Leakage in combatting nutrient pollution*

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Nutrient pollution is a major threat to biodiversity. Designing policy to curb it remains challenging due to leakage across at least two dimensions: pollutant swapping and pollution displacement. We study leakage in the context of a controversial policy in England: 'Nutrient Neutrality' regulation combats pollution in water bodies by restricting local housing construction. We find modest effects on targeted pollutants. However, the policy suffers from severe leakage: other water pollutants increase (pollutant swapping), whereas housing completions fall and rise nearby (displacement). House prices increase. Partial pollution quotas – 'Nutrient Neutrality' targets only residential pollution – admit significant leakage, undermining environmental benefits.

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1 Introduction

Clean water is essential for life. The quality of water is therefore of utmost importance. One of the most common threats to water quality is nutrient pollution.[1] High nutrient pollution can lead to local ecosystem collapse in water bodies, called eutrophication. How can nutrient pollution be addressed?

Nutrient pollution – the contamination of water bodies by excess inputs of nutrients – is one of only two environmental planetary boundaries that humanity has crossed, potentially destabilising the Earth system (Steffen et al., 2015). Yet, policies to address nutrient pollution remain largely understudied.

In the absence of a market for water quality, textbook economics would suggest policy intervention to curb the emission of nutrients into water bodies. However, designing effective policy can be challenging: unless comprehensive in design, any policy may result in leakage, an increase in pollution in unregulated parts of the economy (Bushnell & Mansur, 2011). Two prominent examples of pollution leakage are pollutant swapping and pollution displacement. The former refers to a decrease in targeted pollutants at the expense of an increase in untargeted ones, whereas the latter refers to displacing pollutants to unregulated locations. Does environmental policy designed to reduce nutrient pollution suffer from such leakage, and to what extent does leakage undermine policy efficacy?

This paper studies leakage in the context of a place-based policy that explicitly targets nutrient pollution in water bodies. This novel environmental policy, called 'Nutrient Neutrality', rolled out across England from 2017 onward, aims to reduce nutrient pollution by targeting one specific source of nutrient pollution in locations with low water quality: new local housing and the associated in residential waste water. Nutrient Neutrality prohibits English local planning authorities from granting new housing construction permits unless the nutrient burden from any new residents is fully offset by remedial measures such as wetland restoration.[2] Progress towards reducing nutrient pollution is measured by the level of two major pollutants in local water bodies: nitrogen and phosphorus.

[1] According to the EPA (2025) it is the "most widespread water quality problem facing the US", Natural England (2022b) calls it "a major environmental issue for [...] our most important places for nature". The European Commission (2022) aims to reduce nutrient losses by 50% until 2030.

[2] Nutrient Neutrality follows a long tradition in environmental policy of partial quota and pollutant offset regulations, cf. Section 14 of the German Bundesnaturschutzgesetz 1976, the Virginia Chesapeake Bay Preservation Act 1988 or the Dutch Mineral Accounting System 1998, etc.

We assemble a novel dataset to investigate both direct effects and leakage of Nutrient Neutrality across England at a fine spatial resolution. Exploiting quasi-experimental variation generated by the staggered roll-out of the policy we find that it has modest effects on targeted water pollutants: nitrogen decreases by a marginally significant 15% whereas phosphorus remains unaffected in treated locations. In contrast, the restrictions placed on new housing development significantly affect local housing markets: in treated areas housing completions drop by 18%, while house prices increase by 2%. These direct effects of the treatment highlight the inherent trade-off between environmental benefits and economic costs of environmental policy designed to safeguard biodiversity and ecosystem services.

However, similar to other environmental policies, the regulation of nutrient pollution is prone to incomplete regulation (Fowlie, 2009) which can cause leakage along at least two dimensions: pollution swapping and displacement of pollution sources. First, nutrient pollution in water is a local phenomenon, unlike global pollutants such as CO2. Hence, even national policy designed to address nutrient pollution will inevitably lead to spatial variation in compliance across locations (Keiser & Shapiro, 2019; Currie & Walker, 2019). Regulating pollution in non-compliant locations gives rise to spatial leakage, that is the potential displacement of pollution sources to neighbouring (compliant) locations. In particular, Nutrient Neutrality policy specifically targets locations that are non-compliant in water pollution levels and restricts new housing developments in those locations.

Second, nutrient pollution in water bodies can be driven by a combination of various pollutants. In particular, Nutrient Neutrality policy is partial in targeting only two pollutants, nitrogen and phosphorus, out of potentially many contributors to eutrophication. This partial targeting can give rise to leakage in the form of pollutant swapping (Stevens & Quinton, 2009).

We find evidence on leakage across both dimensions. First, regulated sources of pollution – new residential housing units – from treated locations are displaced to neighbouring locations almost one for one. This implies that the economic cost of the policy is incurred in terms of displacement rather than reductions in housing supply.[3]

Second, we also document evidence of leakage in the form of pollutant swapping: total nitrogen decreases, while we find that water body nitrate concentration

[3] Interestingly, nitrogen pollution in neighbouring locations does not increase, calling the original targeting of residential housing as an effective lever to reduce nutrient pollution into question.

in treated locations increases, and ammonia and nitrite remain unchanged. In contrast, total phosphorus remains unchanged, while both phosphate and orthophosphate increase (sic!) significantly.[4] Interestingly, overall water quality as proxied for by dissolved oxygen saturation or biochemical oxygen demand, unambiguously improves in treated locations. These convoluted effects provide causal evidence on pollutant swapping in line with the environmental science literature on eutrophication (Stevens & Quinton, 2009).

The rich dynamics of direct effects and leakage highlight the challenges of designing effective environmental policy for promoting biodiversity and ecosystem services.

In particular, such policy needs to address natural ecosystem complexity, the economic complexities of changing incentives and the resulting general equilibrium adjustments across space and sectors of the economy, as well as political economy considerations inherent in the design of any new regulation.

Regarding natural ecosystem complexity, promoting biodiversity has led to a shift in focus of environmental policy from point sources of pollution (e.g., Clean Water Act Keiser and Shapiro (2019)) to a focus on diffuse pollution throughout the ecosystem (e.g., Nutrient Neutrality policy). Given the complex biological interactions in the aquatic ecosystem and the diverse sources of pollution, the change in policy objective to biodiversity gives rise to greater uncertainty regarding cause and effect, the curvature of dose-response functions and unintended consequences, such as the pollutant swapping documented here.

Regarding economic complexity, the efficacy of regulation crucially depends on how it changes the economic incentives of polluting agents. In the context of environmental policies such as Nutrient Neutrality, making polluting behaviour costly in one location may displace polluting activity to another location. Similarly, making polluting behaviour costly for one sector of the economy, thereby reducing its emissions, may increase emissions by other sectors. For example, restricting nutrient pollution from residential sources, as mandated by this policy, may actually lead to the conversion of land from residential to agricultural or industrial uses, in turn increasing

[4] The original guidance from Natural England towards non-compliant locations mentions only nitrogen and phosphorus as target pollutants. It remains unclear if reference to 'phosphorus' means total phosphorus, orthophosphate or a combination of the two as target pollutant(s). Only in recent guidance published from August 2022 onward does 'orthophosphate' (as alternative to total phosphorus) appear as explicit target pollutant for riverine water bodies. Hence, for the purposes of this paper we treat only total nitrogen and total phosphorus as target pollutants.

pollution from these alternative sources. Hence, the overall effect on pollution crucially depends on two pollution elasticities: the elasticity of substitution of polluting activities across space, and across sectors of the economy.

Regarding political economy considerations, any new regulation creates costs and benefits, leading to bargaining over their economic incidence across stakeholders. Recent history provides ample evidence of vocal opposition to environmental regulation and the distribution of its economic costs (see Boyer et al. (2020) on the 'gilets jaunes' and Finger et al. (2024) on farmer protests). Nutrient pollution originates from at least three distinct polluting sources: agriculture, industry, and residential. These are in turn represented by farmers, business owners, and residents. Therefore, how to combat nutrient pollution is constrained by the relative power of these constituencies: Nutrient Neutrality, by restricting new housing, primarily targets an underrepresented constituency, future residents. However, this group represents only a minor source of nutrient pollution, especially compared to agricultural nutrient pollution.[5]

In light of these challenges, how could nutrient pollution policy be designed to minimise leakage and increase its overall efficacy? In this paper we show that a partial quota – such as Nutrient Neutrality that only targets residential pollution – admits significant leakage of pollution which undermines environmental benefits. In contrast, a full quota, targeting all sources of pollution and a more comprehensive set of pollutants, is likely to reduce leakage.[6]

However, a quota involves inefficient allocation of pollution across sources and locations generating high economic costs. A market-based allocation (e.g., introducing a cap and trade system for nutrient pollution similar to carbon emissions) has the potential to reduce the economic costs associated with such environmental regulation.

There is a large literature in environmental science on the importance of nutrient pollution for ecosystem services and biodiversity (Steffen et al., 2015; Kanter et al., 2020). However, this paper is the first to bring an economic lens and quasi-experimental methods to the study of nutrient pollution, and how environmental policy can effectively address it. Thereby, we contribute rigorous empirical evidence on both environmental and economic implications to an emerging literature on maintain-

[5] Since the restriction on building residential housing also applies to extensions of existing houses, existing residents are also somewhat affected.

[6] Depending on the objective function of the policymaker (e.g., whether they care about pollution everywhere or just in badly polluted location) a full quota should apply to all sources of pollution and either non-compliant or all locations.

ing and restoring biodiversity across ecosystems endangered by unsustainable levels of nutrient pollution. We complement recent work on other aspects of biodiversity, in particular on the economic effects of species protection (Frank et al., 2025) and of land protection for conservation purposes (Grupp et al., 2023).

There is a large literature documenting the general equilibrium effects of environmental policies and the implied leakage. Several papers document important spatial spillovers: the displacement of traffic from congestion zone pricing (Bou Sleiman, 2025; Herzog, 2024) or the displacement of polluting industries to countries or regions with less stringent environmental regulation (Greenstone, 2002; Broner et al., 2012; Tanaka et al., 2022). There are also a number of papers highlighting how policymakers strategically shift the enforcement of environmental regulation (Cai et al., 2016), or how they allow more settlements in locations where the resulting pollution occurs outside of their jurisdiction (Lipscomb & Mobarak, 2017), causing pollution leakage. We add to this literature by providing the first evidence of similar leakage effects from environmental policy aimed at reducing nutrient pollution and document displacement not only across space but also across pollutants.

Lastly, we contribute to a large literature in urban economics that studies how zoning and other housing supply regulations affect house prices, the quantity of housing and its geography (see Gyourko & Molloy, 2015, for a review). While most of the literature has focused on the effects of regulation in densely populated urban areas (e.g. Parkhomenko, 2023; Duranton & Puga, 2023), we study the effect of regulation on house prices, the quantity of housing and the displacement on construction activity in less densely populated areas. Understanding the effects of regulation in these understudied markets is key as they will likely be at the frontier of any future environmental regulation.

The remainder of this paper is organized as follows. Section 2 provides institutional context and details on the "Nutrient Neutrality" policy. In Section 3 we discuss the data and the empirical strategy. The results from the direct effects of the policy are introduced in Section 4 and the results on leakage in Section 5. Section 6 offers concluding remarks.

