The impact of International Trade on Maritime Ecosystems : Evidence from the California Emission Control Area

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Abstract

This article analyses how the Californian Emission Control Area (ECA) implemented in 2009, has impacted international trade, air pollution, the quality of water and finally a key marine ecosystem, the kelp forest. Using Difference in Difference approach, we find that this policy has led to an significant decrease in trade volume. As a result, we observe a reduction in the level of SO_2 emission, an improvement of the water quality in the ECA and an improvement on the kelp canopy and biomass growth.

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1 Introduction

Pollution is the bane of maritime transports, ships leaving both water and air pollution in their wake. Here we document these facts, and a potential solution, by examining how an environmental regulation at the local level in California (the Ocean-Going Vessel Fuel rule) has improved the marine environment. We find that the enforcement of an Emission Control Area (ECA) along the California coast, has reduced the emissions of Sulphur Oxides (SOx), has improved the concentrations of phytoplankton, and the quality of water. We also find an impact on the growth of a keystone species, the kelp forest.

The ways in which international transport by sea and ocean can impact marine ecosystems are numerous and complex, so a regulation such as the ECA can have a variety of effects, both direct and indirect. Considering the indirect one, shipping is one of the main contributors of SO_x pollution, producing sulphuric acid and acid rain.[1] The deposition of these chemical elements lead to the lowering of the ocean's pH, a process known as ocean acidification that harm calcifying organisms such as coral reefs, shellfish, and plankton (Doney et al., 2007). The effect of ECA on these atmospheric processes and deposition is to our knowledge unknown and not obvious due to the size of ECA that may be too small to reduce the emission of SO_2 and to have a local consequence on acidification. Hence, the first contribution of this paper is to test whether the Californian limited spatial regulation has impacted on SO_2 emission. To tract these emissions, we use the Community Multiscale Air Quality (CMAQ) model developed by Hansen-Lewis and Marcus (2022) to get the emission and distribution of air pollutants. We observe a significant decline in SO2 levels in the second quarter after the ECA takes effect, then the coefficient reaches a plateau at a negative value, indicating a reduction in SO_2 emissions of around 18%.

Considering the direct effect, shipping may influence marine ecosys-

[1] More precisely, during fuel combustion, a significant portion of the fuel sulfur reacts with oxygen gas and emits sulfur dioxide (SO2). Then the products of the oxydification of sulphur dioxide (e.g. SO3), reacts with H2O in the atmosphere to forms sulphuric acid which eventually causes acid rain. Similarly, the oxidation of nitrogen oxides (NOx) emitted by vessels generates nitric acid.

tems through the pollution dispersed by ships into seawater. This include fuel spills, ballast water dispersion and discharge of greywater (from sinks, showers, and kitchens) and blackwater (sewage).[2] These discharges are regulated at the national and international level, but non compliance is still likely.[3] Shipping also increases the risk of deposition of several pollutants such as the amount of anti-fouling paint dispersed, which contain metals (copper) and biocides that are detrimental for plant photosynthesis and growth.[4] It is noteworthy that the Ocean-Going Vessel Fuel Rule was enacted purely in response to air pollution concerns and was not influenced by considerations about the marine ecosystem and then represents an exogeneous and random shock for underwater life.

The second contribution of this paper is to analyze how this ECA, given its negative impact on vessel traffic, may have inadvertently affected the maritime water quality. We use a simple indicator, the concentrations of chlorophyll-a (Chl-a), which serves as a proxy for phytoplankton growth, as well as a more complex indicator of water quality utilizing a wide range of data available in this area of the Pacific at the most disaggregated spatial level. More precisely, this indicator take into account several variables that matter for water quality, such as dissolved oxygen, which is critical for aquatic respiration and organic matter decomposition, but also the concentration of nitrate, phosphorus and the pH level which are linked to eutrophication, water acidity and nutrient cycling. We find both a rapid increase in Chlorophyll-a concentration after the entry into force of the ECA, indicating an improvement in the minimal level of nutrient, and an inprovement of the water quality measured by our indicator.

The third contribution is to analyse the effect of the ECA on a foun-

[2]See Lindgren et al. (2016) for a review. Ballast discharge is one of the cause of invasive species, while greywater and blackwater, due to their high content of nutrients can participate to oxygen depletion and algual bloom.

[3]For instance, the California State Lands Commission that manage these discharges consider that stricter standards are necessary (Wang et al., 2020)

[4]For instance, Johansson et al. (2012) observe that six out of seven antifouling compounds had a detrimental effect on kelp photosynthesis and growth. Cima and Varello (2022) add evidence about the detrimental effect of copper based antifouling formulations and Dafforn et al. (2011) denounce the widespread use of antifouling technologies that incorporate biocides.

dation species (Paine, 1969; Hale and Koprowski, 2018), the kelp forest, which are emblematic of the California coast.[5] Kelp, are large brown algae that represent important biogenic habitats,[6] which functions as a nursery, providing food sources for a multitude of fish, marine mammals and invertebrates (Christie et al., 2009, Teagle et al., 2017).[7] Beyond their importance, we chose to study kelp in reason of their capacity of rapid recovery following catastrophic population losses due to frequent recruitment and fast individual growth rates.[8] In that respect, the California ECA provides an interesting quasi-natural experiment to study whether maritime environmental regulation can made a difference over a short period of time (2007 to 2012).

Our methology is based on standard Difference-in-Differences (DID) methods for all our dependent variables considered, going to the analysis of trade traffics at the port level, to SO2 emission, water quality and kelp biomass and canopy. We define carefully different control groups depending on the variable considered and each individual estimate is subject to scrutiny. For some results, the coefficient obtained is biased upward due to imperfect parallel trends before the treatment; for others, the control group may be affected by the treatment; in each of these cases we discuss in a transparent way how the average treatment effect on the treated may be

[5]Kelp are found in cool, relatively shallow waters close to the shore in several parts of the world. In America along the west coast, from Alaska and extending down to Baja California in Mexico, but also along the coasts of Chile and Argentina. Kelp forests are also located along the western coastline of South Africa, and in the southern coasts of Australia and throughout much of New Zealand's coastline, finally in Europe along the coasts of Norway, the British Isles, and Iceland, and along the Russian Far East coastline, particularly around the Kamchatka Peninsula and the Kuril Islands.

[6]California's kelp forests are primarily composed of two types of kelp: Giant Kelp (Macrocystis pyrifera) and Bull Kelp (Nereocystis luetkeana). Giant kelp is the largest species of kelp and grow at a very high pace under good condition (60 centimeters per day). These kelp can reach 45 meters tall. Bull kelp is an annual species, meaning it completes its life cycle in one year. The plant has a long, slender stem that can reach lengths of up to 35 meters.

[7]These forests also act as crucial carbon sinks, absorbing and sequestering atmospheric CO2.

[8]See Krumhansl et al. (2016). In optimal conditions, kelp can grow by 65 centimeters by day

affected. We also reinforce our results by presenting Synthetic Difference-in-Differences (SDID) methods and Dynamic DID. The accumulation of analyses, tests and estimations of different dependent variables presented in this paper, offer a comprehensive analysis of the effect of the ECA on the marine environment.

Regarding the literature on the consequences of ECAs, our work builds on and contributes to several analysis. Concerning the effect of the North American ECA on air pollution, Anastasopolos et al. (2021) detect a decrease in SO2 concentration for Canadian ports over the period 2010–2016. Still working on this ECA, Hansen-Lewis and Marcus (2022) show that this regulation has reduced fine particulate matter (PM2.5), decreased birth weight and infant mortality in the United States by a very substantial level, estimating that the regulations saved around 200 infant lives every year. Finally, the most related work to our study is Klotz and Berazneva (2022) that by analyzing the California ECA find a displacement of activity to unregulated waters and a reduction of speed in the regulated area. We complement this analysis,[9] by showing a reduction of trade in the ECA and by analyzing the consequences of the ECA on several different topics.

To our knowledge, there is no literature on the effect of ECA on maritime water quality or on foundation species.

We also contribute to a nascent literature that compute water quality index in maritime envionment such as Jha et al., 2015 which provide a similar indicator for the coastal waters of the Andaman Sea in India. Finally, our analysis of the consequences of the ECA is in line with several papers that analyse the kelp canopy and its change in California, showing that the forest has been severely decimated over the past half-century (Krumhansl et al., 2016) and has encountered a dramatic decline since 2014. They find that the main culprits are prolonged warm-water conditions that threaten kelp forest both directly and indirectly (Rogers-Bennett and Catton, 2019).

The reminding part of this article includes the following sections. In

[9]The important contribution of Klotz and Berazneva (2022) is to have shown the avoidance of the ECA by vessels with a very detailed data set using one-minute scale data on the locations of regulated vessels from Automatic Identication System (AIS) transponders.

Section 2, the ECA is explained as well as the empirical strategy to estimate its effects. In Section 3 the trade reduction due to the California regulation is presented. In Section 4, we describe the result on SO_2 emission, chlorophyll and water quality. In Section 5, we focus our attention on the kelp forests. Finally, Section 6 concludes with some policy implications and avenues for future research.

2 Background and Empirical Strategy

2.1 Emission Control Areas

Timing of the Emission Control Areas

The California coast has long been affected by marine pollution due to heavy traffic in the ports of Los Angeles and Long Beach, which are among the largest ports in North America, and, to a lesser extent, by the significant activity in the San Francisco Bay (e.g., the Port of Oakland), San Diego and Huemene. Accordingly, the California Emission Control Area was established in July 2009 to reduce SO_x emissions to a maximum of 1.0 percent (by mass) in ship emissions within 24 nautical miles of the California coast, under the Ocean-Going Vessel Fuel Rule regulation. In August 2012, the North America ECA is enforced requiring the use of low sulfur fuels up to 1% of SO_x within 200 nautical miles of the Canadian and U.S. coasts. The entry into force of the North America ECA is the reason why we stop our analysis in 2012, since the advantage of the Californian Ocean-Going Vessel Fuel Rule temporarily disappears.[10]

Compliance with the law

The enforcement of the ECAs regulation is done by the maritime administration of ports that verifies different documents (bunker delivery notes, the log books and the procedure for fuel oil change) and can inspect sample of fuels.

[10] In January 2014, California ECA is deepened by reducing the content of low sulfur fuels to 0.1% of SO_x

To comply with the law, vessels do not have many solutions. Scrubbers that remove sulfur from the exhaust wasn't authorized to comply (Klotz and Berazneva, 2022), and while the use of liquefied natural gas (LNG) was a solution, it was the most expensive one and has not been adopted at that time (Carr and Corbett, 2015). Hence the only two solutions, where either to avoid this area (as demonstrated by Klotz and Berazneva, 2022) or to use distillate fuels in the ECA. The sulfur content of available distillate fuels has consistently been well below the specified limits. Since 2007, the global average sulfur content for marine gas oil (MGO) and marine diesel oil (MDO) has been 0.15% or lower (IMO, 2015). In fact, as early as 2007, many Pacific Rim ports offered MGO and MDO with sulfur content below 0.1% (Klotz and Berazneva, 2022).

