Water Quality, Policy Diffusion Effects and Farmers Behavior

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Abstract

We exploit the Nitrate Directive setting allowing for a geographical and temporal variation in policy implementation to investigate the impacts of a command-and-control policy on non-point source water pollution in France. We combine novel datasets on surface water quality and hydrographic network, considering upstream/downstream interactions between watersheds, to disentangle the policy diffusion effects on physicochemical and biological outcomes. Our results suggest a decreasing dose-response effect of the policy on nitrate concentration and a global improvement of water quality. We show that wastewater treatments and land use changes are unlikely to drive our results. We then explore changes in farmers behavior and practices as underlying explanatory mechanisms: the policy sharply increased the development of nitrate-fixing crops, improved the efficiency of nitrogen fertilizers use, decreased nitrogen losses to the environment and, perhaps surprisingly, boosted productivity while keeping the amount of nitrogen fertilizers used unchanged, revealing that the technological standards imposed by the regulation triggered a significant change in farmers behavior by better informing them on when and how to put fertilizers, ensuring in turn gains in productivity.

Keywords: Anthropogenic pressure, non-point source pollution, command-and-control policy, nitrogen, biodiversity, information, farmers behavior.

JEL Codes: D04, D80, Q01, Q25, Q53.

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1 Introduction

Human activities have sharply intensified since the second half of the twentieth century. Among them, agriculture became an important source of anthropogenic pressure: while agricultural productivity drastically increased to feed a growing world population, the other side of the coin has been a sizeable degradation of the environment.

During the past half century, the amount of nitrogen has increased more than any other elements in the environment worldwide: households and industrial sewages, but more importantly, runoff from fertilizers applied on lands by farmers have contributed to double nitrogen emissions (Leach et al. (2012)). Nitrates from agricultural sources became the most pervasive chemical contaminant in the worlds groundwater aquifers (WWAP (2013)).

Each year during crop season, farmers apply nitrogen fertilizers on their lands. As plants cannot soak up all the amount of nitrogen they receive, the remaining part is left in the atmosphere or discharged into waters through runoff or leaching (Canfield et al. (2010)). Although nitrogen occurs naturally in the environment, its excess quantity can lead to adverse changes: nitrogen by-products such as nitrates and ammonium may have an impact on *human health* through methaemoglobinemia, a potentially fatal illness for infants causing the blue-baby syndrome (Lundberg et al. (2004)) or can threaten *aquatic biodiversity*, inducing excess quantity of nutrients in waters, which in turn creates algal blooms and dead zones known as the eutrophication process (Canfield et al. (2010)).

The 2017 FAO report states that water pollution from agriculture is "*a global challenge that has increased in both developed and developing countries, undermining economic growth as well as the physical and environmental health of billions of people*." According to OECD (2012), the environmental and social costs of water pollution caused by agriculture exceed billions of dollars per year. To tackle this growing issue, the UN Environment Program recently launched a \$60-million research project gathering experts from around the world to foster global effort, highlighting the importance of protecting the ecological status of waters: "*we must halve the amount of nitrogen we dump into the environment by mid-century or our ecosystems will face epidemics of toxic tides, lifeless rivers, and dead oceans*."

In addition to a substantial increase in nitrogen fertilizers use that raised by around 800% from 1960 to 2000 in the world (Canfield et al. (2010)), nitrogen appears to be used inefficiently, with worsening trends in some countries (Zhang et al. (2015)). The *Nitrogen Use Efficiency* (*NUE*) is an output-input ratio that measures how efficiently nitrogen fertilizers are used. Lassaletta et al. (2014) shows that Asian countries are facing the worst performances: since the 1960's, *NUE* dropped from 56% to 34% in India and from 85% to 30% in China, meaning that most nitrogen is lost to the environment.

The Nitrate Directive, enacted in 1991, requires EU Member States to regulate farming practices in areas vulnerable to nitrate pollution. This regulation imposes to farmers a set of mandatory measures (mainly technological standards): seasonal restrictions and prohibitions on the application of fertilizers, the implantation of nitrate-fixing intermediate crops and grass-buffer strips along rivers, the building of storage facilities for manure and the use of the *nitrogen balance method*, a method allowing to determine the amount of nitrogen to apply on lands as a function of the target yield and the amount of nitrogen remaining in the soil after winter season or from the previous crop. The policy also includes audits to control for the effective enforcement of these requirements by farmers. The Nitrate Directive is a unique piece of regulation. For example, no similar regulation exists in the U.S. The Clean Water Rule enacted by the Environmental Protection Agency in 2015 and recently threatened by an executive order is of a much more limited scope.

We study the effects of the implementation of the Nitrate Directive in France, one of the largest farming countries in the EU where pollution by nitrates is the most severe. The bulk of the Nitrate Directive regulation was implemented in France from 2001. Vulnerable areas cover approximately 70% of the utilized agricultural area and 40% of the territory. The map of vulnerable areas is modified and slightly extended each four years.

This directive has raised many debates on the political stage in France. First, the question of its real effectiveness in improving water quality remains unclear. France has faced litigations and threat of penalties from the European Commission because of a so-called improper application of the European directive and its inability to improve its surface and ground water quality. Second, the application of this policy is a continuous source of discontents, considered as too costly by many farmers in terms of investments and administrative burdens. In 2014, the main French Agricultural Syndicate organized a strike where thousands of farmers were mobilized to protest against the designation of vulnerable areas, and stressed that it became more and more complicated to fulfill the new administrative and environmental norms of the policy.

This paper seeks to shed light on these controversies in examining to what extent the Nitrate Directive improved surface water quality and biodiversity in France. To disentangle the impacts of the policy, we combine novel datasets on surface water quality over the period 1994-2015 with more than 400,000 observations from 2,800 monitoring stations covering all the territory (measurements of physicochemical outcomes such as nitrates, phosphorus, ammonium, dissolved oxygen and chemical oxygen demand (COD) and biological outcomes like chlorophyll A concentration, a proxy for eutrophication, the number of fishes observed and an invertebrate index) and hydrographic network data to provide information on the river flow direction, i.e. upstream-downstream interactions between watersheds.

Contrary to Keiser and Shapiro (2017) that study point source pollutions, the key methodological novelty of our study is the identification of the policy effects on non-point source pollution, that is harder to pin down compared to point-source pollution, as diffuse pollution results from dispersed and non-identifiable emitting sources. Our identification strategy is twofold. First, we break new ground in creating a treatment intensity indicator that measures, for each monitoring station, the proportion of all vulnerable areas that are located in upstream watersheds. We thus account for the fact that an improvement in water quality in a given watershed might affect water quality in watersheds located downstream, allowing us to disentangle policy diffusion effects. Second, we take advantage of the geographical and temporal variation in policy implementation to use a difference-in-differences strategy: we compare changes in outcomes in watersheds more affected by the policy (*high treatment intensity*) and in watersheds less affected by it (*low treatment intensity*) before and after its introduction. We specifically consider surface waters as we think that the policy effects should be more direct in rivers and streams compared to groundwaters in which nitrogen stock accumulates.

Our results show that the Nitrate Directive has significantly reduced nitrate concentrations in surface waters by -1.231mg/L in areas with a treatment intensity higher than 25%. More interestingly, we find that the higher the treatment intensity, the stronger the decrease in nitrate concentrations: results show a significant reduction in nitrate concentration of -0.879mg/L, -1.523mg/L and -2.436mg/L in areas receiving a treatment intensity of [50%-75%[, [75%-100%[and [100%] respectively. We also performed an heterogeneous analysis by seasons and hydrographic districts and found that the biggest drop in nitrate concentration occurs during winter (crop season), and in Loire-Bretagne (a region specifically concerned by nitrogen issues and algal blooms) and Seine-Normandie hydrographic regions. The policy also improved the physicochemical state of surface waters in terms of phosphorus, ammonium, dissolved oxygen and chemical oxygen demand (COD). Finally, we find a noticeable improvement in the biological state of rivers: in areas receiving a treatment intensity higher than 25%, chlorophyll A concentration, a proxy for eutrophication, significantly decreased by -2.699μg/L and the number of fishes significantly increased by 39.25 in the average monitoring station. In addition, we show that wastewater treatments and land use changes are unlikely to drive our results.

In a second part, the study of the mechanisms through which this policy has operated corroborates our findings: using a difference-in-differences strategy, we investigate the potential changes in farmers practices and behaviors imputed to the directive. We find that the policy increased parcels on which nitrate-fixing intermediate crops are applied by 6.6%points, but we observe no impact on grass buffer strips. We also find that the amount of phosphorus and organic fertilizers applied on lands decreased by 3.030kg/ha/year and 1.634kg/ha/year respectively. Surprisingly, the policy did not change the amount of mineral nitrogen fertilizers dumped on plots but it did improve the efficiency of nitrogen fertilizer use: the *Nitrogen Use Efficiency* indicator, measuring how efficiently nitrogen is used, increased by 28.262%points and the *N balance* indicator, estimating nitrogen loss to the environment, has significantly dropped in treated areas (-29.037%points). Hence, the *N output*, an indicator measuring yields in terms of nitrogen, significantly increased by 29.574%points. These results reveal that the technological standards imposed by the regulation triggered a significant change in farmers behavior by better informing them on when and how to put fertilizers, ensuring in turn gains in productivity.

There is, to the best of our knowledge, little robust evidence of whether a command-and-control regulation can effectively mitigate non-point source water pollution (Dowd et al. (2008)). While Duflo and Pande (2007) consider distributional impacts of dams construction in upstream and downstream districts, our study seems to be the first that uses upstream-downstream interactions between watersheds in treatment intensity to disentangle policy diffusion effects in rivers. Most researches that focus on diffuse pollution concern air pollutions (Chay and Greenstone (2003), Jayachandran (2009)). The few research studies that consider non-point source water pollution are essentially correlation studies (Lungarska and Jayet (2014)) or evaluate the effects of water pollution on health like Brainerd and Menon (2014) using seasonal variations in fertilizer use but without controlling for pesticide levels, or assess the seasonal effects of nitrogen losses to the environment (Chhabra et al. (2010)). Though, several papers examine the impacts of water regulations on point-source pollution. Greenstone and Hanna (2014) and Ebenstein (2012) light up the ineffectiveness of water pollution regulations in India and China, when Keiser and Shapiro (2017) show that the U.S. Clean Water Act that provided investments in wastewater treatment plants contributed to significant improvements in U.S. surface water quality. Finally, our results on farmers behavior contribute to a broader literature on environmental regulation and information, showing that a regulatory framework, by enforcing technological standards to decrease pollution (Porter and Van der Linde (1995), Ambec et al. (2013)) and by providing information disclosure (Jensen (2007)), can affect behaviors and lead to an increase in productivity, enforcing a more efficient use of resources and decreasing waste.

The paper proceeds as follows. Section 2 and 3 provide backgrounds on nitrogen anthropogenic pressures and the Nitrate Directive setting. Section 4 describes the data sources. Section 5 examines the impact of the regulation on physicochemical and biological outcomes. Section 6 analyzes the explanatory mechanisms of the policy. Section 7 discusses potential confounding factors. Section 8 concludes.

2 Nitrogen Anthropogenic Pressures

2.1 The Nitrogen Cycle

Nitrogen, the fifth most abundant component in our planet, occurs naturally in the environment. It is converted into multiple chemical forms such as nitrate (NO_3^-), ammonium (NH_4^+), nitrite (NO_2^-), nitrous oxide (N_2O), nitric oxide (NO) or nitrogen gas (N_2) as it circulates into waters, air and soils, through a biogeochemical cycle called the *nitrogen cycle*. As nitrogen N itself is almost inert, it is its inorganic forms, nitrate and ammonium, that have more impacts on land and aquatic ecosystems.

The two main processes of the nitrogen cycle are nitrogen fixation and denitrification (Canfield et al. (2010)). Through the *nitrogen fixation* process, bacteria reduces nitrogen gas N_2 in the atmosphere into ammonium NH_4^+ in lands or waters. In the presence of oxygen, ammonium is oxidized by bacteria into nitrites (*nitrification*) which are in turn oxidized into nitrates (*nitration*). Greenhouse gases N_2 are also produced during this process. As most organisms cannot fix nitrogen, they get it from ammonium or from the reduction of nitrates into ammonium.

Canfield et al. (2010) posit that a substantial amount of the nitrogen transfer from the lands to the oceans stems from a combined loss of anthropogenic nitrogen through rivers and nitrogen atmospheric transport.

2.2 Human-Induced Changes to the Nitrogen Cycle

Over the last century, human activities considerably intensified. In particular, humans started to disrupt the global nitrogen cycle in developing and producing nitrogen fertilizers, introducing agricultural practices boosting crop yields and burning fossil fuels. Intensive agriculture appears to be one of the most sizeable drivers of anthropogenic nitrogen affecting land, water and air quality (Canfield et al. (2010)).

Crops need nitrogen to grow. Each year during crop season, farmers apply nitrogen fertilizers on their lands. Then, rains wash fertilizers off lands into rivers and streams. Crops can only fix a certain amount of nitrogen to grow (on average, only 50% of nitrogen applied is absorbed by plants). When an excess amount of fertilizer is dumped, the remaining 50% are left is transferred either into the atmosphere or into groundwaters by leaching or surface waters through runoffs. This excess concentration of nutrients leads to a lack of oxygen content in water bodies, namely the *eutrophication* phenomenon, creating dead zones (hypoxic areas) and threatening biodiversity. Figure 1 illustrates the disruption of the nitrogen cycle by human activities.

Canfield et al. (2010) report that from 1960 to 2000, nitrogen fertilizers use raised by around 800%, with wheat, rice and maize as main crops. The *nitrogen use efficiency*, a yield-fertilizer input ratio, is typically below 40% for these crops, implying that most applied fertilizers are lost into the environment. Worldwide, ammonium is the most commonly used fertilizer. Through the nitrogen cycle, it can be converted into highly mobile nitrates which in turn pour into waterways.

Since the past half century, nitrogen has increased more than any other elements in the environment worldwide (Leach et al. (2012)) Different policies have been implemented to tackle this growing issue. The EU Nitrate Directive is one of the most prominent one.

3 Political Background

3.1 The Nitrate Directive setting

In 1991 the European Union implemented the Nitrate Directive, a policy aiming at protecting water bodies across European countries by preventing nitrates from agricultural polluting sources and by promoting the use of good farming practices.

The designation of vulnerable areas

This policy was transposed into French law in September 1993 in a decree that defined for the first time *vulnerable areas* as areas containing watersheds that are polluted or threatened by pollution.

1. **Vulnerable area** = area containing surface and ground waters with a concentration of nitrate higher than 50mg/L or between 40mg/L and 50mg/L with no improvement trends and/or showing signs of eutrophication linked with intensive agriculture.

2. **Eutrophication** = excess concentration of nutrients in waterways leading to algae blooms, less oxygen content (hypoxia state) and imbalances in aquatic ecosystems.

3. **Watershed** = area of lands containing portions of surface waters and groundwaters where precipitations collect and flow into a common mouth.

In France, *vulnerable areas* have been designated throughout different waves: 1997, 2000, 2003, 2007, 2012 and 2015. The waves 1997 and 2000 are roughly the same and from that date areas designated as vulnerable evolved very little (an increase of surface areas of less than 10% points from 2000 to 2012). In this study, we focus on the period 1994-2015 due to water quality data constraints and because vulnerable surface areas evolved very little from

1997 to 2015. Figure 2 shows a map of the evolution of vulnerable areas from 1997 to 2015. Table 1 presents the vulnerable areas successive waves.

