ESTIMATING THE EFFECTS OF THE CONSERVATION RESERVE PROGRAM ON WATER QUALITY OF AGRICULTURAL WATERSHEDS IN THE US

A Thesis

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ABSTRACT

Excessive anthropogenic inputs of nitrogen (N) and phosphorus (P) to agricultural watersheds of the contiguous US have a detrimental impact on national water quality. In this paper, we develop a panel fixed effects model to examine the water quality response to the Conservation Reserve Program (CRP), a federal program that reimburses farmland owners to convert their land from agricultural production and restore it to natural habitats. We find that both N and P respond negatively to CRP enrollment, while the responsiveness of the nutrients differentiates between CRP contract types. In addition, we find the N response to continuous CRP enrollment to be more elastic than P. Our results have important implications for the causal inference procedures in the evaluation of conservation programs such as the CRP, while incorporating the effects from other explanatory variables that may preserve strong spatial variability.

BIOGRAPHICAL SKETCH

Tieyue Zhang was born and raised in Taiyuan, China. Prior to graduate school, Tieyue received his undergraduate education from a 2 + 2 joint program where he obtained a Bachelor of Economics from China Agricultural University and a Bachelor of Science in Agricultural and Resource Economics from the University of Maryland in 2020. Soon after, Tieyue attended Cornell to pursue a Master of Science in Applied Economics and Management. His research focused on the causal inference procedures in the contexts of environmental policies and their impacts. Tieyue will be joining the Ph.D. program in Applied Economics and Management at Cornell University in Fall 2022, and is looking forward to continuing his research interests in environmental and resource economics, conservation policy, and water quality for his Ph.D. dissertation.

I would like to dedicate this thesis to my beloved parents.

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1. Introduction

Extensive studies have shown that increased acreage of cultivated land accompanied by fertilizer application leads to higher nitrogen (N) and phosphorus (P) concentration in agricultural watersheds of the United States (Donner et al., 2004; Ruddy et al., 2006). This riverine nutrient export could result in declined water quality, the degradation of aquatic ecosystems, and in more extreme cases, the occurrence of hypoxic zones (Donner et al., 2004). Meanwhile, a study on the Gulf of Mexico hypoxic zone shows the seasonal upsurge of nutrients in coastal waters could impact inland watersheds and may pose potential health risks to the local water supply (Rabotyagov et al., 2014).

In response, USDA Farm Service Agency (FSA) has implemented numerous conservation programs to mitigate the effects of agricultural practices on the environment. Among them, the Conservation Reserve Program (CRP) is the largest land retirement program in the country. Its purpose is to preserve environmentally sensitive areas through agricultural land conversion (USDA). The program is implemented through FSA contracts with agricultural producers, generally for 10 to 15 years, during which the participants replace traditional crops with approved native flora and receive rental payments and cost-share assistance in return (USDA).

The current CRP offers two types of enrollment for producers. First, prospective participants can participate in the bidding process during the general enrollment period. The FSA evaluates submitted offers based on the Environmental Benefits Index (EBI), an index intended to identify land most environmentally valuable for removal from crop production, and make contracts on highly ranked offers. The EBI assesses a broad spectrum of environmental factors, in 1998, FSA opened continuous enrollment which assigns a particular focus on water quality. Land that meets the eligibility criteria can be enrolled in CRP at any time and is not subject to competitive bidding against other land.

In 2020, CRP general signups accounted for over 13 million acres while about 7.7 million acres are enrolled under continuous signup. According to FSA’s annual reports, more than $1.8 billion was spent on the CRP per year (Hellerstein, 2017). Investigating the impact of CRP contracts on water quality improvement constitutes an important component in evaluating the environmental benefits of the program.

In this paper, we assess the response of water quality to CRP enrollment using a panel fixed effects approach. We combine county-level data from 1998 to 2020 for CRP enrollment acreage and match it with measures of the concentration of N and P as water quality attributes. We use an inverse hyperbolic sine transformation to calculate the elasticity of change in water quality for both general and continuous CRP enrollment. We also examine the spatial and temporal relationship between water quality and CRP enrollment, and discuss the potential heterogeneous treatment effects influenced by time, location, and other factors.

We report three important empirical findings. First, CRP enrollment is associated with improvements in water quality. Both N and P concentration respond negatively to more CRP enrollment. Second, land enrolled in continuous CRP has a higher impact on water quality. Specifically, the association between the nutrient concentration levels and acreage enrolled in continuous CRP is larger compared to the general CRP. Our third finding is that N concentrations are more sensitive to CRP enrollment. We find an elastic correlation between the N level and CRP, whereas the P level responds inelastically to the marginal change in CRP acreage.

The balance of this paper proceeds as follows. We discuss the previous literature in Section 2. Section 3 describes our panel fixed effects model specifications. We describe the data we use for analysis in Section 4 and present descriptive statistics in Section 5. Section 6 presents and compares the results of our model specifications. We discuss and conclude in Section 7.

2. Literature Review

Increased discharge of N and P to agricultural watersheds of the United States has degraded water quality on a national scale. Dodds et al. (2009), using the SPARROW water quality model, found that N and P exports in 90% of rivers of 12 US ecoregions exceed the standards set by the United States Environmental Protection Agency (EPA). Reduced water quality caused by riverine nutrient export is highly associated with the cumulative effect of historic landscape change, which impairs the ability of soil to keep nutrients from releasing into the environment (Dodds et al., 2009; Turner & Rabalais, 2003). Many studies have shown that such landscape change primarily takes the form of natural land conversion, resulting in increased fertilizer application as acreage of cropland and pastures expands (Donner et al., 2004; Ruddy et al., 2006; Turner & Rabalais, 2003). Alexander et al. (2007) found that over 70% of N and P inputs to the Gulf of Mexico are attributed to agricultural activities around the Mississippi River Basin. In short, agricultural land use has a significant impact on the water quality of the United States' watersheds.

CRP is the country's largest agricultural conservation program that returns land from cropping to its native land use (USDA). Although initially designated to reduce soil erosion, over 35 years of its history, CRP now provides a broader spectrum of ecosystem service benefits (Hellerstein, 2017; Johnson et al., 2016; Lant, 1991). However, Hellerstein (2017) noted that since CRP reached its peak enrollment of 14.9 million ha in 2007, the program has been declining in size with over 5 million hectares of land expected to have left the program by 2017. This is partially due to the passage of the Agricultural Act of 2014 and the continuing lack of comprehensive assessments of the program may limit future funding sources as well (Hellerstein, 2017; Vandever et al., 2021).

Vandever et al. (2021) provided a more recent assessment of CRP and the outcome of its conservation practices on a national scale. They surveyed land cover attributes of 1786 fields in central and western states and found low soil erosion and high vegetation cover (Vandever et al., 2021). However, this assessment did not estimate or quantify the effects or benefits of the conservation practices. Johnson et al. (2016) furthered this objective by showing that the combined ecosystem service benefits of CRP overweigh the rental payments made to the contracted farmers, while the study remained local as they focused on one watershed in Iowa. As the result, there is a need for a more inclusive evaluation of the effects of the CRP as a whole, particularly on water quality at large watershed level.

The limited studies available so far have mixed findings regarding the impact of CRP on water quality. Sprague & Gronberg (2012) found a positive relationship between total nutrient load (N, P) and the area enrolled in CRP from 133 agricultural watersheds in the US. Building on previous studies, the model in the paper regressed annual mean nutrient export on landscape attributes and nutrient input factors either at the county level or by hydrologic unit. However, the two main attributes, the area in CRP and the area in conservation tillage, are simplified to binary variables while they deserve careful analysis as there might be underlying spatial and temporal relations between these variables and local nutrient export. In contrast, Yin et al. (2021) showed a negative correlation between the total N load and CRP enrollment. While the paper used the Illinois River Basin (IRB) as a representative study area and incorporated remote sensing observations to identify cropland changes, the findings are constrained at a regional level. In both cases, association was found instead of causal inference. Sprague & Gronberg (2012) included an extensive list of environmental attributes to control for riverine transport, including annual temperature, precipitation, soil characteristics, irrigated area, etc. However, besides the simple treatment of CRP in the model, the analysis was done in a cross-sectional scope where the temporal effects were not accounted for. Meanwhile, Yin et al. (2021) studied CRP in IRB at a 15-year temporal resolution and dealt with change in cropland over time, yet did not further identify other potential parameters that might impact water quality.

In summary, previous literature on the effectiveness of CRP is constrained on the subject of water quality, due to the incomprehensiveness in temporal and spatial inclusion. We contribute to this literature by addressing both ends of the methodological process and by looking at the role of continuous CRP contracts in improving water quality. We also explore other explanatory variables that may preserve strong variability in space and nature.

3. Empirical Design

Consider the following panel fixed effects specifications for the estimation of the marginal effects of CRP enrollment on water quality:

$$\sinh^{-1}(WQ)_{iy} = \gamma_1 \sinh^{-1}(CONT)_{cy} + \gamma_2 \sinh^{-1}(GEN)_{cy} + \beta_1 (NT)_{iy} + \eta_i + \eta_y + \epsilon_{iy} \quad (1)$$

$$\sinh^{-1}(WQ)_{iy} = \gamma_1 \sinh^{-1}(CONT)_{cy} + \gamma_2 \sinh^{-1}(GEN)_{cy} + \beta_1 (NT)_{iy} + \eta_i + \eta_y + \eta_{yw} + \epsilon_{iy} \quad (2)$$

$$\sinh^{-1}(WQ)_{iy} = \gamma_1 \sinh^{-1}(CONT)_{cy} + \gamma_2 \sinh^{-1}(GEN)_{cy} + \beta_1 (NT)_{iy} + \beta_2 (ST)_{iy} + \eta_c + \eta_y + \epsilon_{iy} \quad (3)$$

$$\sinh^{-1}(WQ)_{iy} = \gamma_1 \sinh^{-1}(CONT)_{cy} + \gamma_2 \sinh^{-1}(GEN)_{cy} + \beta_1 (NT)_{iy} + \beta (ST)_{iy} + \eta_c + \eta_y + \eta_{yw} + \epsilon_{iy} \quad (4)$$

where WQ_{iy} is the nutrient (N, P) concentration reading by site i and year y; $CONT_{cy}$ and GEN_{cy} represent cumulative continuous and general CRP enrollment in county shares by county c and year y. We exclude observations with zero-valued CRP enrollment, and use the following equation to calculate county shares:

$$\text{CRP share}_c = \frac{\text{Area}_{crp,c}}{\text{Area}_c} \quad (5)$$

where c represents county. We use the inverse hyperbolic sine transformation of WQ_{iy} , $CONT_{cy}$, and GEN_{cy} to estimate γ_1 and γ_2 , which represent the water quality elasticities of CRP enrollment by contract type. Bellemare and Wichman (2020) demonstrated the feasibility of adopting this transformation to estimate elasticities in applied economics research, as the inverse hyperbolic sine function allows for zero-valued observations while retaining similar growth path to the natural logarithm. In our case, this method is also appropriate as both zero and extreme values can be found in both CRP and water quality. We use NT_{iy} and ST_{iy} as additional controls, which are categorical variables for nutrient measure type (i.e. total, dissolved, suspended) and monitoring site type (i.e. lake, steam, wetland) by site i and year y.

The year fixed effects η_y allow for water quality to differ in each year, and the unit-level fixed effects η_i and η_c control for all time-invariant determinants of water quality specific to either monitoring site i or county c. We also examine the performance of our models by introducing additional fixed effects η_{wy}, which control for any hydrological events within watershed w during year y. ϵ_{iy} is the idiosyncratic error.

We adjust sample selection in the following aspects to show the robustness of our results. First, counties may enroll in or retire entirely from either continuous and general CRP for some years during our sample period. We relax the constraint of selecting only observations with positive values for both general and continuous CRP enrollment and allow for zero-valued observations. Second, we are interested in learning how nutrient levels would respond to the increase in CRP acreage. Given that county fixed effects should suffice to control for the variation in county size, we regress our equations on CRP enrollment as acreage instead of county shares. Finally, there are multiple studies addressing the existence of lag time in water quality response to land treatment (Meals et al., 2010; Shortle et al., 2016; Sprague & Gronberg, 2012). We attempt to account for this by allowing for time lags in CRP enrollment from 1 to 3 years, while maintaining the same level of data coverage in our regression samples. We discuss this in more detail in Section 6 and 7.