2.2 Empirical strategy

The standard difference-in-differences model with two time periods fits our research question regarding the causal effect of the ECA policy. We focus our analysis at the ports level in Section 3, and in the ocean in Section 4 and 5, by creating various marine cells in order to capture ECA impacts on marine environment variable and atmospherics emissions. The following equation is estimated:

$$Y_{jt} = \alpha + \beta Area_j ECA_t + Z_{jy} + f_j + f_t + \varepsilon_{jt}, \tag{1}$$

where Y_{jt} represents differents variables, in Section 3 we consider j port's volume importation in volume at time t (defined by month-year), in Section 4, we use i) the sum of SO_2 emission, ii) the concentration of Chl-a, iii) an index of water quality. In Section 5, we analyze the kelp canopies (in m²) and biomass (in kg) at the kelp level j on a quarter dimension t.

$Area_j$ takes one when a port (in Section 3) or a marine 15*15km cell area (in Section 4-5) is affected by the ECA and zero otherwise. Marine cells area

The ECA_t is a dummy that takes one after the implementation of an ECA and zero before.

To interpret a causal result, we need to isolate the effect of other potential confounding factors that possibly occurred during the same period. Then, we control for as many changes in unobservables as possible, by including quarter fixed effects f_t, individual fixed effects f_j and location-time varying characteristics Z_{jy}.

The key coefficient of interest, β, is the interaction term between the time and the location of the treatment. It captures the treatment effect of the ECA on the volume of trade that enters in ports j at the treatment time in Section 3 and the effect of the ECA on air, water pollution and ecosystem in Section 4 and 5.

In contrast to Section 3 and 4 where we use the OLS estimator, we use the Poisson Pseudo-Maximum Likelihood (PPML) estimator (e.g., Santos Silva and Tenreyro, 2006) in Section 5 to account for areas (pixels) where there is no kelp during all the period or where kelp have disappeared.

We cluster the standard errors at the States level for trade to take into account intra-group correlation that are likely for ports in i and $j$of the same state. Indeed these ports may be exposed to the same economical environment and law, or simply that have similar background characteristics for historical or geographical reasons. SO_2 is clusterised as well as the states level. For Chl-a and water quality, data satellite is provided by cells of 15x15 km which are the obervation level of our analysis, we thus cluterize these data at this level. Similarly, our analysis of the kelp canopy and biomass is at the kelp level and then the choice to clusterize at this level.

3 Trade redux

3.1 Data and descriptive statistics

Trade at the ports level and vessels transits data

To analyze the effect of the Emission Control Area (ECA) on economic activities, we focus our analysis on international trade at the U.S. ports level between 2007 and 2012. This data is sourced from the U.S. Import and

Export Merchandise trade statistics, compiled by the U.S. Census Bureau (USA Trade Online). Collected on a monthly basis from more than 400 ports across the United States, this data provides a significant advantage in precisely tracking trade dynamics between the different ports.

Eight ports fall within the treated area, while the control group comprises ports from the Gulf Coast and the U.S. Atlantic Coast (see Appendix A for detailed listings). In our main analysis, we consider all goods traded by ships, encompassing both containerized cargo (primarily manufactured goods) and bulk cargo (such as cereals, oil, minerals, etc.). To ensure robustness, we include an extension in Appendix B that presents results specifically for goods traded via containers (6).

Local Economic condition

To study how the local economic conditions in the hinterland of ports affect import, we use several datasets. To approximate the market potential of each port, we use data on population density and employment at the county level within a 50 km radius of each port. These quarterly data come from the U.S. Census Bureau for population and the U.S. Bureau of Labor Statistics Local Area Unemployment Statistics (LAUS), for unemployement.[11]

To approximate the supply capacity,[12] we use data on workers productivity by functional area from the OECD. We also employ the intensity of night lights obtained from satellite pictures, within a 50 km distance around each port. These data are used in economic development to approximate income at the regional or urban level (Henderson et al., 2012, Candau and Gbandi, 2019). Here our computation is based on the dataset of Li et al. (2020).

[11] More precisely the Quarterly Worforce Indicator

[12] See Head and Mayer, 2014 for a definition in the literature of the trade gravity equation.

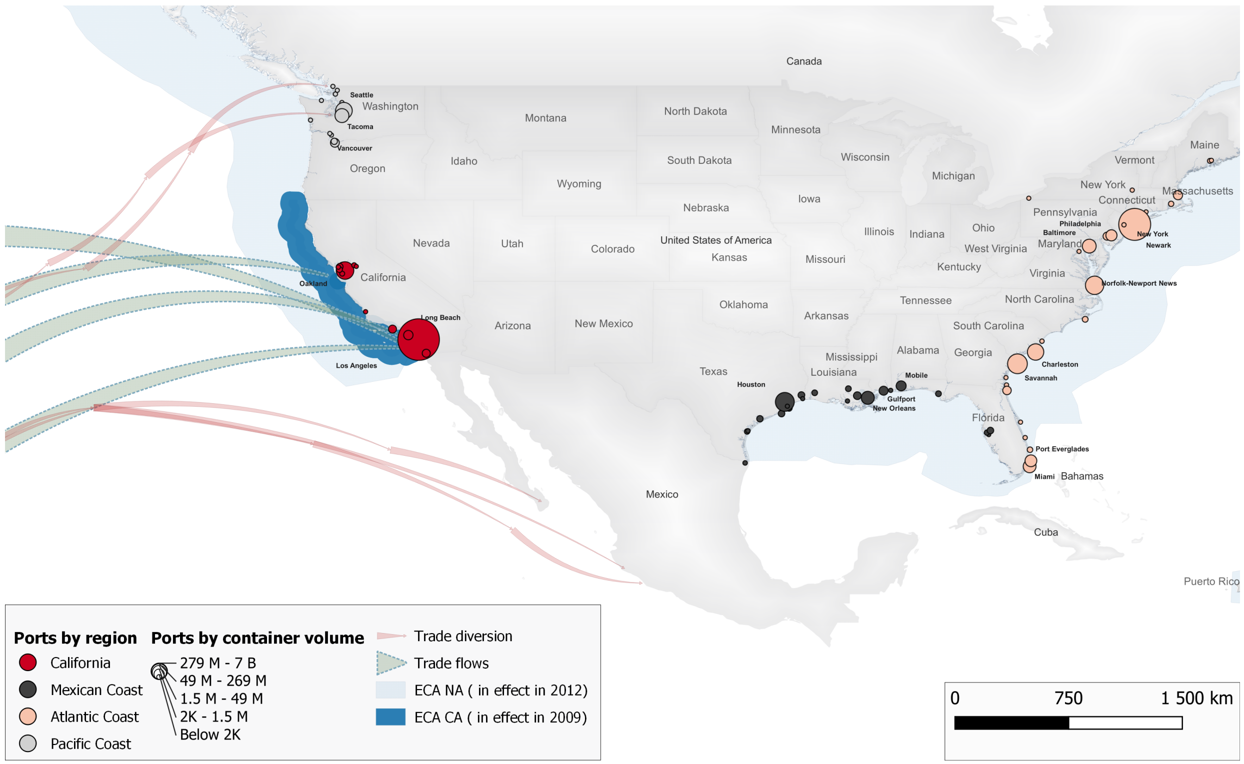
3.2 Treatment and control groups

By commenting Equation (1) we do not define precisely what the term 'affected' by the California ECA recovers. Here we consider a simple definition based on the assignement of the treatment, only Californian ports are treated, $Area_j$ takes one for these ports and zero otherwise.

Using these treated individuals, Equation (1) is estimated several times by changing the control group. We successively consider American ports of the Atlantic coasts and American ports of the Gulf of Mexico (Gulf Coast). The interest to use these ports as a control lies in the fact that they belong to the same nation and moreover undergo the same policy a few years later (the North American's ECA is implemented in August 2012). In comparison with other ports of the Pacific Coast (e.g. other American ports outside California), spillover effects of the California ECA (e.g. trade diversion) are unlikely for the ports of the Atlantic coasts and of the Gulf of Mexico.

Map (1) presents the spatial delimitation of the California ECA as well as ports considered in the two control groups.

Figure 1: California ECA, Treated and Untreated Ports



Note: To represent the sea area of ECA, we use a geodesic lines method (arcs following the path of data) connecting Lat./Long. coordinates by using data from the IMO. Location of ports comes from a projection of the data Global ports (WFP SDI-T - Logistics Database). Trade diversion flows (red) illustrate the potential trade deviation after ECA establishment, using a highly stylised approximation of The World Bank database Port Flows in 2012.
All projections are under EPSG:4326 - WGS 84 coordinate reference system, in QGIS.

3.3 Identification Assumptions

To identify the Average Treatment effect on the Treated (ATT) of the ECA, two key assumptions should be verified: 1) the average outcome among the treated and comparison populations should follow a "parallel trend" in the absence of treatment, 2) the treatment should not have a causal effect before its implementation (e.g. no anticipation). If verified these two conditions ensure that the ATT can be consistently estimated using a two-way fixed effects (TWFE) regression specification with standard clusterization methods.

Obviously the fundamental problem of causal inference is that the first assumption cannot be observed (Holland, 1986). The only parallels that can be analyzed are the ones between the trends of the control and the treated groups; we analyze them for the two groups of control considered in Figure (2), which presents the volume of trade for the control groups and the treated one. The entry into force of the California ECA is represented by a vertical line. Figure (2) illustrates that parallel trends in pre-treatment periods are plausible, American ports of the Atlantic Coast and of the Gulf of Mexico follow a similar trends than the Californian ports in terms of the volume of trade before the implementation of the ECA. Obviously this visualization of the raw data (without any control) does not display a perfect paralell trend in pre-treatment periods (in particular for quarter at the start of the analysis), but a standard pre-trend statistical test has been done (we artificially set the intervention time before 2009, in 2008) and we have found no significant effect.

The most significant challenge that these data displays, is that the implementation of the ECA occured exactly at the same period than what the literature in international trade has called, the Great Trade Collapse, due to the financial crisis of 2008. This obviously complicates the interpretation of what has happenned in the post-treatment period. In particular, the 2007-08 financial crisis might have affected these regions, in such a radical (different) way, that economies differ after that period explaining the relatively poor performance of the trade recovery in California in comparison to control groups (see Fig 2).

For instance the disruption of the supply chain may have led to bankruptcy in Asia implying that trade in California has been more affected than trade in the Gulf of Mexico or in the Atlantic. Such a supply-side explanation contradicts the existing literature, which indicates that trade recovery in Asia preceded that of other economies (Baldwin, 2009).[13] However, there is a simple test to analyse this, if the trade disruption has reduced the export capacity of Asia, then we should observe a similar bad performance of import in other ports of the Pacific, such as in Portland or Vancouver. We do not find such an effect in the data (see next section). A more plausible demand-side explanation might be that California was among the states most severely impacted by the burst of the housing bubble (Bardhan and Walker, 2011). Consequently, the recession and credit restrictions may have had a more pronounced effect in this state, limiting the consumption and import of goods. We however control with ports fixed effects and with several variables (such as employment, economic activity in the hinterland) for this possibility. We also use a flexible area-specific time trends for this chanel of diffusion.