Waves	**1997-2002**	**2003-2006**	**2007-2011**	**2012-2015**
Vulnerable areas surface	213,000	240,000	244,000	255,000
France total surface	550,700	550,700	550,700	550,700
Proportion	39%	43%	44%	46%

Table 1: Vulnerable Areas Successive Waves

The implementation of mandatory measures

The Nitrate Directive is a *command-and-control* policy: on the one hand, a threshold level of pollution and a list of mandatory measures on farming practices, i.e. technological standards, are defined by the regulator (*command*) and on the other hand, the regulatory framework plans to control for the use of good farming practices by randomly performing audits in farms (*control*) and plans to measure on a regular basis the pollution level in French waterways. Dozens of controls are carried out each year among farms per department and a fine has to be paid in case of non-compliance (from €1,500 to €3,000 in case of recidivism). The regulatory framework also provides subsidies for livestock manure storage.

The *first action program* (1997-2000) was a minor program that concerned mainly nitrogen application standards. Our analysis focuses on the *second action program* (2001-2004) defined by a decree in January 2001: from this date, more biding and reinforced measures have to be implemented in vulnerable areas. Some regions can specifically enforce complementary/reinforced measures such as a greater restrictions in nitrogen manure spread on fields. The following programs (2005-2007, 2008-2011, 2012-2015) are in the same vein. Figure 3 displays a historical timeline of the policy with the detailed action programs sets of measures. The measures we focus on are derived from the second action program and remain broadly unchanged from 2001:

- balanced fertilization between estimated nitrogen crop needs and fertilizer inputs
- threshold quantity of 170 kg/ha/year for manure spreading on fields
- nitrogen application standards depending on soil and weather conditions
- respect of periods of prohibition on spreading manure
- respect of storage livestock standards

– record farming practices

– adapted land management regarding crop selection

– development of nitrate-fixing intermediate crops

– development of grass buffer-strips

– restriction of nitrogen input use

Besides enforcing mandatory measures particularly through technological standards, this regulation provides guidance and information to help farmers changing their practices towards better proenvironmental behaviors such as information on crop nitrogen contents, on when and how to put fertilizers and methods like the *nitrogen balance method* to estimate nitrogen amounts left on the ground after winter season or from previous crops.

3.2 A Controversial Policy

The Nitrate Directive raised many debates, considered as too costly by farmers in terms of investments and administrative charges. France also faced litigations and threat of penalties from the European Commission concerning the application of this policy.

We conducted an interview with the Regional Department of Environment that posits two main concerns about the Nitrate Directive in France: concerning its effectiveness, it would appear that it did not have effective impacts in improving water quality, but also, regarding farmers' complaints about the regulatory framework of the policy imposing too much charges and complexity, in particular concerning insufficient storage capacity and investments needs.

Interviews in newspapers corroborate these outlines. In 2014, the main French Agricultural Syndicate organized a strike where 35,000 farmers were mobilized protesting against the future wave of vulnerable areas. One of them stated in *Le Figaro* newspaper: "*This policy imposes too heavy administrative burdens, because of it I will soon start to work at 2 p.m. before being able to work in the fields, since it becomes more and more complicated to fulfill the new administrative and environmental norms.*"

France has also been condemned several times by the European Court of Justice for its inability to improve its surface and ground water quality. It faced different litigations for not having respected the Nitrate Directive: according to the European Court of Justice, the French regulation has been too lenient, especially concerning the dates and durations of prohibition on spreading manure. The European Court of Justice ordered France to revise its action programs, in particular concerning the control and fees in case of non-compliance from farmers. After two years of discussion with the European Commission, litigations finally end.

All these controversies illustrate a genuine need to disentangle the consequences of this policy. In fact, despite the pieces of information either from the ligations with the European Commission or the feedbacks from the Regional Department of Environment and from some farmers, there is very little, if any, robust evidence of whether the effectiveness of this policy is real.

4 Data

We combine French hydrographic network data with novel datasets on surface water physicochemical and biological quality to assess the potential diffusion effects of the policy from upstream to downstream. We use public data and French decrees to have information on the application of Nitrate Directive measures and geographic information on vulnerable areas. Additionally, we use data from the Cultural Practices Surveys to explain the mechanisms of the policy. To control for the potential factors that might confound our results, we use data on wastewater treatment plants date of creation and capacity, land use changes, and monthly climate data (rainfall and temperature). We describe each of these data sources in the following subsections.

4.1 Policy Implementation Information

We first use information from the French law decrees, publicly available on the French government website. These decrees define the Nitrate Directive framework regarding the designation of vulnerable areas and the successive action programs from which are derived mandatory measures. To have spatial data on vulnerable surface areas, we exploit vulnerable areas GIS-based maps from 2000 to 2015 available on the government website. In addition, we contacted the six different Water Agencies to have the successive lists of communes designated as vulnerable over 1997-2015 to complement the information provided by the GIS-based maps. Figure 2 presents the different waves of vulnerable areas from 1997 to 2015, at the watershed level.

4.2 Hydrological Network Data

We used data of the French hydrographic network from the French National Geographic Institute to have information on upstream-downstream relations for each river making up the network. The hydrographic network of mainland France is divided into six main hydrographic districts, which are subdivided into 6108 watersheds, finest scale of catchment areas available from the hydrographic network. This network is composed by 4 types of watersheds depicted in table 2. Figure 4 displays French surface water network and the corresponding designed hydrographic network.

Type of Watershed	**Description**	**Proportion**
Intermediate zone	Zone with at least one upstream and one downstream watersheds	60%
Upstream zone	Zone with no upstream watershed and at least one downstream	34%
Downstream zone	Zone with no downstream watershed and at least one upstream	2%
Isolated zone	Zone with no upstream and no downstream watershed	4%

Table 2: Description of The Hydrographic Network

We exploited two kinds of hydrological data: first, GIS-based maps of the French hydrological network and second, datasets containing all the network arborescences, i.e. the detailed chains of watersheds from the upstream watersheds to the downstream watershed by which rivers are flowing to the sea. From these data, we created a dataset that assigns to each watershed, itself and its upstream watersheds by level (from level 0 to level 99). This final dataset describes the flow direction of each river in terms of watershed and helps us building the treatment intensity indicator required to assess the policy diffusion effects.

4.3 Water Quality Monitoring Stations Data

Novel datasets managed by the French public service Eau France and the national data interface Naïade provided us with surface water quality data such as *physicochemical parameters* (nitrate, phosphorus, ammonium, dissolved oxygen, etc.) and *biological parameters* (chlorophyll A as a measure of quantity of algae in waters, a proxy for eutrophication, number of fishes, invertebrate index). These rich datasets gather all the data collected by Water Agencies and the French Biodiversity Agency. We focus our analysis on surface water as we think that the effect of the policy will be more direct compared to ground waters where nitrogen content N is a stock. Surface water quality has been measured in France since 1971, and from that date, the number of monitoring stations is gradually increasing. The number of analysis per monitoring station has sharply increased from 1993-1994 and the network was sparsely covered before that date. Furthermore, it is noteworthy that not all monitoring stations have the same number of measures per parameters, the total number of measurements varies from one parameter to another.

The water quality monitoring network is homogenized to ensure a properly and objective representation of the actual level of water quality, taking into account not only downstream zones that are usually the most polluted but also median and upstream zones that are supposed to be less affected by pollution. However, the water quality measurements of some polluted areas that need precise and short term follow-up of quality are also included in the datasets and might drive the results upward in terms of pollution.

In our empirical analysis, we focus on the period 1994-2015 and selected data from monitoring stations having at least measurements over 5 years to avoid measurements from short operational follow-up monitoring and to draw up an objective map of surface water quality. We also selected monitoring stations with at least one measurement before 2000 as we want to focus on the second action program that begins in 2001. Our benchmark is a balanced panel of data for which each station has at least one measurement for each year over 1994-2015. But the number of observations is much smaller with the balanced panel, which increases sampling noise. Hence, we chose to perform our study on the selected panel dataset with at least 5 measurements over the period under study and one measurement before the implementation of the policy, as the water pollution trends are similar to the balanced panel. Figure 5 shows a map of the 2,800 water quality monitoring stations of the final dataset.

4.4 Climate Data

To control for any annual or monthly variations due to weather conditions, we use a database from Météo France providing us with information on monthly average temperatures and precipitations over the period under study 1994-2015.

4.5 Farming Practices Data

To explain the mechanisms that have contributed to improve water biological quality regarding anthropogenic nitrogen pressure, we use two agricultural databases: the French Cultural Practices Survey (farming practices) and the National Agricultural Census (land use change).

The French Cultural Practices Survey aims at collecting detailed information on field crops and grasslands at the plot level, describing the cultivation techniques that characterize farming practices, the production strategies of the farm and its environmental approach. These surveys do not cover all the French territory but are representative samples of the main French crops: durum wheat, soft wheat, barley, grain maize, forage corn, rape, sunflower, peas, beet and potato. French departments have preliminarily been chosen for their representativeness in terms of crop. A survey has been done for each crop, in which plots were randomly drawn per department. A grossing-up factor (weight) has been assigned to each drawn crop with respect to its surface area, as larger plots have a higher probability of being drawn. We used the 1993, 2000, 2005 and 2010 surveys to have information on farming practices before and after the policy implementation. This dataset also reports if the plot is located in a vulnerable area county. For the year 1993, as vulnerable areas did not exist yet, we merged the vulnerable area counties of 2007 with 1993 counties. And we checked that the proportion of vulnerable areas is broadly similar in 1993, 2000, 2005 and 2010 (this proportion is on average 70% of the total utilized surface area over time for each date).

To control for extensive margin effects, that is, potential land use changes, since it is possible that the change in water quality is explained by changes in land use, we use data on cultivated croplands from the National Agricultural Censuses of 1988, 2000 and 2010 that covers all the French territory. We control for the evolution of land uses regarding grasslands areas, cereals areas, wheat and maize areas, as wheat and maize are the two main crops cultivated in France.

4.6 Wastewater Treatment Stations Data

Wastewater treatment of rivers and streams is the main potential confounding factor of the Nitrate Directive impacts on water quality. The urban wastewater treatment plants aim at treating sewage from household and industry wastes. We control for it using a public database on Urban Wastewater Treatment Plants from the French government website providing information on the location of the treatment plants, their opening year and their capacity in terms of population equivalents. In 2015, more than 4,000 watersheds contained at least one treatment plant. Figure 6 displays the wastewater treatment plants over the period 1994-2015.

5 Methodology

Our identification strategy is twofold. We first build a treatment intensity indicator to embed the fact that the hydrographic network is connected and that watersheds belonging to a same arborescence communicate in a known direction, the direction of the river flow. We hence build a treatment intensity indicator taking into account upstream-downstream interactions between watersheds in order to compute policy diffusion effects on nitrates and other water quality outcomes. We then perform difference-in-differences regressions (Duflo (2001), Angrist and Pischke (2008)) to disentangle the impacts of the policy on physicochemical and biological outcomes.

In a second part, we perform difference-in-differences regressions to explore changes in farmers behavior and practices as explanatory mechanisms of the policy. As mandatory measures are reinforced and more stringent from the second action program in 2001, we consider that the treatment begins from that date. The study of farmers behavior corroborates the fact that treatment actually begins from 2001 since no significant change is observed before this date.

5.1 Treatment Intensity Indicator And Upstream-Downstream Interactions

The key challenge of this study is to identify policy effects on non-point pollution. Contrary to point source pollution, diffuse pollution is harder to pin down as it results from multiple dispersed and non-identifiable emitting sources. Studying a policy that targets diffuse pollution such as the Nitrate Directive implies to consider diffusion effects, namely, the fact that watersheds are interconnected and that the water quality of a given treated watershed (a watershed containing vulnerable areas) might have an impact on the quality of the watersheds located downstream, as the direction of the river flow is one-sided. Figure 7 represents a simplified scheme of a characteristic arborescence of watersheds. Each arborescence has always one or more upstream watersheds and only one downstream watershed. We rebuild the entire datasets on the hydrographic network in order to have, for each given watershed, all its upstream watershed by level (from 0 to 95 upstream levels, over a total of 6,108 watersheds).

We define T_i as the treatment intensity indicator we will use in the regressions of our empirical analysis. A treatment intensity level T_i will be imputed to watershed i depending on the proportion of vulnerable surface areas contained in i and the proportion of vulnerable surface areas contained in the watershed located upstream of i. We derive the following indicator:

$$T_i = \frac{\sum_{w \in u(i)} TS_w}{\sum_{w \in u(i)} WS_w} \tag{1}$$

where T_i is a treatment intensity assigned to watershed i, $u(i) = \{i,j,k,l,m,...\}$ is a function that assigns to each i itself and its upstream areas, TS_w indicates the treated surface areas (vulnerable surface areas) contained in watershed w and WS_w denotes the total surface areas of watershed w.

According to equation 1, we derive two treatment intensity indicators, one with a single treated group and the other with a control group and treated groups declined into five range of increasing intensities that will enable us to bring to light the policy dose-response effects on nitrates, main outcome of interest. The *25% threshold treatment* attributes each watershed that has a treatment intensity higher than 25% to the treated group. The *6 intensity treatment* assigns each watershed into a treatment group corresponding to its treatment intensity from 0% to 100%, by 25% increments. Table 3 shows the assignment to the treated groups according to these treatment definitions. Figure 8 shows the allocation of each watershed to these two treatment definitions taking into account treatment intensity through upstream-downstream interactions.

Treatment Definition	**Assignmen**	**Intensity**	**Watersheds**
25% threshold treatment	control group	[0%,25%[	3128
	treated group	[25%,100%]	2980
6 intensity treatment	control group	[0%]	1985
	treated group 1	]0%,25%]	1143
	treated group 2	]25%,50%]	477
	treated group 3	]50%,75%]	261
	treated group 4	]75%,100%[	992
	treated group 5	[100%]	1250

Table 3: Treatment Assignment Groups According to the Two Treatment Definitions

5.2 Water Quality Regressions

Using the geographical and temporal variation of the vulnerable area designation as a quasi-experiment and a treatment intensity indicator derived from these treated surface areas, we perform a *difference-in-differences method* to identify the causal impact of the policy. We compare water quality outcomes in high treatment intensity watersheds with low treatment intensity watersheds before and after 2001, testing for pre-trends in outcomes.

Impacts on physicochemical quality

We estimate the impact of the policy on *physicochemical parameters* in treated watersheds relative to control watersheds. We first compute our main outcome of interest: the policy impacts on nitrate concentration, with the two treatment definitions. Then, we regress the 25% threshold treatment on the other physicochemical parameters, i.e. phosphorus, ammonium, dissolved oxygen and chemical oxygen demand (COD) used to quantify the amount of pollutants. Concentrations are all expressed in mg/L except for phosphorus that is expressed in μg/L. We estimate the following regression at the station s and month t levels:

$$PhysicochemicalQuality_{srt} = \beta_l(Treatment_{l,s} \times post_t) + \alpha_{st}X_{st} + \delta_m + \delta_s + \delta_{rt} + \epsilon_{srm} \quad (2)$$

where $PhysicochemicalQuality_{srt}$ denotes the physicochemical variable concentration, $Treatment_{l,s}$ is the treatment intensity variable (l= 1 for *25% threshold treatment* or l= 1,2,3,4,5 for the *6 intensity treatment*, and 0 for stations located in watersheds belonging to the control group), $post_t$ is a dummy variable equal to 1 the years following the policy and 0 before, X_{st} is a matrix of water control variables (rainfall, temperatures, quality of measurement, measurement support, portion analyzed, if observation is raw or has been controlled, analyzed or validated). δ_m denotes month fixed effects and δ_s represents stations fixed effects. The hydrographic district×year fixed effects δ_{rt} allow to capture a yearly fixed effect for each hydrographic district.