4. Data

In this section, we briefly present our data. We construct a panel using data from three sources. First, historical CRP enrollment information entails the unit and intensity of the treatment and delineates the recipient areas of the treatment. We use CRP enrollment data from USDA FSA and Economic Research Service (ERS). A stratified area sample of 48 States (excludes Alaska and Hawaii) was acquired from the FSA website, containing county-level CRP enrollment since fiscal year 1986. We then compare and combine the record from USDA ERS and compile the data into a panel of 2,796 counties uniquely defined by the FIPS code. The processed dataset provides a temporal coverage from the fiscal year 1998 (start of continuous CRP signup) to 2020 and includes the following attributes: general and continuous enrollment (acreage) and enrollment by practice types (i.e. grass, tree, wetland, treeless wetland, other).

Second, we acquire water quality data from the Water Quality Portal (WQP), the largest standardized water quality database co-created by USGS, EPA, and the National Water Quality Monitoring Council (Shen et al., 2020). We extract site-level readings of N concentration from 27,149 monitoring locations and P concentration from 102,271 locations across the country. Water samples include total (TN, TP), dissolved (DN, DP), and suspended (SN, SP) nutrient concentration levels (mg/L). Sampling activities are independent across sites and nutrients. We use these measures as the water quality indicator (dependent variable), as they are closely related to agricultural production. As monitoring sites are located around various hydrological landscapes, we categorize them into three types: lake, stream, and wetland. We aggregate concentration levels as annual averages. In addition, each observation includes locational information of the monitoring site, i.e. the hydrologic unit code (HUC) of each site. We use the accompanying 8-digit HUC to georeference watershed boundaries with site-level water quality readings.

Finally, we acquire ancillary county size data from the US Census Bureau's Statistical Compendia Program to calculate CRP enrollment as county shares. The program surveyed US county statistics every decade from 1990 to 2010, and we use the latest report published in 2011 which is also the approximate midpoint of our sample period. After combining site-level water quality readings with county-level CRP enrollment, we construct two unbalanced panels with 81,986 observations for N concentration across 1,617 counties and 22,740 monitoring sites; and 303,804 observations for P concentration across 2,500 counties and 80,186 sites.

5. Descriptive Statistics

Figures 1 and 2 present the longitudinal structure and spatial distribution of the panels. Each color block represents the cumulative years of availability for the matched data at county level. There are a large number of counties that only attain less than five years of N readings matched with CRP enrollment. Missouri, Pennsylvania, Maryland, Virginia, and Vermont have distinctively longer data coverage compared to other states. Given the typical CRP contract length is from 10 to 15 years, this spatial clustering in data may cause the estimation to deviate from the true impact of CRP enrollment on N levels. We address this constraint in Section 7. Meanwhile, P readings well match with CRP enrollment as data availability exceeds 15 years for most counties and no obvious clustering is observed. This allows us to draw more realistic and reliable conclusions from the regression results.

CRP enrollment

Figure 3 presents the trend in cumulative CRP enrollment. We observe that general CRP reached its peak enrollment level in 2007 and started to decline since then. Hellerstein (2017) offered a possible explanation for this. There has been a shrinkage in the national acreage cap and an increase in commodity prices since 2007, which would result in less incentive for producers to enroll in CRP (Hellerstein, 2017). Meanwhile, the continuous signup has been increasing since 1998, seemingly undisturbed by the policy and economic change that affected the general CRP signup. This simplifies the process of controlling for exogenous factors related to CRP enrollment, so we are able to focus on how the increment in continuous CRP would relate to the changes in water quality while accounting for the trends in general CRP.

Figures 4 – 6 provide further information on state-level trends of different CRP during our sample period. Most states preserve similar trends in CRP, while states like Arizona, Nevada, and Rhode Island experience more abrupt changes in CRP. No general CRP contract was recorded for Rhode Island during the sample period and no continuous contract was recorded for Arizona and Nevada. This attributes to the primary land over and available agricultural land of the states. In particular, for each of these states, only one county has been enrolled in CRP. We observe no significant jurisdictional divergence in how one type of CRP contract would change over time. Hence the unit fix effects in our model would be able to control for variation across counties.

Figures 7 – 9 display maps of the spatial distribution of CRP enrollment acreage at the county level and how it changes over the sample period. For general CRP, there is a spatial pattern that the most change is observed in Kansas, Nebraska, North Dakota, Iowa, and part of Texas and Montana. In addition, less significant changes are also observed across the Upper and Lower Mississippi River Basin. Meanwhile, for continuous CRP, we observe the Corn Belt has been the most active part where new continuous signup is located. Therefore, while CRP is widespread across the country, its nature of targeting excessively farmed land leads to spatial clusters where most CRP acreage is distributed in the Midwest states. This highlights the need for assessment at a country-wide scale as regional studies that focus on midwestern states and watersheds would suffer from selection bias.

Water quality

Figures 10 and 11 present how average N and P concentration levels change over time. We detect significant variation in N levels throughout the sample period and in P levels from 2000 to 2003. There is no overall trend in nutrient levels similar to CRP enrollment. Less fluctuation is found in TN compared to DN and SN, while TP changes more drastically than DP and SP. There is partially due to the limitations in the data availability of N and P readings and the existence of extreme values under these attributes. As no evidence is found that the large number of extreme values were recorded due to measurement errors, we include these observations in our regressions. We further discuss the outliers of nutrient levels in Section 7.

Figure 12 – 17 display maps of N and P concentration as county averages. For TN and TP, concentration levels appear to be higher in regions with more CRP enrollment. However, this does not necessarily imply a positive association between CRP and nutrients. The implementation of CRP tends to focus on agricultural regions. While heavy agricultural activities contribute to the increase in nutrients in local water bodies, we examine the problem from a longitudinal perspective rather than cross-sectional. In other words, we are interested in learning how nutrients everywhere would respond to CRP in the course of time. Furthermore, we find significant gaps in DN, SN, DP, and SP. Most counties do not attain effective site readings for these attributes. in particular, DN, SN, and SP readings are only available in a few states. This partially explains the huge variation found in Figures 10 and 11. In our analysis, we manage to mitigate the impact of this limitation through fixed effects and controlling for nutrient type.

Table 1. Descriptive Statistics

	Median	Mean	Standard Deviation	Minimum	Maximum
Panel A: CRP enrollment (acreage)					
General	2886.1	12178.5	25842.6	0.5	310020.8
Continuous	612.5	2215.0	4352.8	0.1	73398.5
Total	5085.0	14449.0	26839.6	2.7	310109.3
Panel B: CRP enrollment (county share)					
General	0.73%	2.10%	3.30%	0%	24.74%
Continuous	0.15%	0.53%	0.91%	0%	13.65%
Total	1.32%	2.64%	3.49%	0%	26.69%
Panel C: Nitrogen concentration (mg/L)					
Dissolved	0.80	1.62	3.03	0	97.25
Suspended	0.09	0.42	9.27	0	749.78
Total	0.64	1.29	5.11	0	673.33
Panel D: Phosphorus concentration (mg/L)					
Dissolved	0.04	0.13	1.02	0	111.50
Suspended	0.02	0.03	0.04	0	1.39
Total	0.06	0.18	3.02	0	1113.50

We note that in Panel B of Table 1, the lower bound for CRP enrollment as county share is zero. However, this does not contradict Panel A and suggests that there are counties untreated with CRP in our regression samples, as minimal CRP enrollment acreage would appear marginal in terms of county size. Meanwhile, there are in fact zero-valued observations in the CRP data. In this case, having zero CRP enrollment does not indicate a county has never been enrolled in CRP, but means for a given year, a county retires entirely from the program or has yet been enrolled. In other words, all counties in our data must be enrolled in CRP at some point. Section 6 further addresses the treatment of these observations in our analysis.

6. Results

Our main results are shown in Table 2 for N and Table 3 for P. Columns 1 – 4 represent results from Equations 1 – 4 respectively from Section 3, including fixed effects and nutrient type factors. We use nutrient concentration level (including zero-valued observations) as the dependent variable and positive general and continuous CRP as explanatory variables. Columns 3 and 4 include monitoring site factors as an additional control.

Table 2. Relationship between nitrogen concentration and CRP shares

Dependent Variable	Nitrogen			
Model:	(1)	(2)	(3)	(4)
Variables				
Continuous CRP (share)	-3.300***	-2.493	-0.3493	-1.710
	(1.271)	(1.634)	(1.681)	(2.299)
General CRP (share)	-0.6896	-0.6745	-0.7038	-2.718
	(0.6451)	(1.577)	(0.9164)	(2.205)
Nutrient Type: Suspended	-1.183***	-1.193***	-1.067***	-1.133***
	(0.0257)	(0.0272)	(0.0221)	(0.0250)
Nutrient Type: Total	0.1022***	0.0922***	0.1345***	0.1204***
	(0.0064)	(0.0059)	(0.0087)	(0.0073)
Monitoring Site Type: Stream			0.1728***	0.1506***
			(0.0145)	(0.0181)
Monitoring Site Type: Wetland			0.5437***	0.4609**
			(0.1258)	(0.2144)
Fixed-effects				
Year	Yes	Yes	Yes	Yes
Monitoring Site	Yes	Yes		
Watershed × Year		Yes		Yes
County			Yes	Yes
Fit statistics				
Observations	51,118	50,915	51,118	50,915
R^2	0.85230	0.87200	0.54177	0.64339
Within R^2	0.59626	0.63077	0.32985	0.38646

*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

Table 3. Relationship between phosphorus concentration and CRP shares

Dependent Variable	Phosphorus			
Model:	(1)	(2)	(3)	(4)
Variables				
Continuous CRP (share)	-0.8713***	-0.6199*	-0.5356*	-0.2979
	(0.3321)	(0.3544)	(0.3139)	(0.4087)
General CRP (share)	-0.2913***	0.0278	-0.4744***	-0.0256
	(0.0938)	(0.1336)	(0.1208)	(0.1856)
Nutrient Type: Suspended	0.0041	0.0036	-0.0105***	-0.0069**
	(0.0031)	(0.0032)	(0.0035)	(0.0034)
Nutrient Type: Total	0.0796***	0.0793***	0.0760***	0.0772***
	(0.0019)	(0.0019)	(0.0020)	(0.0020)
Monitoring Site Type: Stream			0.0792***	0.0728***
			(0.0036)	(0.0037)
Monitoring Site Type: Wetland			0.3898***	0.2902***
			(0.0510)	(0.0489)
Fixed-effects				
Year	Yes	Yes	Yes	Yes
Monitoring Site	Yes	Yes		
Watershed × Year		Yes		Yes
County			Yes	Yes
Fit statistics				
Observations	209,263	208,858	209,263	208,858
R^2	0.79612	0.83498	0.25218	0.40512
Within R^2	0.04897	0.05821	0.03191	0.02886

*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

In Table 1, column 1 shows that N response to continuous CRP is negative, elastic, and significant at site level. The elasticity of -3.3 implies that a 1% increase in continuous CRP shares is associated with 3.3% lower N concentration. Meanwhile, the coefficients of general CRP are consistently negative in all specifications but not significant. There are several factors that may cause the insignificance of coefficients in our results. First, as discussed in Section 5, our data might not have enough temporal coverage of N readings matched with CRP enrollment that can reflect the realistic CRP contract length. Observations with more than 10 years of N readings are distributed scarcely across the country rather than clustered at county level. Therefore, columns 3 and 4, which specify county-year fixed effects, may not be able to control for the spatial variations very well. Second, we find columns 2 and 4, our specifications with additional watershed – year level fixed effects, also report insignificant coefficients for both CRP types. The variation in water quality that could be related to CRP might get absorbed when we control for potential natural events (i.e. drought, fire, flood, etc.) that would affect nutrient levels across watersheds. We also observe this effect for P estimates in Table 2.

For our set of controls, first, we find the concentration of DN lower than TN concentration and higher than SN. This is significant and consistent in all specifications. We can also observe this relationship between nutrient types in Figure 10 and 11 for both N and P. Total solids in water bodies, which often also applies to total nutrients, are typically calculated as the sum of total dissolved solids and total suspended solids (APHA, 1992; Butler & Ford, 2018). However, this does not cause collinearity in our specification as each observation in our regression samples, regardless of nutrients measurement type, is individually sampled from different sites. In other words, there is no sampling TN and DN that happens at one location on one day.

In addition, we also find N in wetlands has a higher concentration level than in streams, and that N level is the lowest in lakes. This shows the water quality patterns in different hydrological landscapes, as wetlands and streams are often intermediates among uplands and surrounding watersheds and hence have the ability to retain nutrients (Reddy et al., 1999; Trebitz et al., 2019). Furthermore, this also reflects the list of conservation practices mandated by the continuous CRP, as many of them focus on wetland conservation and restoration.