2 Setting

Water is the driving force of all nature on Earth. Water quality is therefore essential for natural and human life alike. Achieving good water quality, however, continues to be a significant challenge. For instance, in England, only 16% of surface waters, including rivers, lakes, and estuaries, are classified as having 'good ecological status' (Natural England & Environment Agency, 2024). In addition, recent river and coastal pollution incidents in England have brought water quality into "sharp public focus" (Natural England, 2022b), warranting policymaker attention.

Like many high-income countries, England has a long history of policies attempting to improve water quality; however, their efficacy remains unclear (Burt et al., 2011): levels of nitrogen, the most widespread pollutant in English rivers, barely decreased over the last four decades (Whelan et al., 2022). High levels of nutrient pollution, most commonly nitrogen and phosphorus, risks oxygen depletion and eutrophication of water bodies, i.e., their ecological degradation and potential collapse.[7] Across advanced economies, the three main contributors to nutrient pollution in water bodies are agriculture, especially fertilizer run-off, industrial waste water and residential waste water.

We study the most recent attempt to address water quality in England by means of a new environmental policy called 'Nutrient Neutrality,' designed by Natural England (NE), a non-departmental public body funded and overseen by the UK Department for Environment, Food and Rural Affairs (Defra). The policy aims to reduce nutrient pollution in water bodies by targeting one specific source of nutrient pollution: new residents and their associated waste water. In particular, Nutrient Neutrality mandates that a given local authority (called Local Planning Authority (LPA)) should withhold planning approval for new residential housing developments unless the additional nutrient emissions of the new population are mitigated by investments in local wetland restoration or equivalent projects (Natural England, 2022a), such that the new developments become 'neutral' in terms of nutrient pollution. Natural England assigns LPAs to fall under their Nutrient Neutrality guidance whenever there is a designated site[8] in 'unfavourable condition' within a water body catchment area (WBC).

[7] In addition to posing grave danger to biodiversity, water body eutrophication also represents an adverse amenity shock to local and downstream populations alike.

[8] A designated site is a Special Protection Area (SPA), a Special Area of Conversation (SAC) or a Ramsar site as designated under the Habitat Regulations 2017.

Thus, the policy gives affected LPAs the implicit choice to either restrict the number of new houses to be approved to zero, or to fully neutralise extra nutrient inflow to water bodies from approved housing with costly investments in extra nutrient outflow (e.g., waste water treatment facilities) or conversion (e.g., wetland restoration). In practice, such mitigation schemes were rarely provided by LPAs, who instead opted to ban new developments in affected areas.

Natural England assigned LPAs to fall under Nutrient Neutrality guidance in a staggered fashion, starting in 2017, reaching 74 LPAs by 2024. Currently 19% of LPAs in England fall under Nutrient Neutrality guidance. Figure 1 provides an overview of the staggered roll-out of the policy across time and space.

3 Data and estimation

To study the effect of Nutrient Neutrality on the local environment and housing market we construct a novel spatially disaggregated dataset that features rich information on environmental and housing market outcomes from four primary datasets.

The first dataset contains information on the 'Nutrient Neutrality' policy, in particular which water bodies were affected by the policy and when. Since there are limited public records on the issuance of Nutrient Neutrality guidance by Natural England, especially at the initial stage of the policy roll-out, this dataset was obtained in direct correspondence from Natural England (see table A1 in the online appendix for details). The treatment areas correspond to water body catchment areas (WBCs) that are defined as an area of land from which all surface run-off flows through a series of streams, rivers and, possibly, lakes to a particular point in the water course such as a river confluence.[9] Therefore, WBCs represent the smallest spatial unit covering an integrated local water system – the median WBC in our sample covers approximately 7×7km in extent. Our unit of observation is defined at the WBC-quarter year level.

The second dataset stems from the Water Quality Archive maintained by the Department for Environment, Food and Rural Affairs (DEFRA). It contains water quality samples collected by the UK Environment Agency from locations across England, including coastal and estuarine waters, rivers, lakes, ponds, canals, and groundwater

[9] Although WBCs do not necessarily align with wastewater treatment plants' catchment areas, which treat residential nutrient pollution, both are highly correlated due to shared spatial features.

sources. These samples serve multiple purposes, such as assessing compliance with discharge permits, investigating pollution incidents, and conducting environmental monitoring. The archive contains data on measurements and samples dating back to 2000 and contains information on the levels of various nutrients, which will be our main environmental outcomes of interest. It contains information on the targeted pollutants: nitrogen (in mg/l) and phosphorus (in mg/l). It also includes measurements of a number of other environmental indicators and of untargeted pollutants, such as dissolved oxygen, biochemical oxygen demand, nitrate, nitrite, phosphate and orthophosphate. For our main results we use the mean reading across samples within a WBC-quarter, while we additionally report the results for the median, minimum and maximum readings in the online appendix. Each sample comes with an exact time and location that we aggregate up to the WBC-quarter level. Since samples are not taking every quarter in every WBC but at irregular intervals this is an unbalanced panel. During the initial outbreak of the Covid pandemic (ie. Q2 and Q3 of 2020) no samples were taken at all, so these quarters are implicitly dropped from the sample.

Third, we use a more standard dataset for the UK housing market, namely the British Land registry data on prices paid from the universe of residential housing transactions in the UK. Based on these transactions and the methodology developed by Ahlfeldt et al. (2023), we calculate quarterly house price indices for all water body catchment areas in England.

Fourth, we obtain data on finished housing constructions from newly issued Energy Performance Certificates and aggregate those to the WBC-quarter level.

Combining these four datasets, we create a novel dataset that allows us to track the effects of the policy on both local environmental outcomes and the housing market. We drop London from our sample as there are no treated areas within the Greater London area and no treated areas with a similar level of urbanization. Furthermore, the London housing market is likely to be driven by a number of other factors, such as geopolitics and international financial markets, that are different to the rest of the country (Badarinza & Ramadorai, 2018). We also restrict the estimation horizon to 21 post-treatment quarters, as we have at least two treated locations at this horizon, to avoid our results being driven by idiosyncratic shocks to one location.

Figure 1 provides an overview of the treated water body catchment areas as well as the staggered roll-out of the policy. Nutrient Neutrality guidance was first imposed on the Poole Harbour SPA/Ramsar in Q2 of 2017 with six additional water body catchment areas being targeted until 2021. In 2022 Natural England did a comprehensive review of nutrient pollution and issued nutrient neutrality guidance for a further 20 water body catchment areas (see Table A1 in the Online Appendix for a detailed overview of treatment timing). To account for this staggered rollout econometrically we employ the dynamic, doubly-robust difference-in-differences estimator developed by De Chaisemartin and d'Haultfoeuille (2024).

4 Direct effects

To estimate the direct effects of the policy on the housing market and targeted pollutants in treated locations, we estimate the following equation:

$$y_{ct} = \beta \left(Post_t \times Treatment_c \right) + \gamma_t + \gamma_c + \varepsilon_{ct} \tag{1}$$

where y_{ct} are the outcomes variables of interests in water body catchment area c and quarter t: housing completions, local house price index, phosphorus levels and nitrogen levels. γ_t and γ_c are quarter and WBC fixed effect, respectively. Standard errors are clustered at the WBC level. For housing completions we shift the start of the treatment period by two years, in order to to account for the fact that the policy affects new planning applications, and that it takes on average two years to go from planning application to completion. The results are displayed in Figure 2. We find mixed results on targeted pollutants: While nitrogen decreases by 0.63 mg/l, there is no detectable effect on phosphorus. We find economically significant effects on the housing market with the number of completions decreasing by 1.8 new housing completions per quarter in treated areas, which is equivalent to a 19% decrease in the mean treated area. In line with a contraction of housing supply we find that house prices increase by £61 per m^2, which is equivalent to a 2% increase in the median WBC. This increase is gradual, but starts shortly after the implementation of the policy. These results highlight the trade-off between environmental benefits and economic costs in the direct effect of the policy. In the Online Appendix we provide additional robustness test for these results. For all environmental outcomes we show results for the quarterly median, minimum and maximum levels of each environmental outcome. Results qualitatively and quantitatively confirm the main results derived from the quarterly mean reading of a given pollution measure (see Figures A1-A9 in Online Appendix A.II). We also show that for all outcomes, the main results are robust to excluding coastal WBCs that could be subject to differential economic and biochemical conditions (see Online Appendix Tables A5-A15, column 2 in comparison to the main result in column 1). Results are likewise robust to excluding treatment locations' neighbours from the staggered roll-out, addressing concerns around potential stable unit treatment value assumption (SUTVA) violations, but results are remarkably stable for agnostic choices of distance buffers around treatment locations (see Online Appendix Tables A5-A15, columns 3-5).[10]

5 Leakage

To estimate the leakage effects across pollutants and locations we estimate two variants of 1. First, we replace the set of targeted pollutants with various other, related nutrient pollutants. Second, we estimate the effects of spillovers and leakage in space by replacing originally treated locations with their neighbours. The latter can be estimated across a wide array of environmental and economic outcome variables. However, since Nutrient Neutrality explicitly targeted housing, and nitrogen appears to be the only targeted pollutant to improve in treatment locations, it seems natural to study and compare spatial displacement of housing construction as well as nitrogen pollution to neighbouring (untreated) locations.

Figure 3 provides an overview of the dynamic effects of nutrient neutrality on untargeted environmental outcomes in locations affected by the policy. There is evidence on pollutant swapping. Nitrate, orthophosphate and phosphate concentrations in targeted water bodies are increasing. At the same time there are no significant changes in the concentration of ammonia. We further find that dissolved oxygen saturation increases in treated locations, while there is some evidence that biochemical oxygen demand decreases – even though there seems to be some mean reversion – indicating that water quality weakly improves as a result of the policy.

When studying the spatial displacement of polluters we find that housing completions in neighbouring locations increases in location in the 0-5 kilometre radius and the 0-10km radius around treated WBCs (see Figure 4). Quantitatively, we cannot reject a one-for-one displacement of housing construction from locations treated by

[10] In results not shown, we confirm that partially excluding or fully including the two latter quarters of 2023, for which only partial water quality data is available does not materially affect results.

the policy to adjacent, neighbouring WBCs. This finding suggests that the policy failed to reduce the overall amount of local housing construction. Curiously, despite their increase in housing construction, neighbouring location do not experience any increases in nitrogen – in other words, while the supposed polluter, residential nutrient pollution, gets displaced, we cannot detect an analogous displacement of pollution. If a reduction in housing completions were to decrease nitrogen levels (as documented in Figure 2) in a causal fashion one would expect an increase in nitrogen pollution from the increase in housing completions in neighbouring locations. The evident lack of such a pollution response in untreated neighbouring locations provides further suggestive evidence that observed decreases in nitrogen may not be driven by reductions in housing completions but instead by other forces.