Impacts on biological quality

We then assess the impact of the policy on *biological parameters*, examining the impact of the policy on chlorophyll A concentration, the number of fishes in rivers and an invertebrate index. Chlorophyll A concentration, expressed in μg/L, is a proxy for eutrophication that measures the quantity of phytoplankton organisms like algae suspended in water. We first estimate the following regression at the station s and month t levels:

$$Eutrophication_{srmt} = \beta_l(Treatment_{l,s} \times post_t) + \alpha_{st}X_{st} + \delta_s + \delta_m + \delta_t + \epsilon_{srmt} \quad (3)$$

where $Eutrophication_{srt}$ denotes chlorophyll A concentration, $Treatment_{l,s}$ is the treatment intensity variable (l= 1 for *25% threshold treatment* and 0 for stations located in watersheds belonging to the control group), $post_t$ is a dummy variable equal to 1 the years following the policy and 0 before, X_{st} s a matrix of water control variables (rainfall, temperature, quality of the measurement, measurement support, portion analyzed, if observation is raw or has been controlled, analyzed or validated). δ_s represents stations fixed effects, δ_m denotes month fixed effects and δ_t year fixed effects.

We then examine the effect of the policy on the stock of fishes observed per monitoring stations:

$$Fishes_{srmt} = \beta_l(Treatment_{l,s} \times post_t) + \alpha_{st}X_{st} + \delta_s + \delta_m + \delta_t + \epsilon_{srmt} \quad (4)$$

where $Fishes_{srt}$ denotes the number of fishes registered by monitoring stations, $Treatment_{l,s}$ is the treatment intensity variable (l= 1 for *25% threshold treatment* and 0 for stations located in watersheds belonging to the control group), $post_t$ is a dummy variable equal to 1 the years following the policy and 0 before, X_{st} is a matrix of water control variables (rainfall, temperatures and taxons, i.e. fish species specifications). δ_s represents stations fixed effects, δ_m denotes month fixed effects and δ_t year fixed effects.

Finally, we study the invertebrate biological index with a simple treatment-control comparison as pre-treatment data are not available for this parameter (as measurements were only available over the period 2008-2015, we are not able to estimate pre-treatment trends). The values of this index are included in the interval [0,1] and measure the ecological status of rivers in terms of invertebrate, for which lower values (close to zero) mean an improved ecological status:

$$InvertebrateIndex_{srmt} = \beta_l Treatment_{l,s} + \alpha_{st} X_{st} + \delta_m + \delta_t + \epsilon_{srmt} \quad (5)$$

where $InvertebrateIndex_{srt}$ denotes the invertebrate index outcomes measured by monitoring stations, $Treatment_{l,s}$ is the treatment intensity variable (l= 1 for *25% threshold treatment* and 0 for stations located in watersheds belonging to the control group), X_{st} is a matrix of water control variables (rainfall and temperatures). δ_m denotes month fixed effects and δ_t year fixed effects. Stations fixed effects cannot be used in this equation as pre-treatment data are not available.

5.3 Farmers Behavior Regressions

To underpin the results of the Nitrate Directive impacts on physicochemical and biological outcomes, we explore farmers behavior and practices as explanatory mechanisms. As the policy directly targeted farming practices, a change in farmers behavior towards more proenvironmental practices after the introduction of the policy might in turn affect water quality. We estimate the following regression at the plot p and year t levels:

$$CulturalPractice_{pt} = \beta(VulnerableArea_{pt} \times post_t) + weight_{pt} + \delta_t + \epsilon_{pt} \quad (6)$$

where $CulturalPractice_{pt}$ denotes different cultural practice outcomes at the plot p level and $VulnerableArea_{pt}$ is the treatment variable equal to 1 if the plot belongs to a county classified as vulnerable, 0 otherwise. $weight_{pt}$ is a grossing-up factor (included in the survey) given to each plot corresponding to the probability of drawing plot p with respect to its surface area, as bigger surface areas have a higher probability of being drawn. δ_t denotes year fixed effects. Geographical fixed effects cannot be used as these datasets are not panel data.

The Cultural Practices Surveys cover the years 1993, 2000, 2005 and 2010 and allow to control for pre-treatment trends before the beginning of the second action program in 2001. For the years 2000, 2005 and 2010, the survey contains a dummy indicating if the plot is located in a county classified as vulnerable. As the proportion of vulnerable/non-vulnerable areas evolved very little from 2000 to 2015, we merged the counties classified as vulnerable in 2007 with the 1993 dataset to have a proportion of plots classified as vulnerable area of approximately 70% for the four dates.

6 Empirical Results: Impacts on Water Quality

6.1 Impacts on Physicochemical Quality

In this section we present our results from the first regression on physicochemical parameters. We begin with nitrate concentration, our main outcome of interest, and then turn to other physicochemical parameters such as ammonium, phosphorus, dissolved oxygen and COD.

Nitrates outcomes

Each winter and spring, farmers fertilize their lands for crop season. We provide evidence of this seasonal effect by computing a Kernel density estimation from nitrate concentration observations in waters. Figure 9 shows the distribution of nitrate concentrations in surface waters from January to December throughout the whole sample. We clearly see a shift in distribution from winter to spring, corresponding to the crop season, with annual mean concentrations between 15 and 25mg/L, while during summer and early fall, the peak concentration is between 0 and 10mg/L. In the empirical results below, we will look at the effect of the policy on nitrate concentration during the crop season, when the concentration in waterways is the greatest.

Treated watersheds display higher average nitrates concentration and higher variations in concentration over 1994-2015. Figure 10 shows the annual mean in nitrate concentrations in surface waters according to the *6 treatment intensity* definition. Watersheds assigned to a higher treatment intensity according to our treatment definition taking into account upstream-downstream interactions also show a higher pollution level. Figure 11 displays the Kernel density estimations based on annual nitrate concentration for the control group and each treated groups. These figures show that nitrate concentration in watersheds belonging to the control group and to the treated group 1 (with a treatment intensity between 0 and 25%) follows a log-normal distribution as concentrations are close to zero, while it follows a normal distribution in watersheds depicting higher treatment intensity where mean concentration is between 10 and 20 mg/L and variance is larger. The evidences brought by these descriptive statistics, i.e. that the higher the treatment intensity the higher the nitrate concentration, consolidates the relevance of our treatment definitions.

Table 4 reports the difference-in-differences regression results of the two treatment definitions, taking into account upstream-downstream interactions between watersheds, on nitrate concentration, at the monitoring station level. Columns 1 and 3 correspond to the *25% threshold treatment* and Columns 2 and 4, to the *6 intensity treatment*. Columns 3 and 4 reports coefficients only for crop season (winter and spring). Column 1 shows that a watershed that has a treatment intensity higher that 25% is associated with a significant decrease in nitrate concentration of -1.231 mg/L. And this reduction is enhanced during crop season (winter and spring) where farmers discharge nutrients to fertilize their lands, as reported in column 3 (-1.563 mg/L). The more striking result is the effect of the *6 intensity treatment* on nitrate in column 2: results show a significant reduction in

	(1)	(2)	(3)	(4)
Dependent variable:	nitrate		nitrate (crop season)	
treated group 25%	-1.231^{***}		-1.563^{***}	
	(0.137)		(0.142)	
treated group 1		-0.282^{**}		-0.308^{**}
		(0.137)		(0.154)
treated group 2		-0.196		-0.315^{**}
		(0.150)		(0.162)
treated group 3		-0.879^{***}		-1.073^{***}
		(0.209)		(0.292)
treated group 4		-1.523^{***}		-1.992^{***}
		(0.220)		(0.243)
treated group 5		-2.436^{***}		-2.899^{***}
		(0.225)		(0.264)
Controls	✓	✓	✓	✓
station FE	✓	✓	✓	✓
month FE	✓	✓	✓	✓
year×hydro district FE	✓	✓	✓	✓
R-squared	0.760	0.760	0.820	0.820
Mean Dep. Var.	15.992	15.992	17.711	17.711
Observations	406,174	406,174	198,058	198,058

Note: This table reports the effects of the policy on nitrate concentration (in mg/L) according to the two treatment definitions. In Columns 1 and 3, the *25% threshold treatment* attributes each watershed that has a treatment intensity higher than 25% to the treated group. In Columns 2 and 4, the *6 intensity treatment* assigns each watershed into a treatment group corresponding to its treatment intensity from 0% to 100%, by 25% increments. Columns 3 and 4 reports coefficients only for crop season (winter and spring). Regressions are run at the station level. Controls include rainfall, temperatures, quality of measurement, measurement support, portion analyzed and if the observation is raw or has been controlled, analyzed or validated. Standard errors are clustered at the watershed level. Significance levels are $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.10$.

Table 4: Impacts on Nitrate Concentration

nitrate concentrations of -0.879mg/L, -1.523mg/L and -2.436mg/L in areas receiving a treatment intensity of [50%-75%[, [75%-100%[and [100%] respectively, bringing to light the dose-response effect of the Nitrate Directive on nitrate concentrations. The strongest decline in nitrate concentration is observed in treated group 5, the watersheds with a 100% treatment intensity, in which nitrate concentration decreased by -2.436 mg/L, and by -2.899 mg/L during crop season. Figure 12 underscores the dose-response effect of the Nitrate Directive on nitrate concentrations including estimates and confidence intervals, according to the two treatment definitions.

We test for pre-treatment trends and bring evidence that there seems to be no pre-trend before 2001 compared to the control group: figure 13 shows the nitrate coefficients and confidence intervals of each year and each treated group of the *6 intensity treatment*, relative to the control group. Impacts are stronger for groups with a higher treatment intensity.

We also perform an *heterogeneous analysis* to deepen our results and understand in which hydrographic districts and during which seasons the reduction is the stronger (where and when the

	(1)	(2)
Dependent variable:	nitrate	
season *Winter*	-1.660^{***}	
	(0.197)	
season *Spring*	-0.540^{***}	
	(0.126)	
season *Summer*	-0.733^{***}	
	(0.136)	
season *Fall*	-0.711^{***}	
	(0.165)	
hydrographic district *Loire-Bretagne*		-3.900^{***}
		(0.361)
hydrographic district *Seine-Normandie*		-1.179^{***}
		(0.401)
hydrographic district *Medit-Rhône*		-0.639^{*}
		(0.377)
hydrographic district *Rhin-Meuse*		-0.560^{*}
		(0.314)
hydrographic district *Adour-Garonne*		0.443^{*}
		(0.256)
Controls	✓	✓
station FE	✓	✓
month FE	✓	✓
year×hydro district FE	✓	✓
R-squared	0.77	0.76
Mean Dep. Var.	15.992	15.992
Observations	406,174	406,174

Note: This table reports the effects of the policy on nitrate concentration (in mg/L) using triple difference-in-differences. Columns 1 presents the effects according to each season and Column 2 relative to each hydrographic districts (Seine-Normandie is not reported as we do not have watershed from the control group in this region). Controls include rainfall, temperatures, quality of measurement, measurement support, portion analyzed and if the observation is raw or has been controlled, analyzed or validated. Standard errors are clustered at the watershed level. Significance levels are $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.10$.

Table 5: Impacts on Nitrate Concentration by Seasons and Hydrographic Districts

policy has been the more effective). Table 5 displays these results.

Loire-Bretagne is the hydrographic region that displays the greatest reduction in nitrate concentration (a significant decrease of -3.900 mg/L) and a result statistically significant at the 0.01 level. Seine-Normandie is also associated with a significant reduction in nitrate concentration of -1.179 mg/L. However, Adour-Garonne is the hydrographic region where the policy did not seem to be effective (an increase of 0.443 mg/L but only statistically significant at the 0.10 level). Turning to the policy effect on seasons, all along the year, it is during the winter when farmers fertilize their lands that we observe the sharpest drop in nitrates concentration in surface waters (-1.660 mg/L).

Other physicochemical outcomes

As depicted in *Section 2* that outlines the nitrogen cycle, the Nitrate Directive might have impacted water quality in terms of other physicochemical parameters than nitrates but involved in the nitrogen cycle such as ammonium. Furthermore, the technological standards imposed on farming practices might also have affected phosphorus from fertilizer runoffs that also contributes to eutrophication. Our results suggest that, besides having decreased nitrate concentrations, the policy improved water quality in terms of other physicochemical parameters: in areas receiving a treatment intensity higher than 25%, we observe a decline in ammonium, phosphorus and COD and an increase in dissolved oxygen.

Ammonium (NH_4^+) comes from agriculture, household wastes or industries emissions. When nitrogen fertilizers are spread on lands or when livestock storage devices are not sufficiently hermetic causing manure runoff, nitrogen is emitted into the environment. Bacteria reduces nitrogen gas in the atmosphere into ammonium in lands or waters through the *nitrogen fixation* process. Then, it takes days or weeks for ammonium to transform into nitrates. A decrease in ammonium should thus be observed in treated areas.

Phosphorus (P) coupled with nitrogen is required to make crops grow. They are the two main fertilizers used by farmers. Mandatory measures enforced in vulnerable areas and subsidies might have had spillovers effects on phosphorus concentration in waters. The subsidies providing financial support to farmers for livestock storage buildings and technological standards on spreading manure (containing nitrogen and phosphorus) on lands might impact the amount of phosphorus in waters.

Dissolved oxygen is a parameter measuring the amount of gaseous oxygen (O_2) dissolved in the water. Oxygen is necessary for aquatic life such as fishes, invertebrates and plants. The eutrophication phenomenon characterized by an excess quantity of nutrients in waters leads to a lack of oxygen in rivers (hypoxia state), which in turn disrupt biodiversity that ends up suffocating and dying (dead zones).

Chemical Oxygen Demand (COD), contrary to oxygen demand, measures the oxygen consumption by chemical oxidants (micro-organisms and others) to oxidize organic and mineral matters in waters. Measuring the chemical oxygen demand is a way to assess the polluting charge of waters.

Table 6 presents the results of the difference-in-differences regression on these parameters according to the *25% treatment intensity*. Column 1 shows that a watershed that has a treatment intensity higher that 25% is associated with a significant decrease in ammonium and phosphorus concentrations of -0.119 mg/L and -0.0268 μg/L respectively. The quantity of dissolved oxygen significantly increased by 0.112 mg/L. Finally, the chemical oxygen demand, positively correlated with water pollution, decreased by 5.33 mg/L in treated areas compared to non-treated areas. Figure 14 illustrates the water trends (mean concentrations) for treated and control groups for each of these physicochemical parameters. Parallel trends of the final regressions taking into account fixed effects are presented in Figure 15.

