number of credits sold.

As described here, coordinate data for all NPS WQT banks are available but only partial purchasing information is available. For some analyses, we utilized only the banks where NPS WQT credits had been sold in the recorded 606 transactions, which was 92 banks. When appropriate, we used the entire database of 266 banks for analysis. Based on the positioning of agricultural land, we estimated that 254 of these banks are agricultural conversion banks (bank type is not available from RIBITS). We state whether we are using all bank sites (266 banks), agricultural conversion banks (254), or only bank data included in transactions (92 banks) in this work.

3.2 Management prioritization data

Spatially-explicit land use prioritization schemes have been developed for the Commonwealth of Virginia and applied in state-level management for years. The Virginia Department of Conservation and Recreation (VADCR) is the primary state agency dedicated to land use planning to protect natural and recreational resources, and makes all prioritization models and maps available to the public for wide use by land use planners (VADCR, 2019). VADCR runs a wide range of programs to balance land use goals based on statewide stakeholder priorities, and allocates millions of dollars in state funding each year for land acquisition and restoration projects based on these maps. These funds are awarded to projects based on statewide models of environmental, economic, and cultural function, and land may be prioritized for wilderness area, soil and water conservation, flooding management, or some combination.

3.2.1 ConserveVirginia Water Quality and Historic Justice data

The ConserveVirginia Water Quality and Historic Justice maps are a discrete targeted prioritization scheme that is based on data from VADCR and other state agencies. These data provide state-level management priorities to meet seven specific environmental goals, and are publicly available through the VADCR featureserver (VADCR, 2020b). ConserveVirginia was developed through a collaboration between state agencies under an initiative established by Governor Ralph Northam, and are intended to be iteratively updated as new data are made available. Table 1 describes how each ConserveVirginia category was developed, and our reasoning for determining relevance to WQT land management activities. The area covered by each category is also shown in Table 1. Categories have some spatial overlap. For reference, the entire area of

Virginia is 110,786.7 square kilometers, so more than half of the state is not categorized for a ConserveVirginia management priority. Because ConserveVirginia data are discrete (all locations are either a priority area or not a priority area for each management goal), they provided an ideal format to identify how well NPS WQT aligns with Virginia's conservation goals.

Table 1. Description of ConserveVirginia categories (Commonwealth of Virginia, Office of the Governor, 2020), and relevance to land management in Virginia agricultural conversion NPS WQT banks (farmland converted to forest) and purchases (construction sites with purchased credits). WQT activities may support, negate, or not significantly impact each management category where spatial intersections occur. These relevance determinations are used in our analysis of integration with state-level conservation goals (see Table 4). VCV = Virginia ConservationVision.

Category (total area covered in square km)	Data description	Relevance to WQT Bank and Purchase land use activities
Agriculture (3,178) and Forestry (5,841)	Comprised of high priority areas in the VCV Agricultural Model and the Department of Forestry's Forest Conservation Value Model. Each priority area in this category is listed as either important for agriculture or for forestry, so may be separated.	**Banks** permanently convert farmland to forests, so establishment of water quality credit banks negate the agriculture conservation subcategory. The Forestry subcategory is not significantly impacted because banks cannot be created on forests. **Purchases** do not impact either agriculture or forestry subcategories. While construction projects may impact these by changing land cover, whether or not an approved construction project purchases WQT credits has a negligible impact.
Natural Habitat and Ecosystem Diversity (25,301)	Considers excellent habitat cores and corridors, climate-resilient areas, rare plant and animal species ranges, and high-quality Brook Trout streams.	**Banks** can support this category through the establishment of forests. **Purchases** can negate it by increasing local nutrient runoff.
Floodplains and Flooding Resilience (3,461)	Selects undeveloped land to conserve or acquire upstream of devastating historical floods across Virginia, as well as VCV prioritized wetlands in both inland and coastal areas. Water quality is considered in prioritizing wetlands for conservation.	**Banks** can increase infiltration and reduce flooding, so can support this category. **Purchases** are required to adhere to water quantity regulations and are therefore assumed to not impact local hydrology, but they do impact water quality in floods so can negate this category.
Cultural and Historic Preservation (7,726)	Includes historic battlefields and other sites included on the National Register of Historic Places and the Virginia Landmarks Register.	**Banks** can negate this category if registered historic farmland is converted to forest to create a WQT bank. **Purchases** do not substantially impact this category. While construction projects may impact this, whether or not an approved

		construction project purchases WQT credits has a negligible impact.
Scenic Preservation (1,711)	Maps national and state designated scenic byways, scenic rivers, and many trails.	Neither **Banks** nor **Purchases** substantially impact this category, so it not included in our analysis.
Protected Landscapes Resilience (3,838)	Represents areas surrounding existing protected zones and areas important to climate resilience and recreation.	**Banks** can support this category by increasing protections. **Purchases** may negate this by decreasing local water quality.
Water Quality Improvement (5,126.58)	Identifies high-priority areas for nitrogen, phosphorous, and sediment reduction by implementing the Chesapeake Bay Program Phase 6 Model at the HUC-12 level. All priority areas are within a 100-400-foot riparian buffer, with wider buffers in areas with steep slopes and headwater streams.	**Banks** can support this category by improving local water quality. **Purchases** negate it by decreasing local water quality.

3.2.2 Virginia ConservationVision data

The discrete ConserveVirginia data layers are helpful for analyzing where NPS WQT supports or negates existing state-level goals, but an important extension of this is to discuss how Virginia could increase integration of WQT with statewide environmental management goals. We include a proposed framework for accomplishing this. For this extended analysis, we use data from the Virginia ConservationVision (VCV) program, which provides more localized detail of land management priorities and complete statewide coverage of land cover suitability.

VCV data is presented as a continuous raster dataset with land use priorities at a 30-meter spatial resolution across Virginia (VADCR, 2020a). These data are used by the state to identify the areas which are important in protecting natural and recreational resources, including water quality. Some of these data are included as a part of ConserveVirginia data layers. Each VCV map assigns a score between 0 and 100, with 100 being the highest priority for management action. These prioritization maps are used in funding allocation decisions across Virginia, and are intended for use by anyone involved in land use planning and conservation decision making (Hazler and Knudson, 2018). We use three subdatasets from VCV for this discussion, the Watershed Model, the Agricultural Model, and the Development Vulnerability model.

The VCV Watershed Model (2017 Edition) describes land use prioritizations for management of water resources, and assigns prioritization scores for conservation, restoration or BMPs, and stormwater management (Hazler and Knudson, 2018). The Watershed Model combines land cover weights (Table 1) with data for watershed integrity, soil sensitivity (slope, K-factor, runoff potential), and landscape position (hydrological zone, drinking water zone) to identify Virginia water quality and watershed integrity priorities. Land use weights are based on default pollutant coefficients for N, P, and sediment from OpenNSPECT, a tool created by the National Oceanic and Atmospheric Association (NOAA) to evaluate water quality impacts of land uses (Hazler and Knudson, 2018). Conservation priority in VCV may be assigned to forest, shore, shrubland, grassland, and wetlands. Restoration priorities are assigned to developed open space, pasture, and cultivated crop land covers.

Stormwater management priorities are assigned for other developed and barren land. Land use data used in the Watershed Model is from the National Land Cover Dataset (NLCD) 2011, and so represent land use before NPS WQT land use conversions (i.e., agricultural conversion WQT banks will be classified as agriculture, not forest).

Table 2. Virginia ConservationVision (VCV) Watershed Model priority weights by land cover. These weights are combined with data for watershed integrity, soil sensitivity (slope, K-factor, runoff potential), and landscape position (hydrological zone, drinking water zone) to produce final prioritization maps. BMP= Best Management Practice.

Conservation Weights		Restoration/ BMP Weights		Stormwater Mgmt. Weights	
Unconsolidated Shore	1.00	Developed, Open Space	0.17	Developed, Low Intensity	0.20
Deciduous Forest	1.00	Pasture/ Hay	0.51	Developed, Med. Intensity	0.34
Evergreen Forest	1.00	Cultivated Crops	1.00	Developed, High Intensity	1.00
Mixed Forest	1.00			Barren Land	0.95
Scrub/ Shrub	1.00				
Grassland/Herbaceous	0.50				
Woody Wetlands	1.00				
Emergent Herbaceous Wetlands	1.00				

The VCV Agricultural model (2015 Edition) quantifies the relative value of lands for agricultural use. Eighty percent of the scoring factor is based on the inherent soil suitability to agriculture, which is created data from the Natural Resources Conservation Service (NRCS). The NRCS identifies prime farmland as areas with the best chemical and physical characteristics for producing sustained high yields (Hazler and Tien, 2015). Twenty percent of the VCV Agricultural value score is based on quality of the foodshed, i.e., the ease of transporting to potential consumers at farmers markets, city centers, or metropolitan areas. 2011 NLCD land cover class was also used as a multiplier to the score. Active agriculture had a score multiplier of 1, while land uses that cannot feasibly be converted to agriculture had a multiplier of 0 (such as high-intensity development), and intermediate land uses are assigned a gradient multiplier (Hazler and Tien, 2015).

The VCV Development Vulnerability model (2015 Interim Edition) provides an index of the risk of natural, rural, or other open space land to developed land use (Hazler, Tien, and Gilb, 2016.). This raster layer is based on travel time to urban and metropolitan areas, and areas with significant recent growth. Land use is again from NLCD 2011. The 0-100 index scores are binned into five 20-point categories, classes I-V. Areas that are not eligible for development, such as lands with conservation easements, are given an index of 0. Already developed land is given a score of 101. A more detailed and statistically rigorous model is currently under development at VADCR.

3.3 Spatial analysis methods

Spatial analyses were completed in ArcMap 10.5.1 (ESRI, 2016). We calculated the net catchment nutrient credit import and export by creating a spatial join with the curated transaction data and National Hydrography Dataset HUC-12 and HUC-8 spatial layers (USGS, 2019), adding all credits sold in each zone, and subtracting all credits purchased in each zone. Transaction distance along stream networks was calculated by creating an Origin-Destination matrix with all banks and purchase sites snapped to NHD flowlines, and selecting matching purchase and bank sites. Transaction distances and net credits were calculated using only the WQT banks involved in recorded transactions.

The Hopkins statistic (H) was calculated to quantify the clustering tendency of banks and purchases. This was accomplished in R according to Equation 1,

$$H = \frac{\sum_{i=1}^{n} y_i}{\sum_{i=1}^{n} x_i + \sum_{i=1}^{n} y_i} \quad (1)$$

where x_i is the distance between each point in the dataset and its nearest neighbor, and y_i is the distance between each point in the dataset and points in a uniform dataset of the same range. Therefore, if the distance between points is significantly smaller than the distance to points in the uniform dataset, H will be close to 1 (Hopkins and Skellam, 1954). Values of H greater than 0.75 indicate a clustering tendency at greater than 90% confidence level (Lawson and Jurs, 1990).