Table 2 shows P elasticities of CRP enrollment. Columns 1 and 3 show that P response is negative, inelastic, and significant to both CRP enrollment. In particular, P is more responsive to continuous CRP than general CRP. In column 1, the elasticities imply that a 1% increase in continuous CRP shares is associated with 0.87% lower P concentration; a 1% increase in general CRP shares is associated with about 0.29% P decrease. Column 3 reports elasticities of similar magnitude, implying that a 1% increase in continuous and general CRP is associated with about 0.53% and 0.47% decrease in P concentration respectively. The impact of general CRP increases when controlling for spatial variation at county level. As described in Section 4, the temporal coverage of P readings is more representative of the typical CRP contract length, and there is no obvious spatial clustering observed. Therefore, it is more reasonable to relax the constraint on site-level fixed effects. Meanwhile, the estimates in columns 2 and 4 remain insignificant for both CRP types when including watershed-year fixed effects. Furthermore, findings by EPA suggest the lag time of P response to environmental treatment such as CRP tends to be longer than N, hence relating to the inelastic nature of P in our results (Meals et al. 2010).

Similar patterns are also found in the control set for P. We find the concentration of TP higher than DP, whereas SP is lower than DP by a small margin. This suggests that different P forms respond similarly to CRP enrollment. We also find higher P concentration in wetlands and lower in lakes. Reddy et al. (1999) further related our findings to the mechanism of P retention in wetlands and streams, stating that the abundance and diversity of vegetation provide wetlands with greater potential for P storage.

Robustness Tests

To obtain a better sense of the aggregate magnitude of the results, we conduct the following robustness tests by making several adjustments to our regression samples. First, we include zero-valued observations in both CRP types. This includes counties before they are enrolled or when they retire entirely from CRP. Second, we estimate the water quality elasticities of CRP acreage instead of county shares. Lastly, we take into account the lag time of water quality by introducing lags up to 3 years, for such amount of lags still allow us to obtain meaningful estimates without significant data loss. Table 4 and Table 5 present results from regression samples containing zero CRP enrollment; Table 6 and Table 7 present results of nutrients responses to CRP acreage; and Table 8 and 9 present results of fixed-effects estimation with lags.

In Table 4, column 1 shows diminished N response to continuous CRP when we allow for zero CRP enrollment. The absolute value of elasticity is smaller than reported in Table 2. However, we still find a negative, elastic and significant response of N to continuous CRP. In this scenario, a 1% increase in continuous CRP shares is associated with 2.2% lower N concentration. Meanwhile, similar to Table 2, the coefficients of general CRP and continuous CRP in all other specifications remain insignificant.

As discussed above, the estimation for phosphorus concertation would provide better insights into the robustness of our proposed fixed-effects models. Table 5 reports estimates of P elasticities of CRP enrollment similar to Table 3. Moreover, we find the magnitude and significance of elasticities to be very close to our original findings. The negative and inelastic response of P is observed for both continuous and general CRP, while the responsiveness remains to be higher for continuous CRP. Furthermore, the results also show similar patterns in our control variables for both nutrients.

Table 4. Relationship between nitrogen concentration and CRP shares (zero-value included)

Dependent Variable	Nitrogen			
Model:	(1)	(2)	(3)	(4)
Variables				
Continuous CRP (share)	-2.194*	-2.292	-0.6548	-1.080
	(1.254)	(1.496)	(1.561)	(2.178)
General CRP (share)	-0.2012	0.4097	-0.7295	-3.408
	(0.5986)	(1.399)	(0.9868)	(2.217)
Nutrient Type: Suspended	-1.151***	-1.161***	-1.010***	-1.091***
	(0.0243)	(0.0257)	(0.0200)	(0.0231)
Nutrient Type: Total	0.0813***	0.0733***	0.0885***	0.0932***
	(0.0051)	(0.0047)	(0.0073)	(0.0061)
Monitoring Site Type: Stream			0.1603***	0.1670***
			(0.0105)	(0.0132)
Monitoring Site Type: Wetland			0.4564***	0.4142**
			(0.1211)	(0.1718)
Fixed-effects				
Year	Yes	Yes	Yes	Yes
Monitoring Site	Yes	Yes		
Watershed × Year		Yes		Yes
County			Yes	Yes
Fit statistics				
Observations	81,981	81,591	81,981	81,591
R^2	0.87349	0.89343	0.52283	0.64274
Within R^2	0.55059	0.59365	0.25212	0.31321

*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

Table 5. Relationship between phosphorus concentration and CRP shares (zero-value included)

Dependent Variable	Phosphorus			
Model:	(1)	(2)	(3)	(4)
Variables				
Continuous CRP (share)	-0.8256**	-0.6048*	-0.5310*	-0.3134
	(0.3329)	(0.3346)	(0.2998)	(0.3837)
General CRP (share)	-0.3010***	0.0028	-0.4282***	-0.1047
	(0.0915)	(0.1271)	(0.1146)	(0.1776)
Nutrient Type: Suspended	0.0015	0.0005	-0.0117***	-0.0097***
	(0.0027)	(0.0029)	(0.0031)	(0.0031)
Nutrient Type: Total	0.0709***	0.0706***	0.0686***	0.0689***
	(0.0015)	(0.0016)	(0.0016)	(0.0016)
Monitoring Site Type: Stream			0.0859***	0.0770***
			(0.0033)	(0.0032)
Monitoring Site Type: Wetland			0.2980***	0.2012***
			(0.0316)	(0.0289)
Fixed-effects				
Year	Yes	Yes	Yes	Yes
Monitoring Site	Yes	Yes		
Watershed × Year		Yes		Yes
County			Yes	Yes
Fit statistics				
Observations	303,804	303,024	303,804	303,024
R^2	0.79096	0.83233	0.24626	0.40537
Within R^2	0.04140	0.04965	0.03110	0.02715

*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

We exclude zero-valued observations in our original specifications for the increment in CRP is not continuous with respect to time but depends on the mandated acreage per contract. This implies an abrupt increment or decline to zero in terms of the intensity of CRP treatment in counties with no existing or expiring contracts. In particular, we are most concerned about the scenario of CRP expirations, as prior conservation practices are likely to have lagged impact on water quality while the sudden return to agricultural production could confound the estimation of the true effects that CRP might take on water quality. Nevertheless, Table 4 and Table 5 suggest that our estimation is not susceptible to the inclusion of observations from CRP counties during pre-enrollment and post-retirement periods.

Table 6. Relationship between nitrogen concentration and CRP acreage

Dependent Variable	Nitrogen			
Model:	(1)	(2)	(3)	(4)
Variables				
Continuous CRP (share)	-0.0062*	-0.0130**	-0.0143***	-0.0221**
	(0.0032)	(0.0051)	(0.0053)	(0.0090)
General CRP (share)	0.0004	-0.0118	-0.0130*	-0.0125
	(0.0041)	(0.0088)	(0.0076)	(0.0135)
Nutrient Type: Suspended	-1.183***	-1.193***	-1.066***	-1.133***
	(0.0257)	(0.0272)	(0.0221)	(0.0250)
Nutrient Type: Total	0.1021***	0.0922***	0.1352***	0.1205***
	(0.0064)	(0.0059)	(0.0087)	(0.0073)
Monitoring Site Type: Stream			0.1726***	0.1507***
			(0.0145)	(0.0181)
Monitoring Site Type: Wetland			0.5473***	0.4643**
		(0.1247)	(0.2139)	
Fixed-effects				
Year	Yes	Yes	Yes	Yes
Monitoring Site	Yes	Yes		
Watershed × Year		Yes		Yes
County			Yes	Yes
Fit statistics				
Observations	51,121	50,918	51,121	50,918
R^2	0.85224	0.87201	0.54191	0.64344
Within R^2	0.59611	0.63079	0.33005	0.38654

*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

Table 7. Relationship between phosphorus concentration and CRP acreage

Dependent Variable	Phosphorus			
Model:	(1)	(2)	(3)	(4)
Variables				
Continuous CRP (share)	-0.0003	-0.0055**	0.0057***	-0.0026
	(0.0012)	(0.0022)	(0.0015)	(0.0024)
General CRP (share)	0.0011	0.0014	0.0006	0.0040
	(0.0018)	(0.0025)	(0.0019)	(0.0030)
Nutrient Type: Suspended	0.0040	0.0036	-0.0106***	-0.0069**
	(0.0031)	(0.0032)	(0.0035)	(0.0034)
Nutrient Type: Total	0.0796***	0.0793***	0.0760***	0.0772***
	(0.0019)	(0.0019)	(0.0020)	(0.0020)
Monitoring Site Type: Stream			0.0792***	0.0728***
			(0.0036)	(0.0037)
Monitoring Site Type: Wetland			0.3875***	0.2904***
			(0.0511)	(0.0489)
Fixed-effects				
Year	Yes	Yes	Yes	Yes
Monitoring Site	Yes	Yes		
Watershed × Year		Yes		Yes
County			Yes	Yes
Fit statistics				
Observations	209,263	208,858	209,263	208,858
R^2	0.79606	0.83499	0.25219	0.40513
Within R^2	0.04868	0.05828	0.03192	0.02888

*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

We also test the water quality elasticities of CRP enrollment acreage, and report the results in Table 6 for N and Table 7 for P. In Table 6, the estimates of N elasticity of continuous CRP are significant across all specifications with values consistently around -0.01. This, as opposed to previous findings, suggests a negative, but inelastic response of N to continuous CRP acreage. Meanwhile, column 3 reports an estimated elasticity of -0.01 for general CRP acreage. We mainly focus on the estimates reported in columns 3 and 4, as county fixed effects better capture the variation in county size. The similarity in the sign and magnitude of estimated elasticities for continuous and general CRP suggests that the responsiveness of N to the marginal change in CRP acreage is weak and undistinguishable between CRP types. In Table 7, column 3 reports a diminutive and positive P elasticity of continuous CRP. In addition, the coefficients of general CRP acreage are not significant in all specifications.

The findings in Table 6 and Table 7 indicate that the responsiveness of nutrients is negligible in terms of the marginal change in CRP acreage. We propose the following reasoning for the confounding results. In this study, CRP enrollment represents the intensity of conservation practices that might be correlated with environmental attributes such as water quality. However, as discussed above, CRP does not change continuously in terms of enrollment acreage. Compared to CRP shares, relating nutrients concentration to the marginal change in CRP acres may not be a realistic representation of the actual variation in land treatment, hence we won't able to draw meaningful interpretations from the estimates.

Lastly, we estimate the water quality response to CRP with time lags from 0 to 3 years, and present results in Table 8 and Table 9 for TN and TP respectively. First, we find TN response to continuous CRP to be negative and elastic for one and three years after the contracts take effect. In Table 8, column 1 reports a 1% increase in continuous CRP shares is associated with a 3.4% decrease in TN concentration, while the TN elasticity of continuous CRP increases with a lag of 1 year, and decreases as the time lag expands to 3 years. Meanwhile, column 3 reports positive estimates for continuous CRP and the coefficients of general CRP remain insignificant across all specifications, regardless of the lags. This may attribute to the inaptitude of applying county fixed effects to N data. As CRP targets environmentally sensitive lands, for counties where water quality (in this case, TN) experiences more drastic deterioration, more continuous CRP shall be implemented, which would result in this positive association. We are able to observe this in column 3, as continuous CRP with a lag of 1 year is associated with a higher increase in TN concentration than in the present year.