	(1)	(2)	(3)	(4)
Dependent variable:	ammonium	phosphorus	dissolved oxygen	COD
treated group 25%	-0.119^{**}	-0.0268^{**}	0.112^{***}	-5.33^{***}
	(0.055)	(0.0116)	(0.037)	(1.973)
Controls	✓	✓	✓	✓
station FE	✓	✓	✓	✓
month FE	✓	✓	✓	✓
year×hydro region FE	✓	✓		
year FE			✓	✓
R-squared	0.48	0.31	0.35	0.44
Mean Dep. Var	0.365	0.1951	9.874	19.123
Observations	408,528	372,402	203,452	76,780

Note: This table reports the effects of the policy on ammonium (mg/L), phosphorus (μg/L), dissolved oxygen (mg/L) and chemical oxygen demand (COD) (mg/L) according to the *25% threshold treatment* definition. Regressions are run at the station level. Controls include rainfall, temperatures, quality of measurement, measurement support, portion analyzed and if the observation is raw or has been controlled, analyzed or validated. Standard errors are clustered at the watershed level. Significance levels are $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.10$.

Table 6: Impacts on Other Physicochemical Outcomes

6.2 Impacts on Biological Quality

In this subsection, we present the impacts of the Nitrate Directive on biological outcomes: we find that the policy contributed to an important decrease in waterways eutrophication and an improvement in the stock of fishes observed and the invertebrate biological index.

Eutrophication is a complex phenomenon that can generate major disturbances of aquatic ecosystems. This process occurs when anthropogenic nutrients (mainly nitrogen and phosphorus) pour into waters, causing algal proliferation representing important stock of biomasses for which decomposition induces a loss of oxygen. This in turn asphyxiates aquatic biodiversity and provokes dead zones. Eutrophication arises during hot seasons (spring and summer) when there is more sunlight and higher temperatures to make algae grow (photosynthesis). The main issue is that nitrogen and phosphorus, the major determinants of eutrophication in continental/coastal waters (CNRS (2017)), are some of the most difficult elements to observe in aquatic environments as they can exist in multiple forms (organic, dissolved) and are emitted from diverse sources (soil, air). The parameter chlorophyll A is the measure we chose to proxy waterways eutrophication: it is a pigment activated with photosynthesis contained by phytoplankton organisms suspended in water.

Fishes might be impacted by excess nutrient emissions in surface waters. An improvement in water quality can lead to more oxygen in waters and so to a higher number of fishes. We hence decided to assess the policy impacts on the number of fishes as an additional biological measure. The dataset on fishes includes 104 fish species living in surface waters such as trout (*salmo trutta fario*), chub (*squalius cephalus*), common rudd (*scardinius erythrophthalmus*) and so on.

Invertebrate biological index is a hydrobiological parameter allowing to appreciate the biological quality and the biodiversity of surface waters. The values of this parameter contained in the interval [0,1] are expressed in Ecological Quality Ratios: the parameter measures the deviation from the good ecological status benchark of 0. Lower values correspond to an improvement in ecological status at the monitoring station where the index has been measured.

Table 7 displays the impact of the Directive Nitrate on eutrophication, fishes and invertebrates. Column 1 shows that a watershed that has a treatment intensity higher that 25% is associated with a significant decrease in chlorophyll A concentrations of -2.699 μg/L. And this reduction is all the more important in spring and summer when algal blooms occur (-3.002 μg/L). Column 3 displays that the policy significantly increased the number of fishes by 39.25 by stations in treated areas. Column 4 shows that the invertebrate index significantly decreases by -0.134 in treated areas, meaning that the ecological status has improved. However, it is noteworthy that the invertebrate index data only covers 2008-2015 and that we can only derive treated-control estimates without controlling for pre-treatment trends: this result has to be interpreted with caution.

	Eutrophication		**Biodiversity**	
	(1)	(2)	(3)	(4)
Dependent variable:	chlorophyll A	chlorophyll A (spring & summer)	stock of fishes	invertebrate index
treated group 25%	-2.699^{***}	-3.002^{***}	39.25^{***}	-0.134^{***}
	(0.717)	(0.772)	(8.63)	(0.02)
Controls	✓	✓	✓	✓
station FE	✓	✓	✓	✓
month FE	✓	✓	✓	✓
year FE	✓	✓	✓	✓
R-squared	0.29	0.31	0.56	0.09
Mean dep. var.	11.31	12.91	176.93	0.514
Observations	159,649	112,918	8,703	5,603

Note: This table reports the effects of the policy on chlorophyll A (μg/L) and the number of fishes according to the *25% threshold treatment* definition. Regressions are run at the station level. Controls for chlorophyll A include rainfall, temperatures, quality of measurement, measurement support, portion analyzed and if the observation is raw or has been controlled, analyzed or validated. Controls for the number of fishes only include rainfall, temperatures and taxons (fish species). Column 4 present treated compared to untreated outcomes as data are only available over 2008-2015 for this outcome. Standard errors are clustered at the watershed level. Significance levels are $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.10$.

Table 7: Impacts on Biological Outcomes: Eutrophication, Fishes and Invertebrates

Figure 15a illustrates the annual means in surface water eutrophication in the treated group and the control group. It also shows that chlorophyll A coefficients in the treated group relative to the control group seems to oscillate around the zero axis before 2005 and starts to decrease from 2005. This time lag might be caused by the fact that the policy begins to have an impact on nitrates and phosphorus a few years before 2005 (it might take some time for farming practices to significantly change). Figure 15c also shows the annual means in the number of fishes in treated and untreated areas. There seems to be a slight trend few years before 2001 (figure 15d) but the confidence interval is still equal or close to zero before 2002, and then seems to move away from the zero axis from this date. Figure 15f shows that from 2008, the invertebrate biological index continues to decrease in the areas receiving a treatment intensity higher than 25%. These findings seem to show that the Nitrate Directive has successfully improved the biological status of waters in terms of eutrophication, stock of fishes and invertebrates.

7 What Explains the Improvement of Water Quality?

The Nitrate Directive, besides designating vulnerable areas in which water quality has to be measured, aims at reducing nitrogen runoffs through a bottom-up approach, i.e. reducing the sources and transfers of nutrients into the environment instead of only treating wastewater once polluted. Figure 3 presents the list of mandatory measures that farmers have to apply within the Nitrate Directive framework. In this section, we show that this policy triggered a sizeable change in farmers behavior towards more proenvironmental practices by enforcing technological standards and informing them on a better balanced fertilization. The policy decreased nitrogen *sources* of pollution: the amount of mineral phosphorus fertilizers and organic fertilizers significantly dropped and it considerably improved *Nitrogen Use Efficiency* (NUE), measuring how efficiently nitrogen fertilizers are used in terms of output/input, $Nbalance$, estimating nitrogen losses to the environment, and $Noutput$, assessing productivity in terms of nitrogen. The policy also sharply increased the development of nitrate-fixing intermediate crops, a practice aiming at reducing nitrogen *transfers* to the environment. The results of this section are derived from the Cultural Practices Survey.

7.1 Farming Practices Reducing Sources of Nitrogen Pollution

Improving the use of nitrogen fertilizers in agricultural production is crucial to tackle the triple challenges of food security, environmental degradation and climate change, as outlined in Zhang et al. (2015). As plants can only fix on average 50% of the amount of nutrients they receive, sources of anthropogenic nitrogen can be reduced by adapting the amount of mineral and organic fertilizers applied on lands with respect to crop needs.

The Nitrate Directive framework aims at reducing the sources of nitrogen inputs by lessening the quantity of mineral fertilizers applied on lands, by respecting the threshold of 170 kg/ha/year for organic fertilizers and by targeting a balanced fertilization (the use of the right amount of nutrients per soil and crop requirement). In this subsection, we consider the amounts of mineral and organic fertilizers applied on lands (nitrogen, phosphorus, manure) and three indicators allowing to assess agricultural performance (*Nitrogen Use Efficiency*, $Nbalance$ and $Noutput$).

To grow crops, farmers use nitrogen N and phosphorus P mineral fertilizers, but also organic fertilizers that contains both nitrogen and phosphorus. In that sense, the policy might have also affected phosphorus concentrations in waters as it aims at reducing all types of fertilizers use.

N is the amount of mineral nitrogen fertilizers applied on plots (in kg/ha/year).

P is the amount of mineral phosphorus fertilizers applied on lands (in kg/ha/year).

Manure corresponds to the amount of organic fertilizers applied on lands (in kg/ha/year).

According to Brentrup and Lammel (2016), three indicators can be derived from inputs (amounts of mineral and organic fertilizers used) and outputs data (yields) to estimate the performances of agricultural production. The *Nitrogen Use Efficiency* ratio provides information on how sustainable nitrogen fertilizers are being used (efficiency). However, this indicator is only one aspect of the sustainability of nitrogen use: to account for environmental degradation due to excess anthropogenic nitrogen, $Nbalanced$, an estimation of the nitrogen losses to the environment derived from the amount of fertilizer used and the yields in terms of nitrogen content, can be a suitable indicator (environment). Additionally, computing the $Noutput$ indicator allows to consider food production in terms of nitrogen content, another important vector of agricultural performance (productivity). Equations below describe how these three indicators are computed.

NUE is the *Nitrogen Use Efficiency* indicator that enables to determine if fertilizers are applied efficiently. It is a ratio indicating the balance between the applied amount of fertilizers and production in terms of N content. Lower values of NUE exacerbate nitrogen pollution. An N content is associated to each type of organic fertilizer used such as bovine, ovine, porcine, goat and poultry manure or liquid manure, and to each type of crop like durum wheat, soft wheat, barley, grain maize, forage corn, rape, sunflower, peas, beet and potato. Information on nitrogen content by type of crops and organic fertilizer are described in table 11. From data on yields, type of crops and amount of fertilizers, we derive the NUE, at the plot level p:

$$NUE_p = \frac{Noutput_p}{Ninput_p} = \frac{yield_p \times Ncontent}{Nfertilizer_p \times Ncontent)} \tag{7}$$

N balance depicts the potential nitrogen N loss to the environment, i.e. what remains in the environment after yield, what has not been soaked up by plants. It is computed at the plot level p:

$$Nbalance_p = (Nfertilizer_p \times Ncontent) - (Nyield_p \times Ncontent) \tag{8}$$

N output is an indicator for productivity, in terms of nitrogen N. Each yield (expressed in 100kg/ha/year) is multiplied by the N content of each crop, at the plot level p:

$$Noutput_p = Nyield_p \times Ncontent \tag{9}$$

Table 8 shows the results of the difference-in-differences regression of equation 5. The amount of phosphorus and organic fertilizers applied on lands decreased by 3.030kg/ha/year and 1.634kg/ha/year respectively. Surprisingly, the policy did not change the amount of mineral nitrogen fertilizers dumped on plots but it did improve the efficiency of nitrogen fertilizer use: farmers significantly increased NUE by 28.262 %points, meaning that nitrogen fertilizers are being used more efficiently in vulnerable areas, and $Nbalance$ decreased by 29.037 %points, indicating that less nitrogen is pouring into the environment.

The perhaps most intriguing result is the significant gain in productivity in areas submitted to the regulation: farmers located in vulnerable areas significantly increased their $Noutput$ indicator by -29.574 %points, meaning that by adopting a more balanced fertilization and not necessarily by increasing the amount of fertilizers applied ($Ninput$, the NUE numerator, is not significant), they considerably increased their outputs in terms of nitrogen.

Figures 16 and 17 depict the outcomes annual means over time and show that the parallel trend assumption holds for all the outcomes. We do not observe parallel trends for phosphorus fertilizers, but a break in trend after the policy implementation associated with a downward slope.

Lassaletta et al. (2014) shows that in most European countries, and in particular in France, the trajectory of yields presents a two-phase pattern: an increase in N yields and N fertilizers from the 1960's to the end of the 1990's, and an increase in N yields and a stabilization (and even a decrease) in N fertilization from the 2000's. Indeed, we show that these effects on improve N management seem to result from the Nitrate Directive regulatory framework in France.

	Amount of fertilizers			**N Indicators**			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Dependent variable:	N	P	manure	NUE	N balance	N output	N input
Vulnerable areas	0.288	-3.030^{***}	-1.634^{**}	28.262^{***}	-29.037^{***}	29.574^{***}	1.238
	(2.000)	(1.100)	(0.667)	(3.630)	(3.629)	(2.718)	(2.522)
Weights	✓	✓	✓	✓	✓	✓	✓
year FE	✓	✓	✓	✓	✓	✓	✓
R-squared	0.019	0.090	0.001	0.011	0.031	0.026	0.011
W. Mean Dep. Var.	126.060	41.331	6.618	97.834	39.101	136.076	175.371
Observations	65,602	65,602	65,602	52,429	52,429	51,974	52,429

Note: This table reports the effects of the policy on mineral and organic fertilizers applied on land, i.e. nitrogen N, phosphorus P and manure, and on indicators measuring agricultural performance in terms of nitrogen, i.e. nitrogen use efficiency, nitrogen balance and nitrogen output. Regressions are run at the plot level. Standard errors are clustered at the plot level. Significance levels are $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.10$.

Table 8: Impacts on Farming Practices Aiming at Reducing Sources of Nitrogen

To dig deeper and better understand these results and in particular the surprising increase in productivity despite the fertilizer use restriction, we extend our analysis to the way farmers belonging to a vulnerable area managed their fertilization compared to the other areas. To answer to this question, we examine different outcome variables related to nitrogen fertilizer assessments by farmers.

N estimated measures if farmers have assessed the theoretical amounts of nitrogen remaining in the grounds before putting in place the crop (before the planting).

N fertilizers applied after winter informs if farmers have adjusted the amounts of nitrogen applied on lands depending on estimated nitrogen in the grounds after winter.

N fertilizers applied from previous crops assess if farmers have adjusted the amounts of nitrogen applied on lands depending on estimated nitrogen in the grounds from previous crops.

Table 9 shows that farmers belonging to a vulnerable area significantly increased the practice consisting in measuring the theoretical amounts of nitrogen remaining in the grounds before the

	(1)	(2)	(3)
Dependent variable:	N estimated	N applied (winter)	N applied (previous crops)
Vulnerable areas	0.070***	0.127***	0.016*
	(0.009)	(0.006)	(0.008)
Weights	✓	✓	✓
year FE	✓	✓	✓
R-squared	0.104	0.067	0.119
Mean Dep. Var.			
Observations	54,455	61,714	61,714

Note: This table reports the effects of the policy on parcels for which (column 1) farmers have assessed the amounts of nitrogen remaining in the grounds, (column 2) farmers have adjusted the amounts of nitrogen applied on lands depending on estimated nitrogen in the grounds after winter and (column 3) from previous crops. Regressions are run at the plot level. Standard errors are clustered at the plot level. Significance levels are $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.10$.

Table 9: Impacts on Fertilization Assessments

crop planting: the number of plots associated to this practice increased by 7 %points in vulnerable areas after the implementation of the policy. Furthermore, plots for which farmers have adjusted the amounts of nitrogen applied according to estimated nitrogen in the grounds after winter and from previous crops increased by 12.7 %points and 1.6 %points respectively. Figure 18 depicts the outcomes annual means over time and shows that parallel trends hold for the three outcomes.

It is noteworthy that besides the strict application of mandatory measures through technological standards, the Nitrate Directive provided information on how to use better farming practices, like the *nitrogen balanced method*, and to adopt more proenvironmental behaviors.

Our findings reveal that the technological standards imposed by the policy triggered a significant change in farmers behavior by better informing them on when and how to put fertilizers, ensuring in turn gains in productivity (enforcing a more efficient use of resources and decreasing waste).