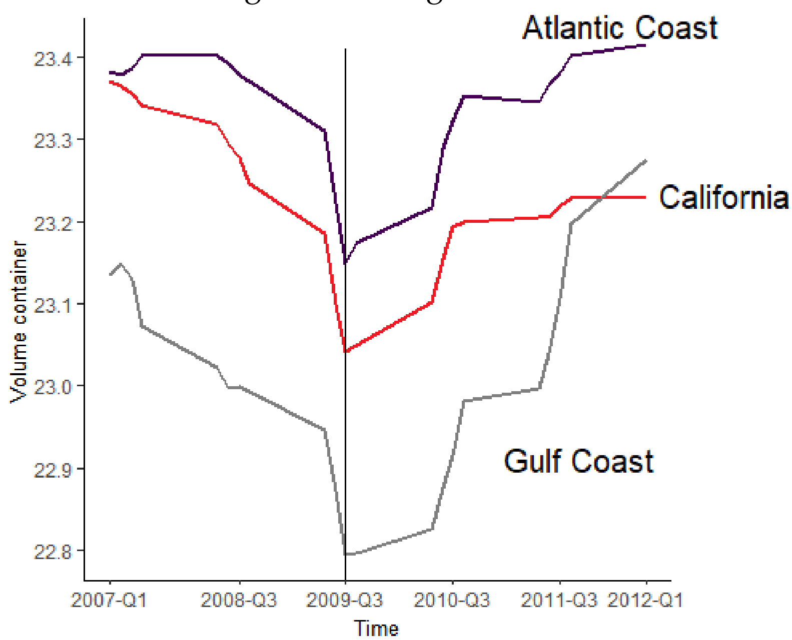
Lastly, to explain that the ECA implemented in 2009 has an effect in the year that follows (and not immediatly), we have to keep in mind precisely that the traffics was in a period of recovery at that time. This indeed implies that the entry of vessels has been progressive, then the choice to comply with the law for a shipowner that enters on the market in 2010 or in 2011 still incurs a fixed cost. One can even assert that the variable cost is even increasing since the price of low sulfur fuel (that should be used in the ECA) is increasing again over that period.

The reliability of the DiD strategy also relies on the absence of anticipatory behavior. Figure (2) indicates that the anticipation effect is not visible, but the violent shock of the 2008's crisis may hide the detection of these kind of behavior. However there is also several reasons linked to the economic rationality of shipowners and carriers that may justify that the anticipation of the law is not a concern here. Indeed, the ECA does not incur only a fixed cost, it also affects the variable costs since vessels have to

[13] See also Bricongne et al. (2012) for a brief literature review on the determinants of the great trade collapse. For french firms, they show that the overall impact of credit constraints on trade has been limited.

use a fuel that is much more expensive when they enter into the regulated area. Hence, vessels have certainly waited until the last moment before to change their road or the fuel used (even if new engines have already been installed).

Figure 2: Change in trade



Note: Control groups are ports of the American Atlantic coast (Velvet), of the American Mexican Gulf of Mexico (Gray). Treated ports are those of the Californian Coast (red). Values are in log.

Finally the SDID method, in the next section, guaranties by definition similar trends before the treatment between treated and untreated ports.

3.4 Difference-in-differences Results

In Table (1, Column 1 and 2), we estimate Equation (1) for the total trade unloaded in Californian ports in volume.[14] In Column 3 and 4, we estimate the same equation but without the biggest port in L.A. in order to

[14]see Appendix B for similar results concerning containers

verify that the very high volume of imports in this port does not biaised the analysis. In particular the parallel trend assumption may be violated by the introduction of this port that has no equivalent in the rest our sample.

Finally, in Column 5 and 6, we consider a placebo test by considering as treated ports in the North of the Pacific Coast (mainly Canadian ports, see Map 3.2, reported in Gray).

In each case, we consider two different control groups, ports of the Gulf Coast (Column 1, 3 and 5) and of the Atlantic coast (Column 2, 4 and 6).

Regarding all ports in California (Column 1 and 2), we find that the ECA had a significantly negative effect on these imports, whatever the control groups. The estimates of β are relatively similar from one group to another and are ranked between -0.18 and -0.23. The highest effect is obtained with ports of the Atlantic coast in the control group, and the smallest effect at the Gulf Coast ports.

Results without the biggest port (Column 3 and 4) are slightly higher but confirm the previous finding.

Table 1: Trade reduction

Treated	California		Without L.A.		Placebo: N. Pacific	
Control	Gulf	Atlantic	Gulf	Atlantic	Gulf	Atlantic
DiD effect	-0.188***	-0.233**	-0.203***	-0.253***	-0.278	-0.382
	(0.0737)	(0.0948)	(0.084)	(0.106)	(0.215)	(0.259)
Timetrend	-0.199	-1.641	0.505***	-1.669	0.282***	-0.145
	(0.733)	(1.296)	(0.087)	(1.308)	(0.0845)	(0.521)
Econ Activity	3.289**	1.051	3.24***	1.002	2.041***	0.994
	(1.480)	(2.132)	(1.497)	(2.152)	(0.364)	(1.419)
Obs	1020	1680	960	1620	900	1560
LLikelihood	-715.2	-1855.8	-699.4	-1817.3	-682.2	-1777.0
R-squared	0.9733	0.9335	0.97	0.93	0.96	0.92

Notes: Upper-script ***: p<0.01, **: p<0.05, *: p<0.1. The dependent variable is the log of trade volume on a monthly basis between 2007 and 2012 from U.S. Census Bureau (Economic Indicators Division USA Trade Online). $Nightlight_{it}$ is the log of night time light intensity in a 50km buffer over each ports from Li et al. (2020). Californian ports are treated. US ports of mexican Gulf are in control in Column 1 and 2. US Atlantic ports coast are in control in Column 3 and 4. In column 5 and 6, we switch treated group by using US Pacific ports coast as in placebo test. All the regressions include quaterly effects, f_t and port fixed effects f_j. Standard errors in parentheses are clusterized at the state level.

Column 5 and 6 provide the same estimation but we now consider as treated other ports of the Pacific Coast. This is a placebo test because no ECA have been implemented there. As discussed earlier (Section 3.2), these estimations provide a simple test of different explanations. With a significantly negative estimate of β then the supply-side explanation of the great trade collapse (due to a reduction of the Asian capacity to export) is verified. At the opposite, if β is significantly positive then the ECA has led to a trade diversion toward these Northern ports. Finally, an unsignificant estimate is what we expect from such a Placebo test. Table (1, Col 3 and 4) confirms this null hypothesis. We can thus conclude that California's Ocean-Going Vessel Fuel Rule implemented in 2009 has significantly reduced trade in the ECA area.

To go beyond the average monthly impact of ECA over the whole pre and post treatment period presented in this Table (1), we present in Figures

(3, 4) the dynamic effects of this policy year after year.

Figure 3: Dynamic effect of the ECA (Atlantic Coast)

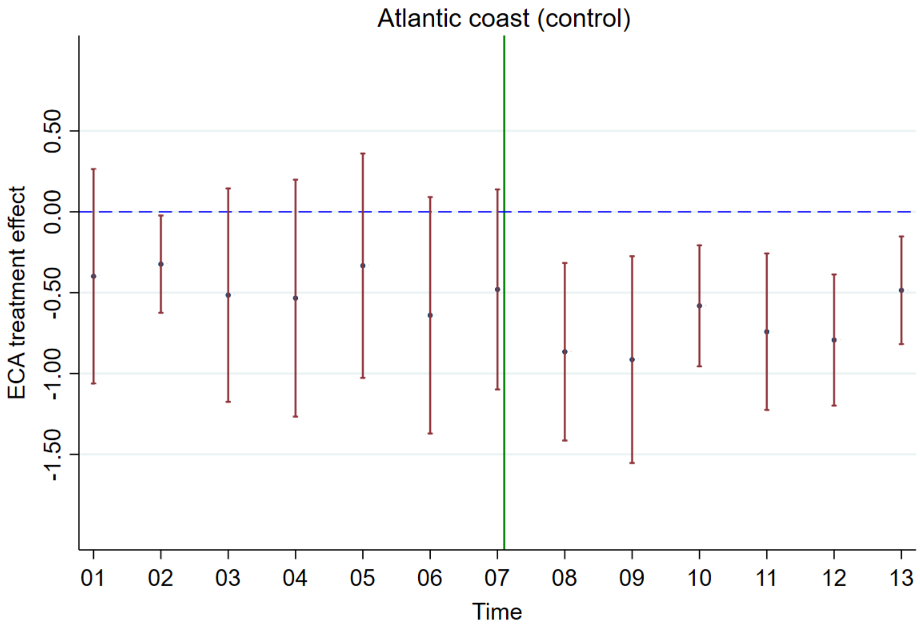
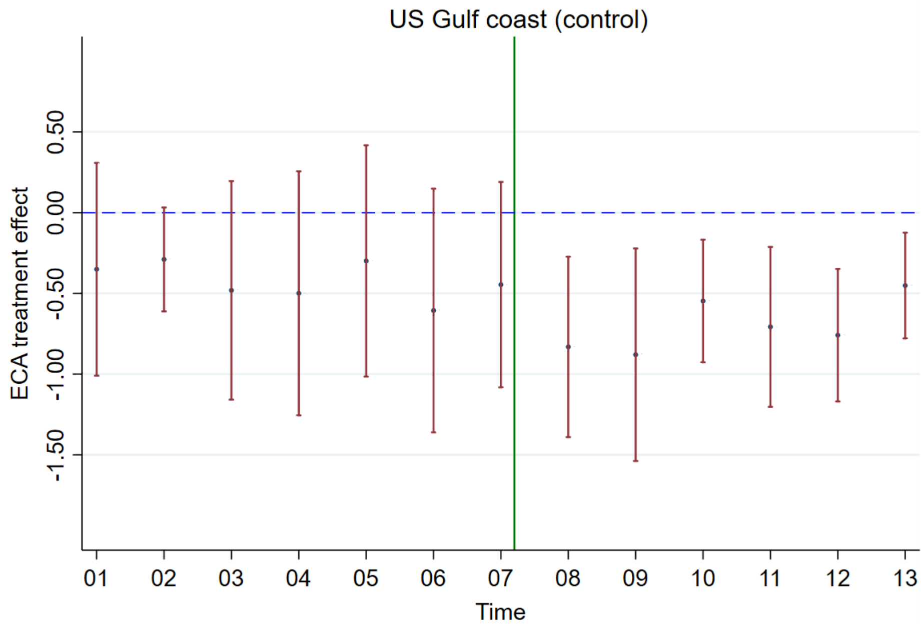


Figure 4: Dynamic effect of the ECA (US Gulf Coast)



This analysis can be improved in several way. First, the lack of data concerning ports in Mexico unfortunatly unables to test the diversion effect toward the South, which is both very likely and also a factor explaining the decrease in import due to the ECA in California. Secondly, better variable of control may improve this analysis. Only night-light data were significant here. Not reported, all the other variables that approximate the local activity were unsignificant (this includes measures of employment, worker productivity, and density; see the data section for descriptions). This outcome is not surprising as these data may either poorly approximate the local economic conditions,[15] or the effects they measure might already be captured by other controls (such as fixed effects or the time trend).

[15]In particular, the drawback of night light pictures are well known, they poorly detect low density areas and are not enough acurate for developed countries (see Gibson et al., 2021).