Table 8. Relationship between total nitrogen concentration and CRP shares (with lags)

Dependent Variable	Total Nitrogen			
Model	(1)	(2)	(3)	(4)
Variables				
Continuous CRP	-3.441**	-4.818**	4.800**	-0.6991
	(1.574)	(2.168)	(1.992)	(2.910)
Continuous CRP, Lag 1	-3.998*	2.277	7.021**	0.0775
	(2.101)	(1.544)	(2.992)	(4.383)
Continuous CRP, Lag 2	-0.7807	1.710	4.914*	-3.881
	(1.251)	(1.577)	(2.764)	(4.358)
Continuous CRP, Lag 3	-2.733**	2.401*	-2.801	-3.154
	(1.368)	(1.227)	(2.393)	(5.117)
General CRP	-0.1782	-0.7103	-1.429	-3.191
	(0.6457)	(1.502)	(0.9066)	(1.992)
General CRP, Lag 1	-0.4329	-1.808	-0.4820	-1.718
	(0.8292)	(1.506)	(0.9401)	(2.161)
General CRP, Lag 2	0.0646	-2.154	0.7527	-0.9388
	(0.8733)	(2.189)	(0.9373)	(2.907)
General CRP, Lag 3	-0.1550	-3.230	0.3894	-2.057
	(0.8857)	(2.370)	(0.9456)	(2.987)
Fixed-effects				
Year	Yes	Yes	Yes	Yes
Monitoring Site	Yes	Yes		
Watershed × Year		Yes		Yes
County			Yes	Yes

*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

Table 9. Relationship between total phosphorus concentration and CRP shares (with lags)

Dependent Variable	Total Phosphorus			
Model	(1)	(2)	(3)	(4)
Variables				
Continuous CRP	-0.7729***	-0.6942*	-0.6245**	-0.3605
	(0.2636)	(0.3808)	(0.2892)	(0.4059)
Continuous CRP, Lag 1	-0.6295**	-0.6671	-0.4055	-0.6890
	(0.2953)	(0.4441)	(0.3463)	(0.5350)
Continuous CRP, Lag 2	-0.1769	-0.7343	-0.7631*	-1.722***
	(0.3015)	(0.4839)	(0.4318)	(0.6479)
Continuous CRP, Lag 3	0.0685	-0.3948	-0.3629	-1.372**
	(0.3384)	(0.4989)	(0.4251)	(0.6526)
General CRP	-0.2453***	-0.0081	-0.4493***	-0.2073
	(0.0774)	(0.1231)	(0.1150)	(0.1706)
General CRP, Lag 1	-0.2648***	-0.1528	-0.3262**	-0.2626
	(0.0851)	(0.1365)	(0.1393)	(0.2147)
General CRP, Lag 2	-0.1069	-0.0068	-0.2671*	-0.3860
	(0.0893)	(0.1398)	(0.1609)	(0.2455)
General CRP, Lag 3	-0.0749	0.0563	-0.2481	-0.3994
	(0.0942)	(0.1447)	(0.1669)	(0.2655)
Fixed-effects				
Year	Yes	Yes	Yes	Yes
Monitoring Site	Yes	Yes		
Watershed × Year		Yes		Yes
County			Yes	Yes

*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

Second, in Table 9, column 1 reports that TP responses to both CRP types are negative, inelastic, and significant at site level for 1 year after enrollment. We find a 1% increase in continuous CRP shares of the previous year is associated with a 0.63% decrease in TP concentration, while a 1% increase in previous general CRP is associated with 0.26% lower TP concentration. Column 3 reports higher elasticity of continuous CRP with a lag of 2 years. Meanwhile, the TP elasticity of general CRP decreases as the time lag expands. However, waterborne phosphorus response to environmental treatment such as the CRP typically takes longer than 10 years (Meals et al., 2010). Therefore, given we only test for limited years of the time lag, the results suggest that the potential impact of CRP on water quality sustains to some extent, but we cannot conclude if there is a pattern in how the elasticities change over years or which lag time best represents the water quality response to the year of CRP enrollment.

7. Discussion and Conclusion

In this paper, we aim to evaluate the efficacy of different CRP types on water quality, which hasn't been extensively studied in the existing economic literature. While the general CRP signup can date back to 1986, in 1998, the federal government also initiated the continuous signup cycle, which highlights water quality incentives in the environmental treatment. Through carefully constructed regression panels that include sufficient water quality attributes and temporal coverage, this research examines the treatment effects of both continuous and general CRP enrollment on waterborne nutrient concentration across the contiguous US. We use a panel fixed effects approach to estimate the N and P elasticities of CRP enrollment as county shares.

The results of our numerical models suggest that both N and P reductions are more responsive to continuous CRP, for general CRP involves conservation practices that produce a broader spectrum of environmental benefits besides water quality. The response of N is elastic to continuous CRP, whereas P responds to both CRP types inelastically. We find water quality response to CRP is significant within 3 years of implementation, while no clear association is found between general CRP and N concentration.

We acknowledge the following limitations in this paper. First, the continuous nature of CRP contracts poses a challenge to our model specifications. Because a typical CRP contract lasts for 10-15 years, the variable of treatment in this paper should be continuous instead of a policy shock. Since the general signup cycle occurs every year and the continuous signup is anytime, for a given county, there could be new enrollments and expirations occurring at the same time. Therefore, our problem would not easily fit into a canonical difference-in-differences model.

Further analyses might examine the feasibility of using indices that incorporate the type of conservation practices and hence better capture the intensity of treatment. Meanwhile, higher resolution would provide further insights into the impact of specific types of CRP conservation practices on water quality.

Second, the existence of extreme nutrient levels also has implications for the results. Extending the observation of abrupt changes in nutrient concentration based on Figures 10 and 11, we identify the outliers in N and P readings and present our findings in Figures 18 and 19. We observe a significant amount of outliers for both nutrients in all forms. This might result in large variation in nutrient levels which we associate with CRP enrollment changes. However, as there is no evidence suggesting that these observations do not reflect true sampling results, the extreme values may attribute to site location, sampling date, or the actual state of waterborne nutrient flows. Hence, we include these observations in the regressions as well as fixed effects to control for variation caused by extraneous factors.

Lastly, as discussed in previous sections, it usually takes years for environmental treatment such as CRP nutrients to take effect in the reduction of nutrient concentration in water bodies. Such time lags include the time for the management practices to take effect, the time required for the delivery of the effect to watersheds, and the time needed for nutrients to respond to the effect (Meals, et al., 2010). Therefore, the time lags included in our analysis would only be sufficient for the response of nutrients as runoffs, as the median watershed residence time for dissolved nutrients is 10 years (Meals, et al., 2010).

Our results have important implications for the evaluation of CRP in particular, and other federal and regional conservation programs more generally. We suggest that long-term evaluation of CRP would be more effective in better capturing the water quality response to the implementation of CRP practices. Building upon the empirical design in this paper, future studies would provide more insights on relating water quality to the valuation of associated environmental benefits.

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Figure 1. Maps of CRP enrollment matched with nitrogen readings

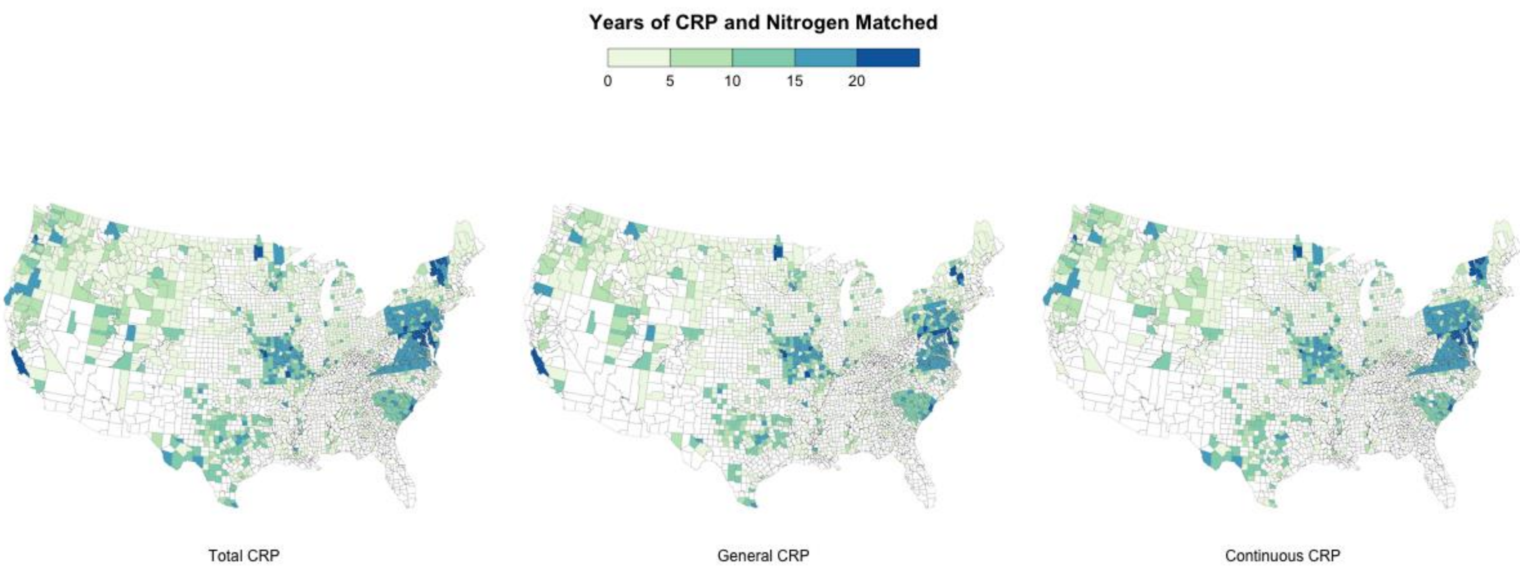

Figure 2. Maps of CRP enrollment matched with phosphorus readings

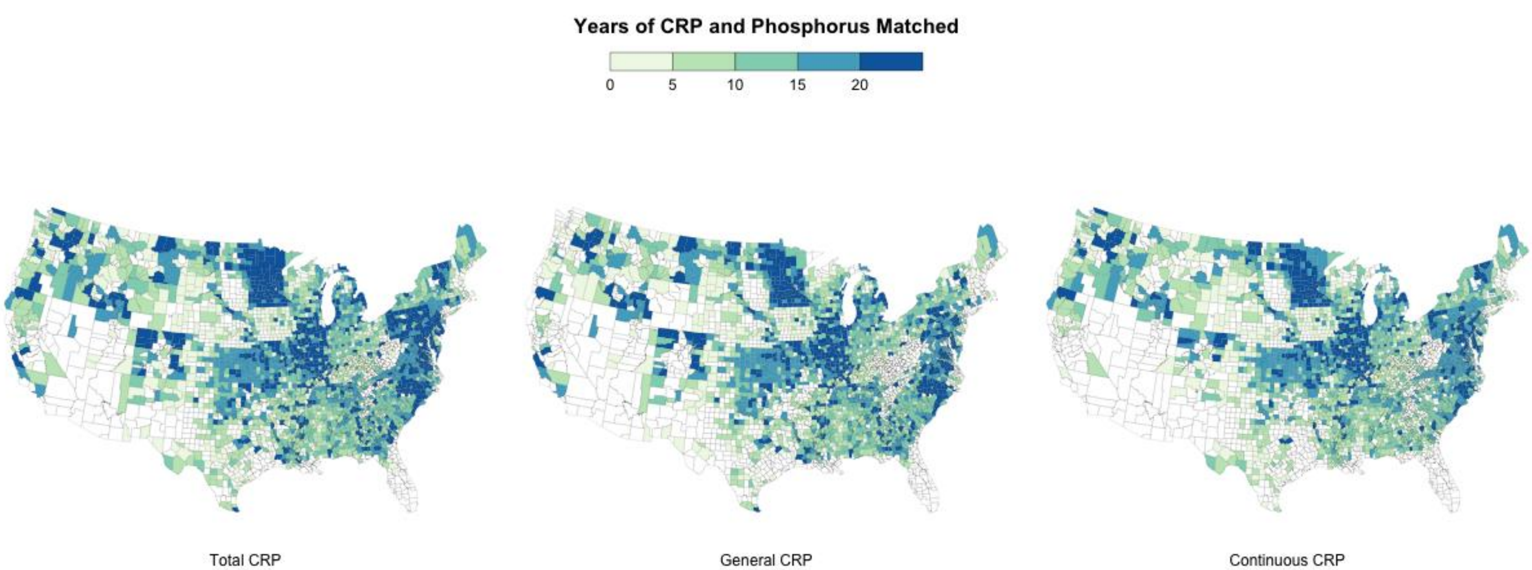

Figure 3. CRP enrollment by contract type (in million acres)