Finally, we identified the relative position of WQT buyers and sellers in each HUC-6 watershed. This was accomplished using the ESRI Trace Downstream tool for all bank and purchase points. The endpoint for the Trace Downstream tool matches the Chesapeake Bay edge-of-tide limit used to calculate water quality credit amounts in CAST.

3.4 Policy analysis methods

ConserveVirginia data outlines zones for certain management priorities. Some, but not all of these priorities are related to NPS WQT activities, as described in Table 1. We identified WQT banks and purchases which fall in each of the relevant management priority zones.

In the data available, WQT banks are formatted as points only and the area and shape of the bank is unknown. Using the point file only would result in an underestimation of the intersections between banks and management categories. In lieu of bank shape data, we developed a method to estimate the shape of agricultural conversion banks.

We first selected the land parcels containing WQT bank points. We then clipped these parcels to contain only agricultural area (row crops or pasture) according to NLCD 2011 land cover, representing land use before any conversions for water quality credits occurred (NLCD, 2011). Banks with no agricultural land are, therefore, not included, and assumed to be banks created through methods other than agricultural conversion. 254 out of 266 parcels with banks contained agricultural land, and are assumed to represent agricultural conversion banks. This resulting layer, agricultural land on bank parcels, was used to be the best estimation of agricultural conversion bank area. This assumes that WQT banks represent conversion of all farmland on the parcel to forest, which may not always be the case. Therefore, our estimation represents an upper limit of the actual bank area. The median bank area using our estimation method was 0.26 square kilometers or 64.7 acres, and the median Virginia farm size in 2017 was .27 square kilometers or 66 acres (USDA, 2019), so our method produced reasonable estimations. Limitations related to this estimation are discussed further in section 4.6.

We intersected the bank area estimates with each of the relevant ConserveVirginia shapefiles. The outcome is an estimate of impact frequency and estimated area of banks that impact each ConserveVirginia category. An example of this analysis is shown in Figure 1 panel A. In this example, the bank is considered to negate the Agricultural Conservation subcategory. The overlapping portion is the area reported as impacting this category. The Natural Habitat & Ecosystem Diversity category is also present in the parcel, but the bank is considered neutral to this category because the agricultural land use areas do not overlap with it.

Purchase sites are also formatted as points, however an estimated area to be disturbed is also included in the data. We defined a buffer area around each purchase point to match the given area disturbed for the permitted project. The buffer function assumes a round impact site. This provides an accurate area, but error is still present in this analysis because the shape of the impacted area is not given. The outcome of the overlay analysis is taken as the best estimate of the impact of purchases to each ConserveVirginia category. An example of this analysis is shown in Figure 1 panel B. As shown, purchases are buffered based on actual recorded disturbance area. Three of the shown purchases overlap with the Water Quality Improvement Category, and so are considered to negate the management goal, and the remaining five purchases are neutral to all categories.

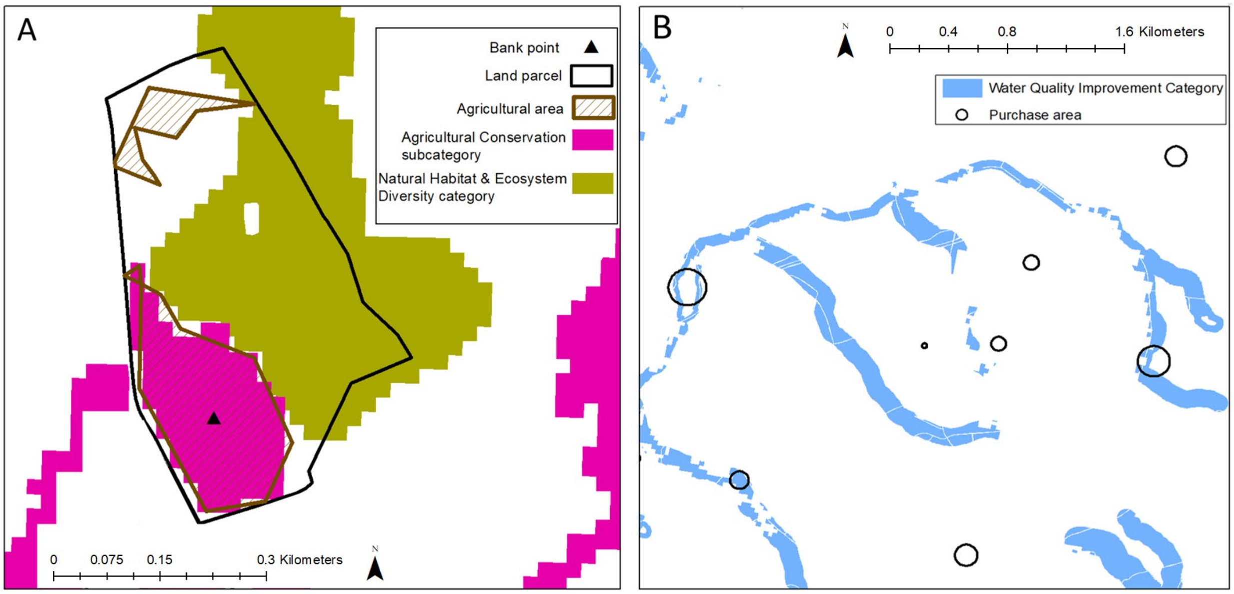

Figure 1. Visualization of the policy analysis with ConserveVirginia management categories and water quality credit bank and purchase areas. Panel A shows agricultural area within a land parcel where the bank point occurred. This "Agricultural area" was used as the estimate for bank shape. For purchase sites (Panel B), the disturbed area in acres is provided in the data from the Virginia Department of Environmental Quality (VADEQ). Both bank and purchase areas contain error due to lack of verified shape data.

As noted above in this section, an estimated 254 of 266 NPS WQT banks were created through the permanent conversion of agricultural land to forest. We use VCV data to demonstrate areas where agricultural conversion would support state-level management goals. We combined the VCV Agricultural Model and Watershed Model data to create a prioritization score, according to equation 2.

$$Priority = 0.5 * (R + (100 - A)) \quad (2)$$

Where *R* is the VCV restoration priority score (1-100), *A* is the VCV agricultural value score (1-100), and *Priority* is the agricultural conversion bank placement priority (1-100). Therefore, a high Priority score identifies areas that VCV has marked as having both high restoration priority and low-value agricultural land. This assumes equal value in agricultural value and restoration priority scores.

Finally, we include an analysis of bank sites with VCV development vulnerability data. This compares bank sites to raster data, so each bank point can be attributed a single development vulnerability value. Unlike in the ConserveVirginia policy analysis where we varied the size of the bank polygon to assess spatial intersections with other polygons, the point data format achieves the most accurate description of bank location on the continuous raster data

4. RESULTS AND DISCUSSION

4.1 Descriptive and spatial analyses

A total of 1167.05 Phosphorous credits were sold in the 606 transactions analyzed, and were purchased by 428 unique CGP-holding (credit purchasing) entities from a total of 92 NPS water quality credit banks. 423 of the credit purchasing entities (99%) made fewer than five water quality credit purchases. The Virginia Department of Transportation (VDOT) held the largest number of transactions, with 87 recorded transactions (14.3%). Our estimation of bank area showed a total of 102.14 square kilometers of agricultural conversion banks with a median size of 0.26 square kilometers or 64.7 acres. This outcome represents a large number of market participants compared with other programs. Many NPS WQT markets have had few or no market participants (Hoag et al., 2017). An active Ohio NPS WQT program sold credits to only 8 WWTPs (Kieser and McCarthy, 2015). The number of participants reported here is limited by the available data (see subsection 3.1), and actual number of credit purchasers is higher.

Figure 2 shows lines between NPS credit purchasers and sellers for all transactions used in this analysis. "Other credit banks" depicted in Figure 2 may also have hosted credit transactions, but data for these transactions are not available, as described in subsection 3.1. The mean Euclidean distance between water quality credit bank and purchase sites was 61 km with a standard deviation of 34 km. The mean distance along the NHD stream network was 165 km with a standard deviation of 105 km. These data are illustrated in Figure 3.

This mean distance between buyers and sellers is comparable to the distance found in the North Carolina stream and wetland mitigation program by BenDor et al. (2009), which found transaction distances of 177 km along the stream network, however in that case purchases were only permitted downstream of banks. Unless there is a local water quality restriction, credit purchasers are permitted to purchase from any bank in a neighboring HUC-8 (within the HUC-6), so it follows logically that purchasers identify the least-cost option within that large allowable zone.

