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EU Regulations to Fight Nutrient Surpluses: the Case of Nitrate Vulnerable Zones

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EU Regulations to Fight Nutrient Surpluses: the Case of Nitrate Vulnerable Zones

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Abstract

This paper investigates the impact of the designation of nitrate vulnerable zones (NVZ) in the European Union (EU), which are mandated by the Nitrates Directive; the most comprehensive regulation for curbing water pollution caused by nitrates from agricultural sources in the EU. Using the OECD agri-environmental indicators database on nutrient balances covering 38 countries and a set of policy variables constructed from EU official documents, we estimate a fixed-effects model to test the impact of the implementation of nitrogen vulnerable zones on nitrogen balances. We find that NVZ regulations reduced nitrogen surplus in countries that designated their whole territories as nitrate vulnerable zones. The estimated reduction is of 10%, equivalent to 12kg/ha/year. NVZ regulations mainly reduced fertilizer use. We provide additional evidence of the NVZ effects by using the synthetic control approach, a method that relaxes the parallel trend assumption, and confirm the environmental benefits of NVZ regulations: treated countries (those with whole territory NVZ) decreased nitrogen bal-

ances relative to their synthetic control counterpart by 40%. More importantly, we find no evidence of NVZ regulation impacts on agriculture production or crop production.

1 Introduction

Both, nitrogen and phosphorus loads are the leading cause of surface water pollution [EUROSTAT, 2017, Bomans et al., 2005] and nitrate groundwater pollution in many areas of the world. Nutrient loads to European waterways are mainly from agricultural sources [European Commission, 2018]. Phosphorus (P) and nitrogen (N) are two essential nutrients for supporting plant growth. Nitrogen is necessary for protein build-up and phosphorus is required for energy use and transfer [Conley et al., 2009]. Nutrient inputs in agriculture are thus fundamental to maintaining and increasing crop and forage productivity [OECD, 2013]. Agricultural areas with sustained nutrient deficits may suffer reductions in soil fertility, while nutrient surpluses are likely to contribute to water and air pollution [OECD, 2013, 2008].

Agricultural activities contribute to nutrient build-up and have significantly affected nutrient cycles [Liu et al., 2010]. Fertilizer use and manure application are some of the most significant ways agriculture supplies nutrients to the environment. While some of those nutrients are taken up by crops and forage, in most agricultural land, nutrient inputs exceed nutrient outputs, creating nutrient surpluses [Bouwman et al., 2013, Liu et al., 2010].

It is estimated that 40-60% of N fertilizer is absorbed by crops and the remainder is lost to the environment [Sebilo et al., 2013]. An excess of nitrogen in surface water leads to excessive plant and algal growth, producing eutrophication. Eutrophic water bodies can suffer biodiversity losses and fish deaths. Nitrate concentrations in groundwater, often caused by excess N applications, pose risks to livestock and human health. Nitrogen volatilisation contributes to higher concentrations of nitrous oxide (N_2O), a potent greenhouse gas, and can lead to soil and water acidification, potentially affecting crop yields and biodiversity [Goulding, 2016].

Due to their relevance affecting water and air quality, several countries have made efforts to curb nutrient emissions from agricultural sources. In the European Union, the

main regulation to reduce nitrogen pollution is the Nitrate Vulnerable Zones (NVZs) policy mandated by the European Union (EU) Nitrates Directive (ND).

The NVZs are those land areas that drain into polluted waters or water sources at risk of nitrate pollution if no action is taken. Farmers in NVZs have to comply with measures included in the Codes of Good Agricultural Practice (CGAP), which each individual EU Member State defines and have to at least include a set of predefined measures defined by the EU. Since 1993, EU member states are required to declare NVZs and revise and update them every four years. States that implement a national action program to tackle nitrogen pollution are not required to designate NVZs; Austria, Denmark, Finland, Germany, Ireland, Lithuania, Luxembourg, Malta, the Netherlands and Slovenia, as well as the region of Flanders and Northern Ireland do not have designated NVZs and therefore they have whole territory programs.

There is an ongoing discussion on whether the NVZs and or the national programs implemented in EU countries to tackle nitrogen pollution have been effective. Implementing the Codes of Good Agricultural Practice can be costly and, if not effective, those practices and regulations that mandate them need to be redesigned to improve their cost-effectiveness.

This article intends to provide additional evidence on the impacts of the NVZs and the national programs in EU countries, by focusing on their effect on N balances in agricultural areas, the main driver of water pollution in EU countries. There are at least two main contributions of this study: (1) to our knowledge, it would be the first empirical study covering a large set of countries using nitrogen balance indicators; (2) it analyses the impact of NVZ regulations on the different components of the nutrient balance, mainly inputs (fertilizer, manure and other inputs) and outputs (crop and forage uptake) and (3) it tests the impacts of NVZ regulations on agricultural and crop production, as well as on phosphorus balances.