3.5 Robustness Check on Trade: Synthetic Difference-in-Differences Results

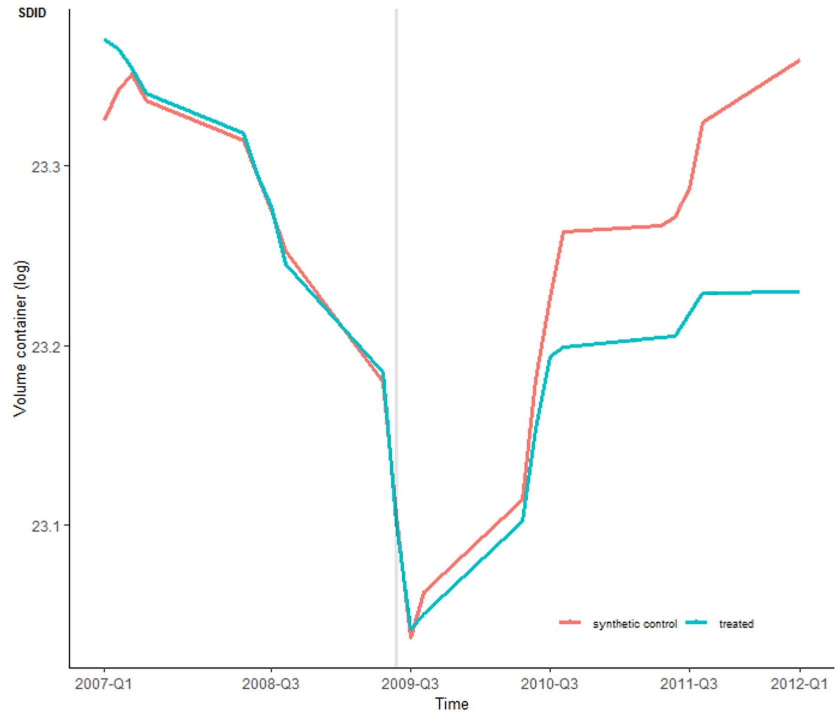
As a robustness test, we use a Synthetic Difference-in-Differences estimation (Arkhangelsky et al., 2021), hereafter SDID. This method enables to reweights and matches pre-exposure trends and thus represent an interesting alternative to the method of *ad-hoc* control group.

The synthetic representation of California comprises ports located in the North Sea, the Baltic Sea, the Mediterranean Sea, the US Atlantic Coast, and the Gulf Coast. Appendix C presents the weight of each area in the building of this synthetic California.

Figure (5) shows the evolution of the trade volume in the synthetic region (in red) and in California ports (in green). We clearly observed a trade destruction due to the California ECA. The ECA had a noticeable impact at the implementation date, which increased over time. Specifically, after the third quarter of 2010, the synthetic region showed a significant increase in the volume of trade, whereas trade flows in California stagnated. This result supports our conjecture that the impact of the ECA becomes more visible when international trade returns to its natural level after the Great Trade Collapse.

In Appendix C we also analyze several placebo tests by considering as treated other ports of the Pacific coast (as in the previous section) as well as ports of the Atlantic coast (in that case, these ports are no longer included in the synthetic group) and ports of the Gulf Coast (then excluded from the synthetic control group). None of these placebo tests is significant, which confirms the distinct effect of the ECA.

Figure 5: SDID on Trade



4 Air and water pollution

The previous section highlighted a reduction in international trade within the ECA region. The question now is whether this reduction has impacted air and water pollution in the area.

We re-estimate our DID Equation (1) with SO_2 emissions, chlorophyll concentration, and our indicator of water quality. These data comes from satellite observations and are available over oceans surface within a 15 by 15 km grid. All our estimations in this section consider these cells of 15x15 km as the individual observations. We lead several analysis on these obervations. First, we consider all the cells in the California ECA as treated. Secondly, to analyze whether the effect of the ECA is spatially heterogeneous by limiting these treated areas to cells with high shipping traffic (exceeding 25 passages in May 2009). To do this we utilize Automatic Identification System (AIS) data, collected by the U.S. Coast Guard. AIS data is particularly valuable for localizing and tracking vessel behavior, as detailed by Klotz and Berazneva, 2022 or Heiland et al., 2019. This data enables us to accurately determine the number of vessels (bulk vessels, containerships and tanker ships) crossing our 15 km by 15 km oceanic grid cells.

For each dependent variable, we have to select a different control group to ensure a parallel trend before the treatment period. For SO2 emissions, using data on the dispersion of sulfur dioxide, we define a fictional ECA along the entire coast of the USA (Atlantic, Gulf of Mexico, and Pacific coasts, excluding California) that shares the same terrestrial reference geographic characteristics as the Californian one, namely a distance of 24 miles from the coast. Similarly for Chlorophyll-a, we take as control the observations (defined within a 15 by 15 km grid as the treated group) from the US Pacific coast and along Baja California in Mexico. Regarding the Water Quality indicator, the control cells are located within the US and Mexican Exclusive Economic Zones (EEZ) along the Pacific coast.

The next section presents these dependant variables as well as control variables.

4.1 Data

4.1.1 Dependent variables on air and water pollution

SO_2 emission

While sulfur dioxide and trioxide emissions does not last in the atmosphere for long periods of time and does travel significant distances, their dispersion and impact on water depends on atmospheric interactions and meteorological factors. We thus follow the strategy of Hansen-Lewis and Marcus (2022) that takes into account the complexity of atmospheric interactions and try to evaluate where emissions polluant are transported. More precisely we use the Community Multiscale Air Quality (CMAQ) model, that provides the SO_2 emitted and transported in each cells/parts of the oceans studied here. This model both contains emission of SOx emitted by ships and relies on meteorological data from sources like the Weather Research and Forecasting (WRF) model to capture atmospheric dynamics accurately.

Chlorophyll-a

Chlorophyll-a (Chl-a) is found in all photosynthetic plants and used as an index for phytoplankton biomass. Its concentration is commonly considered as a measure of ocean health in sustaining a productive aquatic ecosystem. Yet, its excessive accumulation, causing a reduction in the water oxygen content, can negatively affect ecosystem health and functionality.

We use here data from the MODIS sensor of the NASA's Aqua satellite that measure chlorophyll concentrations in the ocean. MODIS Chlorophyll-a product provides an estimate of the near-surface concentration of chlorophyll calculated using an empirical relationship derived from *in situ* measurements of chlorophyll and remote sensing reflectances (Rrs) in the blue-to-green region of the visible spectrum (Hu et al., 2012).

Water Quality Index

Although there is extensive literature on continental water quality for rivers and lakes (Uddin et al., 2021) and of water scarcity (see Candau et al., 2022), indicators of marine water quality are unfortunately less developed and not available for our studied area. We follow the US coastal quality index from U.S. Environmental Protection Agency (EPA) Office of Water and Office of Research and Development (ORD) based on Bricker (1999) and Diaz and Rosenberg (1995) by using four key variables due to their importance for water quality and marine ecosystems health : Phosphorus (PO4), Nitrate (NO3), Chlorophyll (Chl), Dissolved Oxygen (DO).[16] We

[16] Nitrate concentration is expressed in mole concentration of nitrate (NO3) in seawater [mmol/m3]. Chlorophyll concentration is measured in mass concentration of chlorophyll a in seawater (Chl) [mg/m3]. Dissolved oxygen is reported in mole concentration of dissolved molecular oxygen in seawater (O2) [mmol/m3]. pH is recorded as the total

add pH level, which is highly recommended to assess the quality of water (see for instance Sheldon and Alber, 2011).

Dissolved Oxygen is a critical indicator of aquatic respiration and organic matter decomposition (Diaz and Rosenberg, 2008). Conversely, Nitrate, an essential nutrient, can lead to eutrophication when present in excess, thereby affecting marine biodiversity. Chlorophyll serves as a proxy for phytoplankton biomass, indicating primary productivity. Phosphorus, though present in smaller quantities, plays a crucial role in nutrient cycling and can limit primary production in certain marine environments. pH is a significant indicator of water acidity, influencing nutrient solubility and the health of marine organisms (Feely et al., 2004).

We normalized our Water Quality Index (WQI) to standardize the varying scales of different parameters across locations and periods, ensuring a balanced contribution to the final index. We then applied the following formula:

$$WQ = 0.08 \times DO + 0.05 \times pH + 0.4 \times PO4 + 0.4 \times NO3 + 0.05 \times Chla \quad (2)$$

The different weights have been chosen by following the scarce literature on this issue. In particular, we adopt here weights provided by Jha et al. (2015), even if its analysis concerns a very different area (coastal waters of Andaman in India). We have led various robustness checks by changing these weights and systematically find similar results.[17]

Biogeochemistry models enable us to find reliable, localized, and time-variant data for Dissolved Oxygen, Nitrate (NO3), and Phosphorus (PO4). This data is sourced from the Global Ocean Biogeochemistry Hindcast produced by Mercator-Ocean (Toulouse, France) via the European Union-Copernicus Marine Service. This dataset provides three-dimensional biogeochemical fields for the period 1993-2019 at a resolution of 1/4 degree and across 75 vertical levels, utilizing the PISCES biogeochemical model available on the NEMO modeling platform. The dissolved oxygen, nitrate,

scale pH of seawater.

[17] Available on request.

and phosphate data are aggregated into 15 by 15 km grids along the west coast of the USA.

The pH values come from the Global Ocean Surface Carbon database (European Union-Copernicus Marine Service). This product from SOCAT corresponds to a REP L4 time series of monthly global reconstructed surface ocean pCO2, air-sea fluxes of CO2, pH, total alkalinity, dissolved inorganic carbon, saturation state with respect to calcite and aragonite, and associated uncertainties on a 0.25° x 0.25° regular grid. The mean pH of each cell is used.

Chlorophyll data is sourced from the NOBPG2015 dataset, as described above.

4.1.2 Variables of control

Temperature

Sea surface temperature (SST) data is sourced from the Moderate Resolution Imaging Spectroradiometer (MODIS), which measures the temperature of the top millimeter of the ocean's surface. SST is an important variable that helps explain variability in ocean activity (including frequency, density, and strength) and chlorophyll concentration (Yang et al., 2023; Dunstan et al., 2018).

SST data is extracted from NASA's Terra and Aqua satellites and is used at the monthly level. These satellites provide high-resolution, global coverage, enabling comprehensive monitoring of SST.

Precipitation

We use precipitations data compiled by NOAA since ocean adification can be magnified by rainfall near coastal area due to shipping emission impacts (Jagerbrand et al., 2019, Lowles and ApSimon, 1996). Indeed, excessive rainfall can lead to increased nutrient loads in water bodies, causing eutrophication and effects on phytoplakton and harmful algal blooms (Kim et al., 2014). Moreover, precipitation influences the salinity and stratification of ocean waters, which in turn affects marine life and biogeochemical cycles.

Sea Surface Weight

Wave and current intensity can have very different effect on marin environment. On the one hand, moderate wave and water currents disperses spores, and are thus essential to the expansion of species. They also bring up nutrients from the deeper waters and finally by removing sediment and epiphytes from the plant blades, they favor the photosynthesis. However, on the other end, strong intense wave and currents cause physical damage, breaking off fronds or dislodging whole plants from the substrate, leading to a reduction in biomass which can in turn be problematic for water quality.

Waves current intensity are approximated by "the average height of the highest third of surface ocean/sea waves generated by wind and swell" and comes from Hersbach et al. (2023) and the Climate Data Store. In simple terms, the ocean/sea surface wave is depicted as a two-dimensional wave spectrum, which combines waves of different heights, lengths and directions. The measure taken into account here uses the two fundamental parameters of this wave spectrum, which are the wind-sea waves (due to local winds) and swell (due to wind at a different location and time).[18] We refer to this variable in our tables of results as the Sea Surface Weight and use as a control when estimating water quality and Chl-a concentration (less relevant for SO_2).