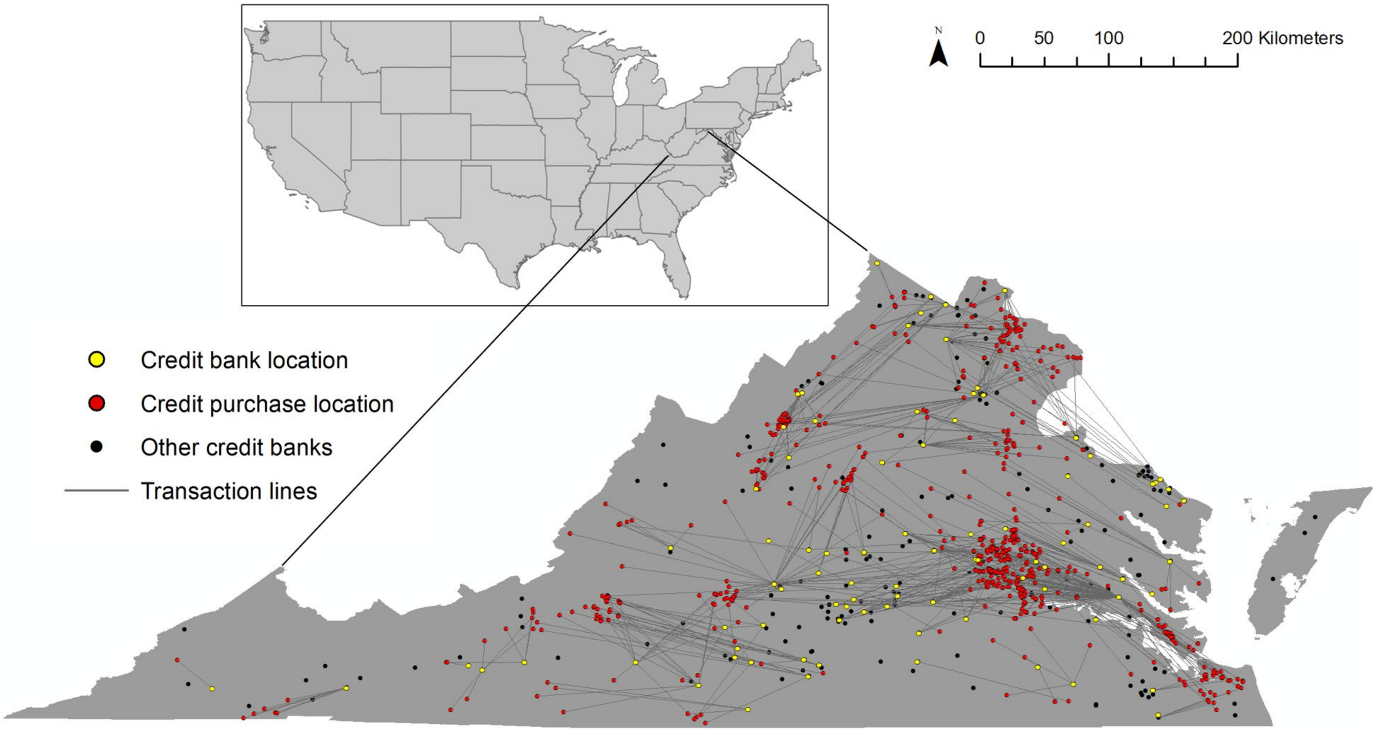

Figure 2. Nonpoint Source (NPS) water quality trading (WQT) credit banks, purchase locations, and transaction lines for all available data. Additional transactions have occurred, but coordinate data are not yet available for reasons described in Section 3.1.

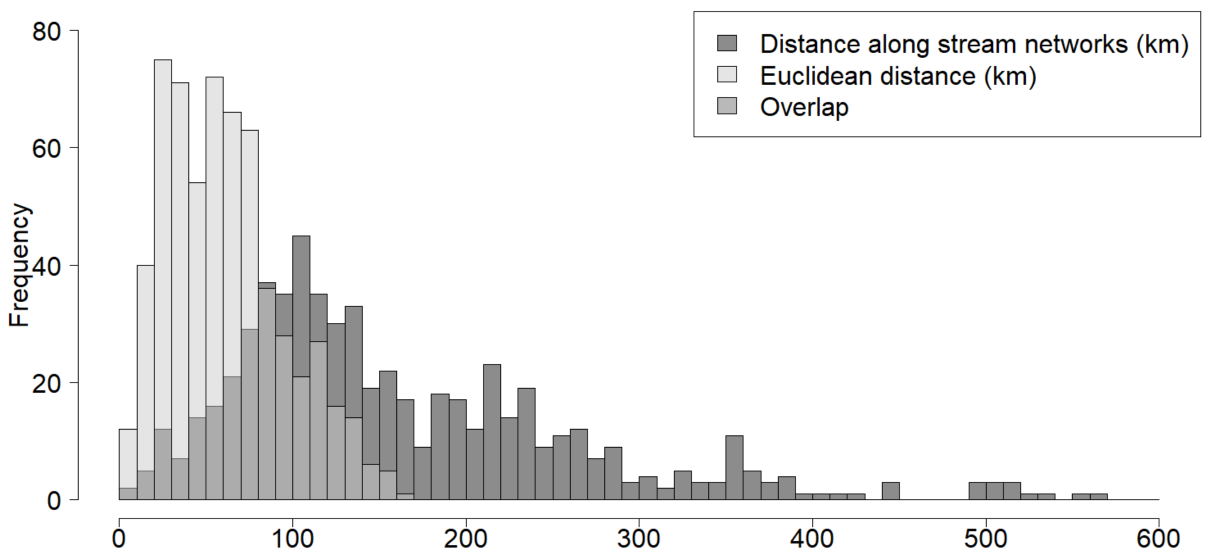

Figure 3. Distance between NPS WQT bank and purchase sites. Distance along stream networks refers to distance along the National Hydrography Dataset (NHD) streams (USGS, 2019).

WQT credit purchases largely occurred in clusters near urban areas. The Hopkins statistic for statewide NPS credit purchases was 0.92, which is above the 0.5 threshold to indicate significant clustering tendency (Hopkins and Skellam, 1954) and above the 0.75 required to show 90% confidence. Visible clusters of purchases occur around cities, most notably Richmond, Virginia. 201 purchases (33% of all purchases) fell within 20 km of Richmond. Other purchasing clusters within

20 km of city centers include 41 purchases near Alexandria, 39 near Harrisonburg, 37 near Virginia Beach, 29 near Roanoke, 24 near Lynchburg, and 20 near Charlottesville. These clusters account for 64% of purchases analyzed.

Credits were most frequently purchased from banks located outside of the HUC-8 watershed boundary, but within the HUC-6. These trades are likely compliant with program rules. Current regulations generally permit purchases within the HUC-8 or adjacent watershed. Credits may not be purchased from outside of a HUC-6 under any circumstances. In areas with local nutrient-based TMDLs or drinking water restrictions, the purchases must be from within the restricted area. Of the transactions available for analysis, the majority (57.4%) of credits were purchased from banks outside the HUC-8 but within the HUC-6 basin boundaries. Very few were purchased within the HUC-12 region (0.5%). 2.2% of trades (13 transactions) occurred across HUC-6 boundaries and are therefore expected to be non-compliant. These data are presented in Table 3.

The net import and export of WQT credits is important for identifying where the benefits and costs of NPS WQT are occurring. Net Phosphorus credits shown in Figure 4 indicate the total outcome of NPS WQT at the scale of HUC-12 (panel A) and HUC-8 (panel B) watersheds. A negative credit balance indicates that more phosphorus purchases have occurred in that area than sales, and vice-versa. Therefore, a positive credit balance indicates that a watershed is improved by the NPS WQT program, and a negative balance suggests that the area could be degraded by the program. Fifteen percent of Virginia HUC-12 subwatersheds, or 192 subwatersheds, have negative credit balances. Of these 192, 84% have a negative balance of less than 10 credits, 13% have a negative balance between 10 and 50 credits, and 3% have a negative balance of greater than 50 credits.

Six percent of Virginia HUC-12 subwatersheds, or 75 subwatersheds, have positive credit balances. Of these 75 subwatersheds, 60% have positive balances of less than 10 P credits, 36% have positive balances between 10 and 50 P credits, and 4% have a positive balance of greater than 50 P credits. Just two banks comprise 27% of credits sold (326.62 credits), with 241 credits sold from Cranston's Mill Pond Nutrient Bank in HUC-020802060604. This is one of the oldest NPS WQT banks in the state (first authorized in 2011) and one of few Virginia banks created through restoration of a bioretention pond rather than agricultural conversion. 85.63 credits were sold from Edgecliff Nutrient Credit Bank in HUC-020700080502, which is an agricultural conversion bank.

At the HUC-8 scale, 31% of watersheds, or 15 watersheds have positive credit balances, and 52%, or 25 watersheds, have negative credit balances (Figure 4 panel B). The highest positive balance is 220.4 credits in HUC-02080107, which is an agriculture-dominated watershed. Watersheds near the Richmond purchasing clusters have the highest negative balances, in HUC-02080206 and HUC-02080106, with -136.28 credits and –117.25 credits, respectively.

Combined, these results show that water quality pollution mitigation practices tend to be exported long distances from urban to rural watersheds under this WQT program. This is aligned with findings for other environmental markets, especially wetland mitigation trading (BenDor et al., 2009). NPS WQT purchases are likely clustered near urban centers because credits are purchased to offset land disturbance associated with development. Accordingly, HUC-8 and HUC-12 watersheds have a negative WQT credit balance near urban areas. Agriculture-dominated watersheds tend to have positive credit balances because most banks are created through the permanent conversion of agricultural land to forest.

A unique and pervasive confluence of water quality risk factors is currently present in urban areas (Kaye et al., 2006), and clustering of purchase sites represents potential additional contributions to existing urban pollution hot-spots. Close monitoring and further hydrologic analysis are warranted to evaluate outcomes of this change and to ensure that NPS WQT does not degrade urban water quality. This includes identifying cumulative impacts of forgone urban BMPs from NPS WQT purchases to assess long-term impacts on urban water quality.

Information about the type of bank (agricultural conversion, urban BMP, etc.), as well as bank maintenance records, are not currently available for all banks. As previously mentioned, bank and purchase shape data are also not available. These data limitations limit thorough analysis of program environmental outcomes by spatially-distributed modeling methods, and prevent identification of bank types that are successful closer to urban centers.

Table 3. Trading within NHD watershed boundaries. Frequency and percent are not cumulative.

Trades within boundaries:	Frequency	Percent of total
HUC-12	3	0.5%
HUC-10	13	2.2%
HUC-8	228	37.8%
HUC-6	346	57.4%
Outside of HUC-6	13	2.2%