The methodology takes advantage of the timing of the implementation of NVZ regulations in the EU, as well as on the progressive accession of countries to the EU. Two main methodologies were implemented: fixed-effects model and synthetic controls. Taking

advantage of the panel data structure, the first method consisted on fitting a fixed effects model. To control for pre-existing trends in nutrient balances, country by time linear and quadratic terms are included. Additional determinants of nutrient balances, such as stocks of chickens, cattle and pigs and crop cultivated area by crop categories are also included. Our results show that NVZ policies were effective only for countries that implemented a whole-territory approach. For those countries NVZ regulations tended to decrease by 10% nitrogen balances. The NVZ policy seems to mainly have reduced the use of N fertilizers. No impacts on phosphorus balances, agriculture, crop production or other nutrient balance components (manure or crop uptake) was found. Results are robust to restricting the sample to EU countries and redefining the NVZ variable.

Following a synthetic control approach, we calculated an averaged treatment unit, using all countries that adopted a NVZ whole-territory approach, as well as a synthetic control using countries outside of the EU region. Nutrient balances in both, treatment and synthetic units, were compared before and after the implementation of the NVZ policy and we detected that nutrient balances in the treatment group decreased by 40% relative to the synthetic control group. We further confirmed that this impact was the largest when compared with placebo tests.

The paper is organized as follows. Section 2 summarized the previous literature on the subject; Section 3 describes the Nitrates Vulnerable Zones regulation; Section 4 describes the database used and the nutrient balance indicators used in the study; Section 5 summarizes the main method used and the identification strategy; Section 6 shows the main results; Section 7 includes robustness tests and the synthetic control results; and finally Section 8 offers a conclusion.

2 Previous literature

The literature on the subject varies according to the time period of study, geographical scope (e.g. EU27 countries, country or region within a country) and methodology used (e.g. simulation or statistical analysis). From the most salient studies found on the topic, only

two analyzed data for the EU27 countries. Grizzetti et al. [2012] assesses the changes in nitrogen and phosphorus loads in European seas during the period 1985-2005. This study measures the annual total nitrogen and total phosphorus loads reaching surface water by estimating the model GREEN, which contains a simplified representation of the processes of nutrient transport and retention in the river basin and a geo-spatial representation of the nutrient sources and physical characteristics that influence nutrient processes. Results show that strategies to reduce phosphorus were more successful than those tackling nitrogen and that policies aimed at point sources were more effectively implemented than those controlling pollution from diffuse sources, including those related to the implementation of the NVZs.

Velthof et al. [2014] analyses EU27 countries from 2000-2008. The model MITERRA-Europe was used to quantify the effects of the measures of the Nitrates Directive. The database of MITERRA-Europe includes N inputs, N outputs, livestock numbers, land use, crop types, soil type, and topography, among other data. Scenarios with and without implementation of the ND were compared. Results indicate the implementation of the ND lowered gas emissions (-3% for NH₃, -6% for N₂O, -9% for NO_x) and N leaching and runoff (-16%).

At least four country-level studies are relevant to mention. Worrall et al. [2009] analyses data from England during 1991-2006. The author performs a trend comparison and finds that only 31% of NVZs showed that water quality got worse while only 29% exhibited a significant improvement, and concludes that NVZs did not have a significant impact. Buckley [2012] examines farm-level data from south Scotland from 16 different farms located in NVZs during 2002-2011. Overall, the 16 farms were using 13% less N and 19% less P in 2011 compared with 2003, to which the authors attribute to the effects of the NVZs.

Kay et al. [2012] analyze nitrate concentrations trends in a NVZs catchment area of South Yorkshire, UK, and find little evidence of changes in nitrate concentrations for a period of 3 decades, implying that NVZs in that area had no impact on water quality.

3 The Nitrogen Vulnerable Zones

A series of governmental environmental policies and measures has been implemented in the EU to decrease N emissions [Velthof et al., 2014]. Directive 91/676/EC of the Council of the European Union, known as the "Nitrates Directive (ND)" is perhaps the most relevant and overarching across Europe to tackle N leaching loss from agriculture [Oenema et al., 2009, Velthof et al., 2014]; it was introduced in 1991. The main objectives of the ND are to reduce water pollution caused or induced by nitrates from agricultural sources and to prevent further pollution from nitrogen.

The ND establishes that member states should implement the following actions: i) to designate all land draining to waters that are affected by nitrate pollution or that could be affected if action is not taken to decrease nitrate leaching (so-called Nitrate leaching Vulnerable Zones or NVZs). The criteria to delimit NVZ is based on nitrate concentrations in surface and ground water bodies exceeding 50 mg/l. In addition, all waters which are found to be eutrophic or in the near future may become eutrophic have to be designated NVZ European-Commission [1997]; ii) establish a voluntary code of good agricultural practices available to all farmers throughout the country, and a mandatory action program, which should be applied in NVZs; iii) implement a monitoring program to assess the effectiveness of the implementation of the Directive and iv) submit every four years a report listing the main actions taken, the designation of NVZs and the status of waters in NVZ.

Member states that implement an action program in their whole territory do not have to designate specific NVZs. Action programs include measures on periods when the land application of fertilizers is prohibited, balanced N fertilization and limits to N manure nitrogen application (170kg/ha/year), and limitations to application of N fertilizers on sloping soils, during wet conditions, and near watercourses [Velthof et al., 2014].