7.2 Farming Practices Reducing Transfers of Nitrogen Pollution

Besides the direct application of fertilizers on lands, nutrients can pour into surface waters through runoffs during rainfall season. The Nitrate Directive measures target a reduction of nitrogen transfers to the environment by compelling farmers to adopting an appropriate land management.

We derive the number of plots that apply nitrate-fixing intermediate crops and grass buffer strips as they are two important land management practices part of the Nitrate Directive framework. These information are available in the *Cultural Practices Survey* for 1993, 2000, 2005 and 2010.

Nitrate-fixing intermediate crop is a fast growing and non-productive temporary crop intended for protecting plots from runoffs, generally between winter and spring cultivations. Using their growth, plants from the vegetation cover soak up nitrates remaining in grounds from the previous productive crop. Among these nitrate-fixing crops are mustard, phacelia, ryegrass and rye. Then, the nitrate-fixing crop is plowed and nitrogen contained by it is recycled for the second crop planting.

Grass buffer strip is a part of a land that is permanently covered by vegetation, in particular along rivers, in order to avoid nitrate discharges from agricultural fields. The buffer strip width shall be at least 5 meters in vulnerable areas, and sometimes 10 meters for areas in which reinforced measures have to be implemented.

From 2003, the implementation of nitrate-fixing intermediate crops and grass buffer strips in vulnerable areas is part of the cross-compliance of the common agricultural policy, i.e. the obligation of adopting certain ecological practices to receive the subsidies from the European policy. In case of non-compliance, the farmer will face a withholding of 3 to 5% of the subsidies he receives.

Results from table 10 illustrates the sizeable effect of the Nitrate Directive on the development of nitrate-fixing intermediate crops: the number of plots on which is used this practice increases significantly from almost 6.6%points in vulnerable areas. In contrast, the policy did not seem to have impacted the development of grass buffer strips in these zones, as the result is insignificant. Figure 19a and c illustrates the annual means in vulnerable and non-vulnerable areas before and after the treatment. Figure 19,b shows that parallel trends hold.

	(1)	(2)
Dependent variable:	nitrogen-fixing crop	grass buffer strip
vulnerable areas	0.066^{***}	-0.022
	(0.005)	(0.014)
Weights	✓	✓
year FE	✓	✓
Mean Dep. Var.		
R-squared	0.045	0.072
Observations	65,602	51,275

Note: This table reports the effects of the policy on plots on which are applied nitrogen-fixing intermediate crop and grass buffer strip. Regressions are run at the plot level. Standard errors are clustered at the plot level. Significance levels are $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.10$.

Table 10: Impacts on Farming Practices Aiming at Reducing Transfers of Nitrogen

8 Discussion

In this section, we control for different potential confounding factors that could drive our results on physiochemical and biological water quality. We first consider wastewater treatments that also convert household, industrial and agricultural sewages into clean water, and second, land use changes since a change in water quality could be attributable to landscape alteration in terms of cereals, wheat, maize or grassland surface areas.

8.1 Wastewater Treatment Plants

A potential confounding factor that could drive our results is the urban wastewater treatments that handle sewage water. We use public data from the French Urban Waste Water Treatment Plants Database allowing us to have the location of treatment plants, their opening year and their capacity in terms of population equivalents.

The period under study runs from 1994 to 2015. In 1994, approximately 4,600 watersheds over a total of 6,008 watersheds did not contain a treatment plant and only 2,000 watersheds have at least one treatment station in 2015: the total number of treatment plants increases gradually over time. We exploit this multiple treatment time setting, well-suited to perform an event study, to assess the impact of the treatment plants on water quality.

To implement this robustness check, we first define a treatment variable for the sewage water treatments: a watershed belongs to the treated group when a new station opens from 1994, while it belongs to the control group when it contains no new station over the period 1994-2015. As each treated watershed face different treatment time, this treatment variable takes the value *Controlgroup* for watersheds with no treatment station and numeric values within the interval [-22,22] corresponding to the years before and after the first station opens, 0 being the year treatment occurs. For instance, if a station opens in 2000 in a given watershed, the treatment variable associated to years 1994, 2000 and 2015 will be respectively -6, 0 and 15. We denote $WastewaterTreatment$ the treatment variable for watershed w:

$$WastewaterTreatment_w = \begin{cases} ControlGroup & \text{if } N_s = 0 \\ T_{y,y\in[-22,22]} & \text{if } N_s = 1 \end{cases} \tag{10}$$

where $WastewaterTreatment_w$ denotes the value of the treatment variable for watershed w, N_s is a dummy variable equal to 0 if watershed w does not contain a new station over 1994-2015, 1 otherwise, y is a time value belonging to the interval [-22,22].

Figure 20 displays the annual means of nitrate concentrations in watersheds belonging to the wastewater treated group and to the control group. In particular, we clearly notice that first, trends are similar between the two groups and second, that nitrate concentration decreases progressively from 2008 in treated group relative to control group. As almost 2,000 watersheds receive a treatment at the end of the period 1994-2015, this decrease in nitrate concentrations at the end of the time period makes sense.

Then, we perform the following event study regression at the monitoring station level s:

$$Nitrate_{smw} = \beta_s WastewaterTreatment_w + \alpha_{sm} X_{sm} + \delta_m + \delta_s + \epsilon_{smw} \tag{11}$$

where $Nitrate_{smw}$ denotes nitrate concentrations measured by stations s, $WastewaterTreatment_w$ is the treatment variable, X_{sm} is a matrix of water control variables (quality of measurement, measurement support, portion analyzed, if observation is raw or has been controlled, analyzed or validated), δ_m denotes month fixed effects and δ_s represents monitoring station fixed effects.

Figure 20 illustrates the results of the event study: the yearly coefficients correspond to the treatment effects of the urban wastewater treatment stations, relative to the control group. Abscissa represents the years before and after the opening of a new station in 0. We clearly see that there is no impact before 0 as the slope is flat. However, after 0, and in particular after $T_{y=+8}$, the nitrate concentration begins to decrease. These results seem to effectively disentangle the wastewater treatment effect.

Finally, we include the $WastewaterTreatment$ variable into equations 2 to control for sewage water treatment effects on water physicochemical quality. Table 12 shows that coefficients remain almost unchanged when taking into account this new variable. These results suggest that waste water treatment effects on water quality are unlikely to drive our findings.

8.2 Land Use Change

The global improvement of water physicochemical and biological state of rivers observed after the implementation of the Nitrate Directive could also be imputed to another relevant factor: the change in land use. In fact, farmers might have changed their cultivated crops which in turn might have affected water quality.

In this subsection, we assess the impact of the Nitrate Directive on water quality outcomes considering the evolution of surface areas in cereals, wheat and maize (the major cultivated crops in France) and grassland. We derive these surface areas from the French Agricultural Censuses of 1988, 2000 and 2010. We associate the 1988 land use values to the period 1994-1999, the 2000 land use values to the 2000-2009 period and the 2010 land use values to the 2010-2015 period. We include the surface areas variables into equations 2 to control for extensive margin effects of land use changes on water physicochemical quality.

Table 13 shows that land use change (in terms of cereal, wheat, maize and grassland areas) is unlikely to drive our results: coefficients remain almost unchanged when adding these controls.

9 Conclusion

The Nitrate Directive that aims at reducing agricultural water pollution from nitrates is a unique piece of regulation that faced many controversies on its effectiveness. While most researches focus on the evaluation of the impact of point source pollution regulations (Greenstone and Hanna (2014), Keiser and Shapiro (2017)), our study, using the Nitrate Directive framework, provides the first estimates of the effects of a command-and-control policy on non-point source pollution.

This paper gathers a bunch of rich datasets on water quality, hydrographic network, climate data, cultural practices and wastewater treatment plants to examine the Nitrate Directive effects on an array of outcomes: from water quality parameters with more than 400,000 observations from 2,800 monitoring stations covering all the territory, to farmers behavior and practices.

Our results show that, in areas with a treatment intensity higher than 25%, this policy significantly reduced nitrate concentrations in surface waters by -1.231mg/L. We also find a dose-response effect of the policy on nitrates: the higher the treatment intensity, the stronger the decrease in nitrate concentrations. The physicochemical state of surface waters has also significantly improved in terms of phosphorus, ammonium, dissolved oxygen and chemical oxygen demand (COD). We find a noticeable improvement in the biological status of rivers, considering eutrophication, stock of fishes and invertebrates. In addition, we show that wastewater treatments, climate and land use changes are unlikely to drive our results.

In a second part, we assess the impact of the policy on farmers behavior and practices as underlying explanatory mechanisms. We find that the amount of phosphorus and organic fertilizers dumped on lands decreased by 3.030kg/ha/year and 1.634kg/ha/year respectively. However, the policy did not change the amount of mineral nitrogen fertilizers used by farmers but it improved the efficiency of nitrogen fertilizer use: it significantly improved the *Nitrogen Use Efficiency* indicator and the *N balance* indicator, estimating nitrogen loss to the environment. The perhaps most surprising and intriguing result of this study is the substantial increase in *N output*, an indicator measuring yields in terms of nitrogen. These findings reveal that the technological standards and the information disclosure provided by the regulation allowed for a better balanced fertilization, ensuring in turn gains in productivity (a more efficient and less wasteful use of resources).

The research questions addressed in this paper are interdisciplinary, lying at the frontier between economic sciences and biology/ecology. This study evaluates the policy diffusion effects on different physicochemical, biological and biodiversity outcomes, using hydrographic data. It also explores sustainable development issues in examining the policy impacts on farming practices and in considering agroenvironmental indicators such as the nitrogen use efficiency indicator.

Finally, this paper brings robust empirical evidences on the effectiveness of a command-and-control policy in reducing pollution and changing behaviors through technological standards. Our findings support the Porter hypothesis stating that a well-designed environmental regulation can trigger innovation (broadly defined) and in turn increase environmental and business performances.