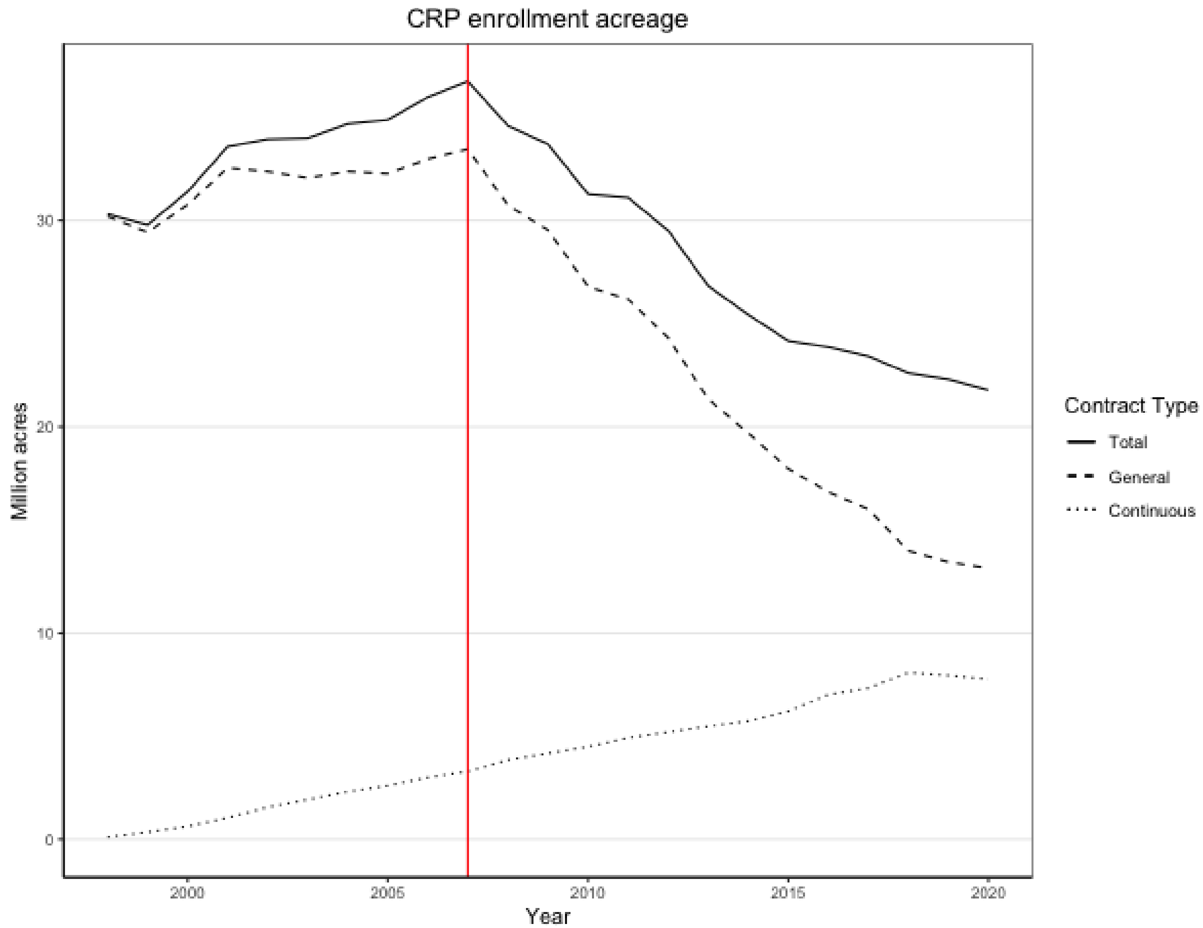

Figure 4. Total CRP enrollment by state: separate scale (in thousand acres)

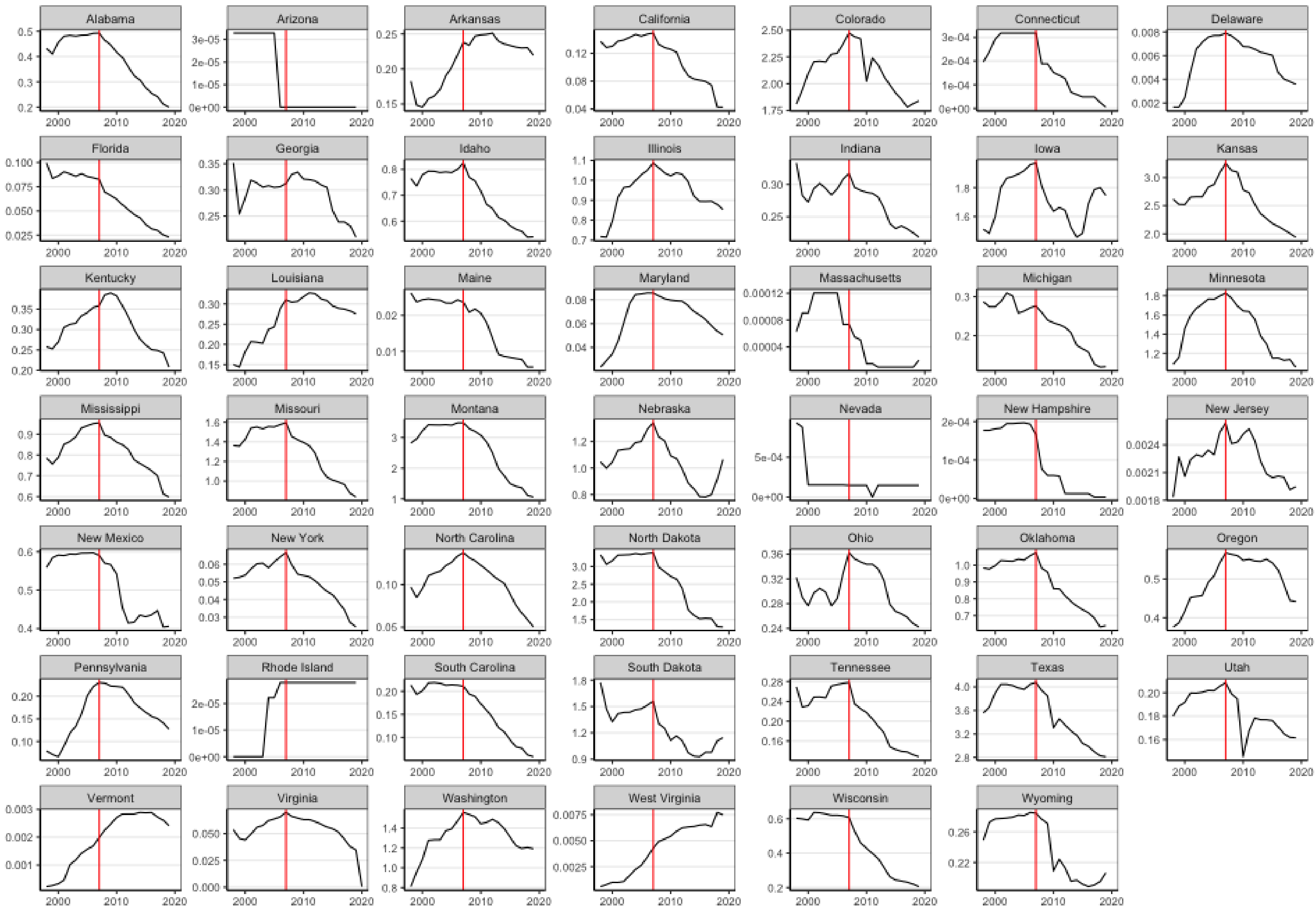

Figure 5. General CRP enrollment by state: separate scale (in thousand acres)

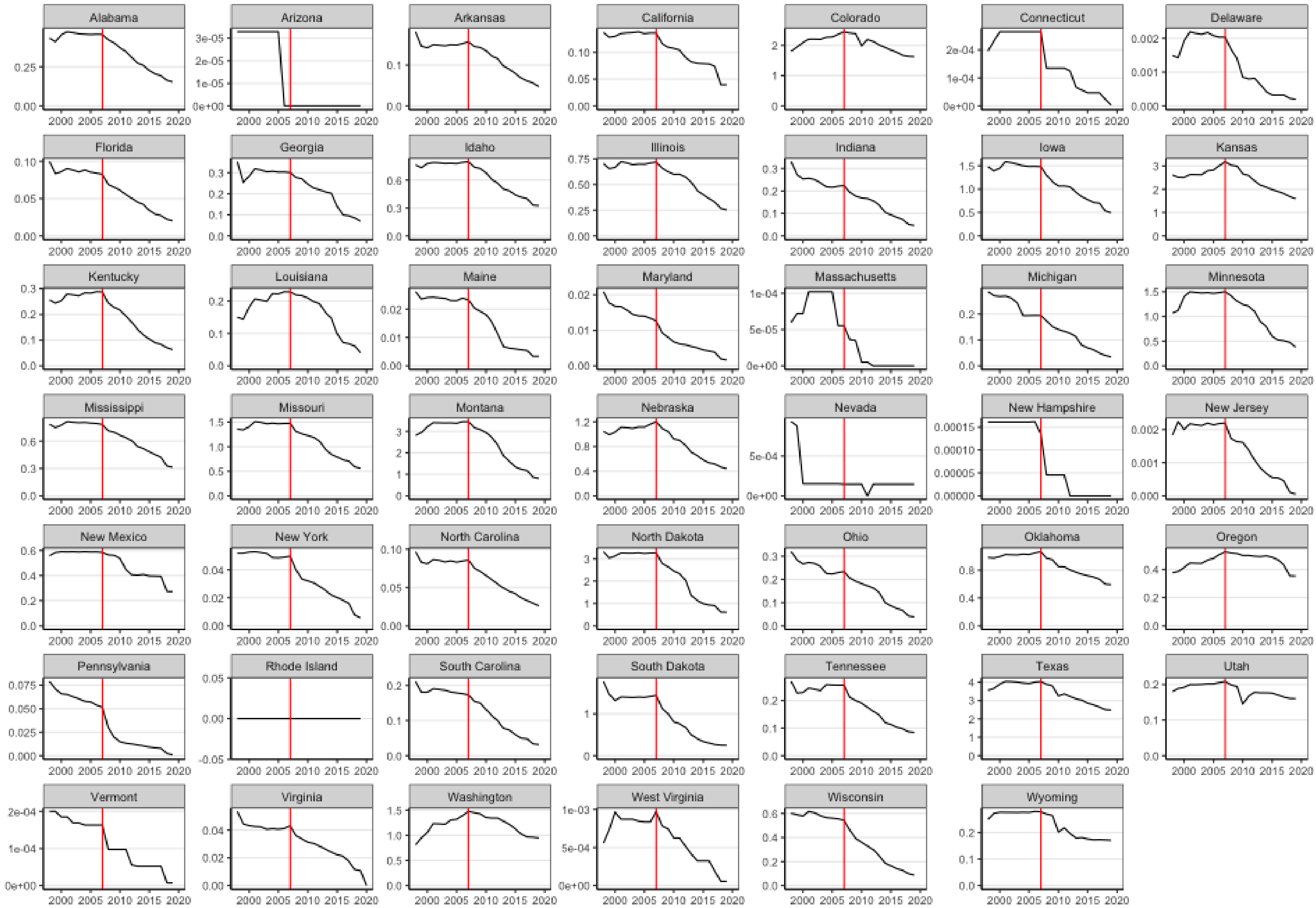

Figure 6. Continuous CRP enrollment by state: separate scale (in thousand acres)

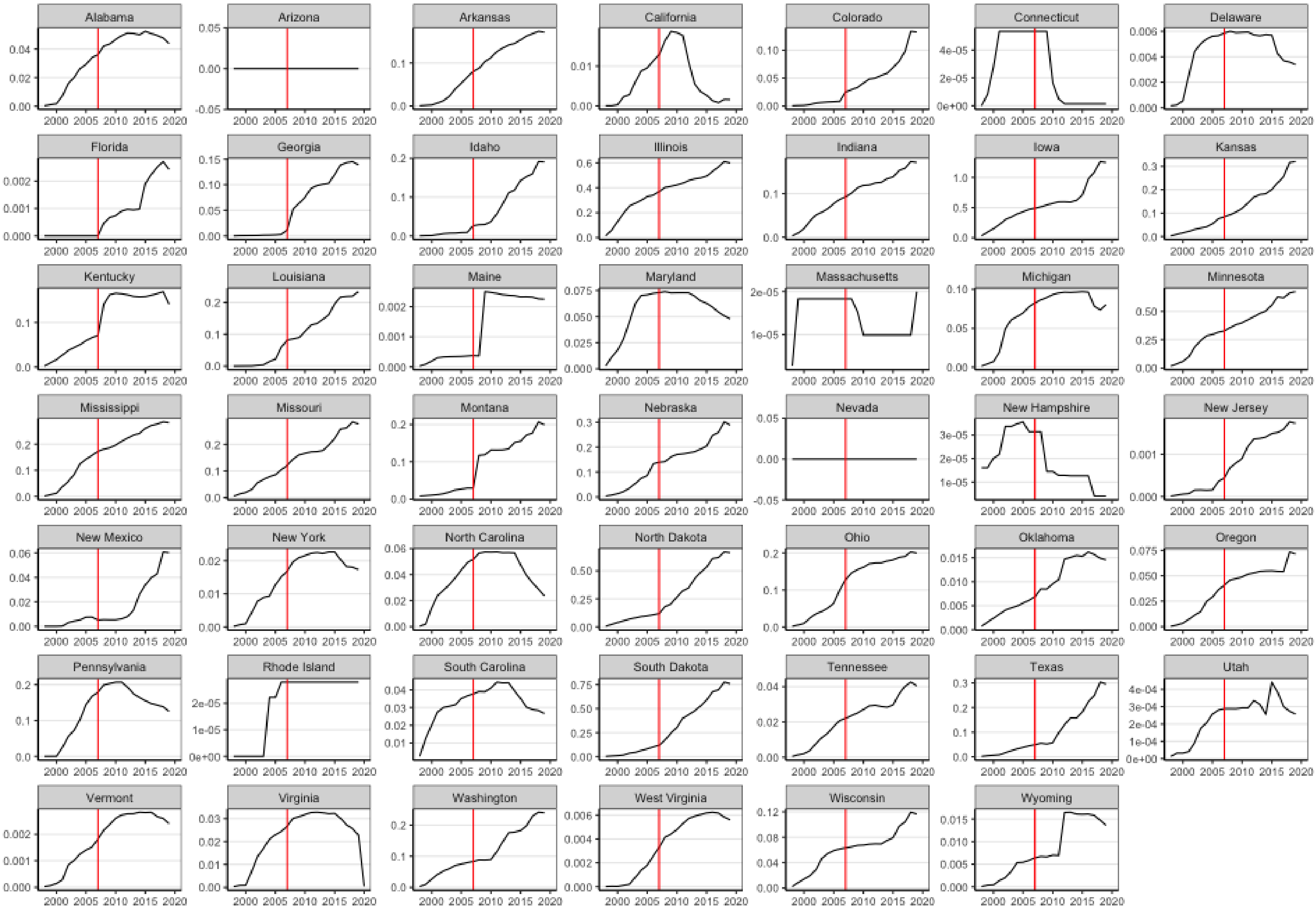

Figure 7. Maps of total CRP enrollment by year (in hundred acres)