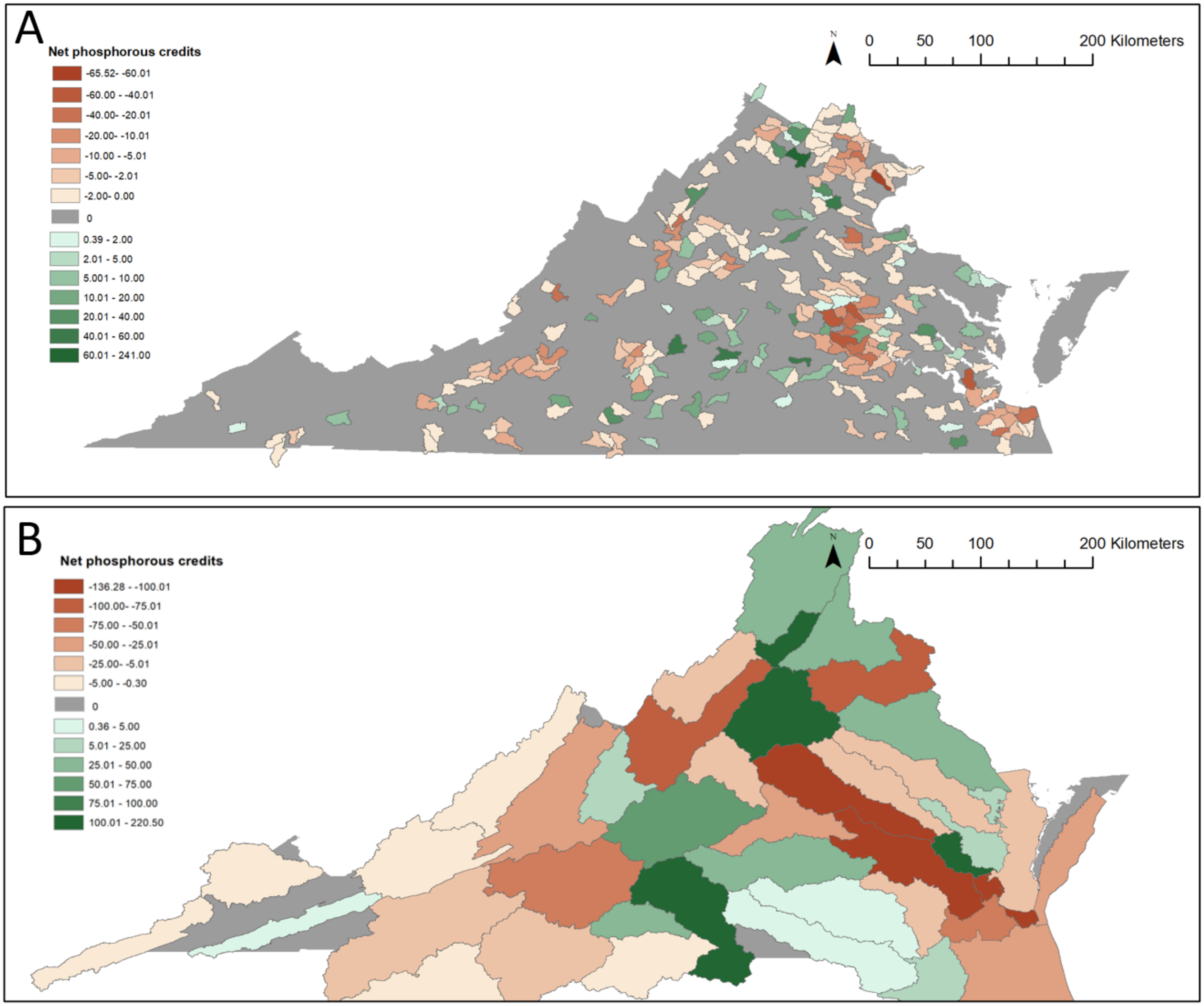

Figure 4. Net credits at the HUC-12 (A) and HUC-8 (B) scales. Negative credit balance indicates more credits purchased than sold within the region.

4.1.1 Potential impact of new regulations on transaction distances

Updated Virginia NPS WQT regulations are being promulgated, which are likely to reduce transaction distances in areas that drain to 303(d) list impaired waters (Virginia code § 62.1-44.19:20). This may mitigate growth of net negative credit balances in urban watersheds compared with existing data, as well as encourage more credit banks in urban areas near potential purchase sites. Therefore, trends under the new trading rules may reveal shorter transaction distances and less inter-watershed migration. However, the new rules maintain the basic structure of enabling nutrient mitigation practices to move away from the site of urban land disturbance activities, and are unlikely fully address clustering of purchases within urban areas.

4.1.2 Distance to river outlet

Virginia NPS WQT is designed to mitigate costs of Chesapeake Bay watershed goals. Therefore, the net outcome at the HUC-6 outlet is relevant to the water quality goals of the program. In most programs, it is desirable for the mitigation activity (bank) to be upstream from the impact site (BenDor et al., 2009), but under current Virginia rules banks may be up or downstream of purchase sites. In Figure 5, we show that some river basins have more banks upstream from purchases, and others show the opposite. Median river basin comparisons in Figure 5 show that purchases tend to occur downstream of banks in the Lower Chesapeake, Potomac, and Roanoke River basins. These median differences are minor in the Potomac or Lower Chesapeake. Given the great distances between banks and purchases, clusters of purchases in urban areas could feasibly contribute to nutrient hotspots in urban areas regardless of whether the bank is located upstream or downstream.

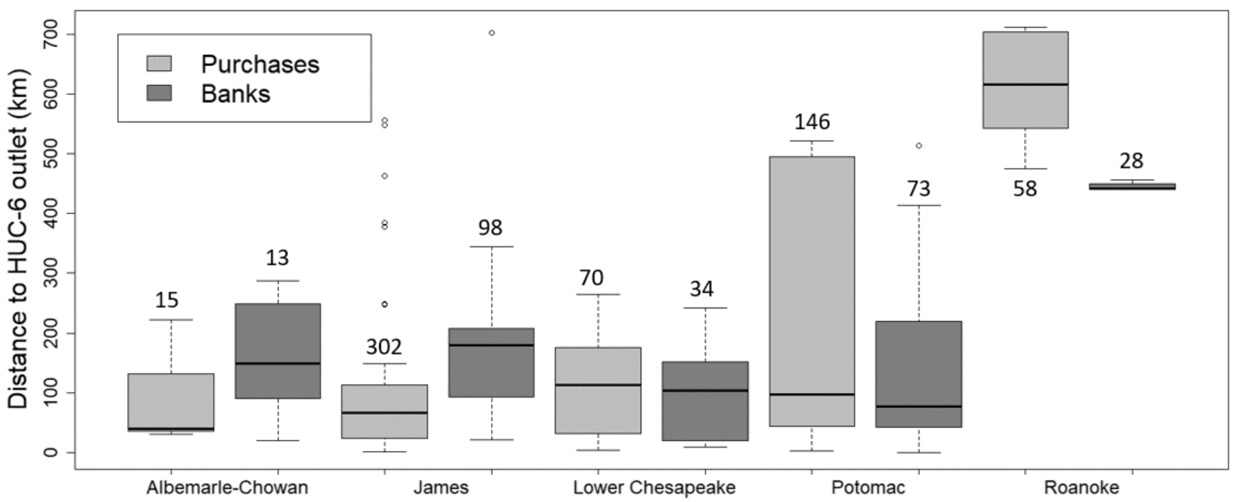

Figure 5. Distances from Purchases and Banks to Hydrologic Unit Code (HUC)-6 river basin outlets. In the James, Lower Chesapeake, and Potomac, this outlet is at the Chesapeake Bay tidal waters. Greater distance to the outlet indicates an activity that is further upstream in the basin. Basins with fewer than 10 purchases are excluded. The number of data points is shown by each plot.

The results in Figure 5 can be explained by the relative location of urban centers (where purchases occur) with rural regions (where banks occur). For example, in the James River Basin banks are generally upstream of purchases because the central part of the basin is agriculturally-dominated, and the lower basin is urbanized.

4.2 Policy analysis

Results of the spatially-explicit policy analysis show that the majority of NPS WQT land use activities do not overlap with any ConserveVirginia management categories (69% of bank area and 96% of purchase area), so are neutral to state-level goals. For purchases, this indicates that purchasing credits does not negatively impact state-level goals most of the time (though concerns about clustering in urban areas described in section 4.1 remain). For banks, this indicates that there is opportunity to better-integrate NPS WQT activities with state-level goals.Figure 6 provides a visual reference of the intersections between ConserveVirginia data and banks (panel A) and purchases (panel B). Only the relevant categories are shown, so neutral categories are excluded. The reasoning for including or excluding each category is described in Table 1.

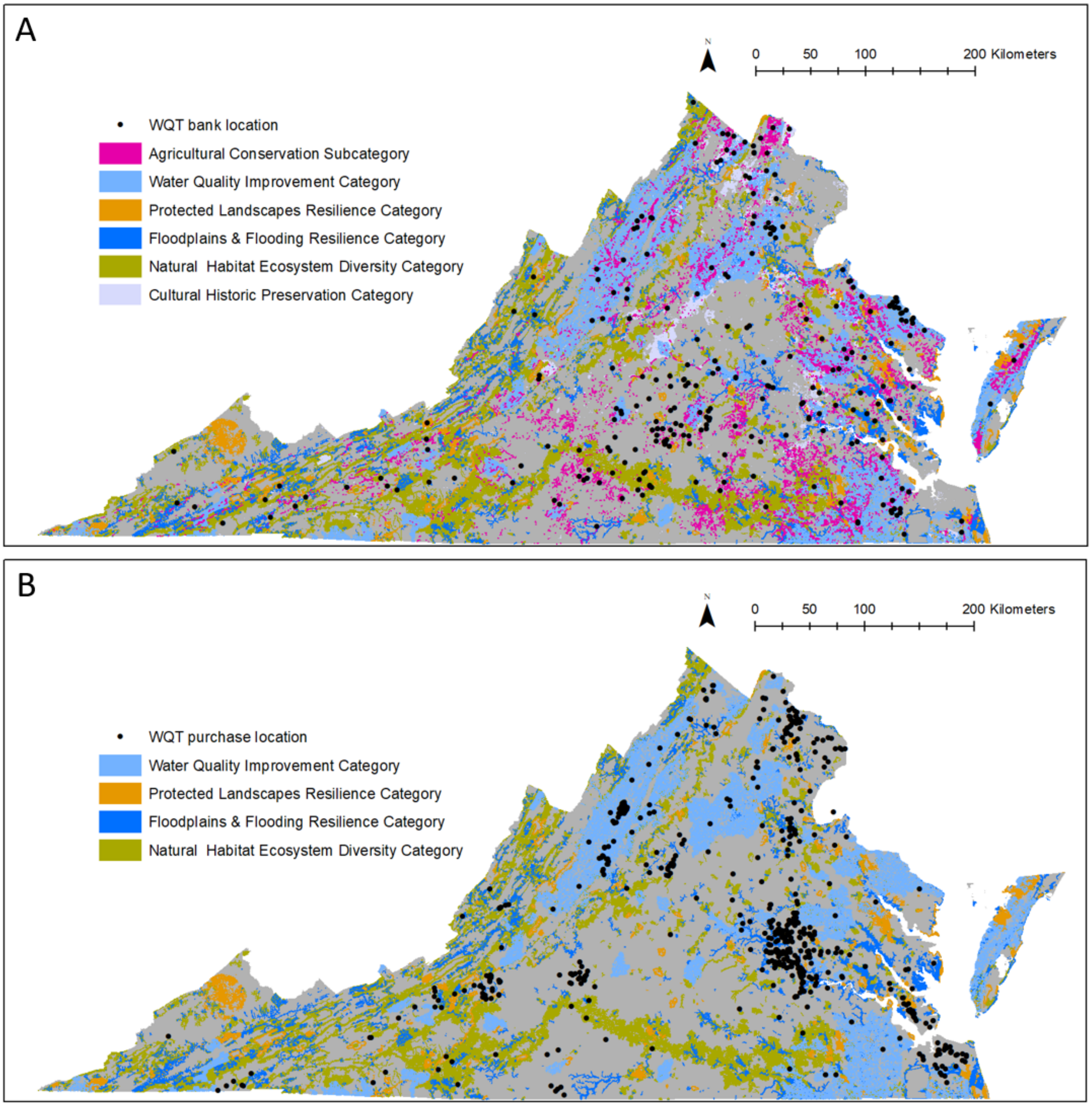

Figure 6. NPS WQT bank sites (A) and purchase sites (B) with the relevant ConserveVirginia target management categories. These panels contain different layers because Panel B excludes categories that are not impacted by water quality credit purchases. Banks and purchases, support, negate, or be neutral to management priorities, for reasons described in Table 1. Intersection frequency is quantified in Table 4. WQT credit banks are most frequently created through converting agricultural land to conserved forest. WQT credits are most frequently purchased to offset construction activities.