Table 1 shows the stipulated timetable for the implementation of the Directive. NVZs needed to be designated as of 1993, but they were revised until the end of 1997. The end of 1998 establishes the period when the deadline for the application of the N manure application limits. For the first period, it grants the possibility for countries to set a limit of 210 kg/ha;

four years later countries need to comply with the 170 kg/ha limit.

Table 1: The timetable for the Implementation of the Directive

Requirement	Stipulated Completion Date
Transposing into National Law	20.12.1993
Monitoring	20.12.1993
Designation of NVZs	20.12.1993
Establishment of Code of Good Agricultural Practices	20.12.1993
Establishment of First Four Year Programme	20.12.1995
Submission of Summary Report to EC	20.06.1996
Completion of the Review of Designations	21.12.1997
Start of the year for Maximum of 210 kg N ha	20.12.1998
Completion of First Programme	20.12.1999
Start of the year for Maximum of 170 kg N ha	20.12.2002
Completion of Second Programme	21.12.2003

Source: [European-Commission, 1997, p. 11]

Table 2 shows the years were NVZs were designated in member states who followed the whole territory approach. Austria, Denmark, Finland, Germany, Netherlands and Luxembourg declared NVZs before 2000, while Ireland, Lithuania, Malta and Slovenia designated implemented action plans in 2007, since they became members of the EU in 2003 and action programs follow a four year cycle.

Table 2: Year of designation of NVZs in countries that followed the whole territory approach.

Country	Year of NVZ designation for whole-territory NVZ countries
Denmark	1994
Netherlands	1994
Germany	1995
Luxembourg	1995
Austria	1996
Finland	1999
Ireland	2003
Lithuania	2007
Malta	2007
Slovenia	2007

In Figure 1 plots the average territory declared as NVZs in countries that, on the contrary, followed the partial territory approach. A sharp increase occurred after 2006, mainly due to the inclusion of Eastern European countries ¹.

Figure 1: Average territory under NVZs in Member States who followed the partial territory approach. Source: Own elaboration based on EC official documents

¹This is the case for Bulgaria, Cyprus, Czech Republic, Estonia, Hungary, Latvia, Poland, Romania and Slovakia, who declared NVZs until 2007

Figure 2 shows the NVZs in member states as of 2015. Light blue color represents all the countries under the whole-territory approach, while dark blue zones correspond to the partial territories declared by each country.

Figure 2: Nitrate vulnerable zones as submitted by EUs Member States in 2015. Source: European Commission. [The current status of NVZs and whole territory designations]. Retrieved May 7, 2019

4 Data

The sample covers 38 countries, including most OECD countries and other European countries for the period 1990-2015. The sample was chosen based on nutrient balance indicators data availability. Nutrient balance indicators were obtained from OECD Agri-environmental Indicators Database [OECD, 2019], which is the most comprehensive publicly available source of internationally comparable data on nutrient balances. Nutrient balances are calculated at the national level, and measure the difference between the total quantity of nutrient inputs entering an agricultural system (mainly fertilizers, livestock manure, atmospheric deposition and biological fixation), and the quantity of nutrient outputs leaving the system (mainly the uptake of nutrients by crops and grassland) [OECD, 2012a][OECD, 2012b]. In the case of nitrogen, the gross nutrient balance includes all emissions of environmentally harmful nitrogen compounds from agriculture into the soil, water and the air, while the net balance excludes

air emissions [OECD, 2012a]. In the case of phosphorus, there are no air emissions so the gross balance is the same as the net balance (Figure 3). OECD nutrient balance indicators are gross balances. Gross balances are expressed in kilograms of nutrient surplus per hectare of agricultural land per year. It is important to bear in mind that these indicators are proxies for environmental pressures at the national level, and do not consider sub-national differences.

Figure 3: Main components of the gross nitrogen and phosphorus balance calculation.

Nutrient balances are driven by a multiplicity of factors. Some of the most relevant ones are related to livestock and crop composition [OECD, forthcoming 2019]. Sources for both variables are found in [FAOSTAT, 2019]. Table 3 summarizes the variables used in this study. Average N and P balances are 79 kg/ha and 9.9 kg/ha per year in covered countries. There is a large heterogeneity in balances across covered countries. Countries with small agricultural areas and high animal stocks, such as Belgium, Korea, Japan and the Netherlands tend to have large surpluses. In contrast, countries such as Iceland, Australia and Canada with large agricultural areas that specialize in crop production tend to have lower surpluses. Fifteen percent of the observations are affected by the NVZs whole territory approach and, on average, 5% of the territories are affected by the partial NVZs approach in sample countries.