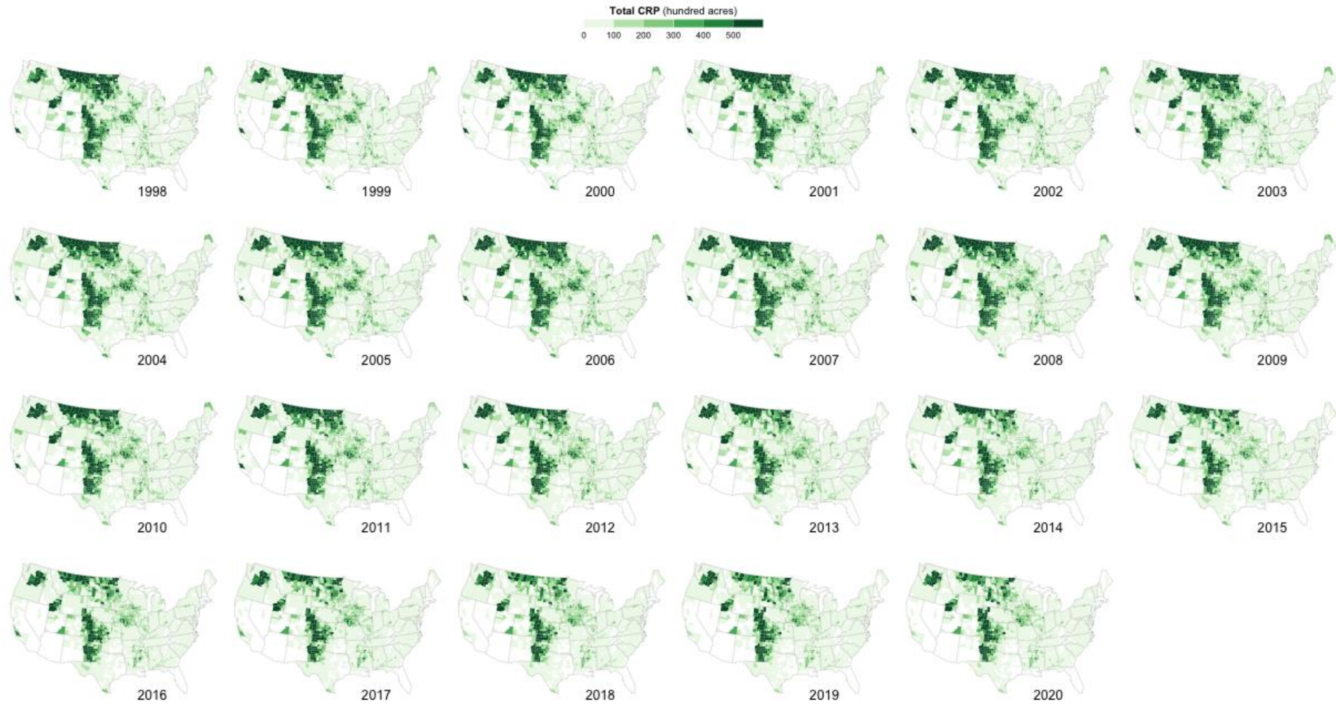

Figure 8. Maps of general CRP enrollment by year (in hundred acres)

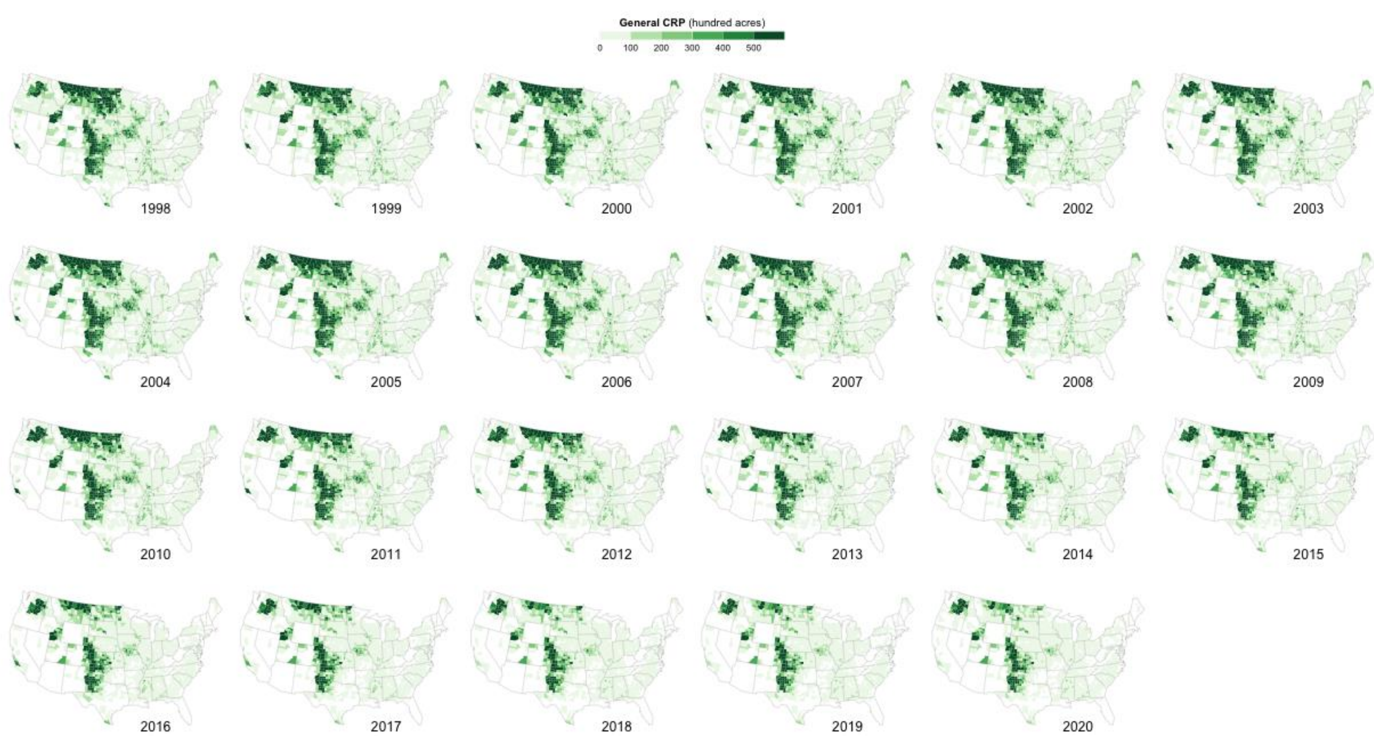

Figure 9. Maps of continuous CRP enrollment by year (in hundred acres)