4.2.1 Integration of NPS WQT banks with state-level policy

Figure 7 shows the estimated area of intersection between ConserveVirginia state-level management goals and NPS WQT agricultural conversion banks. Categories may be supported or negated by NPS WQT bank establishment, as described in Table 1. Agricultural conversion banks covered an estimated 102.14 square kilometers of Virginia. The Agricultural Conservation subcategory was most likely to be negated, with agricultural conversion banks covering an estimated 19.7 square kilometers of land targeted for agricultural conservation. 15.35 square kilometers also intersected with the Cultural and Historic Preservation category, which are generally farms located in a designated historic region. These two categories had substantial spatial overlap. In the Cultural and Historic Preservation category, agricultural conversion WQT banks may change the historic character of a region, but the impact is subjective and site-specific. Desirability of agricultural conversion banks in a designated historic region should be a topic of future community and stakeholder discussions.

Agricultural conversion banks also supported some ConserveVirginia categories, including 3.55 square kilometers of Water Quality Improvement target areas and 3.20 square kilometers of Natural Habitat and Ecosystem Diversity target areas. 101 of the banks had some area that supported ConserveVirginia management priorities, but the total area of banks that supported at least one ConserveVirginia category was only up to 8.87 square kilometers (Figure 8). The total estimated bank area that negated by at least one ConserveVirginia category was 22.39 square kilometers, or 21.9% of all agricultural conversion bank area (Figure 8).

These results indicate that the NPS WQT program is influencing agricultural land use change independently of the state-level management goals set forth by ConserveVirginia. Without policy mechanisms to encourage WQT activity in areas where it supports ConserveVirginia goals, and discourage where it negates those goals, it could be expected that this trend will continue. This indicates that there is potential to better spatially target NPS WQT banks in the landscape where agricultural conversion is desirable to forward state-level goals. Local, tribal, regional, and national land management goals not discussed here should also be considered in developing spatial priorities in Virginia.

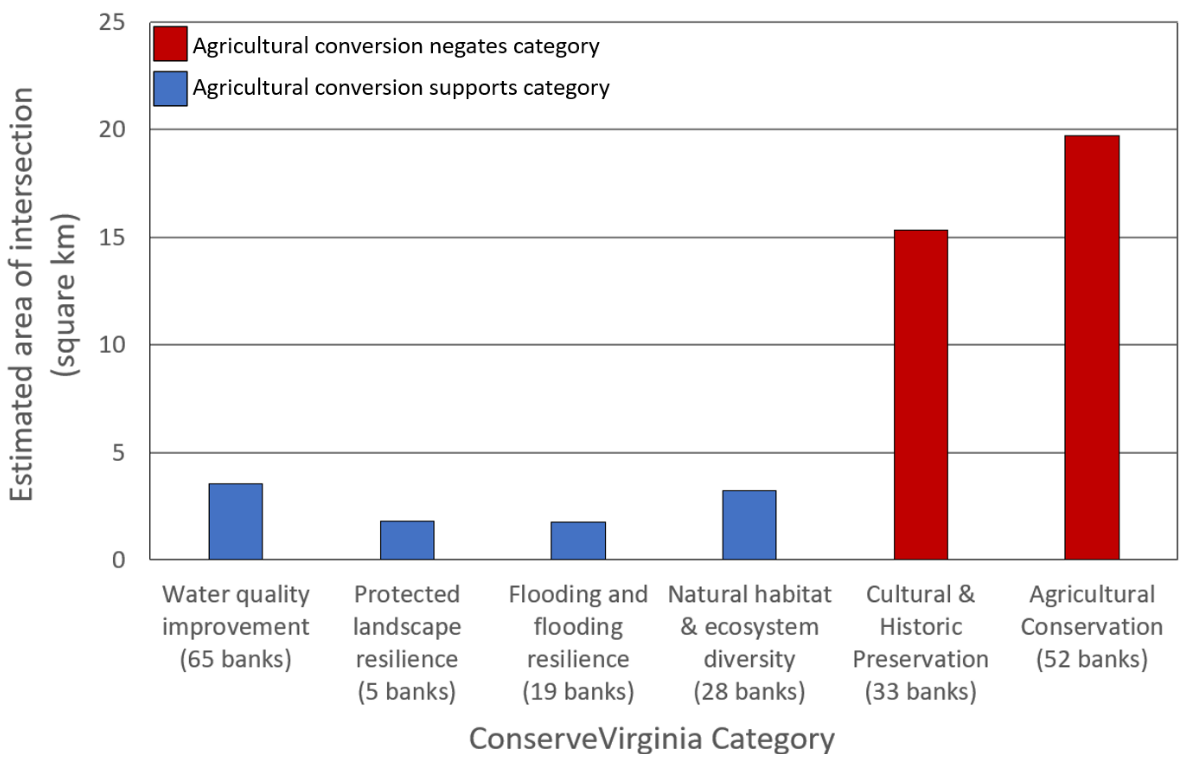

Figure 7. Estimated area of intersection of NPS WQT agricultural conversion banks and relevant ConserveVirginia management categories. The number of banks and area of intersections with each

relevant Conserve Virginia management priority is reported. For example, the Agricultural Conservation subcategory is intersected by 52 WQT banks, with an estimated area of intersection of up to 19.7 sq km.

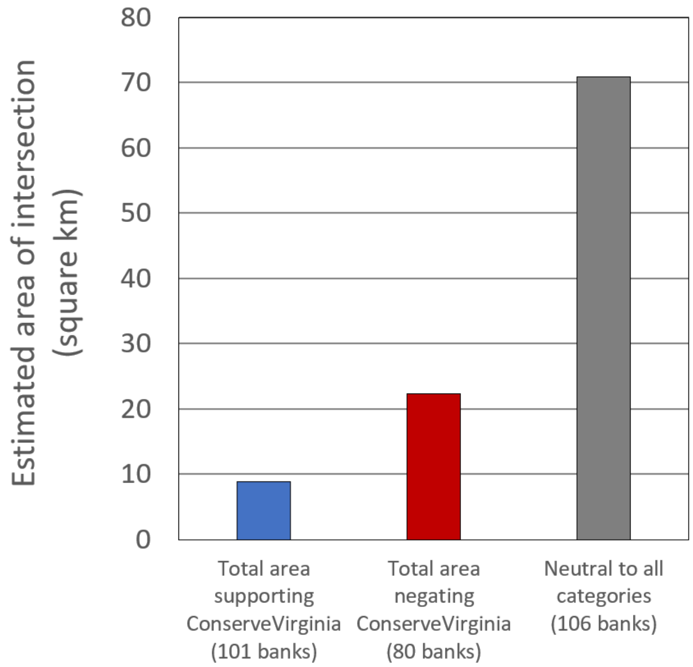

Figure 8. Total estimated area of intersection between NPS WQT agricultural conversion banks and ConserveVirginia categories. The totals account for bank areas that fall in multiple categories, so these totals are less than the sum of columns in Figure 7.

4.2.2 Integration of NPS WQT purchases with state-level policy

Credit purchase sites covered an estimated total of 21.82 square kilometers. Figure 9 shows that an estimated 20.97 square kilometers (96%) of purchase area is neutral to state-level management goals. This result offers optimism that purchases do not usually work directly against the ConserveVirginia priorities. It should be noted that the area impacted by a purchase site is significantly smaller than bank area, but construction activities associated with purchase sites are likely to have a higher per-acre impact on water quality compared with agricultural conversion banks.

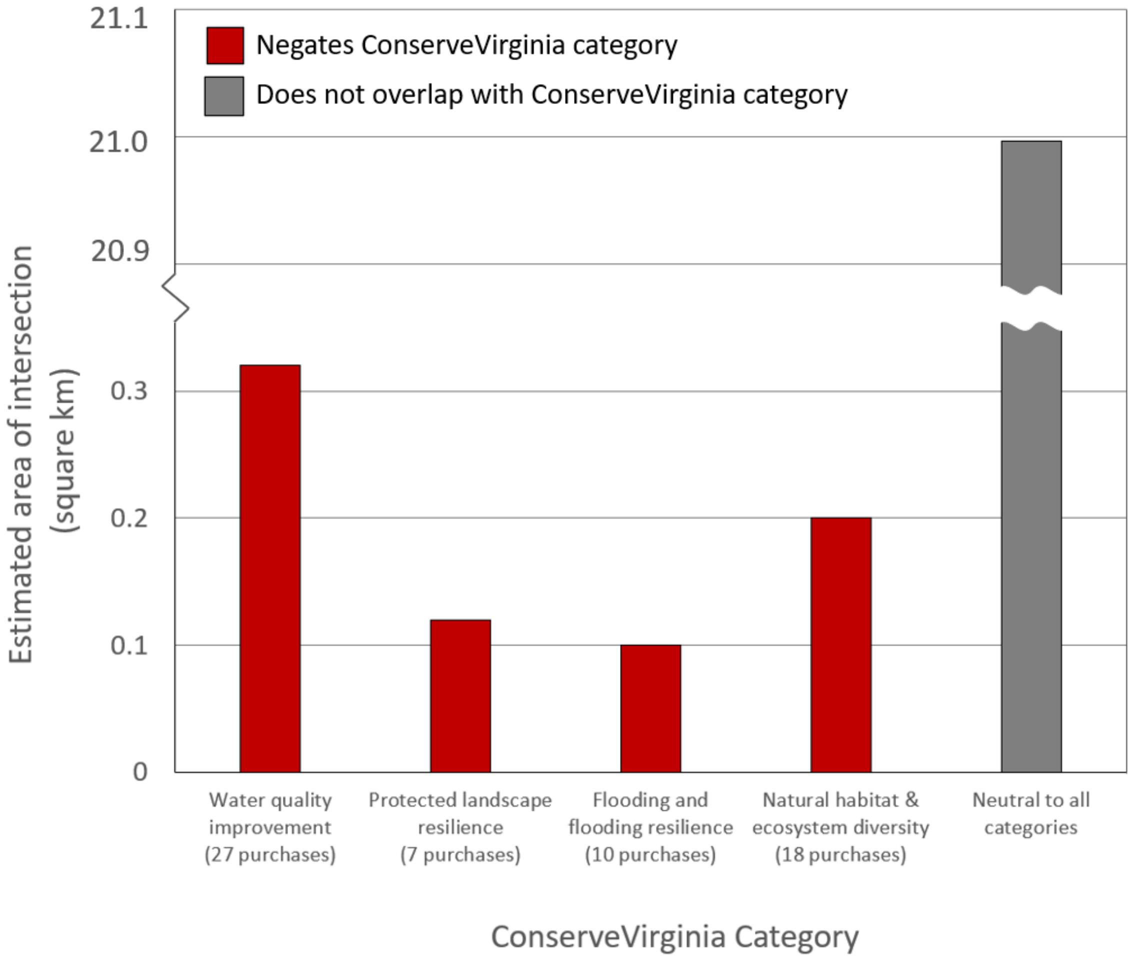

Figure 9. Estimated area of intersection of WQT purchases with relevant ConserveVirginia land use priority categories. Frequency of intersection is also provided. Purchases represent construction activity, which do not support any of the state-level management goals.