What is driving the observed environmental effects if not pollution responses from changes in residential housing, as envisioned by Nutrient Neutrality policy? One dimension in which the policy can be considered successful is by creating strong incentives for local authorities to decrease the amount of targeted pollutants in water bodies, since withholding planning applications for construction directly affects locations' tax income while creating dissatisfaction among constituents. Anecdotal evidence suggests that the decline in nitrogen could be caused by a decrease in untreated sewage and improving waste water treatment, which is usually less effective at phosphorus removal and hence consistent with the observed null effect on phosphorus pollution. In line with such a reading, the increase in nitrate concentration suggests that local waste water treatment plants are constrained in their ability to expand denitrification relative to nitrification processes. Undermining the objective of the policy to combat nutrient pollution, we document phosphate and orthophosphate to see large and significant increases in treated locations following the issuance of Nutrient Neutrality guidance. This surprising result could point to underlying changes in pollution emissions by the largest local source of (ortho-)phosphates, agricultural land use. One hypothetical effect may be that the expansion of residential housing in untreated locations (i.e., pollution displacement) reduces agricultural activity in untreated locations at the expense of treated locations, leading to a potentially large (relative) increase in nutrient pollution in treated locations, undermining the rationale of combating nutrient pollution.[11] Delineating the non-linear biochemical dynamics

[11] Similarly, the absence of any changes in resulting total phosphorus levels in water could be driven by the sediment-bound, slow-moving phosphorus commonly found in water bodies.

of diffuse pollution types in complex local systems is beyond the scope of this paper.

6 Conclusion

Natural capital, such as water, is essential to sustain human life on Earth. Maintaining its quality is costly and involves inherent trade-offs between environmental benefits and economic costs. Both the cost and the benefits depend on the completeness of the regulation and the extent of resulting leakage. The problem of leakage becomes particularly prevalent as policies, trying to safeguard biodiversity, target diffuse pollution across entire local ecosystems, instead of more easily addressed and targeted point pollution.

We show that a recent environmental policy designed to improve water quality in England, called Nutrient Neutrality, results in significant leakage both in terms of pollutant swapping and spatial displacement. We document the direct effects of the policy: the environmental benefits in terms of decreased nitrogen pollution in local water bodies comes at the cost of depressed numbers of new housing completions and substantially increased house prices. We find significant leakage in polluter displacement: targeted locations experience a reduction in housing completions, whereas housing construction in locations adjacent to targeted locations increase one-for-one. We also document pollutant swapping: while some targeted pollutants such as nitrogen decrease, thereby improving water quality, several other pollutants such as nitrate, orthophosphate and phosphate increase, thereby deteriorating water quality. The detrimental effects of leakage are therefore reduce the environmental benefits of the policy, severely undermining its stated objective to combat nutrient pollution and ensure sustainable levels of biodiversity in water bodies.

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A Figures

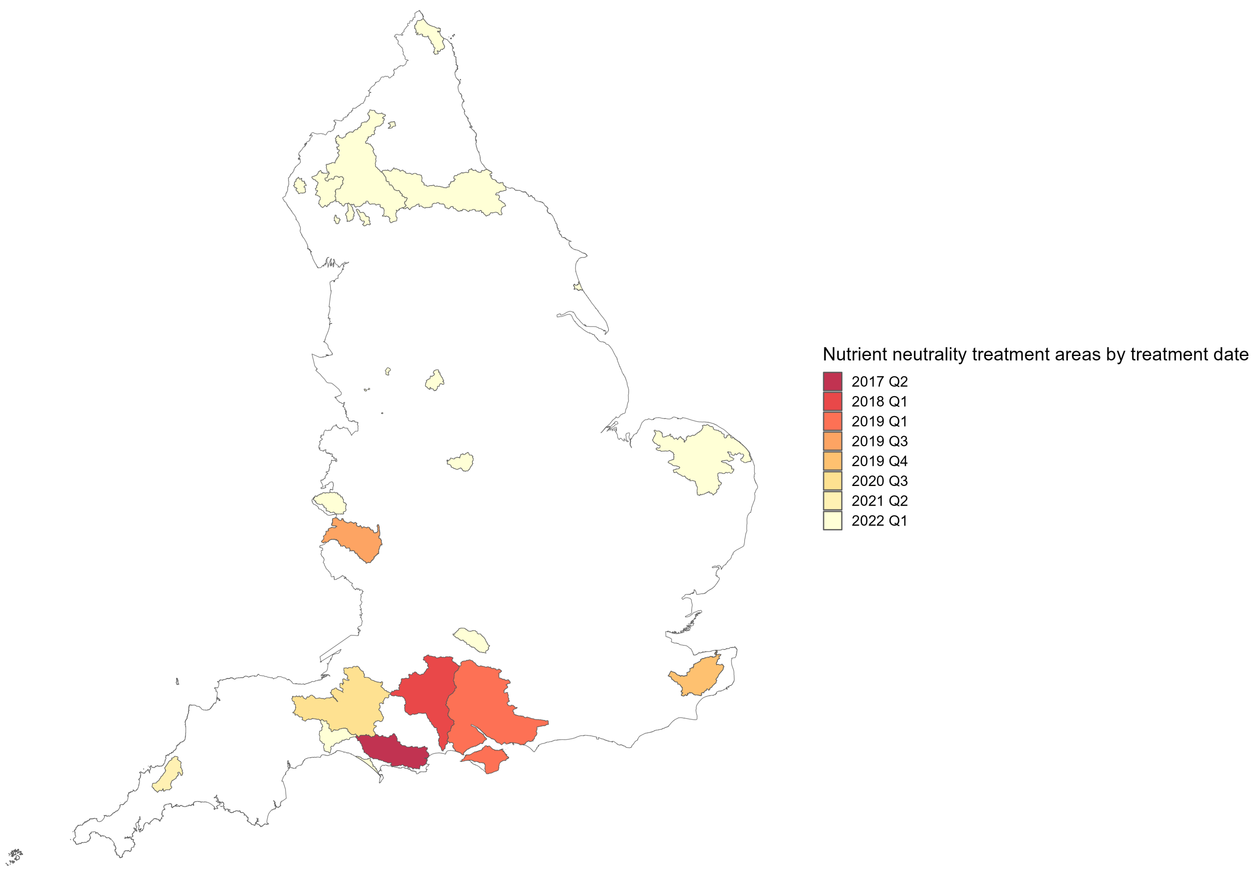

Figure 1: Nutrient Neutrality treatment status by Local Planning Authority

This figure displays the issuance of nutrient neutrality guidance issued by National England across space and time (see Table A1 in the online appendix for further details).

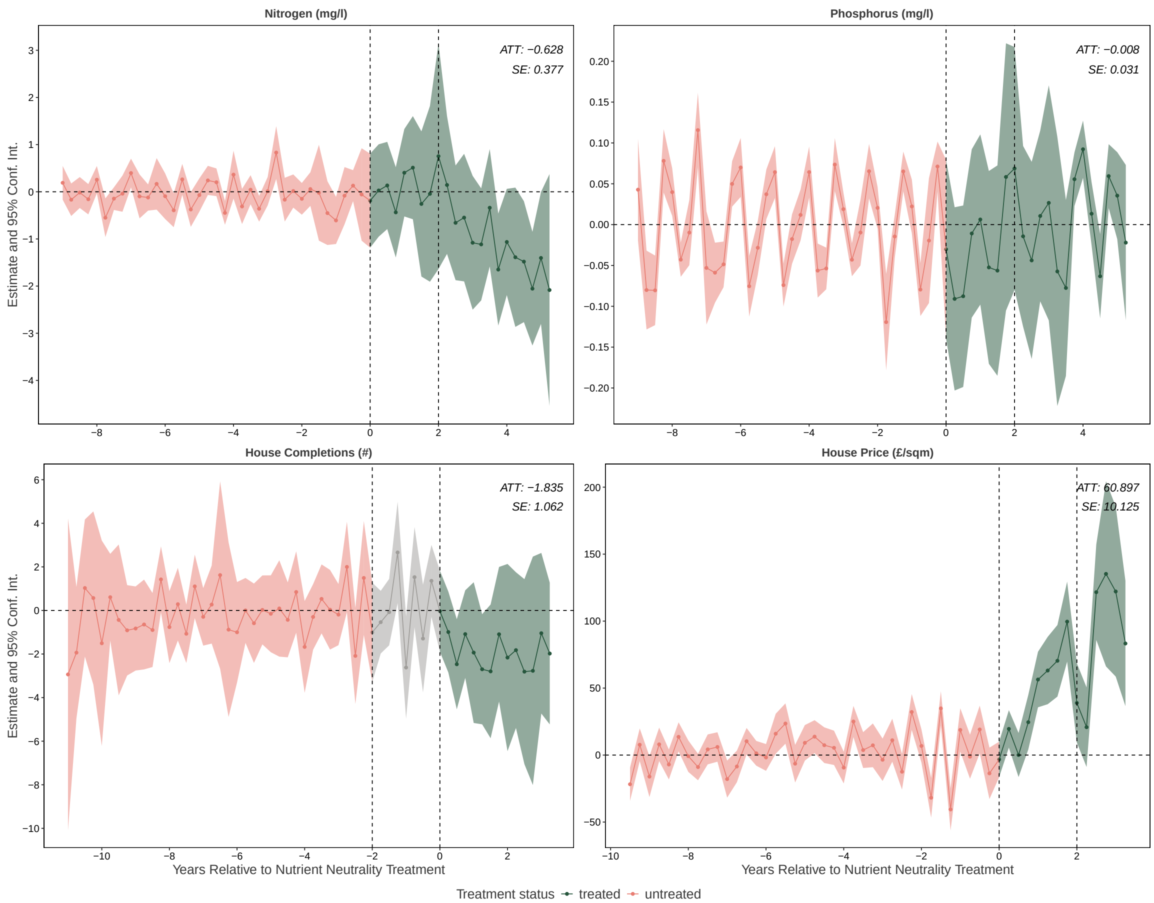

Figure 2: Event studies of main outcomes on Nutrient Neutrality treatment

This figure displays the average treatment effect on the treated of the issuance of 'Nutrient Neutrality' guidance on the the mean level of nitrogen, the mean level of phophorus, the number of housing completions and house prices based on equation 1.