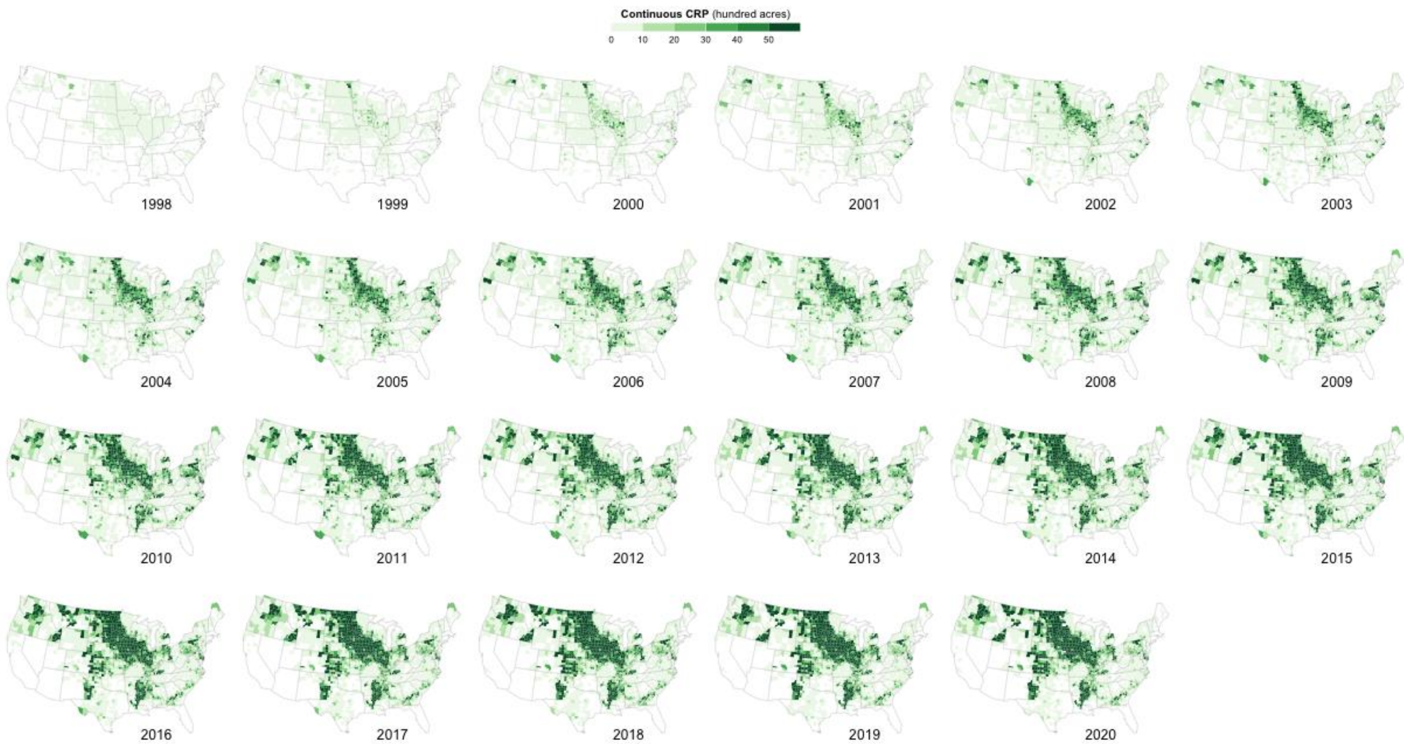

Figure 10. Average nitrogen concentration by type

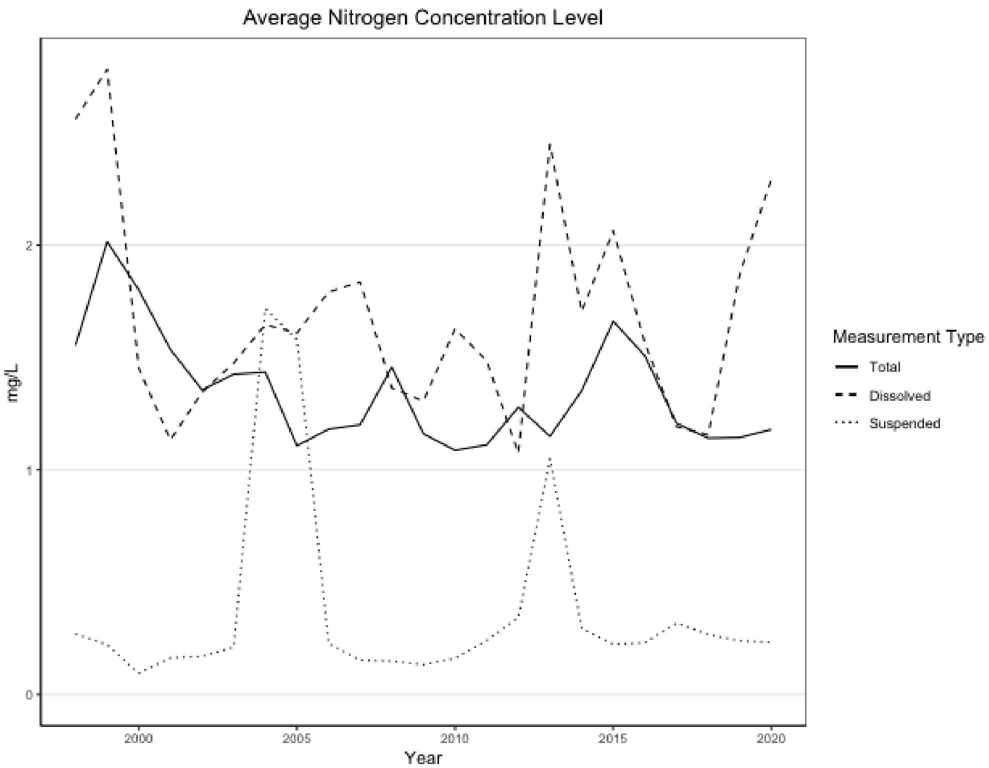

Figure 11. Average phosphorus concentration by type

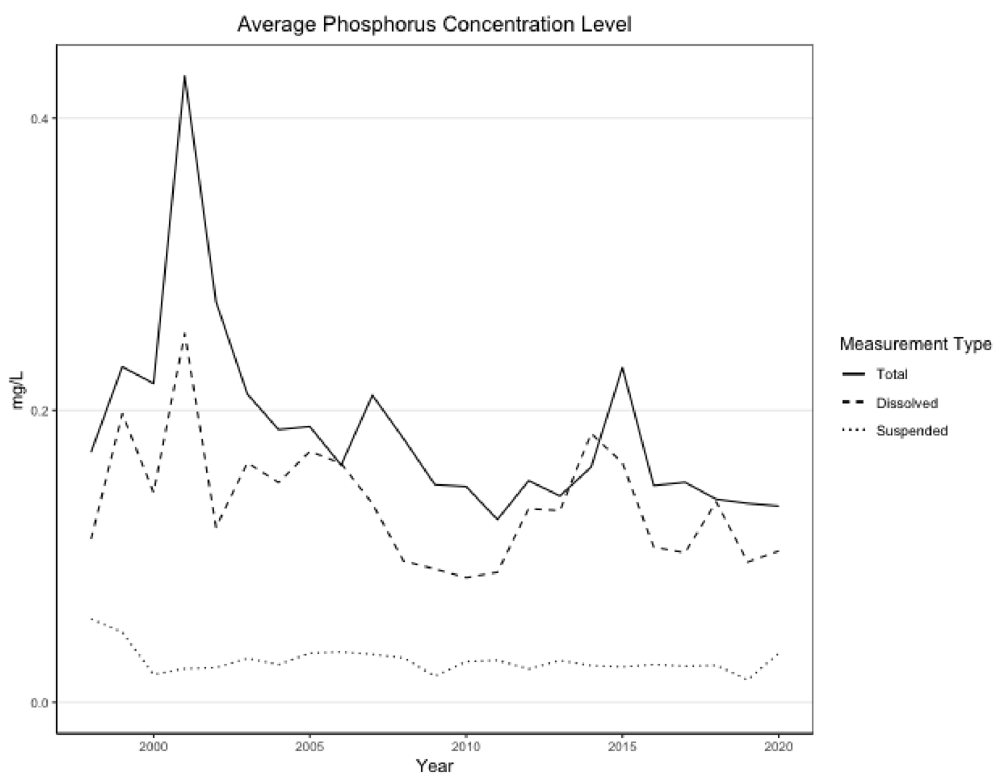

Figure 12. Maps of average total nitrogen concentration by year

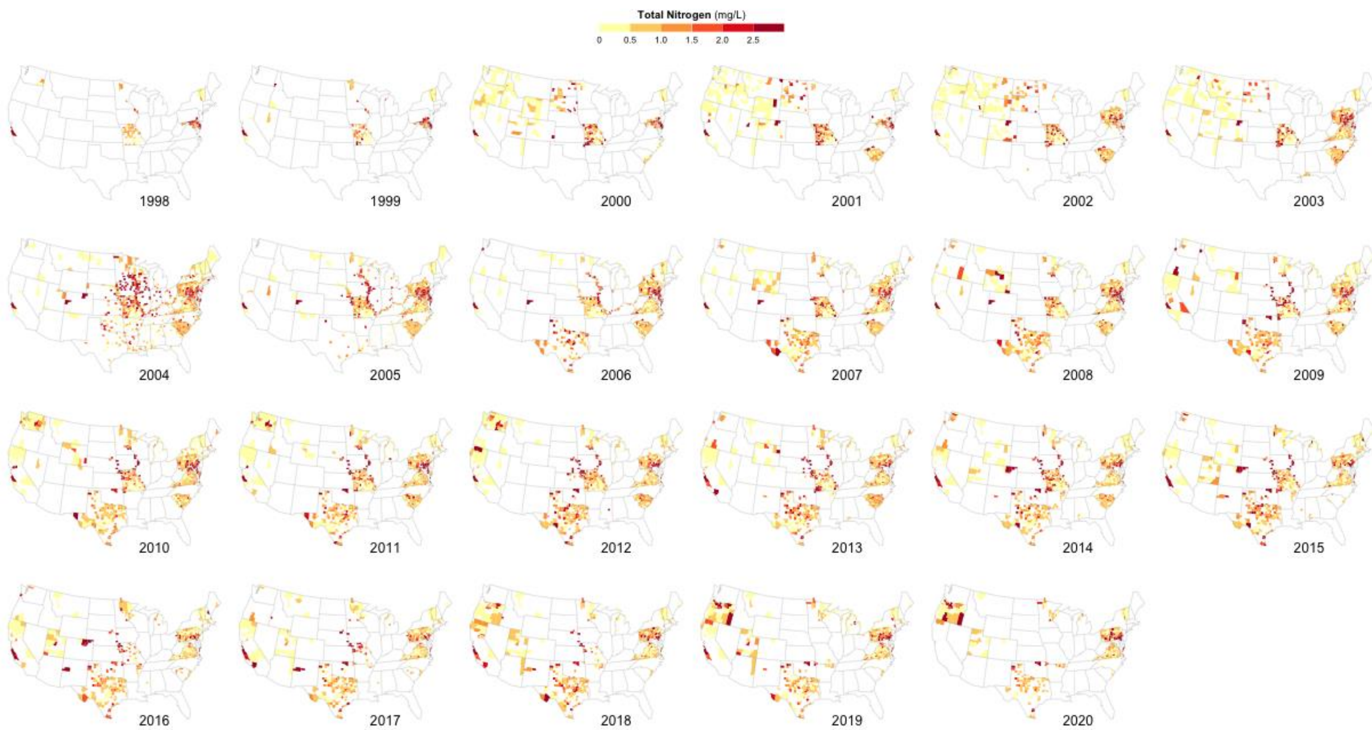

Figure 13. Maps of average dissolved nitrogen concentration by year

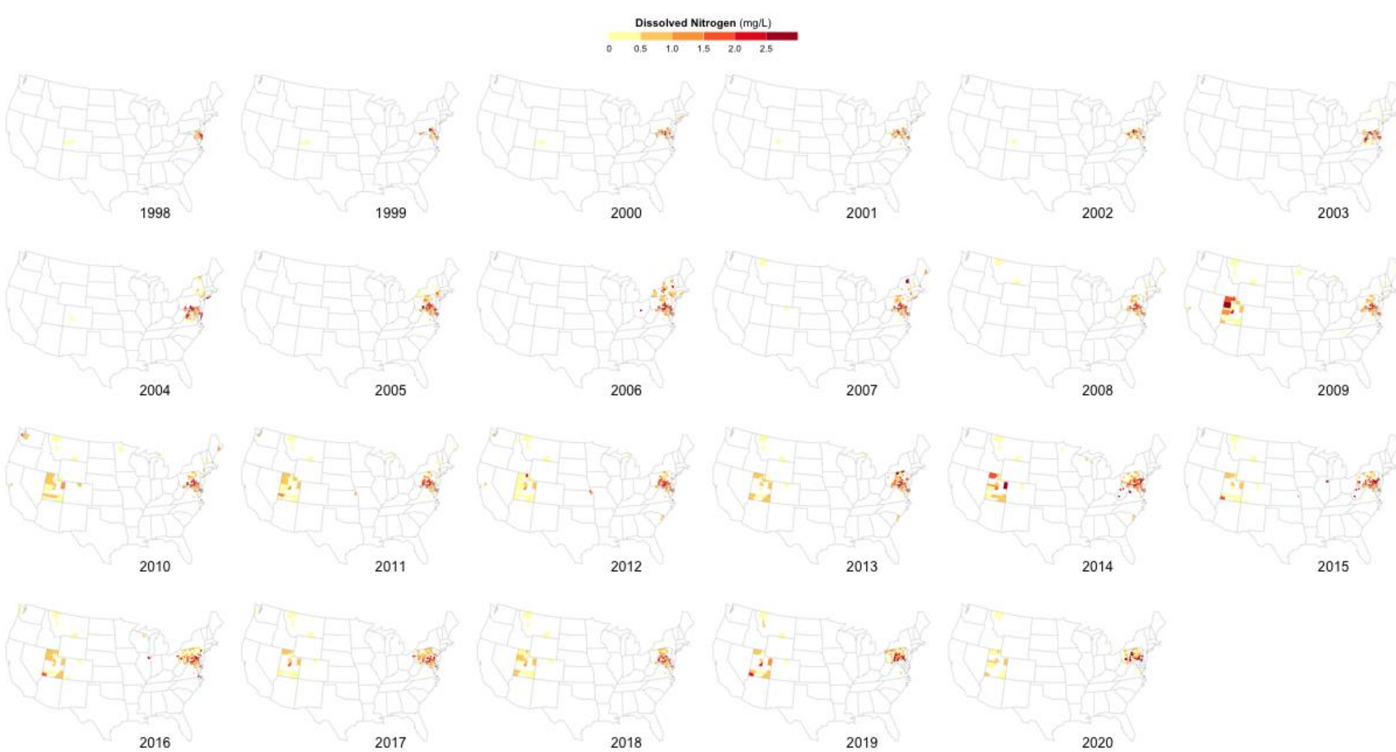

Figure 14. Maps of average suspended nitrogen concentration by year