Table 3: Summary statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
N balance (Kg/ha)	918	79.02	66.90	4.00	346.00
P balance (Kg/ha)	910	9.98	15.15	-9.00	79.36
Agriculture Production (Index 2002-2004=100)	879	99.96	12.10	67.51	193.73
Corp Production (Index 2002-2004=100)	879	99.40	15.89	54.30	225.42
Dummy NVZs Whole Territory	918	0.15	0.36	0.00	1.00
NVZs Partial Territory	918	5.29	13.56	0.00	76.39
Pig stock (1000 heads)	918	1885.19	2879.51	0.27	17097.32
Chicken stock (1000 heads)	918	1211.77	3052.78	0.72	20150.00
Cattle stock (1000 heads)	918	7324.58	16436.08	8.93	103548.20
Feed crops (1000 ha)	918	2685.64	6245.13	0.50	40168.72
Cereal crops (1000 ha)	918	5031.85	10460.07	2.00	65890.41
Oil crops (1000 ha)	880	1739.47	5883.84	0.00	39202.18
Fruits and vegetables (1000 ha)	918	471.68	701.08	1.56	2766.04

Sources: Nutrient balances were obtained from OECD agri-environmental indicators database [OECD, 2019]. Agriculture, crop production indices, livestock and cultivated area by crop category were obtained from FAOSTAT [FAOSTAT, 2019]. Dummy variable NVZs Whole Territory and NVZs Partial Territory were constructed by the authors from European Commission official documents.

5 Methodology

The empirical approach takes advantage of the progressive designation, implementation and expansion of NVZs, as well as of the progressive addition of European countries to the EU. Figure 4 plots the average N balance per hectare for three groups: control, NVZs Whole Territory and NVZs Partial Territory. The control group is defined by those countries that are in the database and are not part of the EU and, therefore do not have any NVZs implementation. The NVZs Whole Territory group is defined by those countries that implemented a whole territory approach and implemented action plans to fight nitrogen pollution in all their territory. The NVZs Partial Territory group is defined by countries that designated specific regions as vulnerable zones. The vertical line at 1999 marks the start of the year during which maximum limits of nitrogen applications per hectare were set in place.

Timing of NVZ designation varied by country, presumably in relation to their commitments to fight nitrogen pollution and related to the size of the country as smaller states such as the Netherlands, Denmark and Luxembourg completed the NVZs designation before October 1994, while larger countries took longer to designate NVZs. We focus on the year when the maximum limits of nitrogen applications were established rather than the dates of NVZs designation as the later only refer to countries defining an area where plans of action should be implemented, whereas the former sets the implementation date.

For the control group, a slight upward trend can be appreciated up to 2003 after which balances tend to decrease. For the NVZs Partial Territory group a downward trend can be appreciated from the beginning of the period up to the point of first NVZs Whole Territory designation, after of which it remains relatively flat and then decreases one more time in 2003. For the NVZs Whole Territory group a downward trend can be observed before 1999, which seems to get more pronounced after 1999. It is also worth mentioning that, as the sample is an unbalanced panel, the decline observed from 1990 to 1991 is also related to the addition of more countries into the sample calculation.

Figure 4: Nutrient balances in European and OECD countries

Considering that NVZs partial and whole designations seem to be related to countries characteristics and that there are pre-existing trends in all groups, the methodology proposed controls for fixed effects and for country by trend dummies, both linear and quadratic:

$$\begin{aligned}
 Nbalance_{ct} = & \beta_1 NVZTotal_{ct} + \beta_2 NVZPartial_{ct} + C + T + X' Cropland_{ct} \\
 & + Z' Livestock_{ct} + \sum_c Country_c * Trend_t + \sum_c Country_c * Trend_t^2 + \varepsilon_{ct}
 \end{aligned} \tag{1}$$

The variable NVZs Total is a dummy, set equal to one if a country takes a whole territory approach for NVZs. The first year at which it takes a value of one is 1999 for the reasons explained before. The variable NVZs Partial takes the value of the share of the territory that was designated NVZs for those countries that adopted a partial territory approach. Since cropland and livestock mixes are important factors defining nutrient balances, controls on both were added. Cultivated area includes cereals, fruits and vegetables, oil crops and feed crops. Livestock includes chicken, pigs and cattle.

6 Results

Main results are shown in Table 4. Specifications (1)-(3) do not include cropland or livestock variables; specifications (4)-(6) include livestock variables and specifications (7)-(9) add

cropland variables. All variables are expressed in logarithms except for the NVZs variables. Including country by time dummies both, linear and quadratic, tends to reduce coefficient estimates.

The largest impact is driven by the inclusion of linear state by trend dummies, implying controlling for both pre-existing declining rates of nitrogen balances in NVZs whole territory countries is important to isolate the impact of the implementation of NVZs policies. According to the results, only the whole territory NVZs approach is statistically significant in all specifications at the 5% level (robust standard errors reported in parenthesis).

The most complete specification (9), which includes livestock and cropland control variables as well as the full set of country by time dummies, indicates that countries that adopted a whole territory NVZs approach reduced their nitrogen balances by 10%. Considering those countries had, on average, nitrogen balances of 122 kg/ha before the policy was implemented, the estimated coefficient implies a 12.2 kg/ha reduction in nitrogen surpluses. Stocks of cattle, pigs and chicken are positively associated with nitrogen surpluses. Cattle is particularly highly associated. A 1% increase in cattle stocks is associated with a 0.7% increase in nitrogen surplus. The impacts of cultivated crops are not clear. Cultivated area of feed, cereals and fruits and vegetables crops are negatively associated with nitrogen surpluses but coefficients are not consistently significant across specifications. Oil crops tend to be positively associated with nitrogen balances but coefficients are not stable and consistently significant. Focusing on specification (9), a 1% increase in the area dedicated to cereal cultivation decreases by 2% nitrogen balances, while a similar increase in the area dedicated to oil crops tends to increase nitrogen balances by 0.09%.