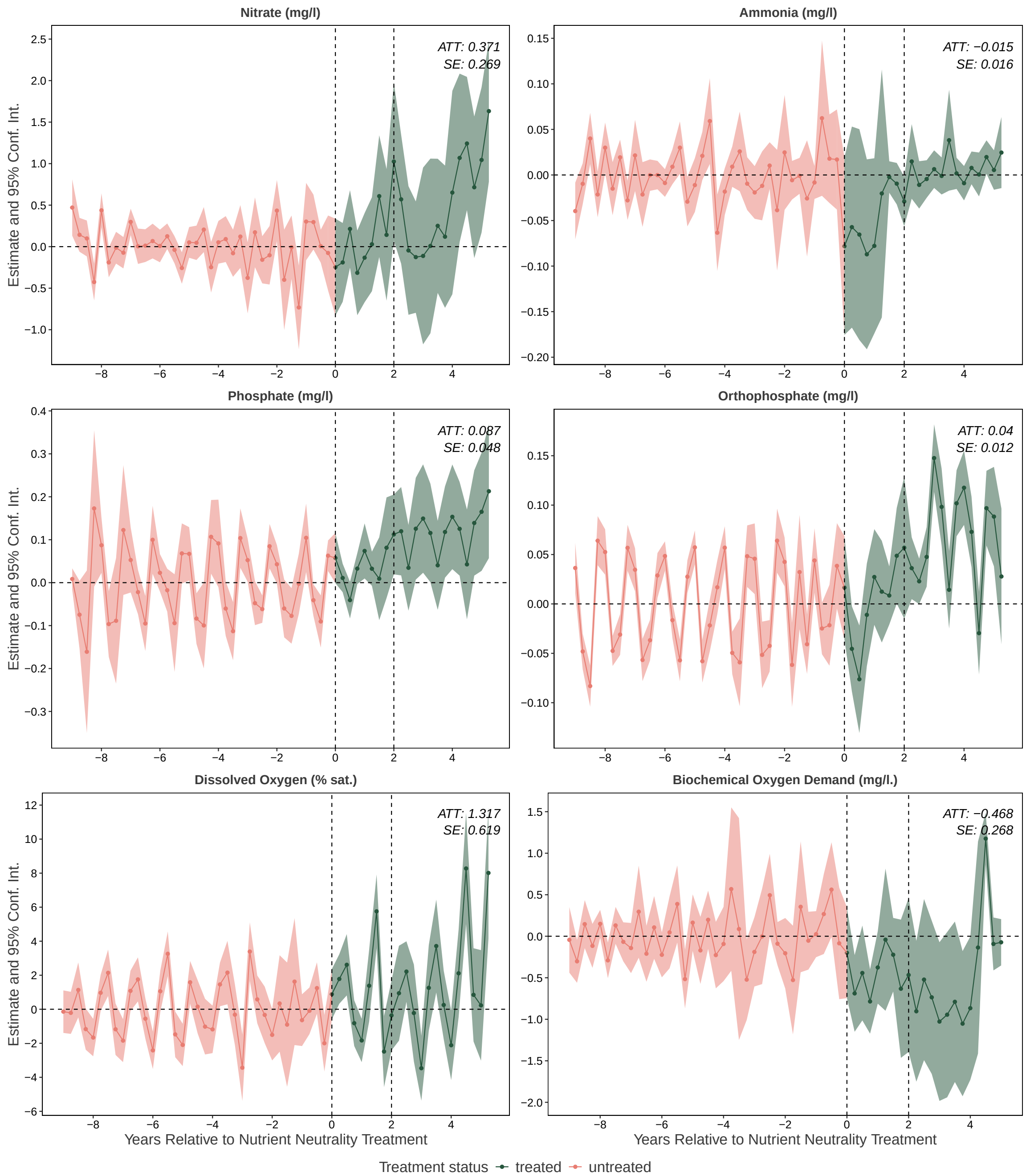

Figure 3: Event studies of other pollutant outcomes on Nutrient Neutrality treatment

This figure displays the average treatment effect on the treated of the issuance of 'Nutrient Neutrality' guidance on the the mean level of nitrate, ammonia, phosphate, orthophosphate, dissolved oxygen and biochemical oxygen demand based on equation 1.

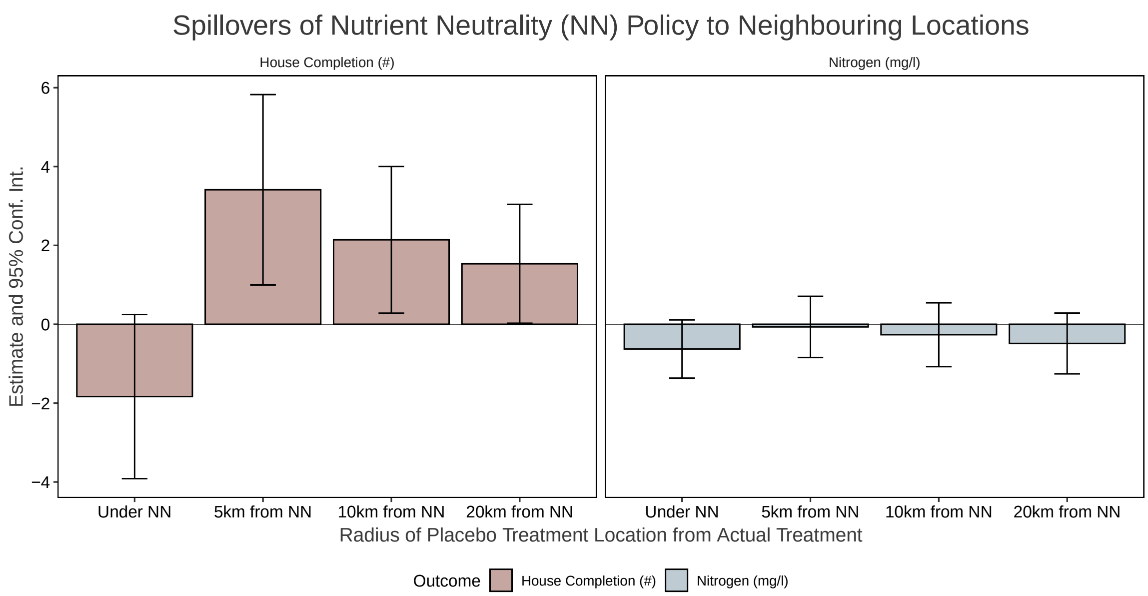

Figure 4: Spillovers of Nutrient Neutrality (NN) treatment to neighbouring locations

This figure displays the average treatment effect on the treated on house completions and mean nitrogen readings based on equation 1. Different bars indicate different locations defined as treatment (from left to right): WBC affected by the policy, WBCs within a 5 km radius of treated locations, WBCs within a 10km radius of treated locations, and WBCs within 20 km of a treated location, where the latter three drop the treated WBCs from the sample.

Online Appendix (not for publication)

A.I Additional tables

Table A1: Rollout of nutrient neutrality policy across designated sites

Water body catchment area	Date
Poole Harbour SPA/Ramsar	2017 Q2
The Solent	2019 Q1
River Avon SAC	2018 Q1
River Camel SAC	2021 Q2
Stodmarsh SAC/Ramsar	2019 Q4
River Wye SAC	2019 Q3
Somerset Levels and Moors Ramsar	2020 Q3
West Midland Mosses Special Area of Conservation	2022 Q1
The Broads Special Area of Conservation/Broadland Ramsar	2022 Q1
Teesmouth and Cleveland Coast Special Protection Area/Ramsar	2022 Q1
Rostherne Mere Ramsar	2022 Q1
Roman Walls Lough Special Area of Conservation	2022 Q1
River Wensum Special Area of Conservation	2022 Q1
River Mease Special Area of Conservation	2022 Q1
River Lambourn Special Area of Conservation	2022 Q1
River Kent Special Area of Conservation	2022 Q1
River Itchen Special Area of Conservation	2022 Q1
River Eden Special Area of Conservation	2022 Q1
River Derwent and Bassenthwaite Lake Special Area of Conservation	2022 Q1
River Clun Special Area of Conservation	2022 Q1
River Axe Special Area of Conservation	2022 Q1
Peak District Dales Special Area of Conservation	2022 Q1
Oak Mere Special Area of Conservation	2022 Q1
Lindisfarne Special Protection Area and Ramsar	2022 Q1
Hornsea Mere Special Protection Area	2022 Q1
Esthwaite Water Ramsar	2022 Q1
Chesil and the Fleet SAC/SPA	2022 Q1

Table A2: Doubly-robust dynamic diff-in-diff: Main outcomes of Nutrient Neutrality

	Nitrogen	Phosphorus	Housing Completion	House Price
	mg/l	mg/l	# of houses	GBP/sqm
ATT	-0.63^{*}	-0.01	-1.83^{*}	60.90^{***}
	(0.38)	(0.03)	(1.06)	(10.14)
Mean Dep. Var.	4.18	0.19	9.62	2658.78
N. WBCs	1100	1428	4058	4058
N. Groups	8	8	7	7
N. Quarters	44	44	46	46
N. Obs	16176	20173	185816	185816

$^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$. Table shows the ATT of Nutrient Neutrality treatment on nitrogen, phosphate, house completion and house price at the Water Body Catchment (WBC) area. Water data sourced from the UK Water Quality Archive. Housing builds measured as the number of completed builds in each quarter, measured by the Energy Performance Certificates for new buildings issued. House prices sourced from the LSE REEF Index, measured as price per square meter. Minimum of two treatment groups in sample. All samples exclude Q3/Q4 2023 and London. "Neighbour Exclusion Radius" removes WBCs that neighbour treated WBCs within the given radius around treated WBCs. Standard errors clustered at the WBC-level.

Table A3: Doubly-robust dynamic diff-in-diff: Other nutrient pollution outcomes

	Nitrate	Ammonia	Phosphate	Orthophos.	Diss. Oxy.	BOD
	mg/l	mg/l	mg/l	mg/l	% sat.	mg/l
ATT	0.37	-0.02	0.09^{*}	0.04^{***}	1.32^{**}	-0.47^{*}
	(0.27)	(0.02)	(0.05)	(0.01)	(0.62)	(0.27)
Mean Dep. Var.	5.04	0.13	0.15	0.21	91.73	2.05
N. WBCs	3732	3741	334	3733	3831	1814
N. Groups	8	8	7	8	8	8
N. Quarters	44	44	44	44	45	44
N. Obs	101122	102071	4916	99988	103861	17341

$^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$. Table shows the ATT of Nutrient Neutrality treatment on nitrate, ammonia, phosphate, orthophosphate, dissolved oxygen and biochemical demand at the Water Body Catchment (WBC) area. Water data sourced from the UK Water Quality Archive. Minimum of two treatment groups in sample. All samples exclude Q3/Q4 2023 and London. Standard errors clustered at the WBC-level.

Table A4: Spillovers in doubly-robust dynamic diff-in-diff: House completion vs N

	House Completion				Nitrogen			
	1	2	3	4	5	6	7	8
ATT	-1.83^{*}	3.41^{***}	2.14^{**}	1.53^{**}	-0.63^{*}	-0.07	-0.27	-0.49
	(1.06)	(1.23)	(0.95)	(0.77)	(0.38)	(0.40)	(0.41)	(0.39)
Placebo Radius	–	5km	10km	20km	–	5km	10km	20km
Mean Dep. Var.	9.62	9.62	9.62	9.62	4.18	4.11	4.11	4.11
N. WBCs	4058	4058	4058	4058	1100	946	946	946
N. Groups	7	7	7	7	8	8	8	8
N. Quarters	46	46	46	46	44	44	44	44
N. Obs	185816	185816	185816	185816	16176	13141	13141	13141

$^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$. Table shows the ATT of Nutrient Neutrality treatment on house completions and nitrogen at the Water Body Catchment (WBC) area. Housing builds measured as the number of completed builds in each quarter, measured by the Energy Performance Certificates for new buildings issued. Water data sourced from the UK Water Quality Archive. Minimum of two treatment groups in sample. All samples exclude Q3/Q4 2023 and London. "Placebo Radius" reassigns treatment status to the WBCs neighbouring treated WBCs (and removes actually treated ones), where the radius of being a "neighbour" varies.