Economic activity

Economic activity along the coast also impacts SO_2 emissions, water quality, and possibly the concentration of Chl-a through industrial pollution, agricultural runoff and urban activities. Since both our control and treated groups for SO_2 are in the U.S., we use unemployment data from the coastal area closest to the treated and untreated cells. These quarterly data come

[18]More precisely, this parameter is four times the square root of the integral over all directions and all frequencies of the two-dimensional wave spectrum.

from the U.S. Bureau of Labor Statistics Local Area Unemployment Statistics (LAUS).

For Chl-a, we use cells near Mexico as the control group and then, because we lack localized data on economic activity along the Mexican coast, we use the intensity of night lights from satellite images as a proxy for economic activity for both the treated and untreated groups. As for unemployment, we takes the nightlight of cells on the coast that are the nearest to the dependant variable/observation analyzed. See the data description in the trade section for this data source.

4.2 Results

While the trade analysis logically lead us to consider that a reduction in traffic can have an impact on air and water pollution, we have no literature to guide us on the effect of the ECA, and some doubts about the size of the ECA that may be both too small in size and too short in time to have an impact. However results presented in Table (2) are quite unanimous about the positive effect of the ECA to limit the negative impact of vessel traffics. Considering SO_2, we observe a significant negative effect of the ECA whatever the control group used. We find that the average reduction of SO_2 emission is between 6 and 8% depending of the zone studied. The concentration of Chlorophyll-a also increases due to the implementation of the ECA (Columns 3 and 4) and finally the quality of water is improved in the emission control area (Columns 5 and 6).

Table 2: Environmental impact of the ECA

	SO_2		Chlorophyll-a		Water Quality Index	
	All	H. traffic	All	H. traffic	All	H. traffic
DID effect	-0.087***	-0.066***	0.219***	0.23***	0.032***	0.05***
	(0.024)	(0.025)	(0.014)	(à.02)	(0.004)	(0.006)
Temperature	0.025*	0.015	-2.32***	-2.59***	-0.90***	-0.86***
	(0.10)	(0.009)	(0.13)	(.0726)	(0.023)	(0.032)
Precipitations	-0.007	-0.013	-0.017***	-0.021***	-0.022***	-0.02***
	(0.025)	(0.245)	(0.004)	(0.005)	(0.0001)	(0.001)
Econ activity	-0.05*	-0.045	-0.02	-0.17*		
	(0.027)	(0.31)	(0.076)	(0.108)		
Sea S Weight			-0.22***	-0.219***	0.025***	0.019***
			(0.012)	(0.015)	(.003)	(.005)
Obs	48940	36955	24790	16247	52519	21871
LLikelihood	1052.76	502.01	165.17	130.20	819.36	362.48
Pseudo R2	0.96	0.95	0.57	0.56	0.76	0.78

Notes: Upper-script ***: p<0.01, **: p<0.05, *: p<0.1. This table presents the effect of California ECA on SO2 emission in Column 1 and 2, the average of Chlorophyll-a concentration (mG/m3) in Column 3 and 4 and an index of water quality in Column 5. Time period: 2007-2011. Concerning SO2 pollution, the sum of emissions in each cells is taken, in Logarithm, on a quarterly basis. The treatment group is defined by the ECA area, using a grid with cells each measuring 15 km by 15 km. The control group is defined by computing an fictional ECA along all the coast of the USA (without California) that has the same characteristics than the Californian one, namely 24 miles of nautical boundarie (with similar cells that have a side length of 15 km).
The column "All" specifies cells with more than 5 ship passages, while those labelled "high traffic" takes into account cells that experience higher vessel traffic with more than 25 ship passages. Regarding Chl-a (Columns 3 and 4): treated cells are identical but the control cells are in the US Pacific coast and along Baja California in Mexico (within a 24-nautical miles limit). Finally for the Water Quality indicator, the control cells are within the US Pacific and Mexican EEZ into a 75km in Columns 5 and 6. Standard errors are clusterized at the state level for Sox and at the individual level for Chlorophyll and Water Quality Index.

As an extension of these results, we estimate the effect of the treatment at different points in time relative to the policy intervention. More precisely, in Figure (4.2), (4.2), and (4.2), we present the event studies for the effect of the ECA on SO_2 emission, the concentration of Chlorophyll-a and the quality of maritime water. We first observe that pre-treatment trends for SO2 are significant one year before the treatment, which raises doubts about the parallel trends assumption upon which the Difference-in-Differences approach is based. However, in the quarter just before the shocks (t-1 and t-2), there is no significant difference between the treated and untreated groups. The results for Chl-a are even less ambiguous, since all the difference between the control group and the treated before the ECA are unsignificant. Similar remarks apply to Water Quality.[19]

Concerning post-treatment periods, we find a clear decrease in SO2 in the second quarter after the entry into force of the ECA (Figure 4.2). The coefficient seems to reach a plateau around a negative coefficient of 0.2 (in log), which represents a reduction of SO_2 of approximatively 18% ($\exp(-0.2) - 1$).

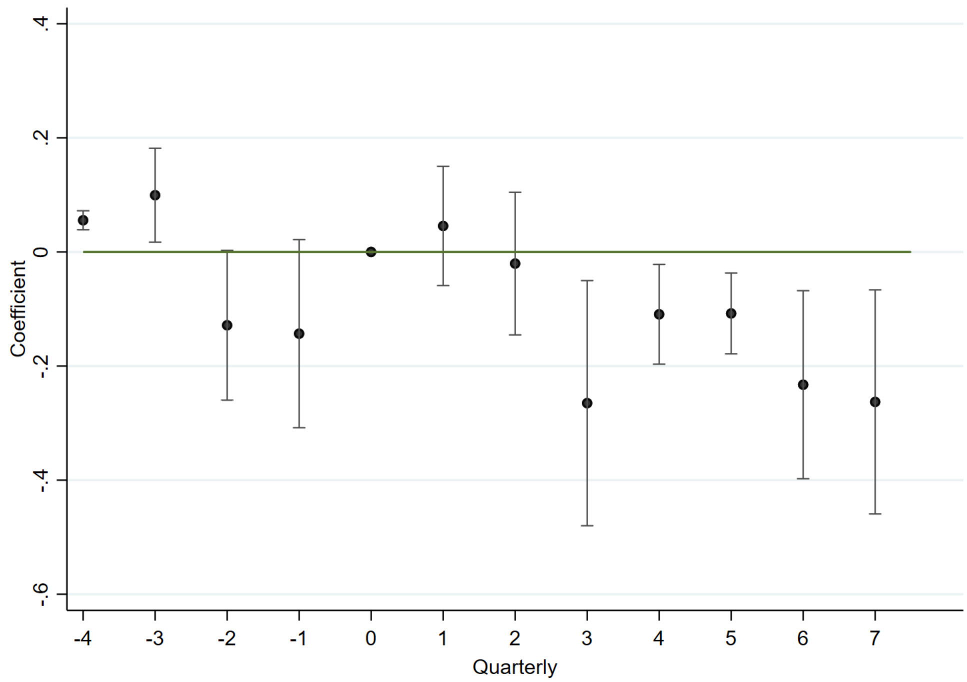
Similarly, we observe a rapid increase in Chlorophyll-a concentration (Figure 4.2), indicating an improvement in the minimal level of nutrients. The result is not perfectly stable since we find a non-significant coefficients at t+5, which may indicate a lack of control over the explanation of the Chl-a variability at that period of time (which corresponds to winter, we discuss seasonal shocks in Section 5). However, the effect of the ECA on Chl-a is persistent over time, as we still observe a positive significant effect ten quarters after the policy's implementation.

We find similar results regarding the water quality index. This indicator, which takes into account dissolved oxygen, water acidity, nutrient solubility, and the health of marine organisms, shows improvement over a long period only after the implementation of the ECA. Indeed, nine quarters after the implementation, we still observe a significant effect, while

[19] We also provide the raw data in Appendix D, they offer partial evidence of the estimation, as we indeed observe that, even without controls, there is a decrease in SO2 levels, an increase in Chlorophyll-a, and overall a smaller degradation of the water quality following the implementation of the ECA in the treated group in comparison to the control group.

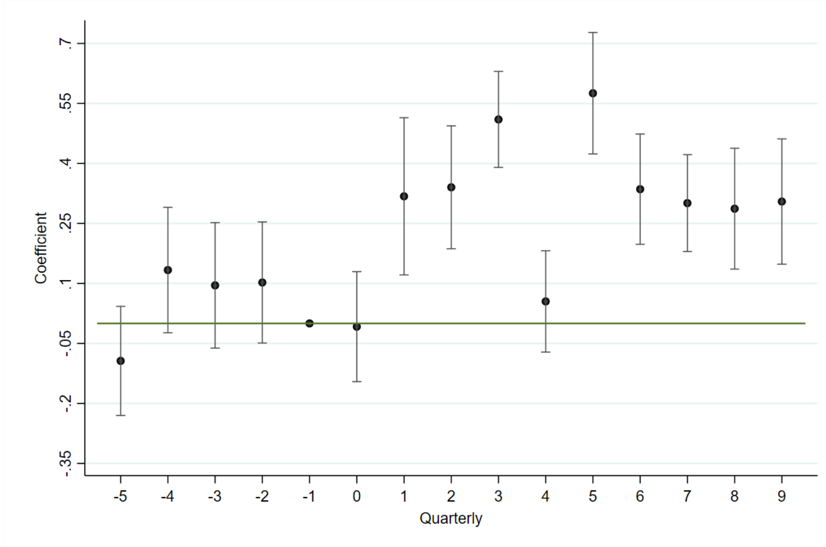
the period preceding the law shows no significant improvement in marine water quality. This suggests that the ECA has had a lasting positive impact.

Figure 6: Dynamic effect of the ECA on SO2



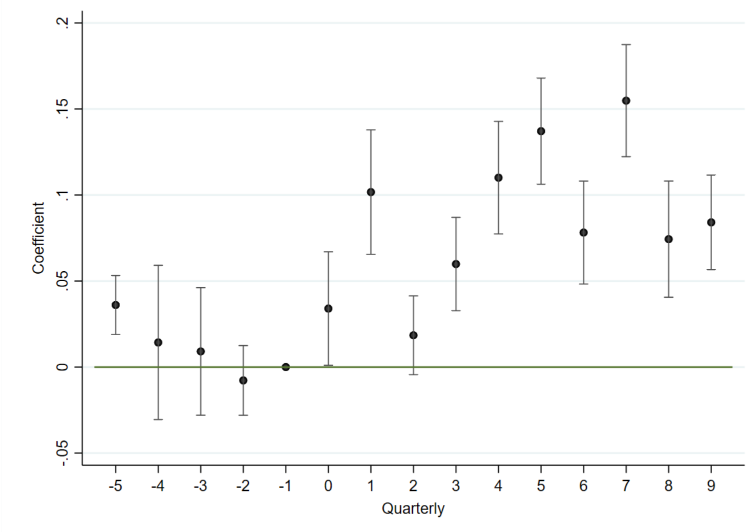
Notes :

Figure 7: Dynamic effect of the ECA on Chorophyll-a



Notes:

Figure 8: Dynamic effect of the ECA on water quality



Notes :

5 Effect on the kelp forests

To analyze the effect of the ECA on the kelp forests, we follow the same empirical strategy than the previous sections and estimate Equation 1 by now considering as dependant variables the canopy and the biomass of kelp. We chose different control groups and covariables as explained in what follows.