This result also suggests that some ConserveVirginia priorities may not be designed to address localized urban impacts of land management actions. Some of the ConserveVirginia management priorities were developed using CAST (see Table 1), which models water quality impacts in the Chesapeake Bay. The localized need for urban BMPs is not explicitly included in development of these layers, and so most purchases avoid impacting these categories. For example, the Water Quality Improvement category was developed using CAST, and the target areas for management are centered in rural mountainous regions of northwestern Virginia (see Figure 6), despite potential localized threats to urban water quality. Therefore, urban water quality concerns may be under-represented in the ConserveVirginia state priorities. To ensure good local outcomes, we suggest that urban localities consider local knowledge and data in evaluating the impacts of NPS WQT purchases, rather than adopting ConserveVirginia in its current format.

4.2.3 Analysis limitations related to NPS WQT shape data estimation

NPS WQT bank and purchase data is currently reported to regulators as points, without shape information. In this study, we estimated the shapes of banks and purchases using methods described in section 3.4. Surveyed boundary data for bank and purchase sites would reduce error introduced by estimating these shapes, and enable a more accurate analysis of NPS WQT impact in the landscape.

The bank shape estimation method that we employed assumes that an entire farm was converted to generate water quality credits. In practice, landowners may convert only a portion of their agricultural land to forest to generate credits. Therefore, the area of intersection with ConserveVirginia categories represents an upper limit of the actual estimated area. We considered alternative methods to identify bank shape, including land use change analysis using remote sensing data (i.e., finding where agricultural land has been converted to forests). Experimentation showed that the agricultural land conversions implemented to create WQT banks are not usually visible using satellite imagery until years following conversion, and no imagery is available for new banks. We also considered back-calculating the bank acreage based on credits awarded to the bank. This also proved infeasible, as the number of credits awarded per acre varies by agricultural type and site-specific baseline requirements, and because the original number of credits awarded to a bank is not available for all sites on RIBITS.

There is also error introduced in the purchase shape estimations. We used a buffer function to achieve the correct site acreage, but the actual purchase sites are likely not round. Error is expected to be highest for road and highway projects, which are linear rather than round. However, purchase sites are much smaller in area than bank sites (median 64.7 acres per bank versus median 2.4 acres per purchase), so shape is less important for purchases than for banks in determining landscape impacts.

4.3 NPS WQT banks as a part of holistic watershed management goals

Our policy analysis results indicate that WQT banks are not fully integrated into other state-led watershed management efforts (Figures 7 and 8). NPS WQT policy could be better aligned with state-level goals by offering a variety of incentive types to landowners in target areas and improving bank management rules. We present one such prioritization model to encourage siting NPS WQT banks in areas that could improve environmental returns. This model, illustrated in Figure 10, identifies areas with low VCV agricultural value and high restoration priorities according to equation 2. This model could be used as a multiplier on credit generation schemes, so that high priority areas receive a higher per-acre credit return. According to this prioritization, only six of 254 agricultural conversion WQT banks fall in areas in the 90-100 priority range, which indicates that the current program does not intrinsically follow this prioritization.

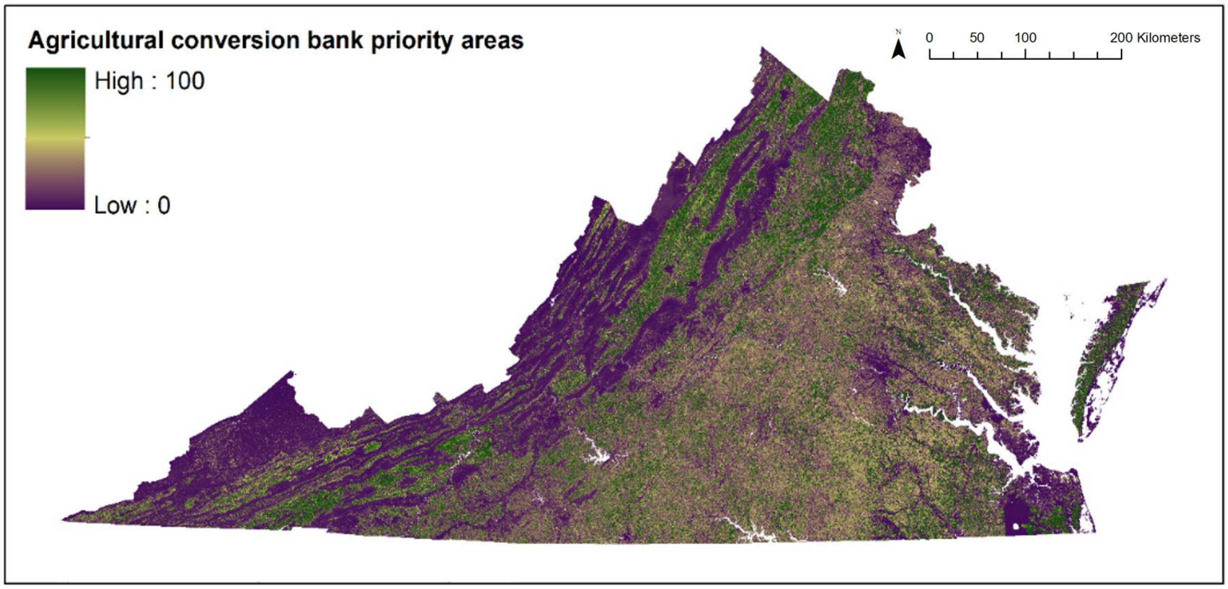

Figure 10. Prototype framework for identifying priority areas for agricultural land conversion created using VCV data. This is based on areas with high restoration priorities and low agricultural value (see Equation 2).

Identifying areas where it is desirable to convert agricultural land to forest should be a holistic and stakeholder-led process. More investigation is warranted to balance priorities and determine ideal weights for agricultural value and restoration priorities. For this reason, we do not consider this framework to be a final product, but a prototype to initiate discussion.

Other policy alternatives exist to achieve better integration of NPS WQT and state-level management goals. Credit purchases from banks in priority areas could be subsidized by the state, making them more competitive than banks in non-priority areas. A third incentive for landowners in priority areas could be to allow the state to sponsor establishment of the bank in high-priority areas, or to sponsor the additional cost of a site-specific bank management plan to increase environmental returns. This option is at odds with current rules, under which state-led cost-share programs implemented by VADCR are only allowed to pay for actions to help the banks meet baseline requirements, and the landowner or bank sponsor must cover the additional up-front costs for credit generation (VADEQ, 2008).

Each of these options would require independent environmental and economic analysis, but share in common that they require a prioritization scheme specific to WQT land use activities.

For WQT markets to garner participation, prospective participants must perceive the program as straightforward and easy to use (Hosterman, 2008). Incorporating new rules that increase environmental integrity, without making the program more complex for participants, can be accomplished in part through deployment of automated brokering systems (Saby et al., 2021). Accordingly, we recommend that any market reconfiguration to improve ecological returns from WQT should be accomplished through an automated brokering system that retains and improves the ease-of-use in the Virginia NPS WQT program.

4.3.1 Improving WQT bank management to meet multiple environmental goals

Though Virginia's NPS WQT banks may meet nutrient reduction goals required by the program rules, they are not currently optimized for ecological value and to meet multiple environmental goals. Agricultural land conversion is achieved through establishment of a forest, though as we have noted the species composition of the new forest is not regulated and are largely single-species pine plantations to mitigate cost of plantings and maximize timber profitability. Forests with greater biodiversity have been shown to provide more robust and numerous ecosystem services compared with single-species forests, including better habitat quality and greater resilience to climate change (Anderegg et al., 2018; Jactel et al., 2009; Sakschewski et al., 2016), but do not produce more credits under WQT and are more costly to establish.

More holistic management of WQT banks could be incentivized through permitting stacking credits for water quality, carbon sequestration, habitat restoration, flooding resilience, and other state-led management goals. Credit stacking could further incentivize landowners to produce credits by increasing the number of potential purchasers, though should only be applied when scientific methods are developed to ensure proper accounting for equivalency between buyers and sellers (Gren and Ang, 2019; Lentz et al., 2014). Future research should identify methods to improve WQT land conversion credit rules to meet multiple environmental goals. For example, this could mean developing site-specific management plans and tree species mixes to optimize achievement of ConserveVirginia management goals, limit the extent and impact of timbering, or maximize carbon sequestration.

4.4 WQT banks as prevented development

Our analysis revealed that 19.7 square kilometers of NPS WQT bank area had been targeted by ConserveVirginia for agricultural conservation, and therefore negates the state land use management goals. However, if these bank areas had been developed rather than converted to forest for WQT, watershed management goals could arguably have been negated more dramatically. The resulting question is, do agricultural conversion banks represent converted farmland, or prevented urban development? We explored this question by comparing bank locations with VADCR's Development Vulnerability map, demonstrated in Figure 11. We summarize the results in Table 5. The single bank listed on undevelopable land is Cranston Mill Pond, which is undevelopable because this bank was created by restoring a bioretention area, which was classified as "Open Water" in NLCD.