Table A5: Doubly-robust dynamic difference-in-differences: Nitrogen

	Nitrogen				
	1	2	3	4	5
ATT	-0.63^{*}	-0.63^{*}	-0.66	-0.66^{*}	-0.71^{*}
	(0.38)	(0.38)	(0.42)	(0.38)	(0.41)
No Coastal		✓			
Neighbour Exclusion Radius			5km	10km	20km
Mean Dep. Var.	4.18	4.18	4.42	4.52	4.66
N. WBCs	1100	1100	895	817	659
N. Groups	8	8	8	8	8
N. Quarters	44	44	44	44	44
N. Obs	16176	16176	13123	12007	9814

$^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$. Table shows the ATT of Nutrient Neutrality treatment on water quality at the Water Body Catchment (WBC) area. Water data sourced from the UK Water Quality Archive. Minimum of two treatment groups in sample. All samples exclude Q3/Q4 2023. "No Coastal" excludes all coastal WBCs from sample. "Neighbour Exclusion Radius" removes WBCs that neighbour treated WBCs within the given radius around treated WBCs. Standard errors clustered at the WBC-level.

Table A6: Doubly-robust dynamic difference-in-differences: Phosphorus

	Phosphorus				
	1	2	3	4	5
ATT	−0.01	−0.01	−0.00	−0.01	−0.01
	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)
No Coastal		✓			
Neighbour Exclusion Radius			5km	10km	20km
Mean Dep. Var.	0.19	0.19	0.20	0.20	0.21
N. WBCs	1428	1428	1154	1035	837
N. Groups	8	8	8	8	8
N. Quarters	44	44	44	44	44
N. Obs	20173	20173	16366	14832	12126

$^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$. Table shows the ATT of Nutrient Neutrality treatment on water quality at the Water Body Catchment (WBC) area. Water data sourced from the UK Water Quality Archive. Minimum of two treatment groups in sample. All samples exclude Q3/Q4 2023. "No Coastal" excludes all coastal WBCs from sample. "Neighbour Exclusion Radius" removes WBCs that neighbour treated WBCs within the given radius around treated WBCs. Standard errors clustered at the WBC-level.

Table A7: Doubly-robust dynamic difference-in-differences: House Completion

	House Completion				
	1	2	3	4	5
ATT	-1.83^{*}	-1.83^{*}	-1.62	-1.84	-1.86
	(1.06)	(1.06)	(1.15)	(1.17)	(1.16)
No Coastal		✓			
Neighbour Exclusion Radius			5km	10km	20km
Mean Dep. Var.	9.62	9.62	10.23	10.39	10.20
N. WBCs	4058	4058	3375	3039	2419
N. Groups	7	7	7	7	7
N. Quarters	46	46	46	46	46
N. Obs	185816	185816	154398	138942	110422

$^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$. Table shows the ATT of Nutrient Neutrality treatment on house completions at the Water Body Catchment (WBC) area. Housing builds measured as the number of completed builds in each quarter, measured by the Energy Performance Certificates for new buildings issued. Minimum of two treatment groups in sample. All samples exclude Q3/Q4 2023 and London. "No Coastal" excludes all coastal WBCs from sample. "Neighbour Exclusion Radius" removes WBCs that neighbour treated WBCs within the given radius around treated WBCs. Standard errors clustered at the WBC-level.

Table A8: Doubly-robust dynamic difference-in-differences: House Price

	House Price				
	1	2	3	4	5
ATT	60.90***	60.90***	62.72***	62.10***	66.08***
	(10.14)	(9.64)	(10.27)	(9.59)	(9.52)
No Coastal		✓			
Neighbour Exclusion Radius			5km	10km	20km
Mean Dep. Var.	2658.78	2658.78	2660.38	2667.92	2686.39
N. WBCs	4058	4058	3375	3039	2419
N. Groups	7	7	7	7	7
N. Quarters	46	46	46	46	46
N. Obs	185816	185816	154398	138942	110422

$^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$. Table shows the ATT of Nutrient Neutrality treatment on house prices at the Water Body Catchment (WBC) area. House prices sourced from the LSE REEF Index, measured as price per square meter. Minimum of two treatment groups in sample. All samples exclude Q3/Q4 2023 and London. "No Coastal" excludes all coastal WBCs from sample. "Neighbour Exclusion Radius" removes WBCs that neighbour treated WBCs within the given radius around treated WBCs. Standard errors clustered at the WBC-level.

Table A9: Doubly-robust dynamic difference-in-differences: Nitrate

	Nitrate				
	1	2	3	4	5
ATT	0.37	0.37	0.41	0.41	0.43
	(0.27)	(0.27)	(0.26)	(0.27)	(0.28)
No Coastal		✓			
Neighbour Exclusion Radius			5km	10km	20km
Mean Dep. Var.	5.04	5.05	5.22	5.29	5.41
N. WBCs	3732	3727	3118	2808	2254
N. Groups	8	8	8	8	8
N. Quarters	44	44	44	44	44
N. Obs	101122	101019	84451	76230	61478

$^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$. Table shows the ATT of Nutrient Neutrality treatment on water quality at the Water Body Catchment (WBC) area. Water data sourced from the UK Water Quality Archive. Minimum of two treatment groups in sample. All samples exclude Q3/Q4 2023. "No Coastal" excludes all coastal WBCs from sample. "Neighbour Exclusion Radius" removes WBCs that neighbour treated WBCs within the given radius around treated WBCs. Standard errors clustered at the WBC-level.

Table A10: Doubly-robust dynamic difference-in-differences: Nitrite

	Nitrite				
	1	2	3	4	5
ATT	−0.00	−0.00	−0.00	−0.00	−0.00
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
No Coastal		✓			
Neighbour Exclusion Radius			5km	10km	20km
Mean Dep. Var.	0.04	0.04	0.04	0.04	0.04
N. WBCs	3738	3732	3124	2813	2258
N. Groups	8	8	8	8	8
N. Quarters	44	44	44	44	44
N. Obs	102575	102464	85596	77232	62292

$^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$. Table shows the ATT of Nutrient Neutrality treatment on water quality at the Water Body Catchment (WBC) area. Water data sourced from the UK Water Quality Archive. Minimum of two treatment groups in sample. All samples exclude Q3/Q4 2023. "No Coastal" excludes all coastal WBCs from sample. "Neighbour Exclusion Radius" removes WBCs that neighbour treated WBCs within the given radius around treated WBCs. Standard errors clustered at the WBC-level.

Table A11: Doubly-robust dynamic difference-in-differences: Ammonia

	Ammonia				
	1	2	3	4	5
ATT	−0.02	−0.02	−0.02	−0.02	−0.02
	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
No Coastal		✓			
Neighbour Exclusion Radius			5km	10km	20km
Mean Dep. Var.	0.13	0.13	0.13	0.13	0.13
N. WBCs	3741	3735	3127	2818	2264
N. Groups	8	8	8	8	8
N. Quarters	44	44	44	44	44
N. Obs	102071	101960	85222	76959	62119

$^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$. Table shows the ATT of Nutrient Neutrality treatment on water quality at the Water Body Catchment (WBC) area. Water data sourced from the UK Water Quality Archive. Minimum of two treatment groups in sample. All samples exclude Q3/Q4 2023. "No Coastal" excludes all coastal WBCs from sample. "Neighbour Exclusion Radius" removes WBCs that neighbour treated WBCs within the given radius around treated WBCs. Standard errors clustered at the WBC-level.

Table A12: Doubly-robust dynamic difference-in-differences: Phosphate

	Phosphate				
	1	2	3	4	5
ATT	0.09*	0.09**	0.10**	0.12**	0.10
	(0.05)	(0.04)	(0.05)	(0.05)	(0.07)
No Coastal		✓			
Neighbour Exclusion Radius			5km	10km	20km
Mean Dep. Var.	0.15	0.15	0.16	0.16	0.15
N. WBCs	334	334	266	244	201
N. Groups	7	7	7	7	7
N. Quarters	44	44	44	44	44
N. Obs	4916	4916	4049	3716	3209

$^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$. Table shows the ATT of Nutrient Neutrality treatment on water quality at the Water Body Catchment (WBC) area. Water data sourced from the UK Water Quality Archive. Minimum of two treatment groups in sample. All samples exclude Q3/Q4 2023. "No Coastal" excludes all coastal WBCs from sample. "Neighbour Exclusion Radius" removes WBCs that neighbour treated WBCs within the given radius around treated WBCs. Standard errors clustered at the WBC-level.

Table A13: Doubly-robust dynamic difference-in-differences: Orthophosphate

	Orthophosphate				
	1	2	3	4	5
ATT	0.04***	0.04***	0.05***	0.05***	0.05***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.02)
No Coastal		✓			
Neighbour Exclusion Radius			5km	10km	20km
Mean Dep. Var.	0.21	0.21	0.22	0.23	0.23
N. WBCs	3733	3728	3119	2811	2257
N. Groups	8	8	8	8	8
N. Quarters	44	44	44	44	44
N. Obs	99988	99885	83500	75432	60894

***$p < 0.01$; **$p < 0.05$; *$p < 0.1$. Table shows the ATT of Nutrient Neutrality treatment on water quality at the Water Body Catchment (WBC) area. Water data sourced from the UK Water Quality Archive. Minimum of two treatment groups in sample. All samples exclude Q3/Q4 2023. "No Coastal" excludes all coastal WBCs from sample. "Neighbour Exclusion Radius" removes WBCs that neighbour treated WBCs within the given radius around treated WBCs. Standard errors clustered at the WBC-level.

Table A14: Doubly-robust dynamic difference-in-differences: Dissolved Oxygen

	Dissolved Oxygen				
	1	2	3	4	5
ATT	1.32**	1.35**	1.16*	1.21*	0.95
	(0.62)	(0.64)	(0.61)	(0.69)	(0.65)
No Coastal		✓			
Neighbour Exclusion Radius			5km	10km	20km
Mean Dep. Var.	91.73	91.71	91.51	91.51	91.68
N. WBCs	3831	3801	3200	2887	2321
N. Groups	8	8	8	8	8
N. Quarters	45	45	45	45	45
N. Obs	103861	103442	86672	78377	63294

$^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$. Table shows the ATT of Nutrient Neutrality treatment on water quality at the Water Body Catchment (WBC) area. Water data sourced from the UK Water Quality Archive. Minimum of two treatment groups in sample. All samples exclude Q3/Q4 2023. "No Coastal" excludes all coastal WBCs from sample. "Neighbour Exclusion Radius" removes WBCs that neighbour treated WBCs within the given radius around treated WBCs. Standard errors clustered at the WBC-level.

Table A15: Doubly-robust dynamic difference-in-differences: Biochemical Oxygen Demand

	Biochemical Oxygen Demand				
	1	2	3	4	5
ATT	-0.47^{*}	-0.47	-0.42	-0.39	-0.24
	(0.27)	(0.29)	(0.28)	(0.28)	(0.33)
No Coastal		✓			
Neighbour Exclusion Radius			5km	10km	20km
Mean Dep. Var.	2.05	2.05	2.06	2.07	2.04
N. WBCs	1814	1813	1536	1398	1130
N. Groups	8	8	8	8	8
N. Quarters	44	44	44	44	44
N. Obs	17341	17340	14810	13555	10825

$^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$. Table shows the ATT of Nutrient Neutrality treatment on water quality at the Water Body Catchment (WBC) area. Water data sourced from the UK Water Quality Archive. Minimum of two treatment groups in sample. All samples exclude Q3/Q4 2023. "No Coastal" excludes all coastal WBCs from sample. "Neighbour Exclusion Radius" removes WBCs that neighbour treated WBCs within the given radius around treated WBCs. Standard errors clustered at the WBC-level.