Something to bear in mind is that the variables used to estimate the impacts of NVZ are measured at the national level and hence we cannot rule out that NVZ policies in NVZs in countries that followed a partial approach did not have an impact on balances in those areas.

To further understand the mechanisms through which the NVZ policy impacts nutrient balances Table 5 shows the results for each of the broad components of the nitrogen

Table 4: Estimated impacts of NVZs policies on nitrogen balances

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
NVZs Whole Territory	-0.277*** (0.0510)	-0.144** (0.0572)	-0.131** (0.0515)	-0.260*** (0.0603)	-0.168** (0.0624)	-0.109*** (0.0391)	-0.251*** (0.0566)	-0.149** (0.0647)	-0.102** (0.0485)
NVZs Partial Territory	-0.00348* (0.00178)	0.00217 (0.00155)	-0.000191 (0.00163)	-0.00143 (0.00175)	-4.59e-05 (0.00156)	0.000151 (0.00187)	-0.000929 (0.00149)	0.000503 (0.00153)	0.000447 (0.00192)
Pig stock				0.132 (0.0875)	0.350*** (0.125)	0.313** (0.118)	0.194** (0.0915)	0.372*** (0.130)	0.292*** (0.104)
Chicken stock				0.161*** (0.0554)	0.119*** (0.0393)	0.0898** (0.0382)	0.238*** (0.0521)	0.142*** (0.0472)	0.106** (0.0414)
Cattle stock				0.198 (0.160)	0.597*** (0.147)	0.725*** (0.212)	0.321** (0.138)	0.636*** (0.147)	0.711*** (0.199)
Feed crops (Ha)							-0.121 (0.190)	0.0326 (0.127)	-0.0778 (0.102)
Cereals crops (Ha)							0.0295 (0.288)	-0.248 (0.212)	-0.270** (0.122)
Oil crops (Ha)							0.132** (0.0586)	0.00865 (0.0510)	0.0901* (0.0529)
Fruits and vegetables (Ha)							-0.204* (0.107)	-0.154 (0.0917)	-0.0759 (0.0943)
Observations	974	974	974	944	944	944	880	880	880
R-squared	0.210	0.431	0.588	0.273	0.597	0.656	0.359	0.608	0.669
Number of country_id	40	40	40	39	39	39	38	38	38
Country FE	YES	YES	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES	YES	YES
Country*Trend FE	NO	YES	YES	NO	YES	YES	NO	YES	YES
Country*Trend2 FE	NO	NO	YES	NO	NO	YES	NO	NO	YES

In all specifications, the dependent variable is the logarithm of nitrogen balances per hectare. All independent variables, except for NVZs policies, are expressed in logarithms. Robust standard errors in parenthesis, *** p<0.01, ** p<0.05, * p<0.1.

balances, namely, inputs such as fertilizer, manure and other inputs (mainly biological fixation) and outputs such as nutrient uptake by crop harvest and forage. We use the specification that controls for cropland, livestock and country by trend dummies, both linear and squared. Results from Table 3 suggest that countries that adopted the NVZ whole territory approach reduced fertilizer use and did not have a significant impact in any of the other components of the balance. The estimated effect of NVZ policy for those countries is a reduction of 7.6%. These results also help explaining some of the relationships obtained between cultivated crops, livestock and nitrogen balances. Cattle, pig and chicken stocks are associated with higher manure inputs. Cereal and oil crops are associated with higher nitrogen fertilizer but also with higher N inputs from other sources, such as nitrogen fixation and atmospheric deposition. Cereal crops also tend to be positively associated with higher crop uptake. Because cereal and oil crops tend to impact both inputs and outputs, no clear relationship with the balance is found in Table 4.

NVZ policies may have had an impact on production by restricting the amount of inputs used on land and also due to the implementation of stricter good practices. They could have also reduced phosphorus balances due to the imposition of pro-environmental practices and overall fertilizer restrictions. Table 6 shows the results of the full specification P balance, agriculture production and crop production FAO indexes. None of the NVZ policies seem to have a significant impact on P balances, agriculture or crop production, suggesting that the policies may have had a limited impact on production levels and also on other environmental threats.