5.1 Data

5.1.1 Kelp canopy and biomass

Data on kelp comes from Bell et al. (2023)[20] which provides data on the growth and coverage of kelp forests on the Californian coast. The location

[20]See Kelpwatch.org for a visual representation at https://kelpwatch.org/map

of kelp is detected by different satellites (Landsat 5, 7 and 8) and defined at a 30 x 30 meters resolution. The coverage of the kelp forest is an average on three months based on season and provide a time series of cloud-free imagery. We use two indicators, the canopy indicator that measures in each pixel the area of kelp observed (in m^2), and the kelp biomass that approximate the total mass of living kelp (in kg) within each pixel. Estimates of kelp canopy biomass are derived from the relationship between satellite surface reflectance and empirical measurements of kelp canopy and biomass.[21]

5.1.2 Variables of control

We keep here the control variables presented in the previous section, namely Temperature and Precipitation, to control for changes in climatic conditions, as well as Sea Surface Weight to assess variations in currents and waves. There is indeed several papers that show the importance of these variables (e.g. Dayton et al., 1992, Smale, 2019). Time effects at the quarter level and kelp fixed effects are also introduced as indicated in Equation (1) to control for common temporal shocks (e.g. extreme climatic conditions) and kelp-specific characteristics (such as the existence of different species, particular geo-located conditions, and so on).

5.2 Identification issues

Contrasting with the previous trade analysis (and economics in general), the following study on kelp holds a distinct advantage: some of the Stable Unit Treatment Value Assumptions (SUTVA) are indisputably ensured (Rubin, 1974). Kelp do not consider the different potential outcomes, and thus, there's no selection bias (as we usually understood it) or anticipation. However, several other challenges persist due to the unknown heterogeneous effects of the ECA on kelp, due to a possible lack of control and to the potential contamination of the control group by the regulation.

[21] The two Santa Barbara Coastal Long Term Ecological Research project study sites, Arroyo Quemado and Mohawk reefs, were used to validate the Landsat estimated kelp fractions against canopy biomass and other diver-estimated variables

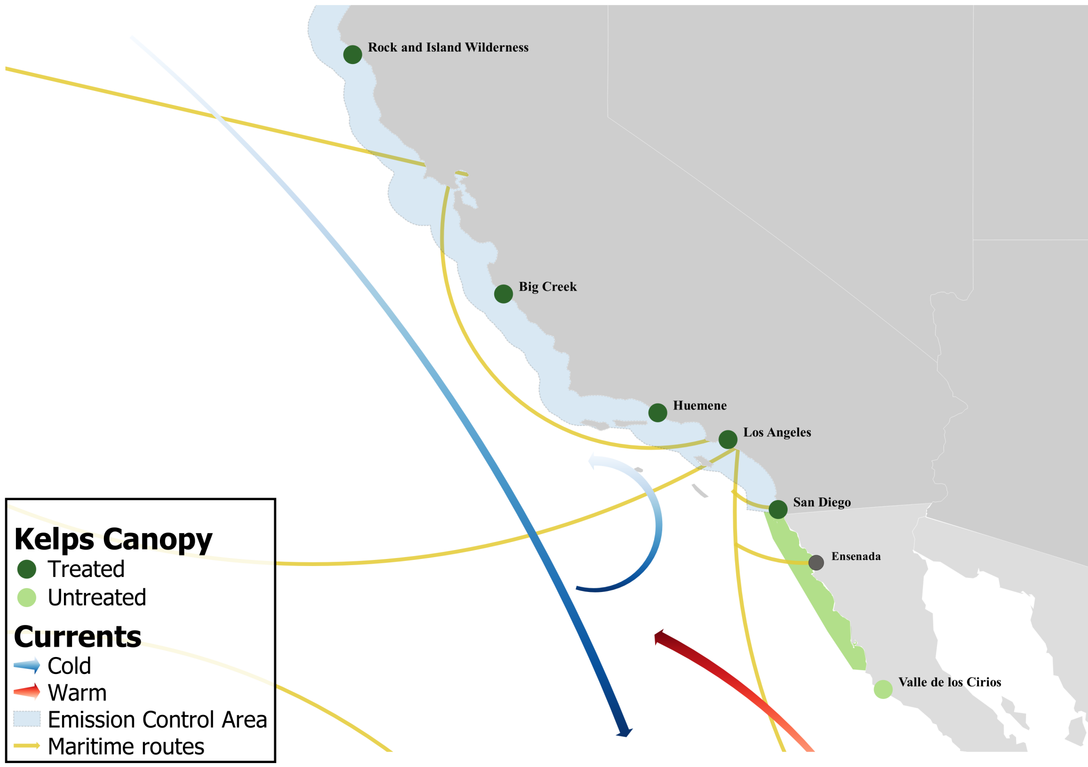
5.2.1 Treated and control group

The effect of the ECA for kelps along the California coast is without doubt very heterogeneous, due to the different species of kelp[22] and to the maritime route of ships. We thus decide to focus on one particular area, which are the kelp forest near the Greater Los Angeles metropolitan area. As already mentioned, the ports of Los Angeles and Long Beach are among the largest ports in North America, they are the entry door of the Pacific trade with Asian countries and form the largest seaport complex in the U.S accounting for 28% of the total value of U.S. maritime trade in 2010 (US, 2010). Then the impact of the reduction of international trade, presented in Section 3, invite us to consider the effect of the ECA in this area. Since this zone has long been affected by pollution, a rapid recovery of the kelp forest could serve as an interesting example of possible ecosystem restoration in a challenging human environment. Our treated group of kelp comprise all the kelps that are near the Greater Los Angeles metropolitan area using a buffer of 50 km from the L.A. port. We refer to this treated group as L.A. to keep it short. In Appendix E we consider four other treated areas inside the ECA, to analyze the kelp forest in Rock Islands, Big Creek, Huemene and San Diego, we find similar results.

While the data compilation is particularly comprehensive for California (including the size and growth of kelp, for example), data are scarce outside this state. However, this information is well-documented in the South (see Map 9), on the Baja California peninsula along the Mexican coast. Inside this area we chose three different control groups/methodology to verify the robustness of our results.

[22]Giant kelp (Macrocystis pyrifera) in the southern regions, bull kelp (Nereocystis luetkeana) in northern parts, Elkhorn Kelp (Pelagophycus porra) around the Channel Islands and so on.

Figure 9: Kelp in the ECA and in Baja California



Note: The green circles regarding the kelp canopy represent the buffers of the analyzed data from Bell et al. (2023). Maritime routes are a highly stylised representation based on the SO2 emission of vessels in 2012 from EDGAR, the Emissions Database for Global Atmospheric Research. The California Current is schematised and simplified from Checkley and Barth (2009). All projections are under EPSG:4326 - WGS 84 coordinate reference system, in QGIS.

Due to the limited data available outside California, our analysis is potentially affected by two biases: the violation of the parallel trends assumption and the contamination effect of the treatment on the control group. Below, we explain the mechanisms that may lead to these biases. Before entering into these details, let's briefly analyze how our coefficient can be biased.

When the parallel trends assumption does not hold, the expected changes in outcomes for the treated and control groups would differ even in the absence of treatment. Let's denote the expected growth rates in the absence of treatment for the treated and control groups as γ_T and γ_C. Concerning the contamination effect, we consider a negative externality p that affect the control group due to the ECA. With these notation, the result obtained when estimating β is:[23]

$$\widehat{\beta} = ATT + E[\gamma_T - \gamma_C] + E[p], \tag{3}$$

Because we do not observe the growth rates of kelp in the absence of treatment for the treated γ_T, we cannot determine in which direction $\widehat{\beta}$ is biaised when the parallel trends assumption does not hold. In contrast, the negative externality p leads to inflate our coefficient and then to overestimate the thrue ATT.

Ensenada We first chose as a control the port of Ensenada in the Baja California outside the ECA (see Map 9). This location is at the junction of the convergence of the cold California Current and the warm North Equatorial Current, which together influence the Gulf of California. These characteristics imply that if not treated, kelp inside the ECA would benefit from the same conditions as those in Ensenada. Data regarding the kelp canopy and biomass inside the ECA and in this control group present sim-

[23]To show this, we introduce simple notation, such as $Y^c(Area, ECA)$, where Area and ECA are defined as previously taking 1 (or respectively 0) for the treated (control) and the post (pre) treatment period. The upper-script c represents the counterfactual, being equal to 1 in a state of the world where Area is treated (0 otherwise). For instance $Y^0(1,1)$ represents the potential outcome, or counterfactual, of the treated after the treatment if has not been treated. By denoting p the increase in the pollution that negatively may affect Baja California due to the ECA, such as its growth in the post-period is now$Y^0(0,1) - p$, the coefficient obtained may be approximated by:

$$\widehat{\beta} = ATT + \Big(E[Y^0(1,1)] - E[Y^0(1,0)]\Big) - \Big(E[Y^0(0,1) - p] - E[Y^0(0,0)]\Big),$$

if we now assume that the parallel trend does not hold and equals to $E[\gamma_T - \gamma_C]$ such as $E[Y^0(1,1)] - E[Y^0(1,0)] - E[Y^0(0,1)] - E[Y^0(0,0)] = E[\gamma_T - \gamma_C]$, we get by substitution:

$$\widehat{\beta} = ATT + E[p] + E[\gamma_T - \gamma_C],$$

where ATT is the Average Treatment on the Treated.

ilar change before the treatment (see Appendix E). Ensenada has indeed several characteristics that are similar to L.A., it is for instance the second busiest port in Mexico after Veracruz (in the Gulf of Mexico) and the only deep-water port in the state of Baja California.

However, one issue with this control is that if the ECA causes a trade diversion toward that port (which is visible on raw data, see Appendix E), the control group is affected, due to the dispersed pollution of an influx of vessels circumventing Californian ports and rerouting towards Ensenada. Consequently, our estimation takes the risk of amalgamating the positive influence of the ECA on the treated areas with the negative repercussions on the kelp in the control group.

However, this estimation remains of interest from an ecological point of view, as it underscores the detrimental effects of maritime transport on kelp, not confined solely to the ECA-designated area but extended to to the control group.

Baja California (without Ensenada) To indirectly test how the previous contamination bias affects our result we run again our DiD analysis, but we exclude kelp near Ensenada from a control group that takes all the Baja California peninsula. One can indeed argue that kelp in this area are those which are the most affected by a potential trade diversion toward Mexico. Hence, under that assumption, we minimize the contamination term $E[p]$. Obviously we cannot rule out that diversion still affects our control group, we then chose a third different control group that is the farest away (in our database) of our treated group .

Valle de los Cirios We consider a control zone that is far from maritime lanes (see Map 9) and about 250 km from the nearest Mexican port of Ensenada, on the coast of the Valle de los Cirios, which is a wildlife protected area. Moreover this area is along the North Equatorial Current, which flows southwards along the Baja coast, and then potentially dispersed the hypothetical remaining diverted pollution away from our control group.

5.3 Results

Table (3) presents the results using the three different control groups presented previously, for the kelp canopy and biomass. Regardless of the empirical strategy used, we find a significant positive coefficient.

When comparing Ensenada and Baja California without it, we find that the coefficient is higher in the second case, which is contrary to what we expected from our discussion of Equation (3), at least concerning the external negative effect of the ECA on the control. Indeed, we anticipated a smaller coefficient without Ensenada due to a reduced contamination effect in that case. One explanation is that the violation of the parallel trend assumption goes in the opposite direction and dominate the contamination bias. A more optimistic view may be that the difference between the coefficients estimated are not significant. Finally, when considering the control group located near the coast of Valle de los Cirios, we observe an even stronger effect.