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Figures

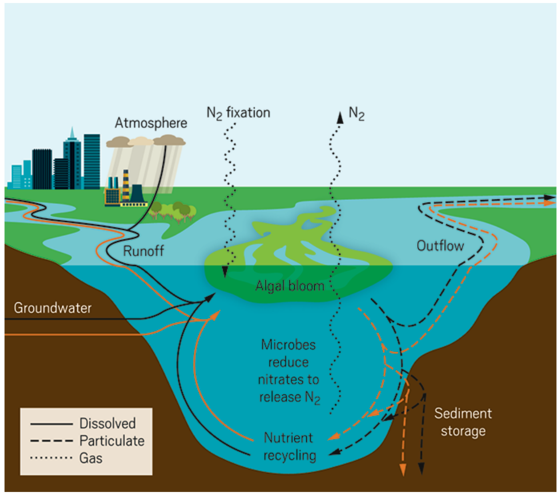

Figure 1: The Nitrogen Cycle and Anthropogenic Nitrogen Pollution Sources

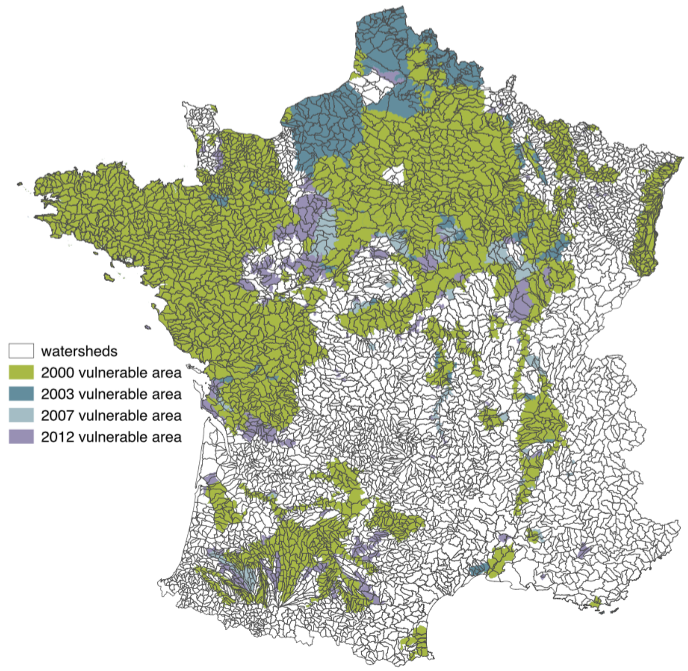

Figure 2: Vulnerable Areas Waves from 2000 to 2015

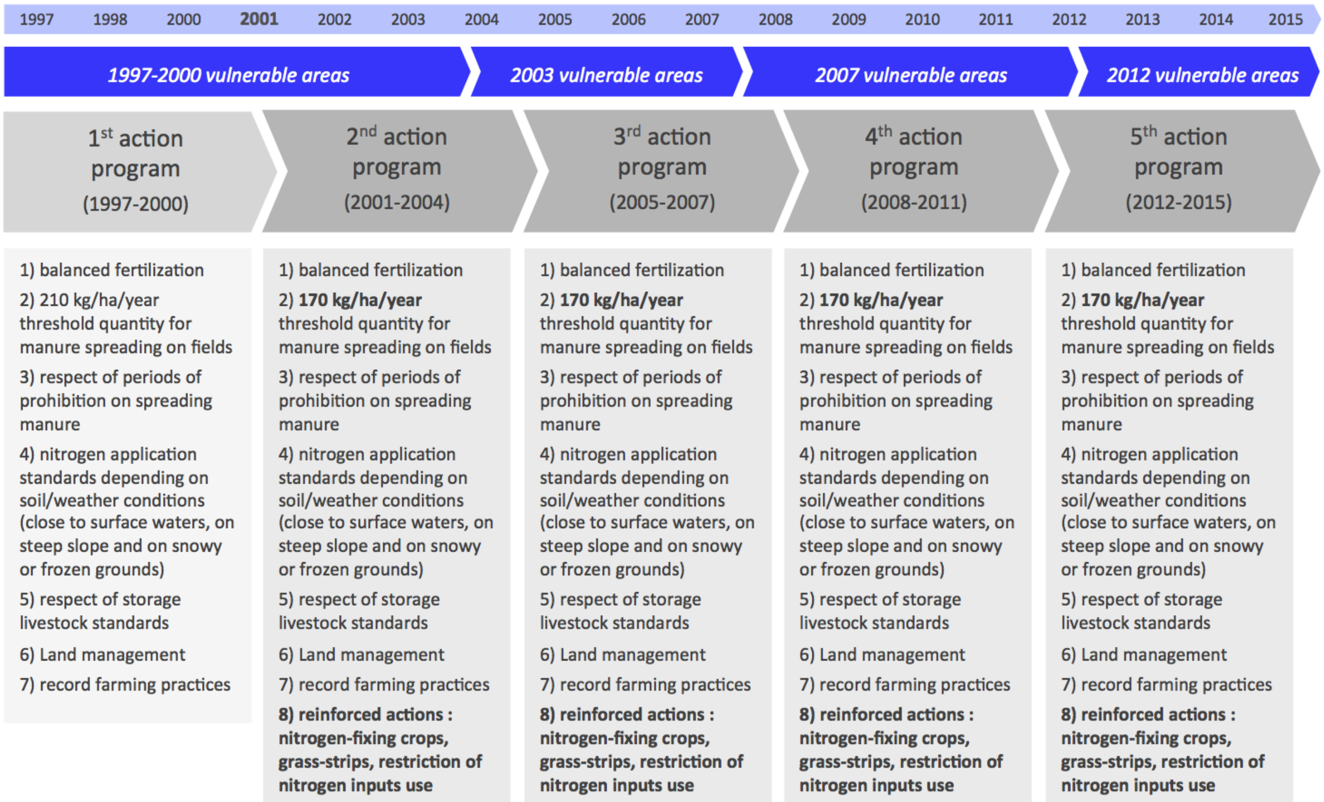

Figure 3: Historical Timeline of Nitrate Directive Action Programs

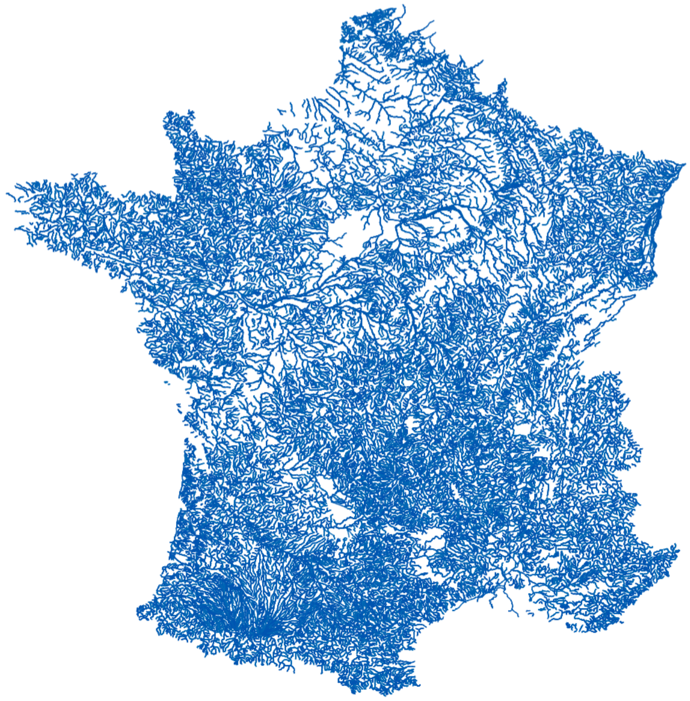

Figure a: River and Stream Network

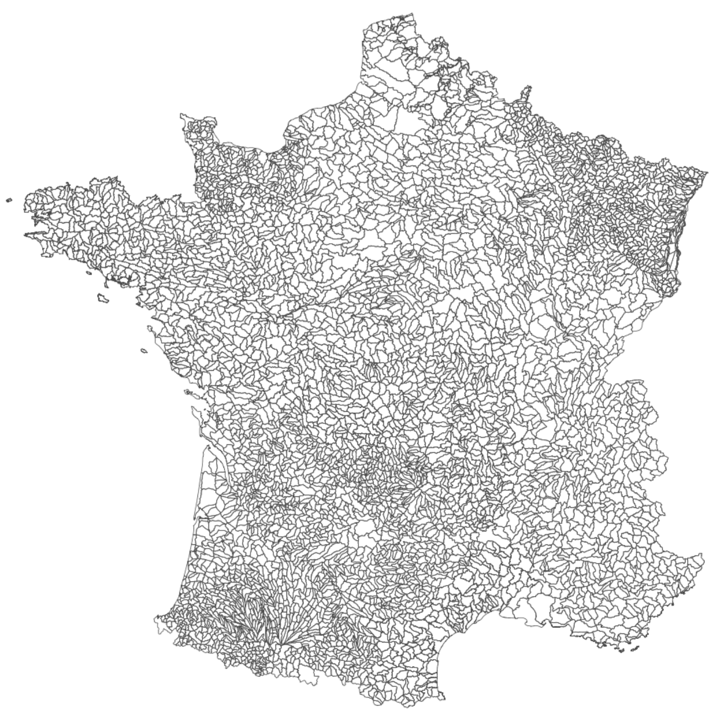

Figure b: Watersheds (hydrographic zones)

Figure 4: Hydrographic Network

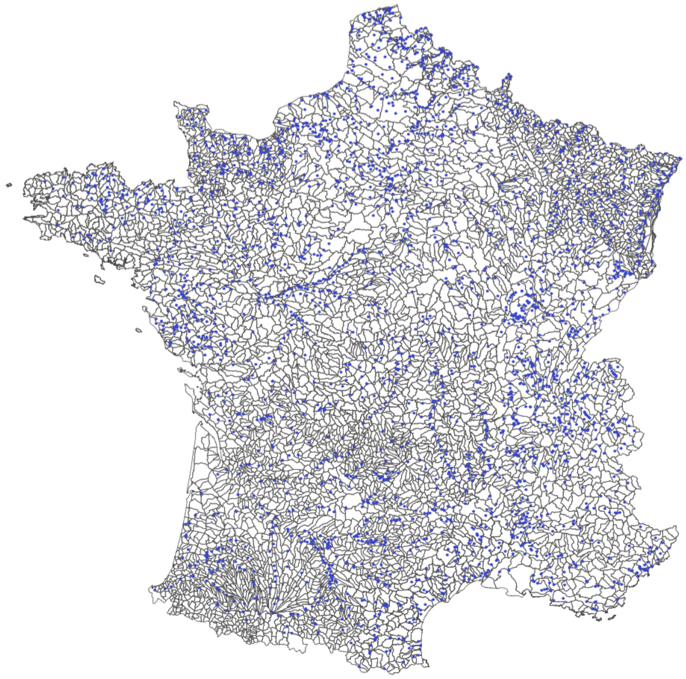

Figure 5: Water Quality Monitoring Stations

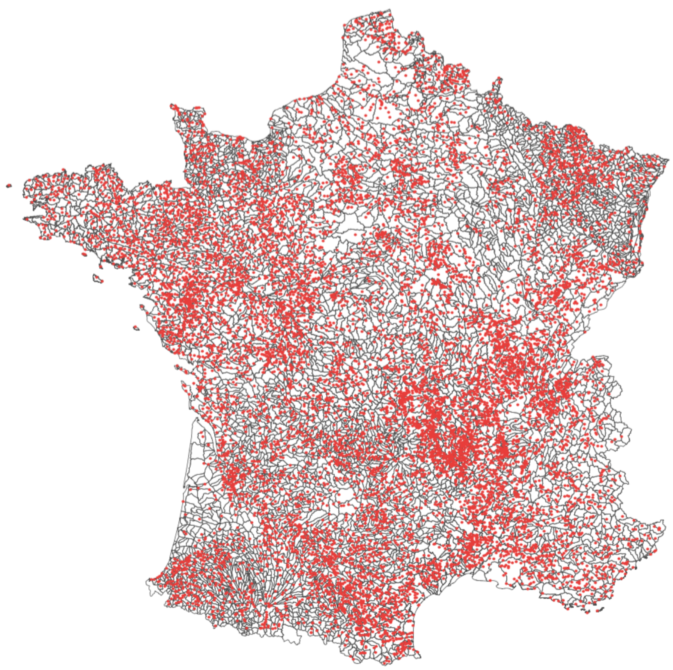

Figure 6: Waste Water Treatment Plants

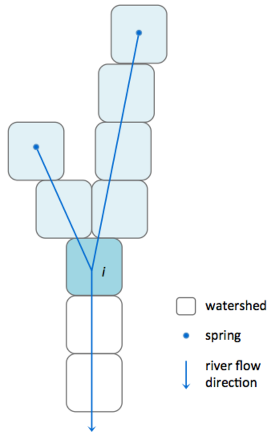

Figure 7: Chain of Watersheds Diagram

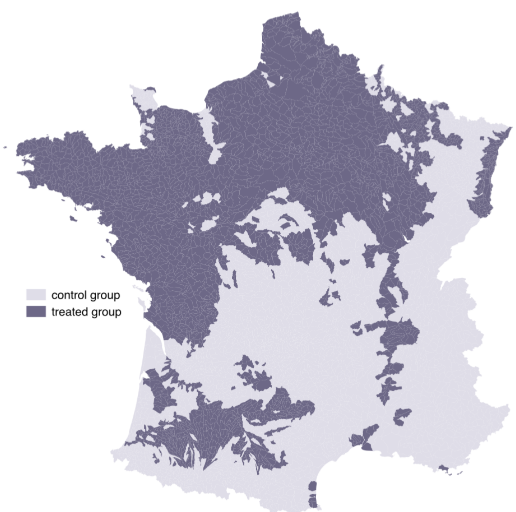

Figure a: 25% Threshold Treatment Group

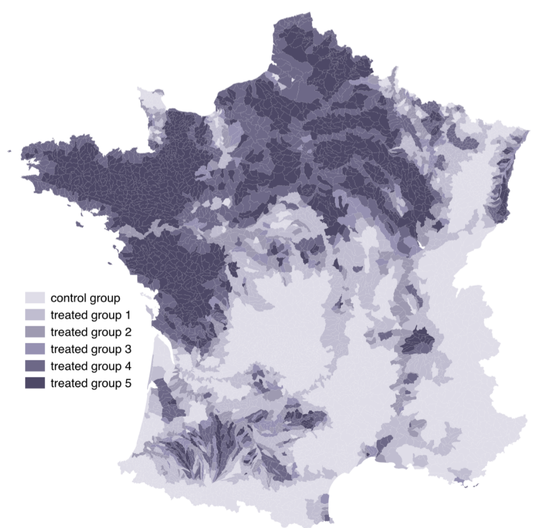

Figure b: 6 Intensity Treatment Groups

Figure 8: Treatment Group Definitions at the Watershed Level

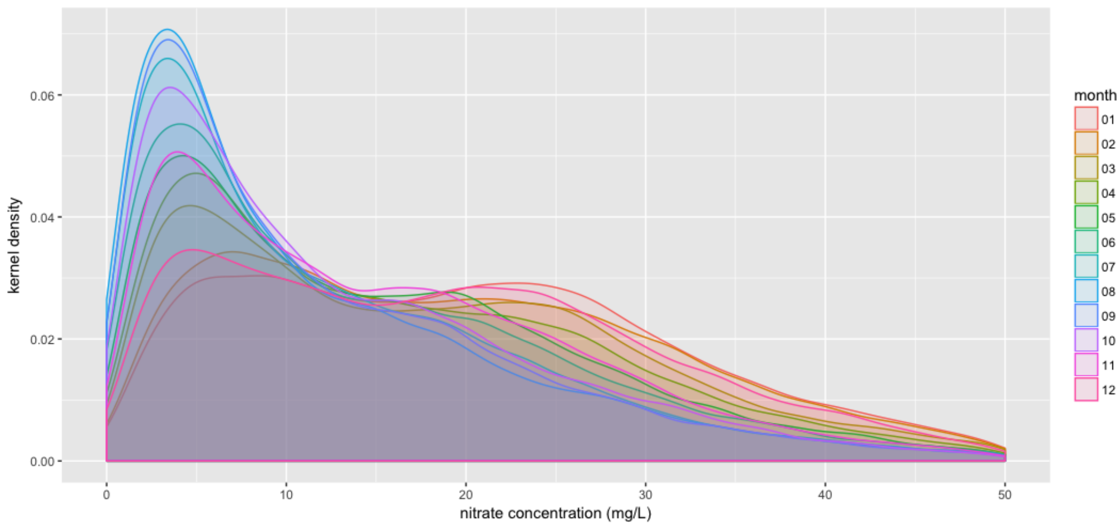

Figure 9: Seasonal Effect on Nitrate Concentration in Surface Waters

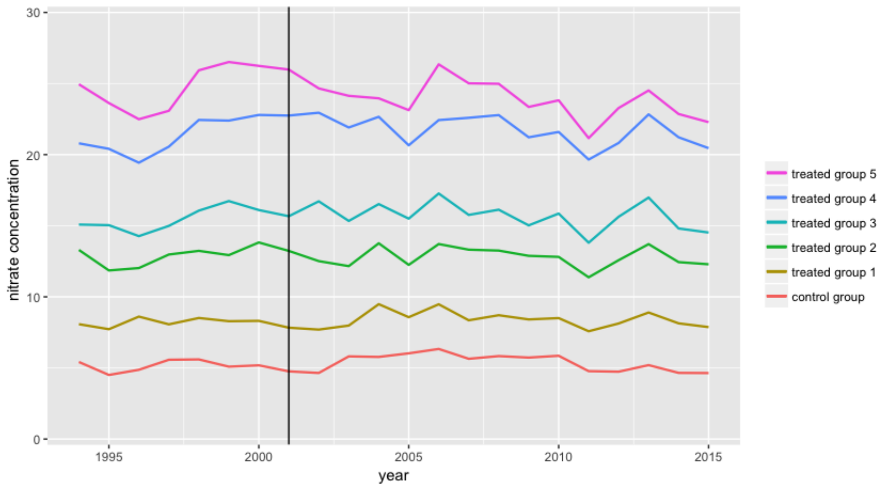

Figure 10: Surface Water Trends in Nitrate Concentrations in Control and Treated Watersheds

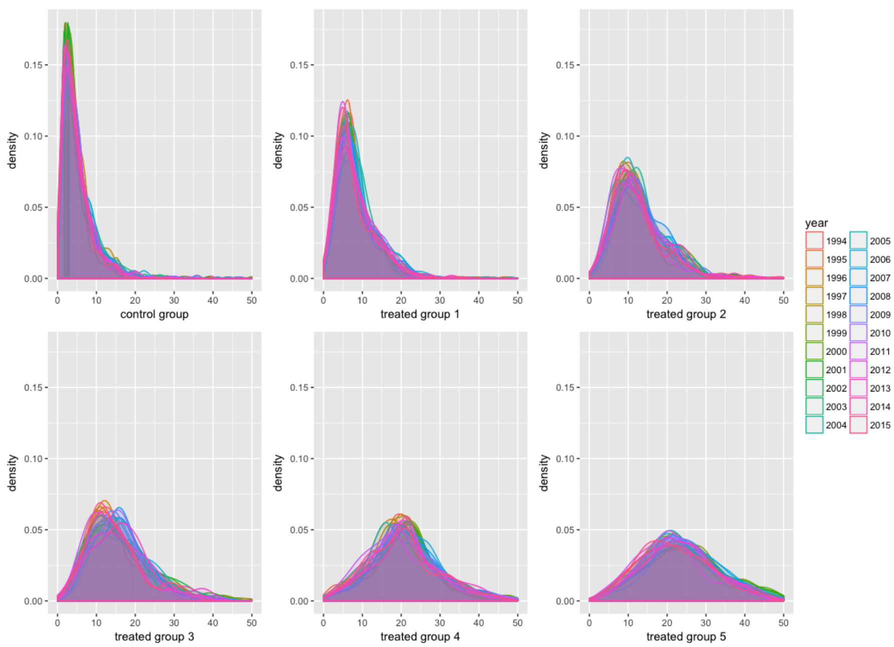

Figure 11: Kernel Densities Estimation of Nitrate Concentrations per Treated Groups