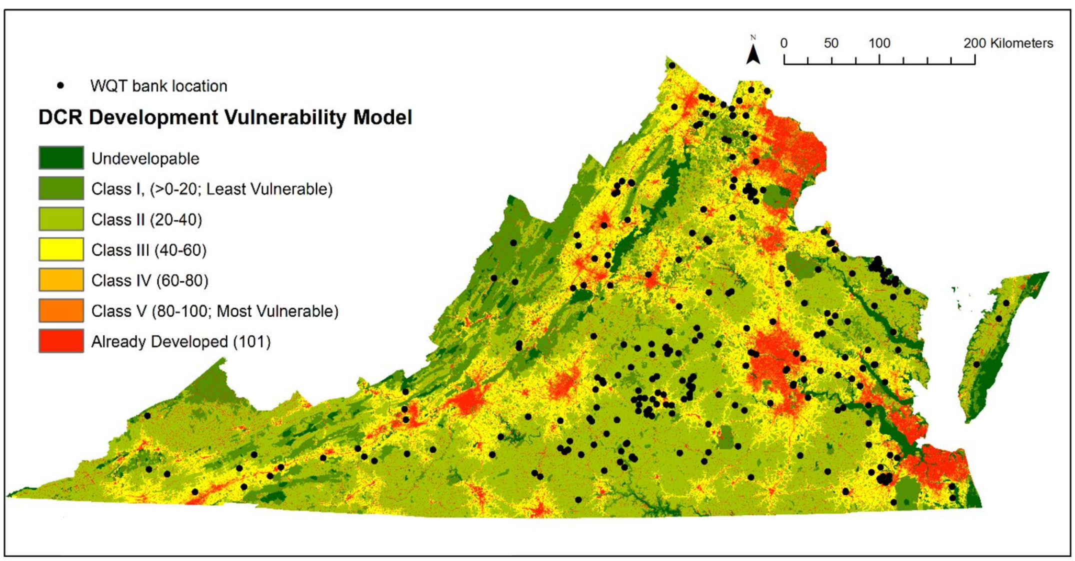

Figure 11. NPS WQT banks and the VCV Development Vulnerability raster. Banks in highly vulnerable areas may represent prevented development. We therefore suggest that the motivation for establishment of NPS WQT banks should be considered as a part of future research.

Table 5: Development vulnerability of NPS WQT banks.

Development vulnerability class	Number of banks	% of total banks
Undevelopable	1	0.4
I	31	11.7
II	136	51.1
III	72	27.1
IV	15	5.6
V	2	0.8
Already developed	9	3.4

26 banks (9.8%) are centered in areas that are vulnerable to or already developed, which could indicate that a WQT bank was established in lieu of eventually being sold for urban development. This has important implications for the evaluation of environmental tradeoffs in NPS WQT, and should be a consideration when establishing a prioritization scheme for siting NPS WQT banks. Future research should identify factors in the decision-making process for landowners who create banks through agricultural conversion, and explore the potential benefits of incentivizing bank establishment in areas with high vulnerability to development.

Integrating water resource management goals enables better water quality outcomes (Bernhardt et al., 2008). We have suggested methods to help NPS WQT accomplish this by incentivizing spatial prioritization and improving the ecological value of credit banks. We discuss that banks located in areas that are vulnerable to development may represent "prevented development," and thus contain positive ecological returns that are not currently accounted for in credit calculations. We recommend updating water quality bank management practices to include site-specific plans to meet multiple environmental goals.

4 CONCLUSIONS

Landscape-scale outcomes of NPS WQT are a key part of evaluating program success, but have rarely been evaluated in the literature due to lack of available program data. In this study, we curate data from Virginia's growing NPS WQT program, evaluate landscape-scale outcomes, and suggest a path forward.

We find that this NPS WQT program has resulted in the transfer of water quality BMPs from urban to rural areas, with impact sites (purchases) highly clustered in urban areas (H=0.92). Purchases also tend to be far from mitigation sites (banks), at an average distance of 164.6km along the NHD stream network. We note that new regulations introduced in 2020 could reduce average transaction distances going forward, but purchase clustering in urban areas remains a concern. Spatial trends should be continually monitored to avoid exacerbation of urban pollution hotspots, and updated trading rules may be needed to reduce risk to urban areas. Further research is needed to evaluate the environmental impacts of purchase clusters in urban areas, and to provide more detailed assessment of water quality outcomes for the agricultural conversion methods employed in NPS WQT.

Based on our policy analysis, we conclude that NPS WQT could be better integrated with state-level environmental management goals using existing state prioritization data. Currently, NPS WQT bank area negates (22%) or is neutral to (69%) the ConserveVirginia management priorities, but Virginia ConservationVision land use prioritization data may be helpful in integrating these sites with existing goals. More detailed analysis and simulation is needed to identify expected environmental outcomes of the integrated state-level goals.

Our analysis was limited by a lack of spatial boundary data for banks and purchases. More thorough program evaluation would be possible if shape data was reported for both purchase and bank sites (rather than point data). We also recommend that bank type, management plans and maintenance records, and all transaction information be made available on the RIBITS platform to increase transparency and enable more thorough program evaluation.

Overall, this preliminary into Virginia's NPS WQT outcomes suggest that there is much to be explored in evaluating the efficacy of NPS WQT markets in achieving environmental goals. Reducing NPS pollution in a cost-effective manner is a key challenge for environmental managers in the 21st century, and WQT may be a part of a long-term solution. However, our results suggest that allowing market-based mechanisms to control outcomes across the landscape introduces environmental risks that have not been fully mitigated through research or policy. More can be done to ensure that NPS WQT policies abide by the principle to "first, do no harm," popularized in healthcare applications. Landscape-scale patterns discussed here are only one part of evaluating the efficacy of NPS WQT, and this research lays the groundwork for more direct monitoring and detailed simulation of NPS WQT tradeoffs.

ACKNOWLEDGEMENTS

We thank the Virginia Department of Environmental Quality, in particular Ms. Sara Felker and Ms. Holly Sepety for their contributions to water quality credit purchasing data curation for this work. We also acknowledge the Department of Education Graduate Assistance in Areas of National Need (GAANN) Sustainable Water Infrastructure Systems fellowship, which provided funding for this work.

REFERENCES

Abdalla, C., Borisova, T., Parker, D., Saacke Blunk, K., 2007. Water quality credit trading and agriculture: recognizing the challenges and policy issues ahead. Choices 22, 117–124.

Accatino, F., Creed, I.F., Weber, M., 2018. Landscape consequences of aggregation rules for functional equivalence in compensatory mitigation programs. Conservation Biology 32, 694–705. https://doi.org/10.1111/cobi.13084

Anderegg, W.R.L., Konings, A.G., Trugman, A.T., Yu, K., Bowling, D.R., Gabbitas, R., Karp, D.S., Pacala, S., Sperry, J.S., Sulman, B.N., Zenes, N., 2018. Hydraulic diversity of forests regulates ecosystem resilience during drought. Nature 561, 538–541. https://doi.org/10.1038/s41586-018-0539-7

BenDor, T., Brozović, N., 2007. Determinants of spatial and temporal patterns in compensatory wetland mitigation. Environmental Management 40, 349–364. http://dx.doi.org/10.1007/s00267-006-0310-y

BenDor, T., Sholtes, J., Doyle, M.W., 2009. Landscape characteristics of a stream and wetland mitigation banking program. Ecological Applications 19, 2078–2092. https://doi.org/10.1890/08-1803.1

Bernhardt, E.S., Band, L.E., Walsh, C.J., Berke, P.E., 2008. Understanding, Managing, and Minimizing Urban Impacts on Surface Water Nitrogen Loading. Annals of the New York Academy of Sciences 1134, 61–96. https://doi.org/10.1196/annals.1439.014

Boyd, J., Burtraw, D., Krupnick, A., McConnell, V., Newell, R.G., Palmer, K., Sanchirico, J.N., Walls, M., 2003. Trading cases five examples of the use of markets in environmental and resource, in: The RFF Reader in Environmental and Resource Policy. Resources for the Future Washington, DC, pp. 56–65.

Branosky, E., Jones, C., Selman, M., 2011. Comparison tables of state nutrient trading programs in the Chesapeake Bay watershed. World Resources Institute, Washington, DC.

Commonwealth of Virginia, Office of the Governor, 2019. Chesapeake Bay TMDL Phase III Watershed Implementation Plan. Richmond, Virginia. Last accessed 10/13/2020. https://www.deq.virginia.gov/Portals/0/DEQ/Water/ChesapeakeBay/Final%20Phase%20III%20WIP/Virginia_Chesapeake_Bay_TMDL_Final_Phase%20III_WIP%20(2).pdf

Commonwealth of Virginia, Office of the Governor, 2020. ConserveVirginia 2020 Update. Richmond, Virginia. Last accessed 10/13/2020. https://www.dcr.virginia.gov/conservevirginia/conservevirginia-official-v2.pdf.

Corrales, J., Melodie Naja, G., Rivero, Rosanna.G., Miralles-Wilhelm, F., Bhat, M.G., 2013. Water quality trading programs towards solving environmental pollution problems. Irrigation and Drainage 62, 72–92. https://doi.org/10.1002/ird.1805

Corrales, J., Naja, G. M., Bhat, M. G., & Miralles-Wilhelm, F., 2014. Modeling a phosphorus credit trading program in an agricultural watershed. Journal of Environmental Management, 143, 162-172. https://doi.org/10.1016/j.jenvman.2014.04.031

Corrales, J., Naja, G.M., Bhat, M.G., Miralles-Wilhelm, F., 2017. Water quality trading opportunities in two sub-watersheds in the northern Lake Okeechobee watershed. Journal of Environmental Management 196, 544–559. https://doi.org/10.1016/j.jenvman.2017.03.061

Crossman, N.D., Bryan, B.A., 2009. Identifying cost-effective hotspots for restoring natural capital and enhancing landscape multifunctionality. Ecological Economics 68, 654–668. https://doi.org/10.1016/j.ecolecon.2008.05.003

DeBoe, G., Stephenson, K., 2016. Transactions costs of expanding nutrient trading to agricultural working lands: A Virginia case study. Ecological Economics 130, 176–185. https://doi.org/10.1016/j.ecolecon.2016.06.027

ESRI, 2016. ArcGIS Desktop: Release 10.5.1. Redlands, CA: Environmental Systems Research Institute.

Faeth, P., 2000. Fertile ground. World Resources Institute, Washington, DC.

Fisher-Vanden, K., Olmstead, S., 2013. Moving pollution trading from air to water: potential, problems, and prognosis. Journal of Economic Perspectives 27, 147–72. http://dx.doi.org/10.1257/jep.27.1.147

Ghosh, G., Ribaudo, M., Shortle, J., 2011. Baseline requirements can hinder trades in water quality trading programs: Evidence from the Conestoga watershed. Journal of Environmental Management 92, 2076–2084. https://doi.org/10.1016/j.jenvman.2011.03.029

Giri, S., Qiu, Z., Zhang, Z., 2018. Assessing the impacts of land use on downstream water quality using a hydrologically sensitive area concept. Journal of Environmental Management 213, 309–319. http://dx.doi.org/10.1016/j.jenvman.2018.02.075

Gren, I.-M., Ang, F., 2019. Stacking of abatement credits for cost-effective achievement of climate and water targets. Ecological Economics 164, 106375. https://doi.org/10.1016/j.ecolecon.2019.106375

Griffith, A.W., Gobler, C.J., 2020. Harmful algal blooms: a climate change co-stressor in marine and freshwater ecosystems. Harmful Algae 91, 101590. http://dx.doi.org/10.1016/j.hal.2019.03.008

Hazler, K. R. and Knudson, N. 2018. Virginia ConservationVision: Watershed Model 2017 Edition. Natural Heritage Technical Report 18-16. Virginia Department of Conservation and Recreation, Division of Natural Heritage, Richmond, Virginia.