Table 5: Estimated impacts of NVZ policies on nitrogen balances components

	N fertilizer	N Manure	N Other inputs	N Crop harvest	N Forage
NVZ Whole Territory	-0.0767** (0.0313)	-0.0157 (0.0126)	-0.0217 (0.0163)	0.00919 (0.0251)	-0.00206 (0.0301)
NVZ Partial Territory	0.000303 (0.000600)	-5.37e-05 (0.000268)	0.000891 (0.000551)	0.000203 (0.000795)	0.000231 (0.000731)
Pig stock	0.0922 (0.0599)	0.115*** (0.0365)	-0.0248 (0.0167)	-0.112** (0.0461)	0.0245 (0.0487)
Chicken stock	0.101** (0.0395)	0.0580*** (0.0195)	-0.00826 (0.0249)	0.0387 (0.0263)	0.0139 (0.0405)
Cattle stock	0.451*** (0.150)	0.340*** (0.0445)	0.0370 (0.0398)	0.0460 (0.0801)	0.0862 (0.125)
Feed crops (Ha)	-0.144 (0.116)	-0.0340* (0.0172)	0.00583 (0.0272)	-0.0732 (0.0963)	0.0426 (0.0948)
Cereals crops (Ha)	0.435*** (0.137)	-0.00776 (0.0290)	0.0770** (0.0374)	0.856*** (0.149)	0.0889 (0.173)
Oil crops (Ha)	0.123** (0.0514)	0.0160 (0.0107)	0.0526*** (0.0106)	0.0172 (0.0250)	-0.0312 (0.0386)
Fruits and vegetables (Ha)	-0.0199 (0.0684)	-0.0224 (0.0179)	-0.0251 (0.0270)	0.0260 (0.0599)	-0.00582 (0.0618)
Observations	884	884	884	884	884
R-squared	0.842	0.952	0.881	0.664	0.539
Number of country_id	38	38	38	38	38

All independent variables, except for NVZ policies, are expressed in logarithms. Dependent variables are expressed in logarithms.

N fertilizers, manure and other inputs are inputs in the balance, while N crop harvest and forage are outputs. Robust standard errors in parenthesis, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

All specifications include country, time, country by trend and country by trend squared fixed effects.

Table 6: Estimated impacts of NVZ policies on P balance, agriculture and crop production

	P Balance	Agriculture Production	Crop Production
NVZ Whole Territory	-0.0810 (0.0822)	0.00103 (0.0144)	0.0231 (0.0206)
NVZ Partial Territory	-0.00310 (0.00546)	-0.000378 (0.000319)	-0.000341 (0.000747)
Pig stock	0.466* (0.259)	0.000443 (0.0329)	-0.123*** (0.0419)
Chicken stock	0.310** (0.130)	0.0580*** (0.0146)	0.0327 (0.0307)
Cattle stock	0.692*** (0.240)	0.208** (0.0969)	0.0920 (0.0602)
Feed crops (Ha)	-0.127 (0.191)	0.0203 (0.0586)	-0.0546 (0.118)
Cereals crops (Ha)	-0.579** (0.243)	0.174** (0.0726)	0.493*** (0.149)
Oil crops (Ha)	0.124* (0.0659)	0.0359* (0.0181)	0.0247 (0.0304)
Fruits and vegetables (Ha)	-0.283 (0.229)	0.0739** (0.0363)	0.212*** (0.0590)
Observations	748	846	846
R-squared	0.747	0.803	0.672
Number of country_id	36	37	37
Country FE	YES	YES	YES
Year FE	YES	YES	YES
Country*Trend FE	YES	YES	YES
Country*Trend2 FE	YES	YES	YES

All independent variables, except for NVZ policies, are expressed in logarithms. Dependent variables are expressed in logarithms. Robust standard errors in parenthesis, *** p<0.01, ** p<0.05, * p<0.1.

7 Additional tests

To further test the robustness of the estimates, we performed two additional exercises. In the first, we restricted the sample to only include those countries in the EU and that, by law, must have a NVZ policy. The identification strategy in this case relies on the timing at which the policy was implemented and also on the timing at which countries joined the EU.

Table 7 shows the battery of results focusing on EU countries. Estimates are similar in magnitude to the ones using the full sample and suggest NVZ policies in whole territories reduced nutrient balances by 9.4%, while NVZ policies in partial territories did not have a statistically significant impact on balances. Except for chicken stocks, pig and cattle stocks are positive and statistically significant.

In the second exercise we re-defined NVZ timing to reflect the time at which countries designated NVZ, rather than the time at which it was implemented. This change particularly impacts those countries that were EU members and that had designated NVZ areas at the time it was mandated. Table 8 reports the estimates for designated NVZ policies for the full sample and also for the restricted sample focusing on EU countries. In both cases the impact of NVZ whole territory is positive and statistically significant.