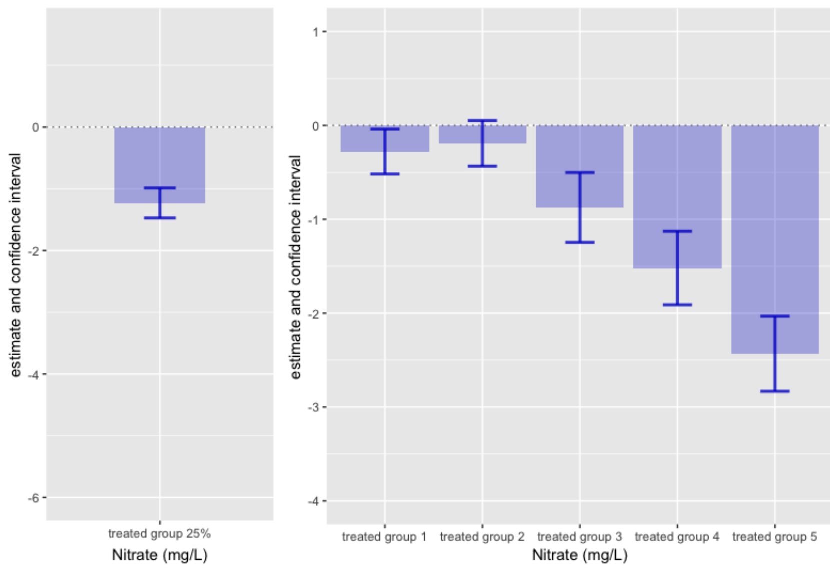

Figure 12: Impacts on Nitrate Concentrations

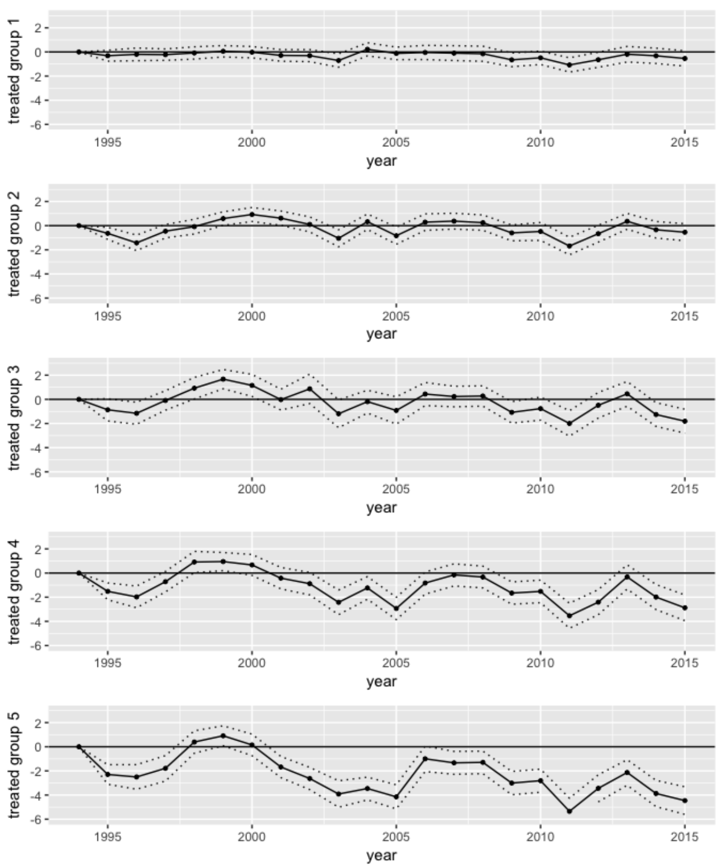

Figure 13: Parallel Trends for Nitrate Outcomes

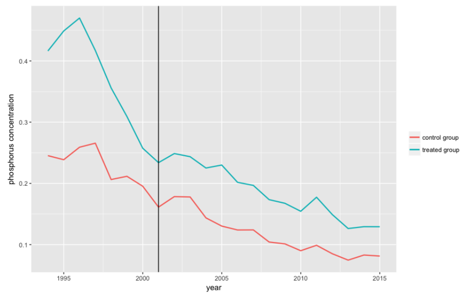

Figure a: Phosphorus

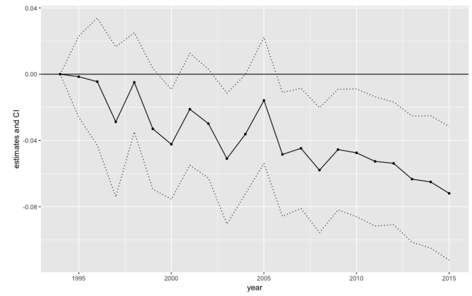

Figure b: Phosphorus

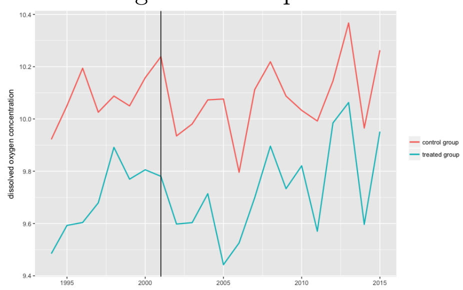

Figure c: Dissolved Oxygen

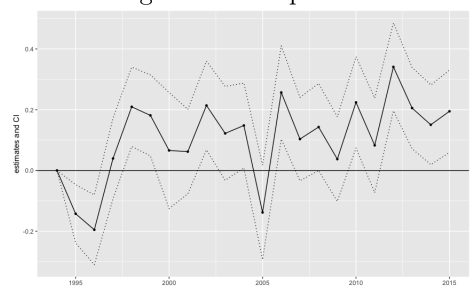

Figure d: Dissolved Oxygen

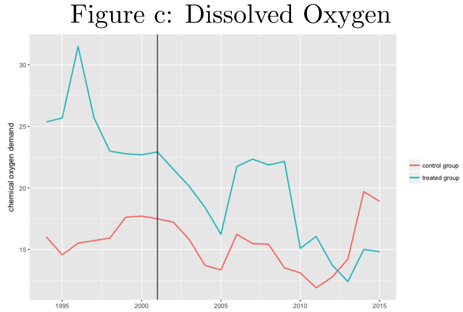

Figure e: Chemical Oxygen Demand

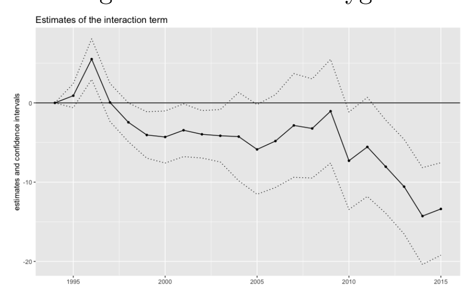

Figure f: Chemical Oxygen Demand

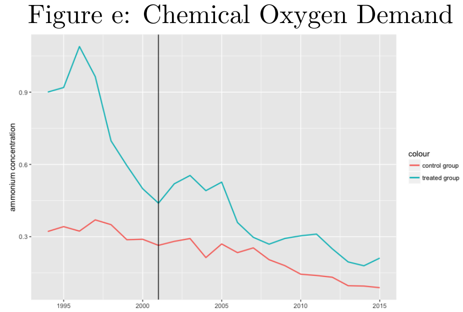

Figure g: Ammonium

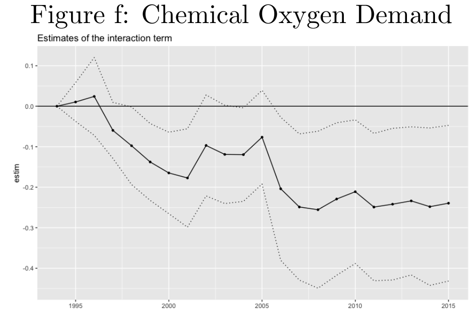

Figure h: Ammonium

Figure 14: Annual Means (left graphs) and Parallel Trend Coefficients (right graphs) by Treatment Groups: Other Physicochemical Outcomes

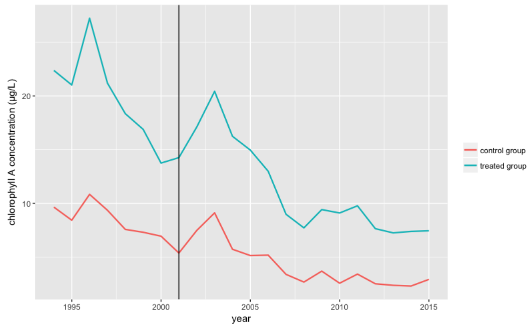

Figure a: Chlorophyll A

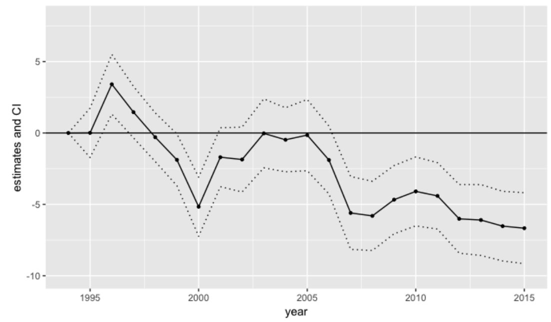

Figure b: Chlorophyll A

Figure c: Number of Fishes

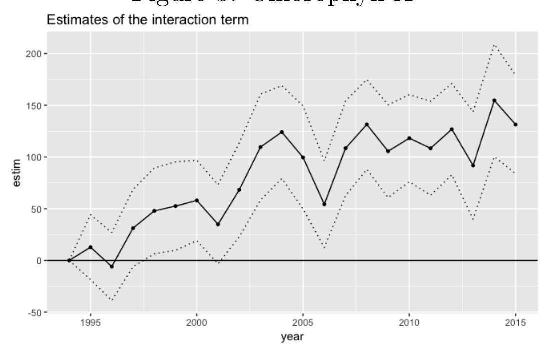

Figure d: Number of Fishes

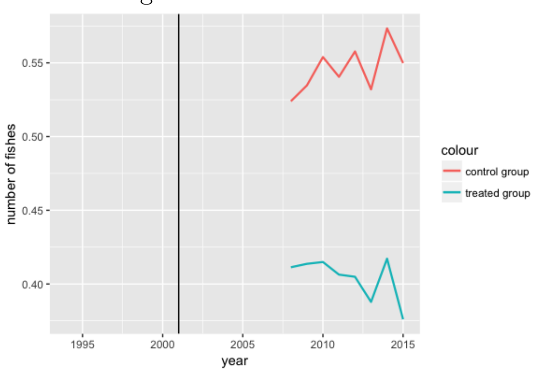

Figure e: Invertebrate Index

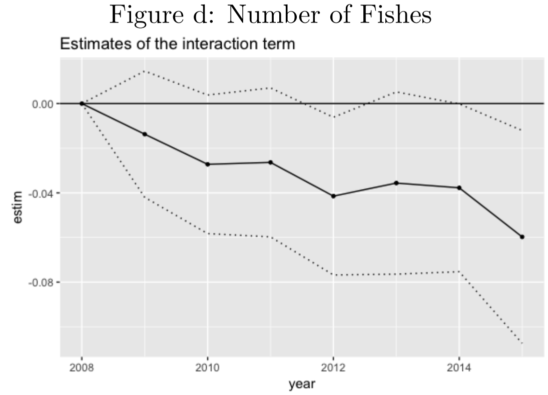

Figure f: Invertebrate Index

Figure 15: Annual Means (left graphs) and Parallel Trend Coefficients (right graphs) by Treatment Groups: Biological Outcomes

Figure a: N mineral fertilizer

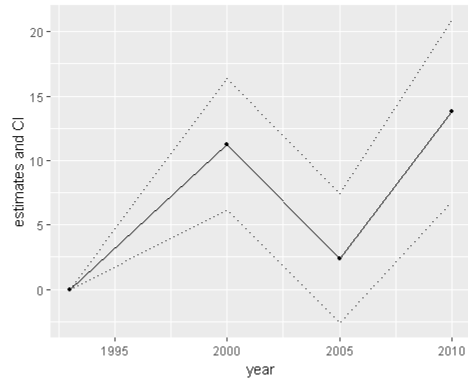

Figure b: N mineral fertilizer

Figure c: P mineral fertilizer

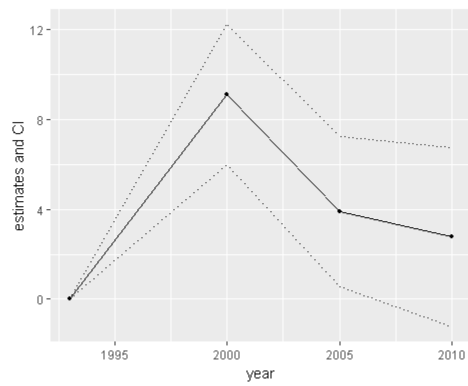

Figure d: P mineral fertilizer

Figure e: Manure

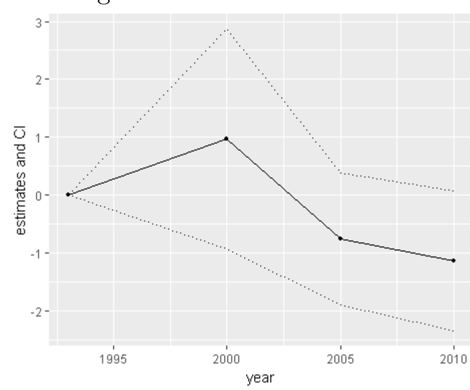

Figure f: Manure

Figure 16: Annual Means (left graphs) and Parallel Trend Coefficients (right graphs) in Vulnerable and Non-Vulnerable Areas: Mineral and Organic Fertilizers