A.II Additional figures

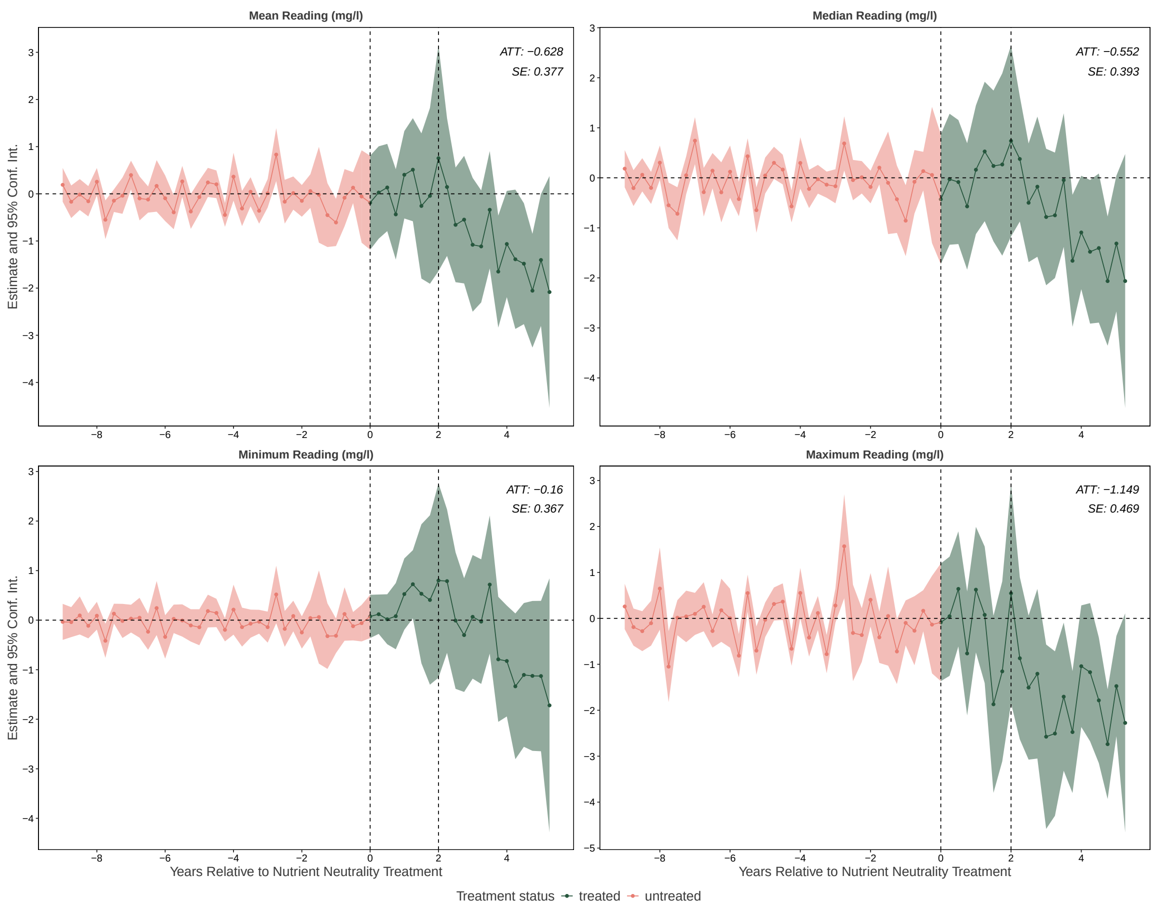

Figure A1: Event studies of nitrogen measures on Nutrient Neutrality treatment

This figure displays the average treatment effect on the treated of the issuance of 'Nutrient Neutrality' guidance on the the mean, median, minimum and maximum level of nitrogen per quarter, based on equation 1.

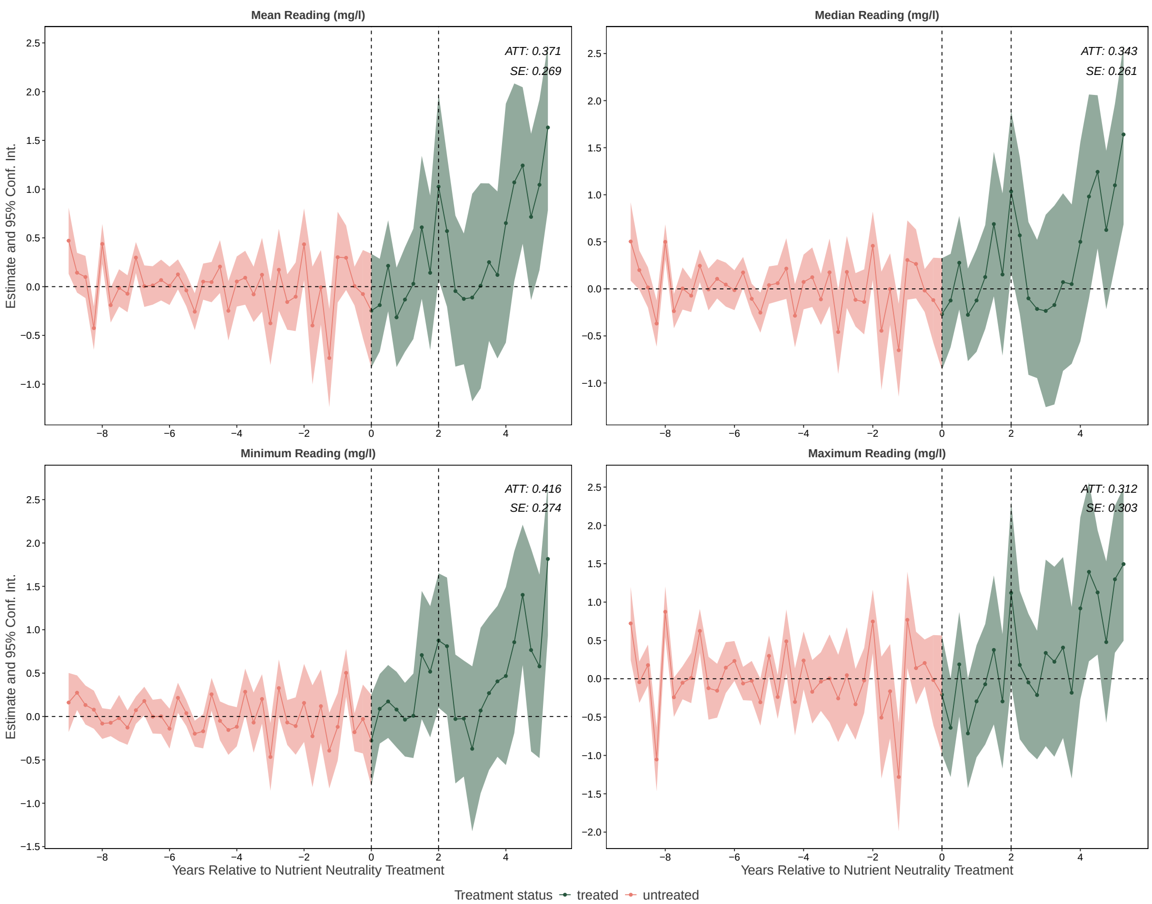

Figure A2: Event studies of nitrate measures on Nutrient Neutrality treatment

This figure displays the average treatment effect on the treated of the issuance of 'Nutrient Neutrality' guidance on the the mean, median, minimum and maximum level of nitrate per quarter, based on equation 1.

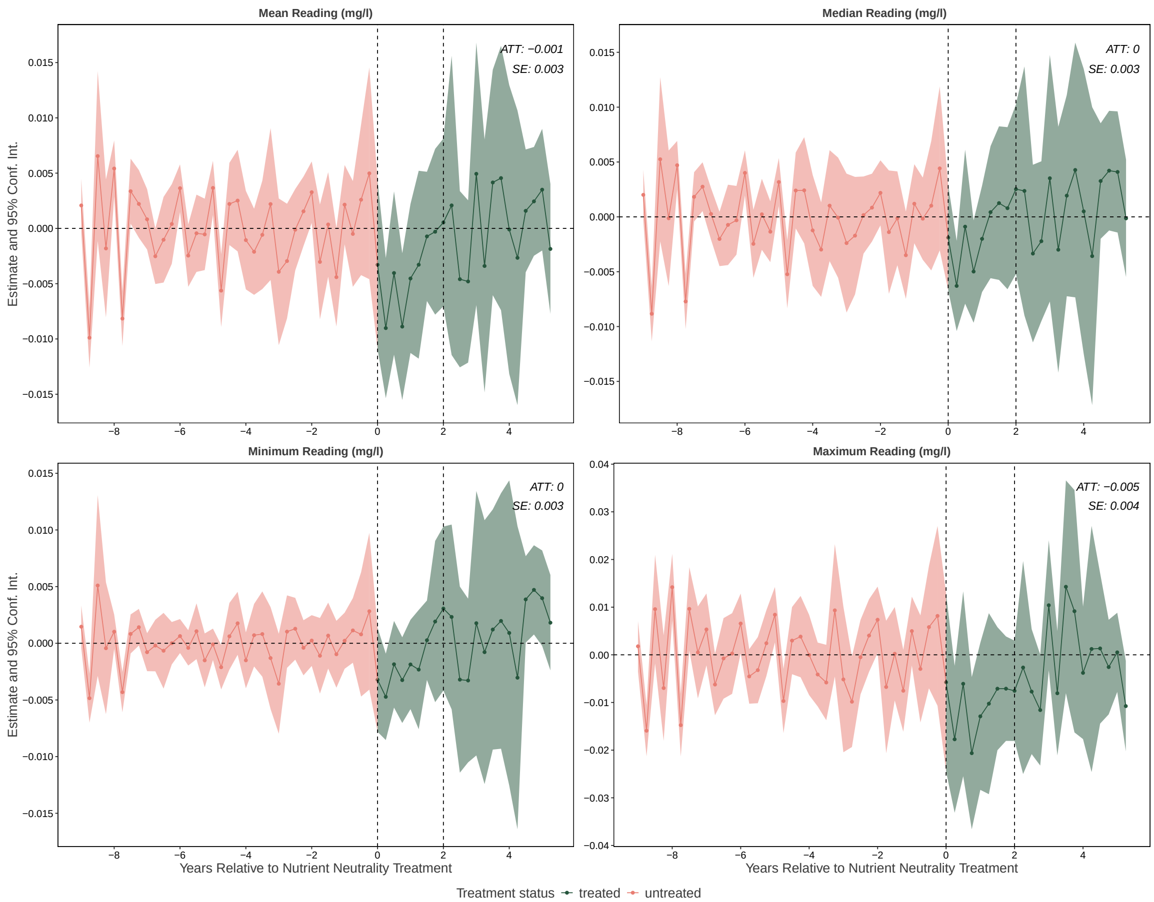

Figure A3: Event studies of nitrite measures on Nutrient Neutrality treatment

This figure displays the average treatment effect on the treated of the issuance of 'Nutrient Neutrality' guidance on the the mean, median, minimum and maximum level of nitrite per quarter, based on equation 1.