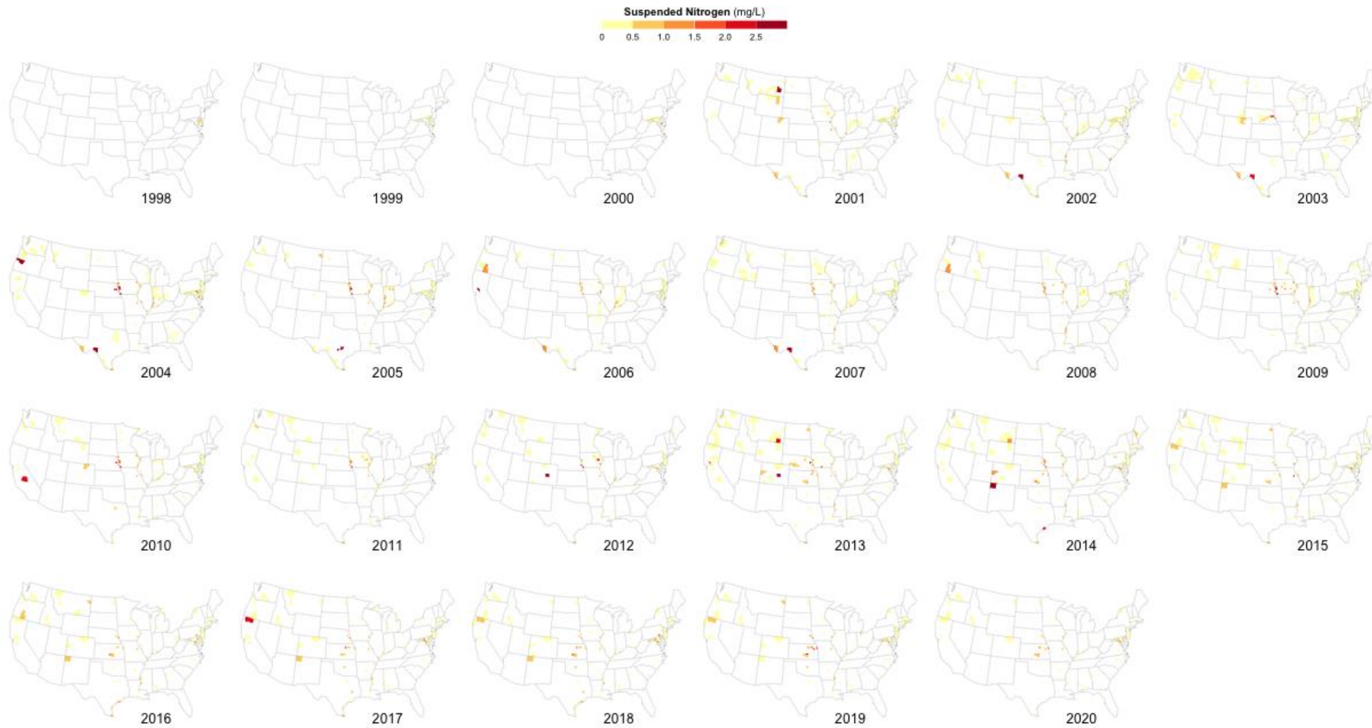

Figure 15. Maps of average total phosphorus concentration by year

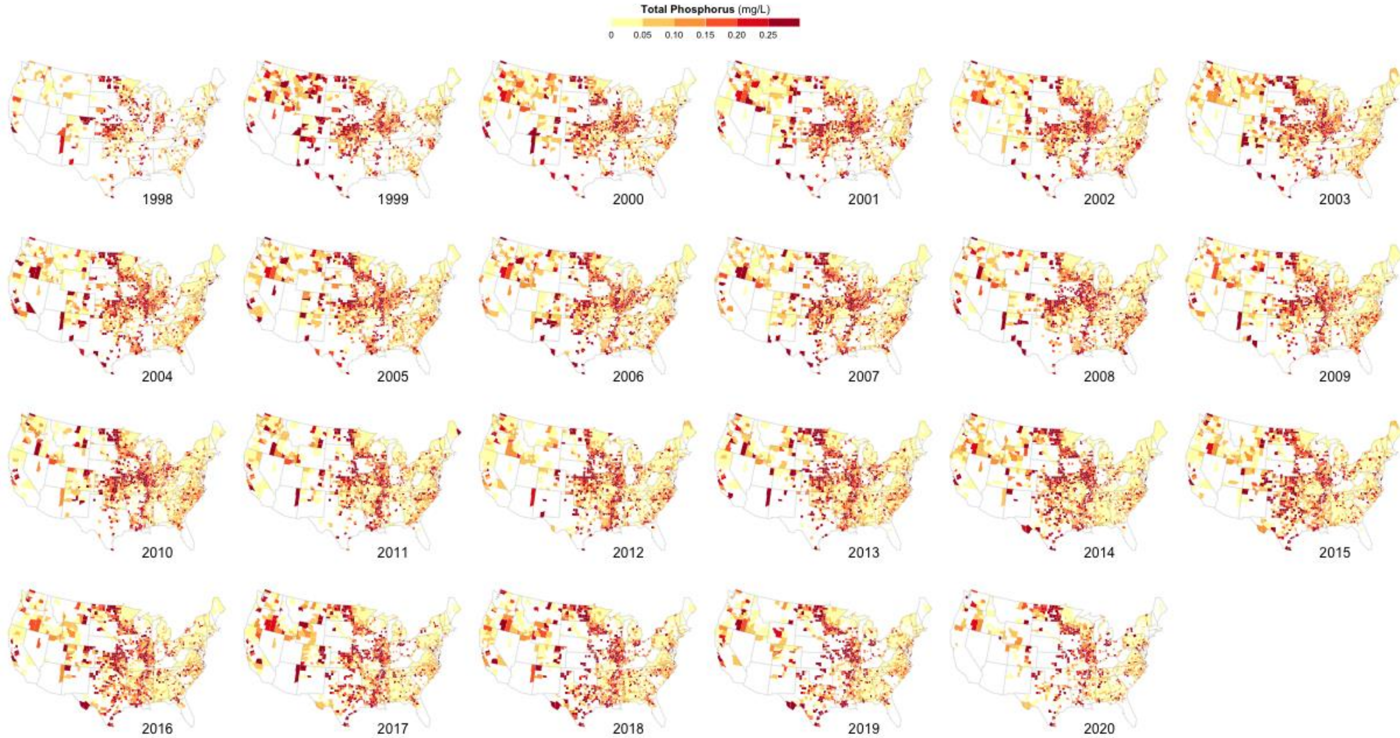

Figure 16. Maps of average dissolved phosphorus concentration by year

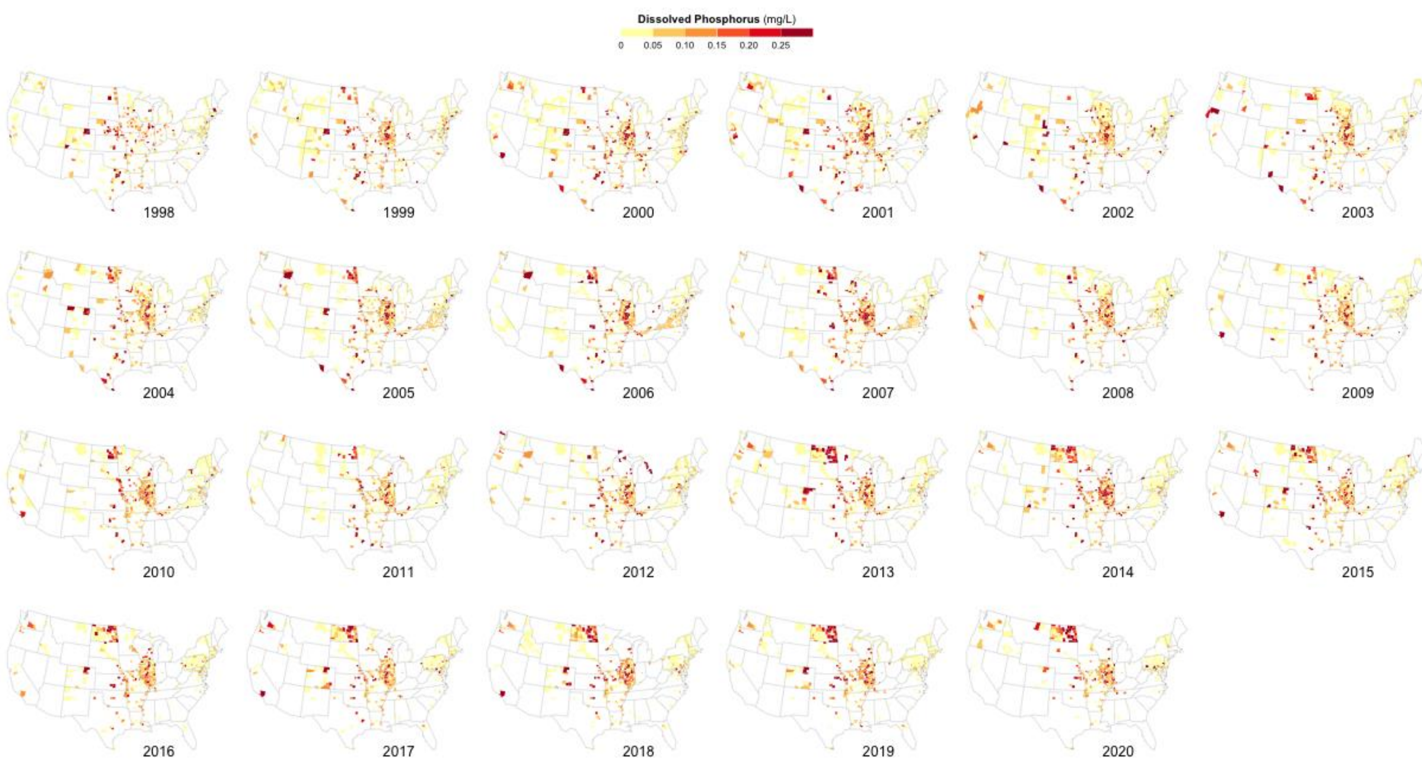

Figure 17. Maps of average suspended phosphorus concentration by year

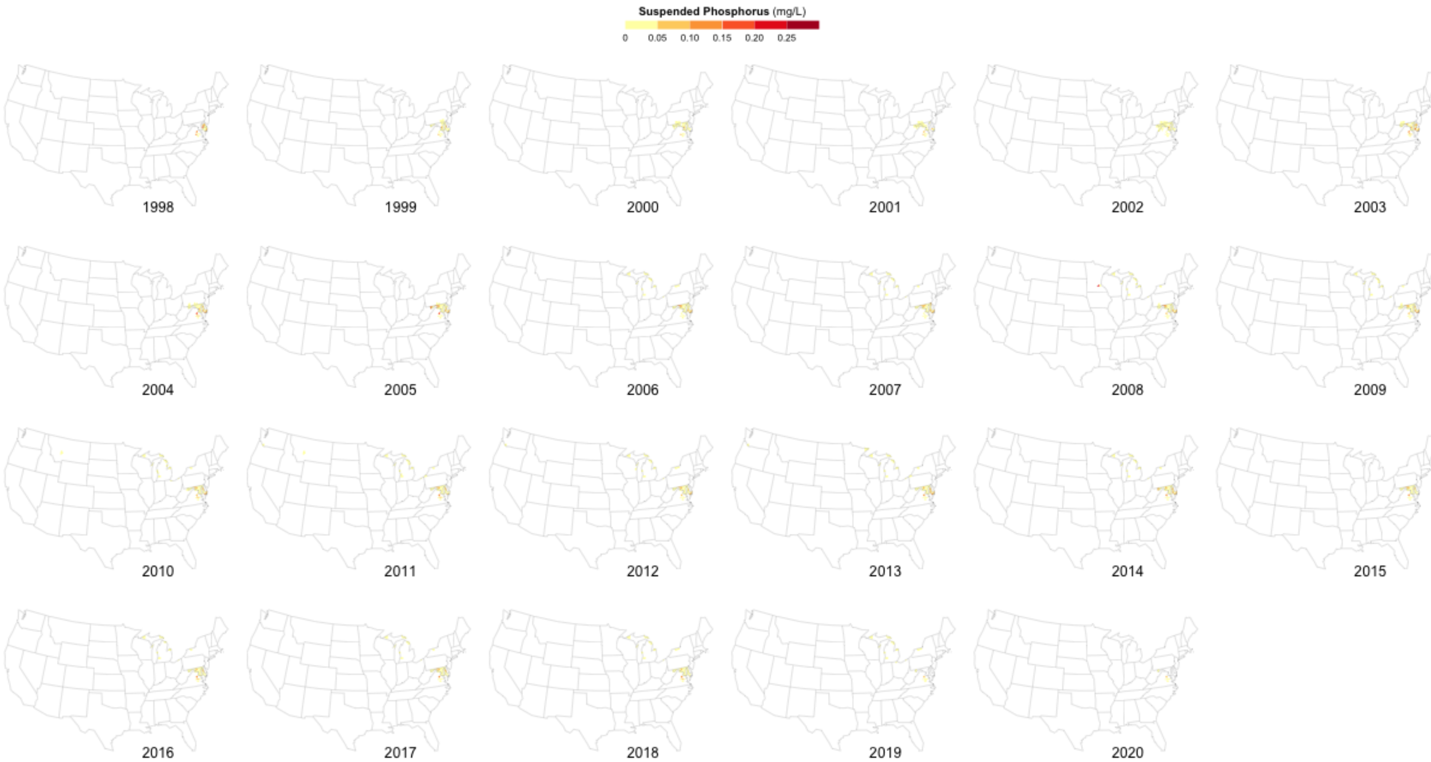

Figure 18. Outliers in nitrogen concentration by type

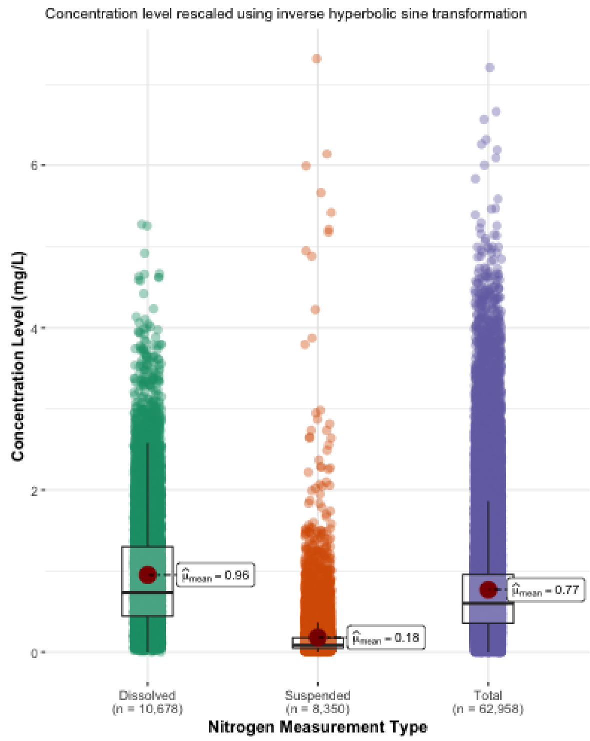

Figure 19. Outliers in phosphorus concentration by type