Table 7: Estimated impacts of NVZ policies using designation of NVZ policies

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
NVZ Whole Territory	-0.203*** (0.0566)	-0.166** (0.0607)	-0.187** (0.0684)	-0.250*** (0.0598)	-0.167** (0.0658)	-0.110** (0.0463)	-0.232*** (0.0647)	-0.136* (0.0671)	-0.0942* (0.0534)
NVZ Partial Territory	-0.00186 (0.00183)	0.00153 (0.00159)	-0.000834 (0.00181)	-0.00112 (0.00183)	4.62e-05 (0.00170)	0.000270 (0.00214)	-7.09e-05 (0.00183)	0.000561 (0.00173)	0.000586 (0.00214)
Pig stock				0.104 (0.148)	0.537*** (0.134)	0.533*** (0.103)	0.230 (0.170)	0.532*** (0.140)	0.491*** (0.106)
Chicken stock				0.256*** (0.0864)	0.102 (0.0623)	0.0600 (0.0493)	0.272*** (0.0751)	0.111 (0.0675)	0.0620 (0.0500)
Cattle stock				0.0710 (0.186)	0.554*** (0.167)	0.748*** (0.251)	0.189 (0.181)	0.626*** (0.167)	0.789*** (0.240)
Feed crops (Ha)							-0.326 (0.204)	-0.0429 (0.146)	-0.110 (0.117)
Cereals crops (Ha)							0.280 (0.253)	-0.213 (0.245)	-0.310* (0.172)
Oil crops (Ha)							0.111* (0.0575)	0.00848 (0.0565)	0.0766 (0.0610)
Fruits and vegetables (Ha)							-0.226* (0.116)	-0.163* (0.0949)	-0.0874 (0.106)
Observations	660	660	660	642	642	642	615	615	615
R-squared	0.293	0.429	0.585	0.327	0.602	0.653	0.411	0.612	0.665
Number of country_id	27	27	27	27	27	27	27	27	27
Country FE	YES	YES	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES	YES	YES
Country*Trend FE	NO	YES	YES	NO	YES	YES	NO	YES	YES
Country*Trend2 FE	NO	NO	YES	NO	NO	YES	NO	NO	YES

In all specifications, the dependent variable is the logarithm of nitrogen balances per hectare. All independent variables, except for NVZ policies, are expressed in logarithms. Robust standard errors in parenthesis, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 8: Estimated impacts of the designation of NVZ policies on nitrogen balances

VARIABLES	All sample	Only NVZ countries
NVZ Whole Territory	-0.0828** (0.0405)	-0.0795* (0.0392)
NVZ Partial Territory	0.000511 (0.00195)	0.000666 (0.00216)
Pig stock	0.295*** (0.106)	0.494*** (0.103)
Chicken stock	0.106** (0.0413)	0.0585 (0.0488)
Cattle stock	0.719*** (0.204)	0.821*** (0.240)
Feed crops (Ha)	-0.0943 (0.105)	-0.135 (0.123)
Cereals crops (Ha)	-0.265** (0.121)	-0.295 (0.174)
Oil crops (Ha)	0.0867 (0.0534)	0.0737 (0.0615)
Fruits and vegetables (Ha)	-0.0762 (0.0945)	-0.0887 (0.107)
Observations	880	615
R-squared	0.668	0.665
Number of country_id	38	27
Country FE	YES	YES
Year FE	YES	YES
Country*Trend FE	YES	YES
Country*Trend2 FE	YES	YES

In both specifications, the dependent variable is the logarithm of nitrogen balances per hectare. All independent variables,

except for NVZ policies, are expressed in logarithms. Robust standard errors in paren-

thesis, *** p<0.01, ** p<0.05, * p<0.1

7.1 Synthetic control approach

The differences trajectories in nitrogen balances followed by the control group and the Member States with whole territory NVZs (Figure 4) raise the concern that there may be unobserved covariates that differ between the comparison groups and whose effects on the outcome variable vary over time. To the degree to which those unobserved effects are captured by country and time trends, results presented in previous sections provide consistent estimates of the impacts of NVZ policies. This sub-section provides yet an alternative potential solution which hinges on the synthetic control method.

The synthetic control method, pioneered by Abadie and Abadie [2005] and Abadie et al. [2010] is an alternative approach for programme evaluation that relaxes the parallel trends assumption. Abadie et al. [2010] developed this method in the context of comparative case studies, where only one or a few subjects receive an intervention while a larger set remain untreated. The key idea behind this method is that the outcomes from the control units are weighted in order to provide, in the absence of treatment, a valid and more robust counterfactual for the treated unit. As pointed out by Kreif et al. [2016] *a synthetic control unit is defined as the time-invariant weighted average of available control units, which prior to the intervention have similar preintervention characteristics and outcome trajectory to the treated unit*. According to Abadie et al. [2010], in contrast to the DiD method, the synthetic control method allows the effects of observed and unobserved predictors of the outcome to change over time, while assuming that preintervention covariates have a linear relationship with outcomes posttreatment.

To proceed with this method we constructed a synthetic whole territory NVZ unit as a weighted average of potential countries, with weights chosen so that the resulting synthetic NVZ best reproduces the values of a set of predictors of nitrogen balance in EU member states before the unified implementation of the whole territory NVZs in 1999. Because the synthetic NVZ is meant to reproduce nitrogen balance that would have been observed in EU member states before the unified implementation of the NVZs in 1999, we discard from the donor pool European countries which adopted the partial territory NVZ.

7.1.1 Results

Table 9 shows the nitrogen balance values predictors (expressed in logarithms). The results compare the pre-treatment characteristics of the actual Member States who implemented the whole territory NVZs with that of the synthetic ones. The table confirms that treatment and control units differ substantially in terms of area of cultivated crops and stocks of pigs.