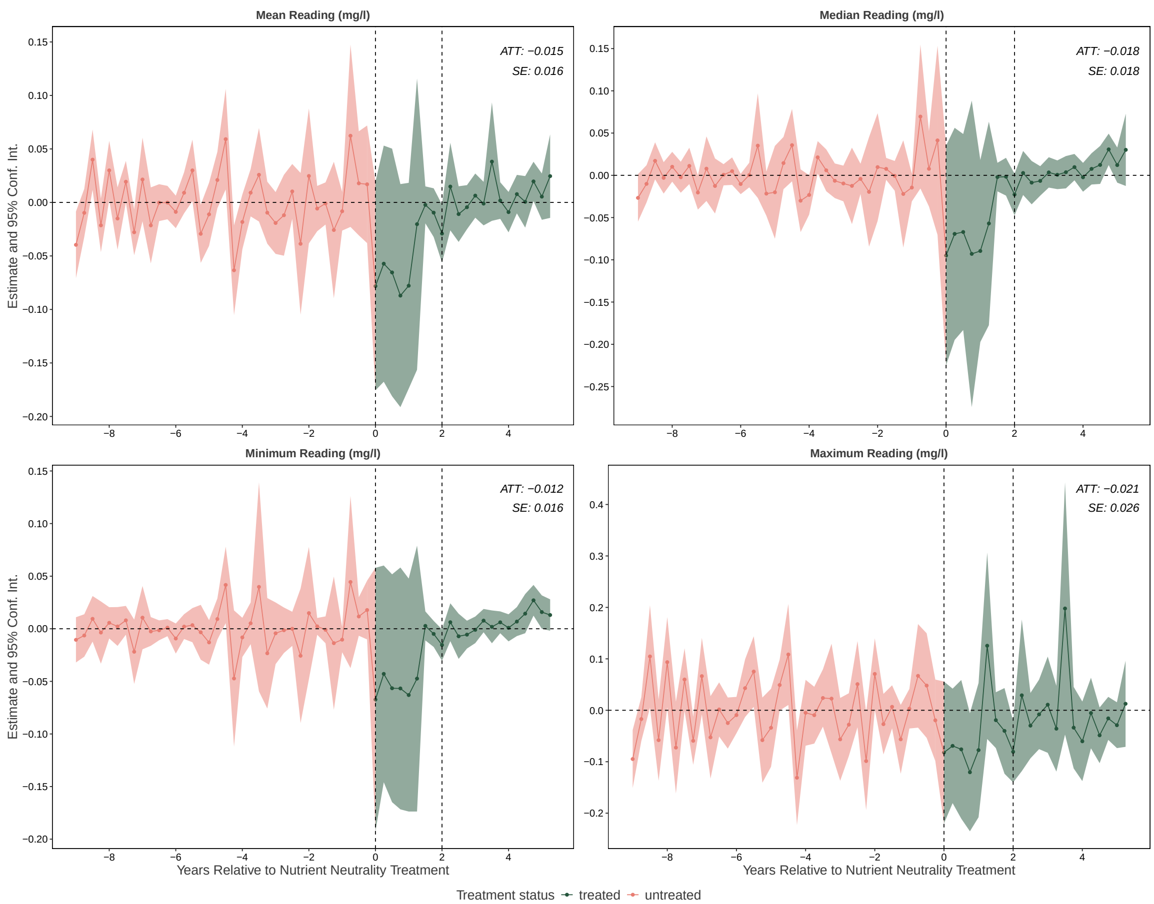

Figure A4: Event studies of ammonia measures on Nutrient Neutrality treatment

This figure displays the average treatment effect on the treated of the issuance of 'Nutrient Neutrality' guidance on the the mean, median, minimum and maximum level of ammonia per quarter, based on equation 1.

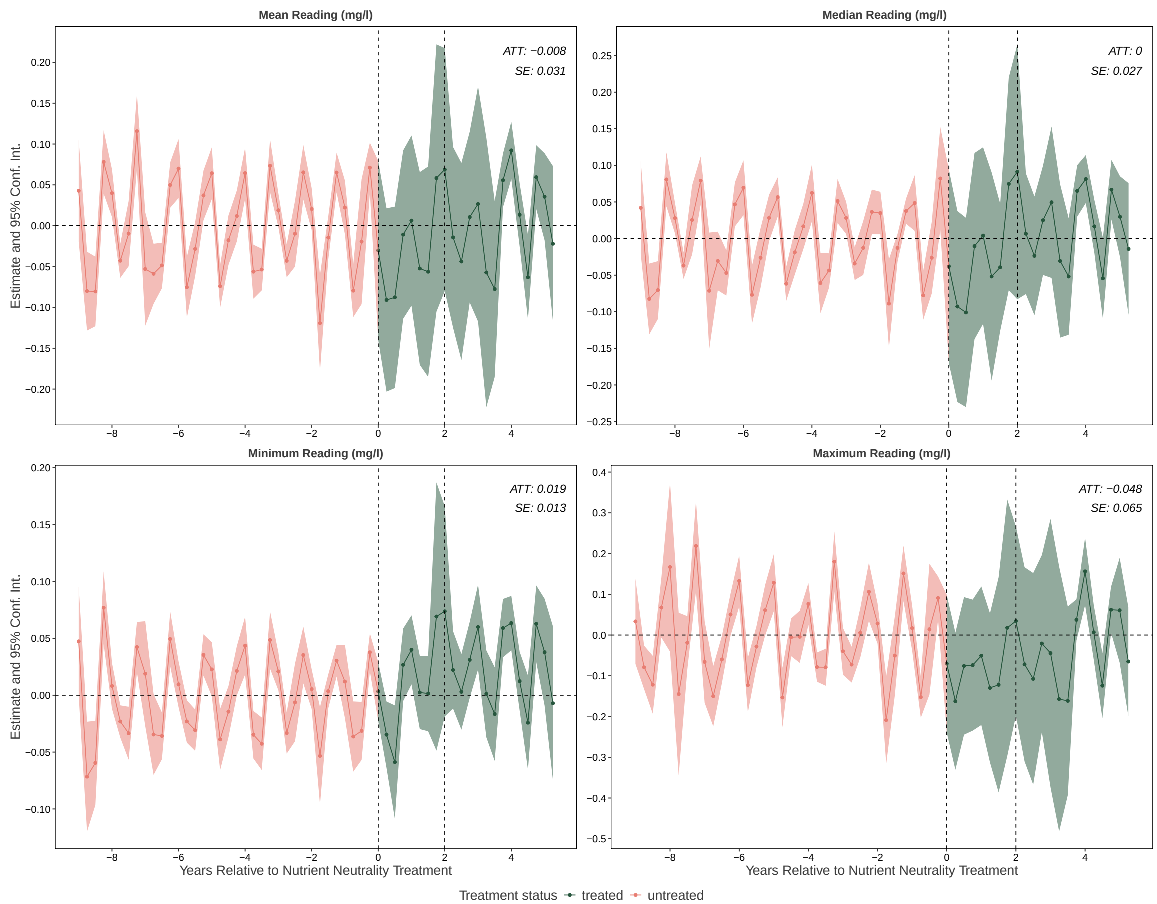

Figure A5: Event studies of phosphorus measures on Nutrient Neutrality treatment

This figure displays the average treatment effect on the treated of the issuance of 'Nutrient Neutrality' guidance on the the mean, median, minimum and maximum level of phosphorus per quarter, based on equation 1.

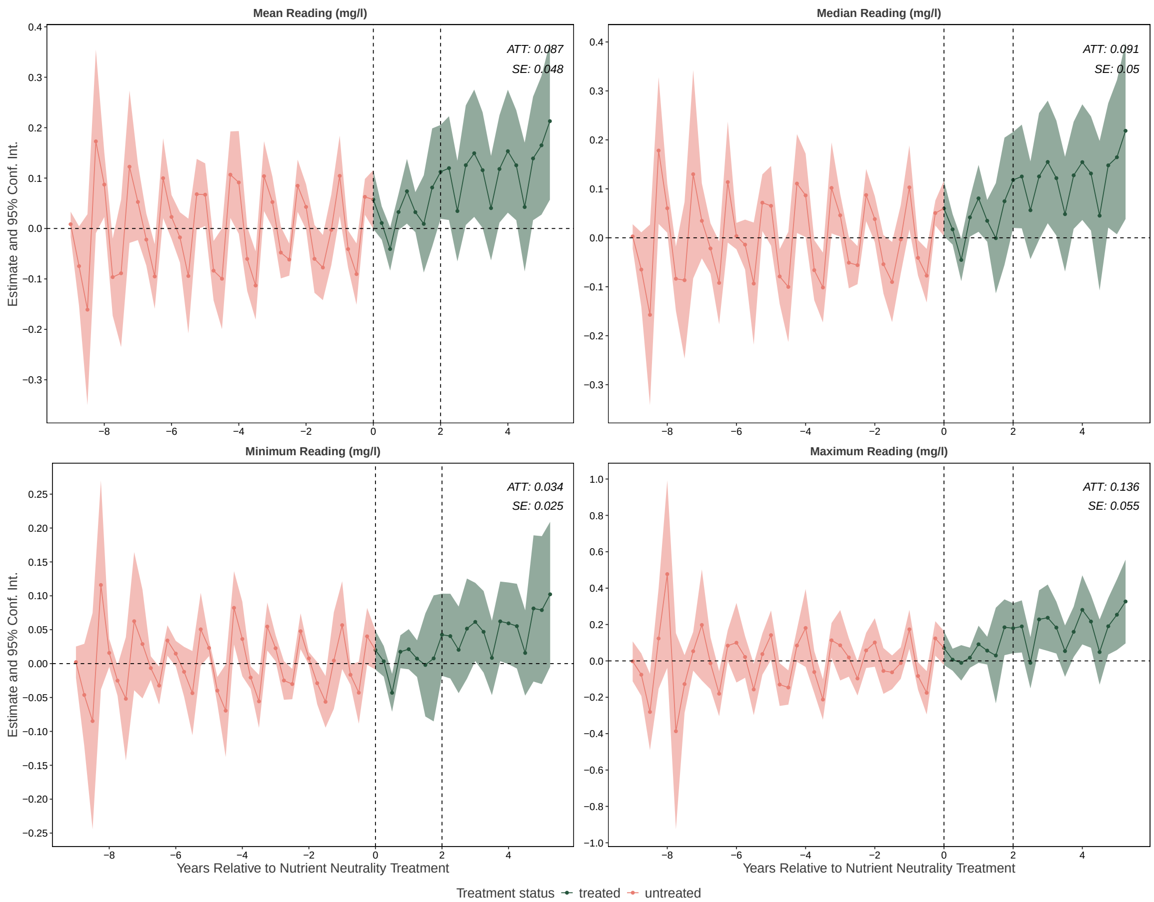

Figure A6: Event studies of phosphate measures on Nutrient Neutrality treatment

This figure displays the average treatment effect on the treated of the issuance of 'Nutrient Neutrality' guidance on the the mean, median, minimum and maximum level of phosphate per quarter, based on equation 1.