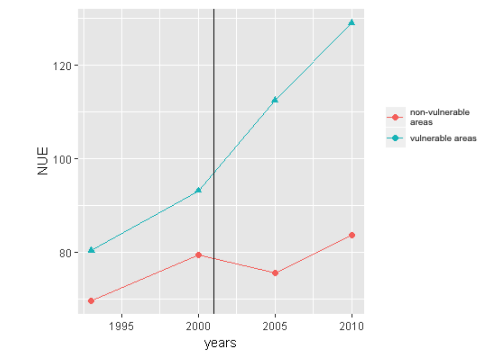

Figure a: NUE

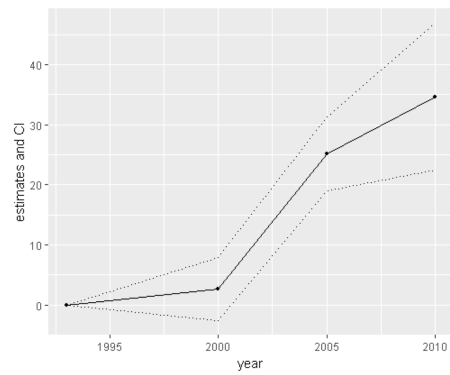

Figure b: NUE

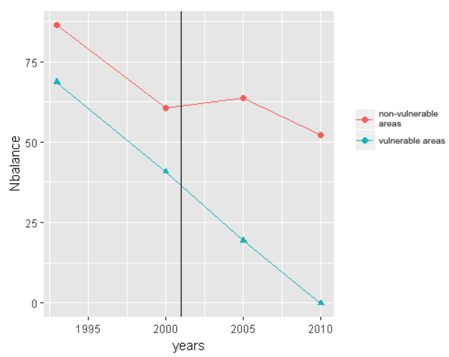

Figure c: N balance

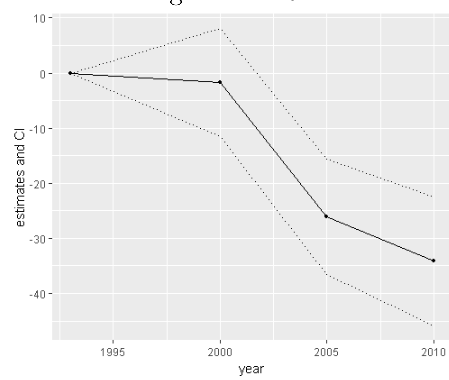

Figure d: N balance

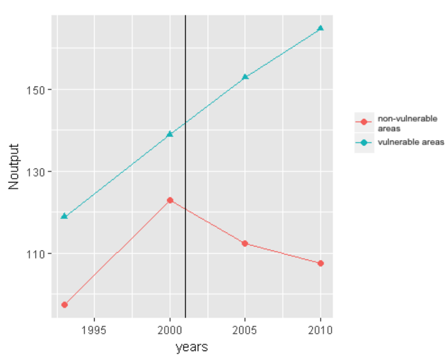

Figure e: N output

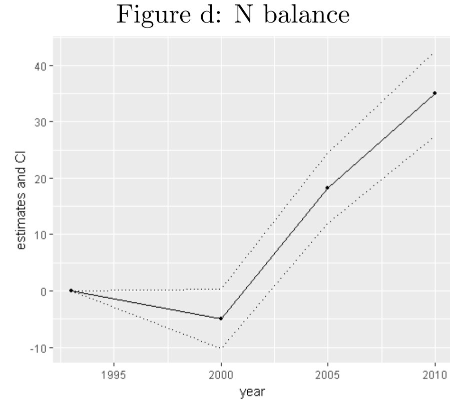

Figure f: N output

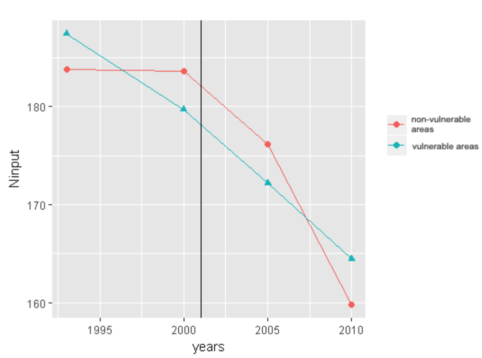

Figure a: N input

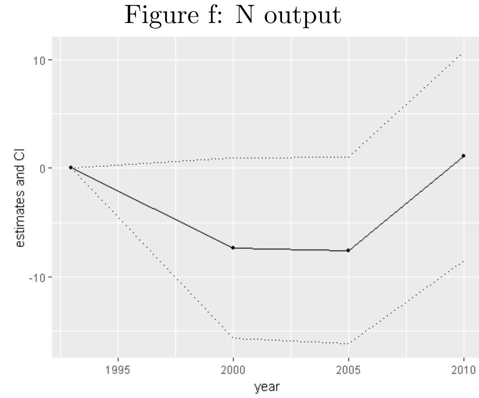

Figure b: N input

Figure 17: Annual Means (left graphs) and Parallel Trend Coefficients (right graphs) in Vulnerable and Non-Vulnerable Areas: Nitrogen Indicators

Figure a: N estimated

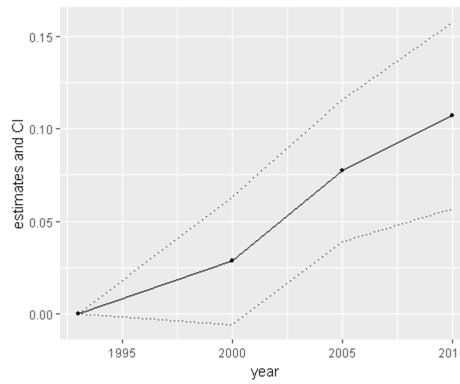

Figure b: N estimated

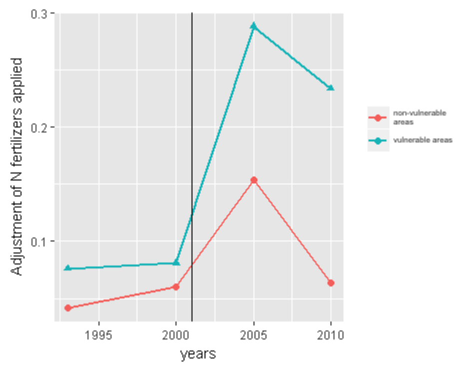

Figure c: N applied (after winter)

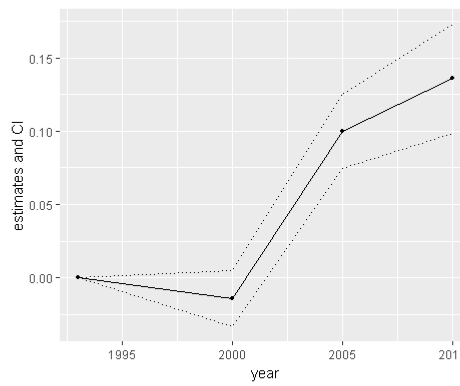

Figure d: N applied (after winter)

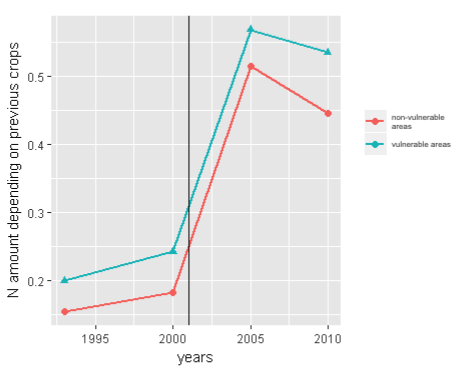

Figure e: N applied (after previous crops)

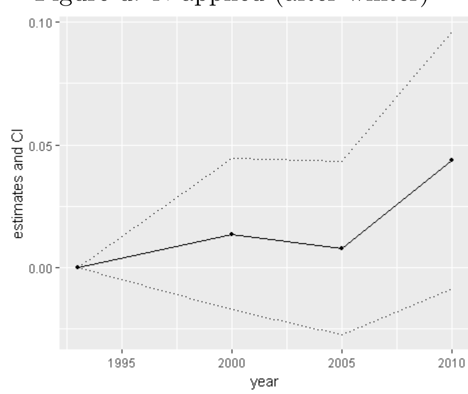

Figure f: N applied (after previous crops)

Figure 18: Annual Means (left graphs) and Parallel Trend Coefficients (right graphs) in Vulnerable and Non-Vulnerable Areas: N Fertilization Management

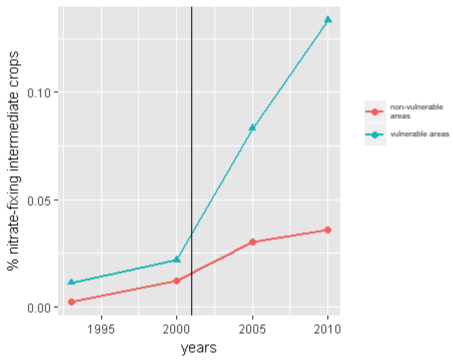

Figure a: Nitrate-Fixing Crops

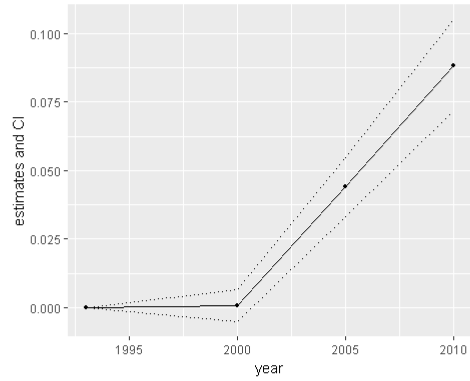

Figure b: Nitrate-Fixing Crops

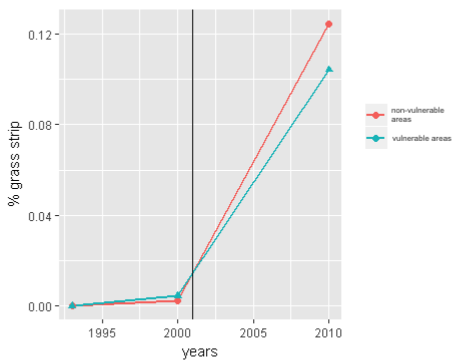

Figure c: Grass Buffer Strips

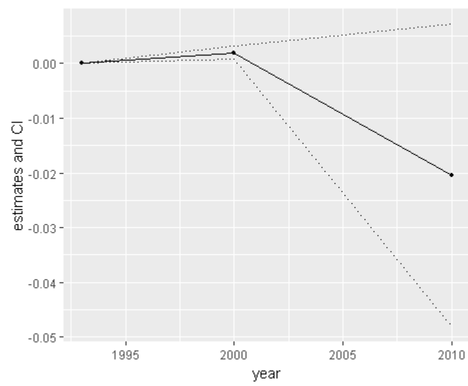

Figure d: Grass Buffer Strips

Figure 19: Annual Means (left graphs) and Parallel Trend Coefficients (right graphs) in Vulnerable and Non-Vulnerable Areas: Nitrate-Fixing Crops and Grass Buffer Strips

Figure a: Wastewater Treatment (Annual Means)

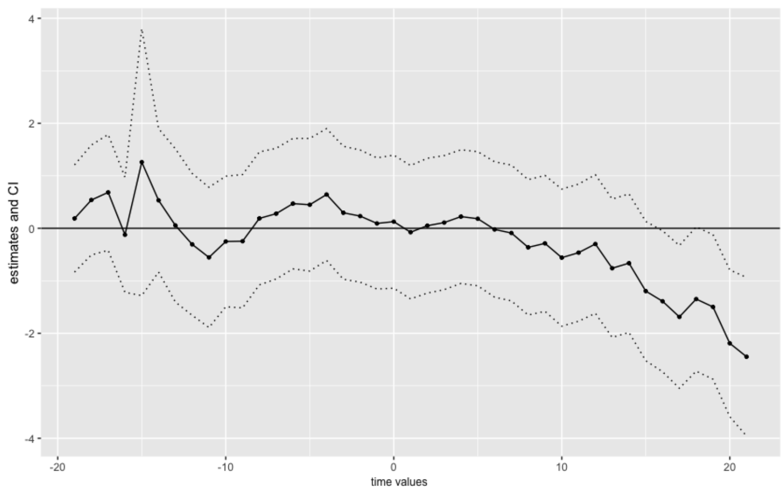

Figure b: Wastewater Treatment (Event Study)

Figure 20: Annual Means (left graphs) and Event Study Coefficients (right graphs) by Treatment Groups

Tables

Culture/Effluent	**Description**	**Type**	**N content**	**Unit**
Culture	soft wheat	grain	2.10	kg/100kg
Culture	durum wheat	grain	1.80	kg/100kg
Culture	rape	grain	2.90	kg/100kg
Culture	grain maize	grain	1.20	kg/100kg
Culture	forage corn	straw	0.81	kg/100kg
Culture	peas	grain	3.10	kg/100kg
Culture	barley	grain	1.50	kg/100kg
Culture	sunflower	grain	2.40	kg/100kg
Culture	beet	root	1.10	kg/100kg
Culture	triticale	grain	1.60	kg/100kg
Culture	potato	starch	0.34	kg/100kg
Effluent	bovine	manure	5.00	kg/ton
Effluent	bovine	liquid manure	5.00	kg/ton
Effluent	calf	liquid manure	2.50	kg/ton
Effluent	duck	manure	10.00	kg/ton
Effluent	ovine	manure	6.70	kg/ton
Effluent	ovine	liquid manure	6.00	kg/ton
Effluent	porcine	manure	6.00	kg/ton
Effluent	porcine	liquid manure	5.00	kg/ton
Effluent	goat	manure	6.10	kg/ton
Effluent	poultry	manure	25.50	kg/ton
Effluent	poultry	liquid manure	10.50	kg/ton
Effluent	rabbits	liquid manure	8.50	kg/ton

Note: This table reports the N content for each type of yields (by crop) and for each type of manures (by livestock). N content estimated in the different types of livestock effluents come from AgroParisTech, the Paris Institute of Technology for Life, Food and Environmental Sciences. N content in yield by type of crops come from Comifer, The French Committee of Sustainable Fertilization Practices Study and Development.

Table 11: Nitrogen content by crop yields and organic fertilizers

Dependent variable:	(1) nitrate	(2)	(3) ammonium	(4) phosphorus	(5) dissolved oxygen	(6) DCO
treated group 25%	-1.241^{***}		-0.118^{**}	-0.0256^{**}	0.109^{***}	-4.477^{***}
	(0.138)		(0.055)	(0.0115)	(0.037)	(1.728)
treated group 1		-0.286^{**}				
		(0.136)				
treated group 2		-0.202				
		(0.152)				
treated group 3		-0.895^{***}				
		(0.206)				
treated group 4		-1.546^{***}				
		(0.221)				
treated group 5		-2.442^{***}				
		(0.225)				
WastewaterTreatment	✓	✓	✓	✓	✓	✓
Controls	✓	✓	✓	✓	✓	✓
station FE	✓	✓	✓	✓	✓	✓
month FE	✓	✓	✓	✓	✓	✓
year FE					✓	✓
year×hydro district FE	✓	✓	✓	✓		
R-squared	0.760	0.760	0.48	0.31	0.43	0.34
Mean Dep. Var.	15.992	15.992	0.365	0.1951	9.903	18.609
Observations	406,174	406,174	408,528	372,402	203,402	76,780

Note: This table reports the effects of the policy on nitrate concentration. Regressions are run at the station level. Controls include quality of measurement, measurement support, portion analyzed and if the observation is raw or has been controlled, analyzed or validated. Standard errors are clustered at the watershed level. Significance levels are $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.10$.

Table 12: Impacts on Water Biological Outcomes Including Waste Water Treatments

Dependent variable:	(1) nitrate	(2) nitrate	(3) ammonium	(4) phosphorus	(5) dissolved oxygen	(6) DCO
treated group 25%	-1.268^{***}		-0.127^{**}	-0.0294^{**}	0.110^{***}	-5.485^{**}
	(0.137)		(0.058)	(0.0185)	(0.038)	(2.634)
treated group 1		-0.296^{**}				
		(0.142)				
treated group 2		-0.322^{**}				
		(0.154)				
treated group 3		-0.954^{***}				
		(0.226)				
treated group 4		-1.598^{***}				
		(0.218)				
treated group 5		-2.347^{***}				
		(0.223)				
total agricultural area		0.000^{***}				
		(0.000)				
cereal surface		-0.000^{***}				
		(0.000)				
wheat surface		0.000^{***}				
		(0.000)				
maize surface		-0.000^{**}				
		(0.000)				
grassland surface		-0.000^{***}				
		(0.000)				
Land use change	✓	✓	✓	✓	✓	✓
Controls	✓	✓	✓	✓	✓	✓
station FE	✓	✓	✓	✓	✓	✓
month FE	✓	✓	✓	✓	✓	✓
year FE					✓	✓
year×hydro district FE	✓	✓	✓	✓		
R-squared	0.760	0.760	0.48	0.31	0.43	0.34
Mean Dep. Var.	15.992	15.992	0.365	0.1951	9.903	18.609
Observations	406,174	406,174	408,528	372,402	203,402	76,780

Note: This table reports the effects of the policy on nitrates and other physicochemical parameters concentration including land use change controls (utilized agricultural area, cereal surface, wheat surface, maize surface and grassland surface). Regressions are run at the station level. Controls include quality of measurement, measurement support, portion analyzed and if the observation is raw or has been controlled, analyzed or validated. Standard errors are clustered at the watershed level. Significance levels are $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.10$.

Table 13: Impacts on Water Biological Outcomes Including Land Use Changes

Appendix A. Placeholder