Overall, although the magnitude of these coefficients varies from one control group to another and does not lend itself to straightforward explanations - potentially due to various drawbacks such as lack of controls or an imperfect counterfactual - we can cautiously conclude that changes in vessel traffic due to the ECA, whether due to a slowdown at L.A. or to an increase along the Mexican coast, have an effect on the biomass and canopy of kelp.

Control variables exhibit the expected signs; for instance, higher temperatures have a detrimental effect on kelp biomass and canopy. Similarly, Sea Surface Weight, which serves as a proxy for storms and intense waves that cause physical damage to kelp, also has a negative effect. The fact that these controls are not always significant is likely due to the quarter fixed effects absorbing the impact of these variables when their variability is small.

Table 3: Impact of the ECA on Kelp canopy and Biomass

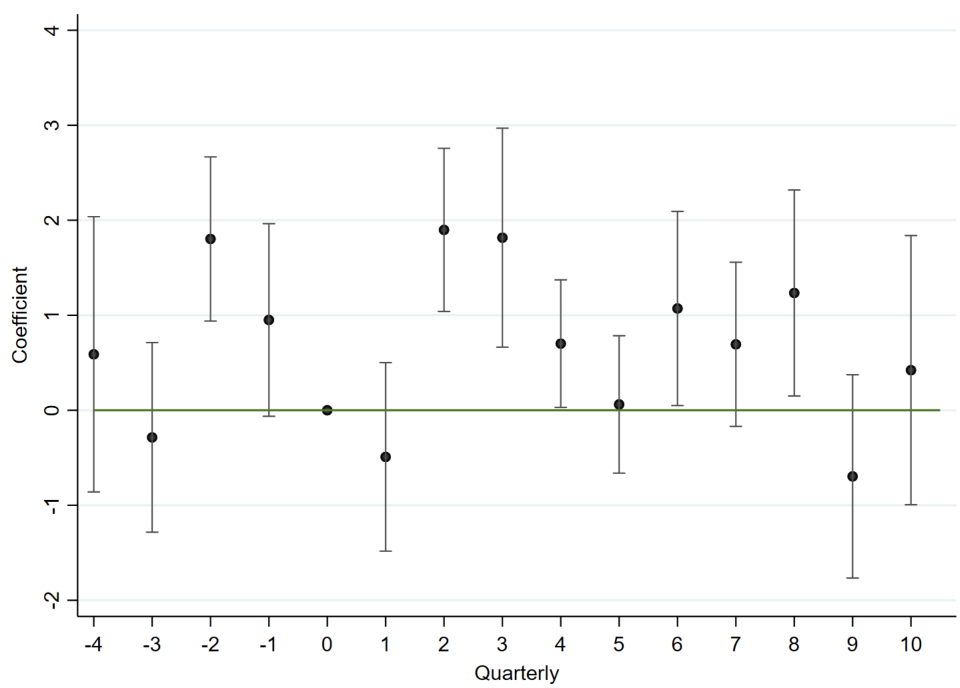
	Ensenada		Without Ensenada		V. de los Cirios	
	Biomass	Area	Biomass	Area	Biomass	Area
DID effect	0.517**	.525**	1.28***	1.29***	1.16***	1.17***
	(.245)	(0.248)	(0.33)	(0.33)	(0.505)	(.505)
Temperature	-6.10***	-5.89***	-1.95	-1.85***	-0.29	-0.18
	(1.41)	(1.41)	(1.36)	(1.38)	(1.68)	(1.68)
Sea S. Weight	-0.52	-.556	-0.18	-0.17	-2.03***	-2.04***
	(.368)	(.34)	(0.37)	(0.39)	(0.257)	(0.25)
Precipitation	.209**	0.21**	0.29*	0.28*	-0.27	-0.27
	(0.10)	(0.10)	(0.15)	(0.15)	(0.32)	(0.32)
Econ activity	6.90***	6.96***	7.36*	7.32*	2.48	2.46
	(2.21)	(2.20)	4.19	(4.12)	(0.32)	(2.62)
Observations	284.843	284.843	362.396	362.396	792.734	792.734
Pseudo R2	0.49	0.49	0.45	0.45	0.41	0.41

Notes: Superscript ***: p<0.01, **: p<0.05, *: p<0.1. This table presents the effect of the ECA (Emission Control Area) in California on kelp growth and canopy along the Californian coast near the Los Angeles ports, relative to kelp along three other coastal groups. The first control group, named Control Area, refers to kelp located along the Mexican coast between San Diego and 100 km south of Ensenada. This group is considered a suitable counterfactual for the Los Angeles ports due to the shipping traffic along this coast. The second control group, named Valle de los Cirios, is a more specific group located 200 km south of Ensenada and characterized as a protected area. The third group is based on the first group (Control Area) but without kelps around Ensenada city. The treated group consists of kelp forests around the Los Angeles ports. The dependent variable is kelp biomass, expressed in kg, and kelp area at the surface, expressed in m^2. The temperature variable is the mean sea surface temperature in cell j, collected from NOAA, expressed in logarithmic form. Sea surface velocity is the mean sea surface velocity in cell j, also expressed in logarithmic form. The precipitation variable is the sum of precipitation in cell j, expressed in logarithmic form on a monthly basis from NOAA. Due to the presence of zeros, the PPML (Poisson Pseudo-Maximum Likelihood) estimator is used. Quarter fixed effects and individual kelp fixed effect are selected. Standard errors are clustered at the 15 km x 15 km grid cell level.

Below, we present the dynamic effect of the ECA on kelp using our different control groups.

A concerning issue is displayed by the pre-trends of Figures (5.3), (5.3) and (5.3). Indeed, for some periods before the policy, we observe that treated and untreated kelps do not evolve in a similar way, specifically in quarter t-2 for Ensenada, in t-3 and t-4 for Baja California, and again in t-2 and t-1 for kelp along the coast of Valle de los Cirios. These figures thus confirm the potential violation of the parallel trend assumption and the bias of the estimated coefficient. In particular, the positive significant coefficients obtained in the pre-trends in Figure (5.3) and (5.3) may indicate that we overestimate the effect of the ECA. However, Figure (5.3), which displays no obvious tendency (being positively significant at t-4 but negatively significant at t-3 and unsignificant at t-2 and t-1), shows a similar positive effect in the post-period as other figures. This indicates that, despite the bias, the ECA has a significant effect. We perform other multiple robustness checks in Appendix E, with alternative specifications and control groups, and we consistently find a similar pattern.

Figure 10: Dynamic effect of the ECA (Ensenada)



While we find from Figure (5.3), (5.3) and (5.3) a positive significant effect of the ECA, we also observe some quarter with unsignificant coefficients. In particular despite the several control introduced and the temporal effect on quarter, we certainly do not control enough for the natural and seasonal variations. Indeed, the seasonal reduction of the kelp canopy is typically most noticeable towards the end of summer and into early fall due to warmer water temperatures (Cavanaugh et al., 2019). Furthermore, storms and strong wave action in late fall and winter can also physically remove kelp from the substrate, temporarily reducing the canopy (Reed et al., 2011). It is noteworthy that Quarter 5 (and 9), which corresponds to the period of October, November, and December, is consistently unsignificant in the three different analyses. This is reassuring since we indeed expect that the ECA has no effect against these climatic conditions, but obviously, further research is necessary to better control for these cyclical changes.

In brief, while acknowledging the real limitations of our study, we consider the positive impact of the ECA on kelp is not due exclusively to random noise and cyclical change or methodological flaws, but by the whole mechanism presented here, going to international trade to air and water pollution.

Figure 11: Dynamic effect of the ECA (Baja California)

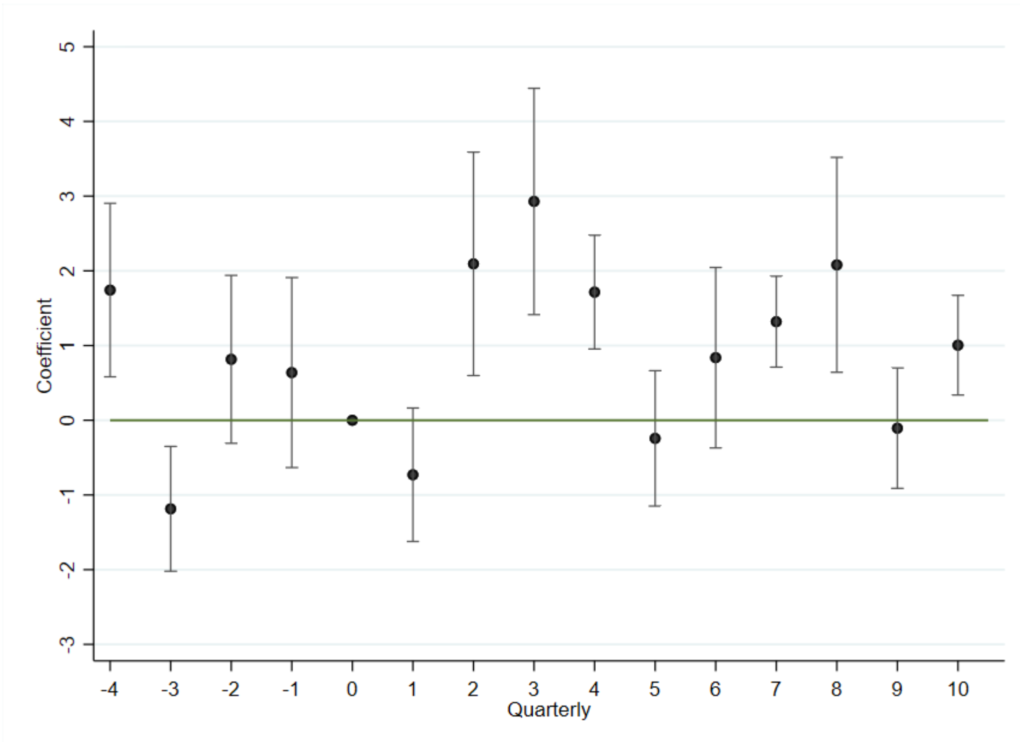
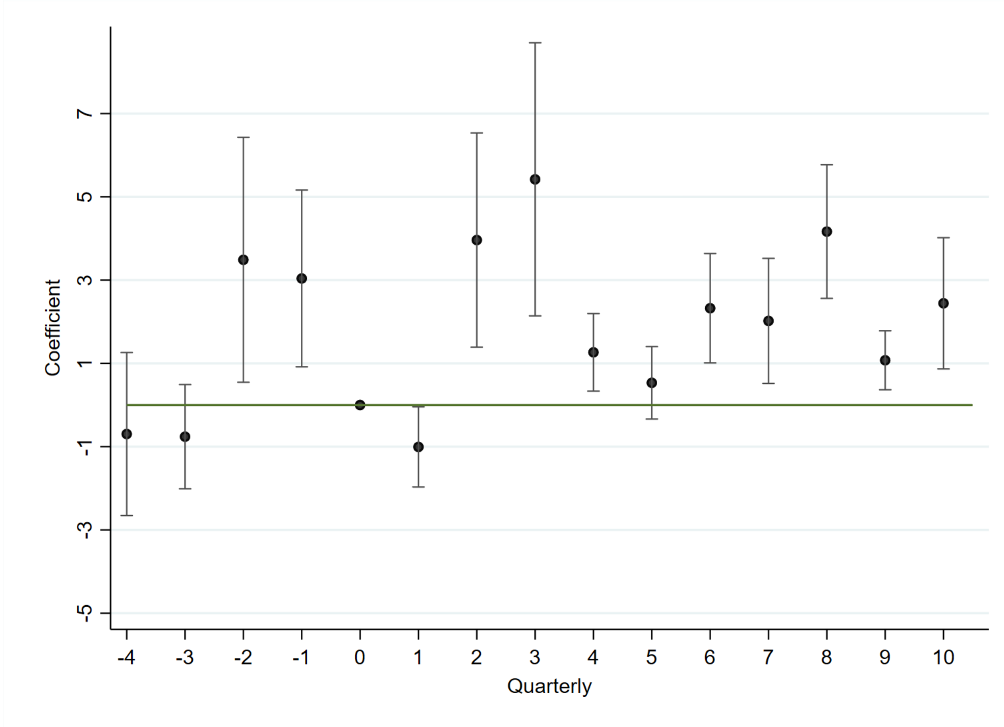