Table 9: Comparison between treatment, control and synthetic units

Variable	Treated	Synthetic	Control
Pre-1999 Nitrogen Balance	4.79	4.79	3.72
Cereals	14.84	15.24	11.01
Oilcrops	12.74	12.74	8.78
Feed	14.28	12.67	10.03
Fruit and vegetables	12.06	13.77	11.83
Stock pigs	15.23	15.13	12.87
Stock chickens	13.41	15.27	13.19
Stock cattle	15.92	15.94	15.36

All variables are in logs.

Figure 5 displays nitrogen balance in EU Member States who implemented a unified NVZ whole territory policy in 1999 and its synthetic counterpart during the period 1990 to 2015. Notice that nitrogen balances in the synthetic NVZ very closely track the trajectory of this variable in EU Member States in the treatment group for the entire pre-implementation period. Combined with the high degree of balance on all nitrogen balance predictors (Table 9), this suggests that the synthetic NVZ group provides a sensible approximation to the Nitrogen balance trend after 1999 in the absence of the NVZs whole territory unified approach.

Figure 5: Trends in Nitrogen balance: whole territory NVZs vs. synthetic whole territory NVZs

Figure 6 plots the yearly estimates of the impacts of NVZ whole territory approach, that is, the yearly gaps in nitrogen balances between EU Member States who followed this policy and its synthetic counterpart. Figure 6 suggests that the NVZ policy had a large effect on nitrogen balance, and that this effect increased over time. The magnitude of the estimated impact of the whole territory NVZs in Figure 6 is substantial: the average gap between three years before the implementation (1997 to 1998) is equal to -0.07 , while the average gap in the last three years of our data (2013 to 2015) is equal to -0.40 .

Figure 6: Nitrogen balance gap between EU Members States who adopted Whole territory NVZs and the synthetic control group

7.1.2 Inference about the Nitrogen Vulnerable Zone Whole territory approach policy effect.

To evaluate the significance of our estimates, we pose the question of whether our results could be driven entirely by chance. How often would we obtain results of this magnitude if we had chosen a country at random for the study instead of EU Member States who implemented whole territory NVZs.

To answer this question, we use placebo tests. Similar to Abadie [2005], Bertrand et al. [2004] and Abadie et al. [2010] we run placebo studies by applying the synthetic control method to countries that did not implement any of the NVZs policies (partial or whole territory). If the placebo studies create gaps of magnitude similar to the one estimated for EU Member States who followed the whole territory approach, then the analysis does not provide robust evidence of a negative effect of NVZs whole territory on nitrogen balances. If on the other hand, the placebo studies show that the gap estimated for EU Member States is unusually large relative to the gaps for the countries that did not implement NVZs, then the analysis provides significant evidence of a negative effect of NVZ on nitrogen balances.

We proceed by iteratively applying the synthetic control method used to estimate the effect of NVZ under whole territory approach in EU Member states who followed this policy to every other country in the control group (e.g. those countries who did not implement any type of NVZ policy). In each iteration we reassign in our data the NVZ control intervention to one of the 11 countries in the control group, shifting EU Member States who followed NVZ under whole territory approach to the donor pool. That is, we proceed as if one of the countries in the donor pool would have implemented NVZ under the whole territory approach, instead of those who actually did. We then compute the estimated effect associated with each placebo run. This iterative procedure provides us with a distribution of estimated gaps for the states where no intervention took place.

Figure 7 displays the results for the placebo test. The coloured lines represent the gap associated with each of the 11 countries runs of the test. That is, the gray lines show the difference in Nitrogen balance between each country in the donor pool and its respec-

tive synthetic version. The superimposed black line denotes the gap estimated for the EU Member States who implemented whole territory NVZs. As the figure makes apparent, the estimated gap for the latter group during the 1990-2015 period is unusually large relative to the distribution of the gaps for the countries in the donor pool. There is only one exception, but for that one pre-intervention gap trend is negative several periods before the intervention.

As Figure 7 indicates, the synthetic method provides a convincing fit for nitrogen balances prior to the whole territory NVZ implementation as the trend is close to zero. The pre-intervention mean squared prediction error (MSPE) in EU Member States under whole territory NVZ (the average of the squared discrepancies between nitrogen balance in these countries and in its synthetic counterpart during the period 1990-1999) is about 0.11. The pre-NVZ median MSPE among the 11 countries in the donor pool is about 0.27, also quite small, indicating that the synthetic control method is able to provide a good fit for nitrogen balance prior to NVZs for the majority of the countries in the donor pool.

Figure 7: Nitrogen balance gaps in NVZs under whole territory and synthetic NVZs under whole territory.

8 Conclusions

The Nitrates Directive is one of the most important regulations in the EU to control pollution caused by nitrates from agricultural sources and to prevent further such pollution.

It has been more than two decades since its inception and yet its impacts are not entirely clear. This research finds that one of the Nitrates Directive mandates, the establishment of Nitrate Vulnerable Zones, effectively reduced nitrogen surpluses, a leading cause of water and air contamination in EU countries, in agricultural soils in countries that adopted a whole-territory approach to Nitrate Vulnerable Zones. Moreover the regulation in those countries did not seem to have affected agriculture or crop production. Further research is needed to uncover the implications of reduced nitrogen surpluses on water contamination and potentially on health.

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