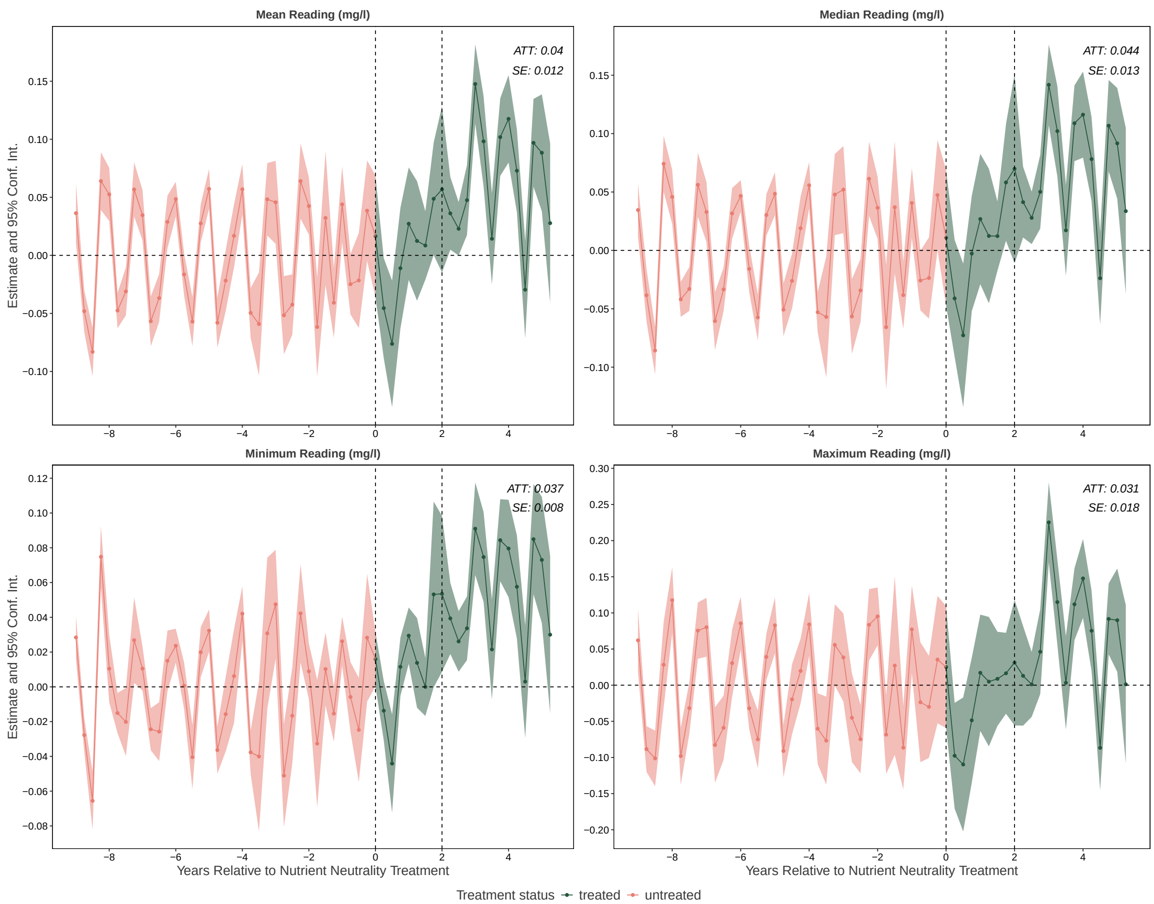

Figure A7: Event studies of orthophosphate measures on Nutrient Neutrality treatment

This figure displays the average treatment effect on the treated of the issuance of 'Nutrient Neutrality' guidance on the the mean, median, minimum and maximum level of orthophosphate per quarter, based on equation 1.

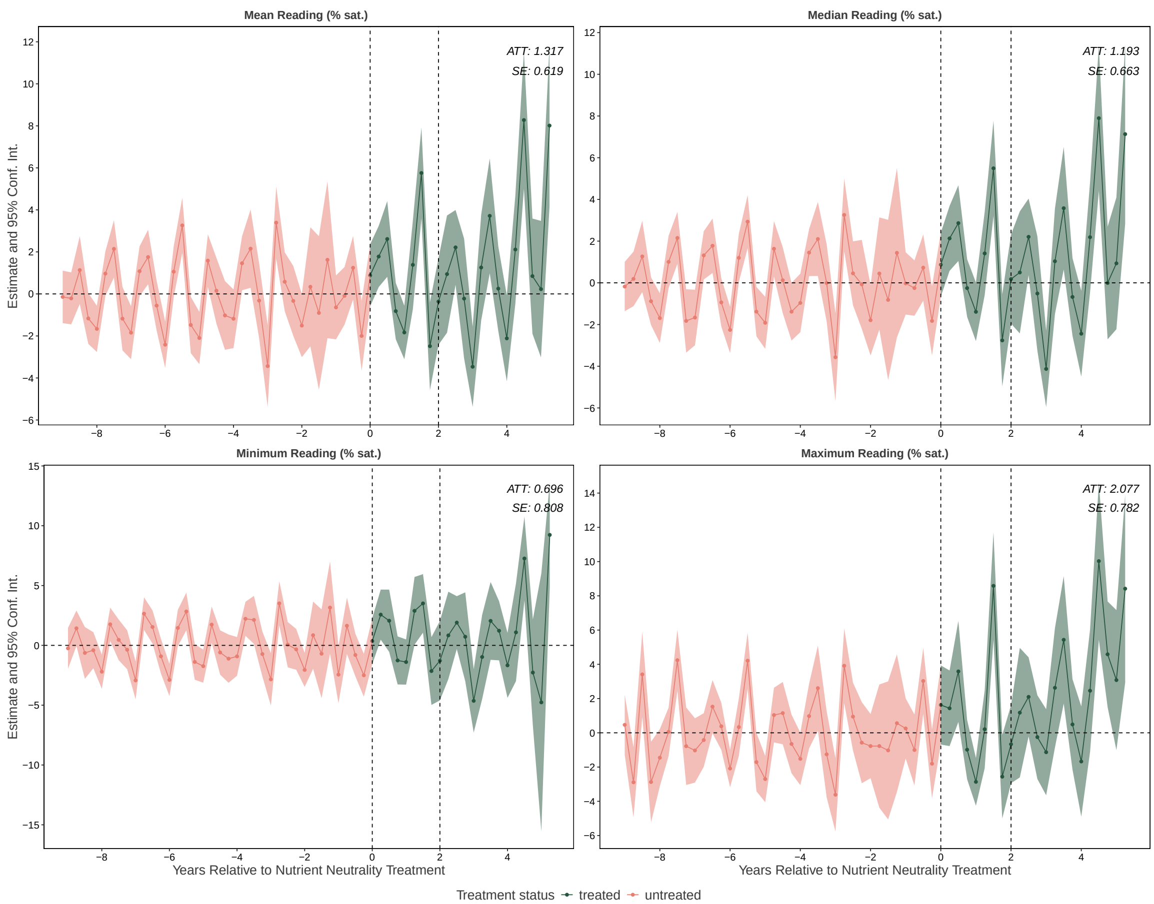

Figure A8: Event studies of dissox measures on Nutrient Neutrality treatment

This figure displays the average treatment effect on the treated of the issuance of 'Nutrient Neutrality' guidance on the the mean, median, minimum and maximum level of dissox per quarter, based on equation 1.

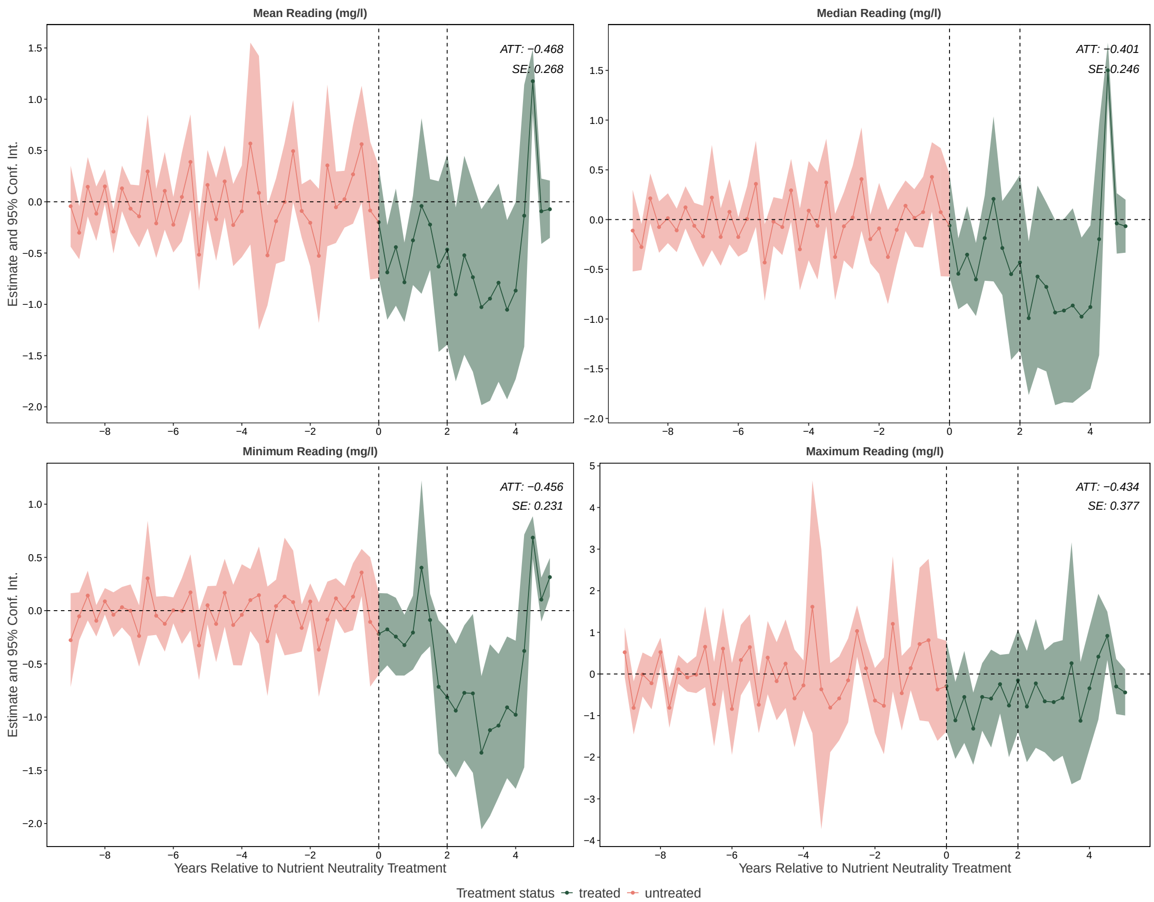

Figure A9: Event studies of bod measures on Nutrient Neutrality treatment

This figure displays the average treatment effect on the treated of the issuance of 'Nutrient Neutrality' guidance on the the mean, median, minimum and maximum level of bod per quarter, based on equation 1.