Hazler, K. R. and Tien, T. 2015. Virginia ConservationVision: Agricultural Model, 2015 Edition. Natural Heritage Technical Report 15-13. Virginia Department of Conservation and Recreation, Division of Natural Heritage, Richmond, Virginia. 43 pp.

Hazler, K.R., Tien, T., and Gilb, R. 2016. Virginia ConservationVision: Development Vulnerability Model, 2015 Interim Edition. Natural Heritage Technical Report 16-14. Virginia Department of Conservation and Recreation, Division of Natural Heritage, Richmond, Virginia.

Heberling, M.T., Thurston, H.W., Nietch, C.T., 2018. Exploring Nontraditional Participation as an Approach to Make Water Quality Trading Markets More Effective. JAWRA Journal of the American Water Resources Association 54, 586–593. https://doi.org/10.1111/1752-1688.12648

Hoag, D.L., Arabi, M., Osmond, D., Ribaudo, M., Motallebi, M., Tasdighi, A., 2017. Policy utopias for nutrient credit trading programs with nonpoint sources. JAWRA Journal of the American Water Resources Association 53, 514–520. http://dx.doi.org/10.1111/1752-1688.12532

Hopkins, B., Skellam, J.G., 1954. A New Method for determining the Type of Distribution of Plant Individuals. Annals of Botany 18, 213–227. https://doi.org/10.1093/oxfordjournals.aob.a083391

Hosterman, H., 2008. Incorporating environmental integrity in water quality trading: Lessons from the Willamette. Masters project. Duke University, Nicholas School of the Environment and Earth Sciences.

Jactel, H., Nicoll, B.C., Branco, M., Gonzalez-Olabarria, J.R., Grodzki, W., Långström, B., Moreira, F., Netherer, S., Orazio, C., Piou, D., Santos, H., Schelhaas, M.J., Tojic, K., Vodde, F., 2009. The influences of forest stand management on biotic and abiotic risks of damage. Annals of Forest Science 66, 701–701. https://doi.org/10.1051/forest/2009054

Kaye, J.P., Groffman, P.M., Grimm, N.B., Baker, L.A., Pouyat, R.V., 2006. A distinct urban biogeochemistry? Trends in Ecology & Evolution 21, 192–199. https://doi.org/10.1016/j.tree.2005.12.006

King, D.M., Herbert, L.W., 1997. The fungibility of wetlands. National Wetlands Newsletter 19, 10–13.

Kieser, M. S., & McCarthy, J. L. Water Quality Trading in Ohio. 2015. *Use of Economic Instruments in Water Policy*, 209.

Lawson, R.G., Jurs, P.C., 1990. New index for clustering tendency and its application to chemical problems. Journal of Chemical Information and Computer Sciences 30, 36–41. http://dx.doi.org/10.1021/ci00065a010

Lee, J.T., Bailey, N., Thompson, S., 2002. Using Geographical Information Systems to identify and target sites for creation and restoration of native woodlands: a case study of the Chiltern Hills, UK. Journal of Environmental Management 64, 25–34. https://doi.org/10.1006/jema.2001.0495

Lentz, A.H., Ando, A.W., Brozović, N., 2014. Water Quality Trading with Lumpy Investments, Credit Stacking, and Ancillary Benefits. JAWRA Journal of the American Water Resources Association 50, 83–100. https://doi.org/10.1111/jawr.12117

Moore, S.K., Trainer, V.L., Mantua, N.J., Parker, M.S., Laws, E.A., Backer, L.C., Fleming, L.E., 2008. Impacts of climate variability and future climate change on harmful algal blooms and human health. Environmental Health 7, S4. https://doi.org/10.1186/1476-069X-7-S2-S4

Nobles, A.L., Goodall, J.L., Fitch, G.M., 2017. Comparing Costs of Onsite Best Management Practices to Nutrient Credits for Stormwater Management: A Case Study in Virginia. JAWRA Journal of the American Water Resources Association 53, 131–143. https://doi.org/10.1111/1752-1688.12487

Patterson, J.J., Smith, C., Bellamy, J., 2013. Understanding enabling capacities for managing the 'wicked problem' of nonpoint source water pollution in catchments: A conceptual framework. Journal of Environmental Management 128, 441–452. https://doi.org/10.1016/j.jenvman.2013.05.033

R Core Team, 2017. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

Randhir, T.O., O'Connor, R., Penner, P.R., Goodwin, D.W., 2001. A watershed-based land prioritization model for water supply protection. Forest Ecology and Management 143, 47–56. https://doi.org/10.1016/S0378-1127(00)00504-1

Ruhl, J., Salzman, J.E., 2006. The effects of wetland mitigation banking on people. FSU College of Law, Public Law Research Paper.

Saby, L., Goodall, J.L., Band, L.E., Bowes, B.D., Fults, M., 2021. Enhancing Environmental Efficacy of Water Quality Trading through Automation: A Case Study in Virginia's Nutrient Trading Program. JAWRA Journal of the American Water Resources Association, In Press. http://dx.doi.org/10.1111/1752-1688.12903

Sakschewski, B., von Bloh, W., Boit, A., Poorter, L., Peña-Claros, M., Heinke, J., Joshi, J., Thonicke, K., 2016. Resilience of Amazon forests emerges from plant trait diversity. Nature Climate Change 6, 1032–1036. https://doi.org/10.1038/nclimate3109

Stephenson, K., Norris, P., Shabman, L., 1998. Watershed-Based Effluent Trading: The Nonpoint Source Challenge. Contemporary Economic Policy 16, 412–421. https://doi.org/10.1111/j.1465-7287.1998.tb00529.x

Stephenson, K., Shabman, L., 2016. Nutrient Assimilation Services for Water Quality Credit Trading Programs: A Comparative Analysis with Nonpoint Source Credits. 45, 24–43. https://doi.org/10.1080/08920753.2017.1237240

Stephenson, K., Shabman, L., 2017. Where did the agricultural nonpoint source trades go? Lessons from Virginia water quality trading programs. JAWRA Journal of the American Water Resources Association 53, 1178–1194. http://dx.doi.org/10.1111/1752-1688.12565

Stubbs, M. 2014. Environmental Regulation and Agriculture. Congressional Research Service; 7-5700; R41622.

Trainer, V.L., Moore, S.K., Hallegraeff, G., Kudela, R.M., Clement, A., Mardones, J.I., Cochlan, W.P., 2020. Pelagic harmful algal blooms and climate change: lessons from nature's experiments with extremes. Harmful algae 91, 101591. http://dx.doi.org/10.1016/j.hal.2019.03.009

U.S. Army Corps of Engineers (USACE), 2020. Website. Regulatory In-Lieu Fee and Bank Information Tracking System (RIBITS). Last accessed 08/27/2020. https://ribits.ops.usace.army.mil/ords/f?p=107:285:16889382521564::NO.

U.S. Geological Survey (USGS), 2019. National Hydrography Dataset (ver. USGS National Hydrography Dataset Best Resolution (NHD). Last accessed 10/13/2020. https://hydro.nationalmap.gov/arcgis/rest/services/nhd/MapServer.

U.S. Department of Agriculture (USDA), 2019. 2017 United States Summary and State Data. National Agricultural Statistics Service Geographic Area Series. Vol. 1, part 51.

U.S. Environmental Protection Agency (USEPA), 2003. Water quality trading policy statement. EPA Office of Water Policy, Archive document.

USEPA, 2018. EPA, USDA Encourage co-regulators to use market-based and other collaborative approaches to address excess nutrients. Last accessed 11/13/2020. https://www.usda.gov/media/press-releases/2018/12/04/epa-usda-encourage-use-market-based-and-other-collaborative

USEPA, 2019a. Memo from EPA assistant administrator David P. Ross to regional administrators, 02/06/2019, Subject: Updating the EPA's WQT Policy to Promote Market-Based Mechanisms for Improving Water Quality.

USEPA, 2019b. EPA and USDA Launch Innovative Nutrient Financing Webinar Series to Help Improve America's Water Quality. EPA Office of Water News Release. Last accessed 11/13/2020. https://www.epa.gov/newsreleases/epa-and-usda-launch-innovative-nutrient-financing-webinar series-help-improve-americas

Virginia Department of Environmental Quality (VADEQ), 2008. Trading Nutrient Reductions for Nonpoint Source Best Management Practices in the Chesapeake Bay Watershed: Guidance for Agricultural Landowners and Your Potential Trading Partners. https://www.deq.virginia.gov/Portals/0/DEQ/Water/PollutionDischargeElimination/VANPSTradingManual_2-5-08.pdf. Last accessed 10/13/2020.

Virginia Department of Conservation and Recreation (VADCR), 2019. An Overview of the Virginia Natural Heritage Program. Richmond, Virginia. Last modified: 03/07/2019. Last accessed 10/13/2020. https://www.dcr.virginia.gov/natural-heritage/mission

VADCR, 2020a. Virginia ConservationVision. Richmond, Virginia. Last modified: 08/20/2020. Last accessed 10/13/2020. https://www.dcr.virginia.gov/natural-heritage/vaconvision

VADCR, 2020b. 2_cons_va (FeatureServer). Division of Natural Heritage. Richmond, VA. Service ItemId: f239744c163948bb8bba9948ad03bded. Last accessed 10/13/2020. https://services1.arcgis.com/PxUNqSbaWFvFgHnJ/arcgis/rest/services/2_cons_va/FeatureServer

Wang, L., Thompson, T., McDonald-Buller, E.C., Webb, A., Allen, D.T., 2007. Photochemical Modeling of Emissions Trading of Highly Reactive Volatile Organic Compounds in Houston, Texas. 1. Reactivity Based Trading and Potential for Ozone Hot Spot Formation. Environ. Sci. Technol. 41, 2095–2102. https://doi.org/10.1021/es061273i

Yang, G., Best, E.P.H., 2015. Spatial optimization of watershed management practices for nitrogen load reduction using a modeling-optimization framework. Journal of Environmental Management 161, 252–260. https://doi.org/10.1016/j.jenvman.2015.06.052