Figure 12: Dynamic effect of the ECA (Valle de los Cirios)



6 Conclusion

> The numbers of living creatures of all Orders whose existence intimately depends on kelp is wonderful ... I can only compare these great aquatic forests of the southern hemisphere with the terrestrial ones in the intertropical regions. Yet if in any country a forest was destroyed, I do not believe as many species of animals would perish as would here from the destruction of kelp. Darwin, 1839

The effects of Emission Control Areas (ECAs) have been demonstrated across a wide range of domains, ranging from reducing international trade and pollution to improving public health, particularly by impacting on infant mortality rates (Hansen-Lewis and Marcus, 2022, Klotz and Berazneva, 2022). In this article, we seize the opportunity presented by the implementation of the California ECA to investigate how decreased trade in this region has influenced the maritime ecosystem through its impact on air and water pollution.

Our study confirms that the California ECA has effectively reduced the region's trade volume. Moreover, we find that the ECA has played a significant role in reducing SO2 emission and water pollution and finally can have a role to restore the kelp canopy. This result is a rough approximation of the impact of maritime transport, and there are avenues for further research to better understand how maritime traffic affects marine life. Firstly, our analysis is limited regarding the spatial scale and thus regarding the external validy. Secondly, the internal validy is also challinging, since there are too few observations of the maritime life to improve the current analysis. More funds and research should be devoted to have a get a better understanding how the maritime ecosystems evolves and on a broader geographical scale.

Despite all these discrepancies, the overall consistency of the findings across the different variables used here strengthens the argument that ECAs can have an impact to protect the marine environment. This underscores the need for targeted legislation to preserve vital ecosystems. The importance of such measures is heightened by the fact that the 2012 North American ECA effectively neutralized California's "advantage" by making trade diversion to avoid this state's ECA unnecessary. As a result, it is plausible that the significant decline of Californian kelp forests between 2012 and 2019 was partially due to the return of pre-ECA maritime traffic levels. This hypothesis, however, remains to be thoroughly explored as well as the potential benefitial effect of the North American ECA. Our study represents merely an initial step in the broader investigation of how regulating maritime transport can shape life in oceans and seas.

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Appendix A : Ports, trade and kelps data

Table 4: Ports list by coast

Atlantic	Baltimore, Boston, Brunswick, Charleston, Chester, Fernandina, Jacksonville, Miami, New York, Newark, Newport, Norfolk-Newport, New Philadelphia, Port Everglades, Portsmouth, Richmond-Petersburg, Savannah, West Palm Beach, Wilmington (Delaware), Wilmington (NC)
Pacific	Blaine, Everett, Portland (Oregon), Seattle, Tacoma, Vancouver
US Gulf	Freeport, Galveston, Gulfport, Houston, Mobile, New Orleans, Panama City, Port Manatee, Tampa
California	Long Beach, Los Angeles, Oakland, Port Hueneme, Port San Luis, San Diego, San Francisco, San Pablo Bay

Table 5: Descriptive statistics : ports and trade

		Atlantic	California	Gulf coast	Pacific
Ports (n)		20	8	9	6
Total trade	Sum	1034663	388243	795288.2	85595.58
	Mean	862.219	808.8395	1472.756	237.7655
	Max	5040.177	5626.146	8343.297	1007.886
	Min	0.002377	0.002883	14.2906	0.002415
Container trade	Sum	273685.6	240558.7	61679.55	47270.01
	Mean	228.0713	501.164	114.2214	131.3056
	Max	1874.375	3297.804	780.946	630.8402
	Min	0.000044	.000582	5.438289	.000439
Nightlight	Sum	28636.45	9995.617	9807.896	4452.119
	Mean	23.86371	20.8242	18.16277	12.367
	Max	44.15893	35.08021	27.64756	16.62469
	Min	8.700286	3.536488	5.782262	8.845824

Notes: Total trade and container trade are expressed in thousand of tons.

Appendix B: Container

Table (6) reproduces Table (6) presented in the text by considering only trade in containers. Such an analysis is done as a robustness check and is interesting in the sense that total trade includes trade by bulkers, which concerns trade in agricultural goods, mineral and oil. This may be problematic for the parallel trend assumption, since Califirnia is an important agricultural producer while the Gulf Coast is the hub of oil and gas trade. Hence by analysing only trade by container, we have more similar flows. We find in Table (6) very similar results for containers than those presented in the text for total trade.

Table 6: Container Trade reduction

Treated	California		California without L.A.		Placebo: N. Pacific	
Control	Gulf	Atlantic	Gulf	Atlantic	Gulf	Atlantic
DiD effect	-0.155**	-0.248**	-0.179***	-0.279***	-0.138	-0.416
	(0.063)	(0.11)	(0.07)	(0.122)	(0.160)	(0.301)
Timetrend	0.128***	-2.33***	0.655***	-2.36	0.207	-0.569
	(0.821)	(2.038)	(0.097)	(2.058)	(0.153)	(0.907)
Night light	3.421*	-0.316	3.387*	-0.375	3.325***	0.749
	(1.66)	(3.355)	(1.677)	(3.39)	(0.69”)	(2.47)
Obs	1020	1680	960	1620	900	1560
LLikelihood	-7382.5	-2197.6	-690.5	-2147.5	-833.2	-2155
R-squared	0.970	0.9095	0.96	0.90	0.97	0.91

Notes: Standard errors are clusterized at the state level. ***<0.01, **: p<0.05, *: p<0.1. The dependent variable is the volume of trade between 2007-2012 on a monthly basis by container. All the regressions include quaterly-year effects, f_t and port fixed effects f_j.

Appendix C: Synthetic Difference in Difference

Figure (13) presents the weight of each area in the building of this synthetic California. Not surprisingly, the European zones, in particular the North Sea and the Mediterranean Sea have a smaller weight than their american counterparts (respectively 0.178 for the North Sea and 0.155 for Mediterranean Sea versus 0.204 for the Atlantic Coast and 0.258 for the Gulf Coast. The Baltic Sea with a weight at 0.201 has a similar importance than the Atlantic Coast).

Figure 13: California SDID weight

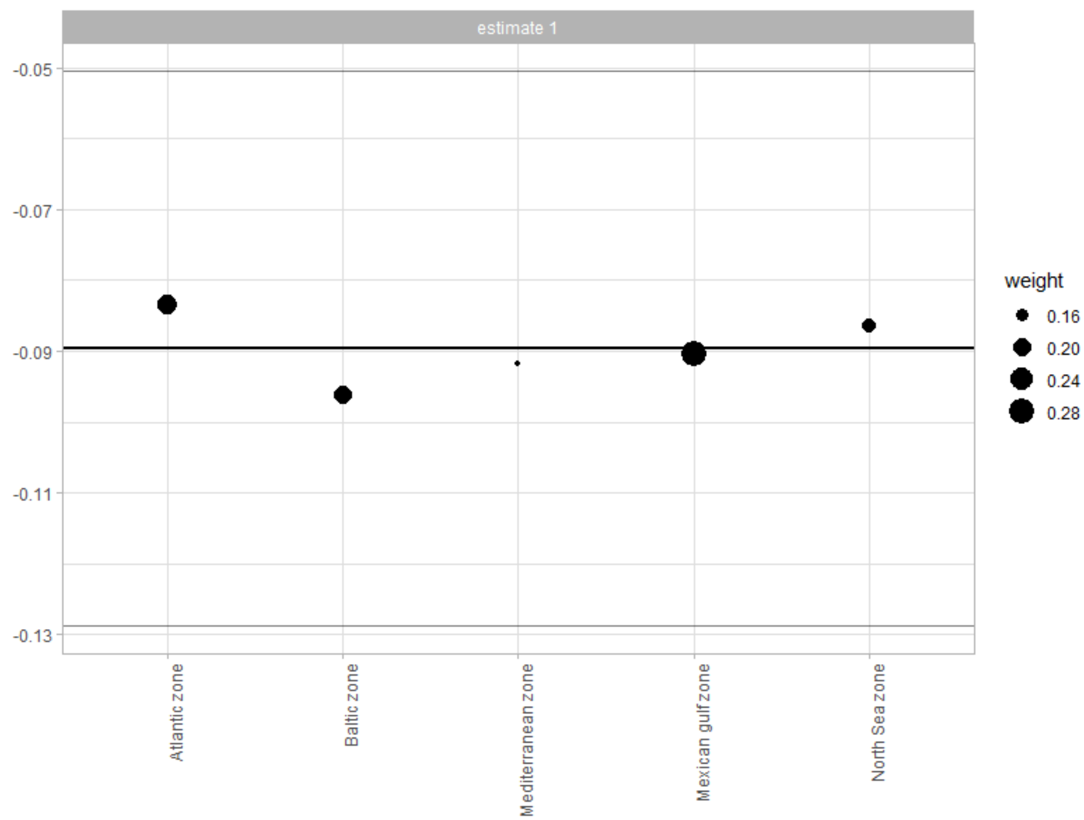


Table (7) present the SDID estimation, the ECA implementation in California has led to a decrease in trade of 7% which is smaller than the result obtained with the DiD but still significant at the 0.1 level. In contrast, when we consider regions where the ECA has not been implemented as treated (Columns 2, 3, and 4), we find no significant results. These placebo tests confirm what has been observed in the DiD analysis.

Table 7: SDID results

Treated	California	North Pacific	Atlantic coast	Gulf coast
SDID	-0.075*	0.007	-0.01	0.046
	(0.039)	(0.05)	(0.05)	(0.042)

Appendic D : Stylized facts on environmental variables

We report here the raw data for SO_2 in Figure (6), Chl-a in Figure (6) and water quality in Figure (6), for both the control and the treated groups which are represented by shaded dots of different colors. We also present the trends, without any controls, before and after the implementation of the ECA, to determine if simple statistics can capture the effects at play. We indeed observe an improvement in the concentration of Chl-a after the ECA in the treated group and a smaller decrease in the water quality index in the ECA than in the control group. It is also clear that the raw observations are highly cyclical, which is a particular challenge to analyze these changes over such a short period of time. Indeed, the fact that the Northern ECA was implemented in 2012 is a significant temporal constraint that imposes a limitation on analyzing the effects of the California ECA within a window of only three years (2019-2012), which limits the possibility of averaging the data to obtain smoother variations.

Figure 14: Change in SO_2

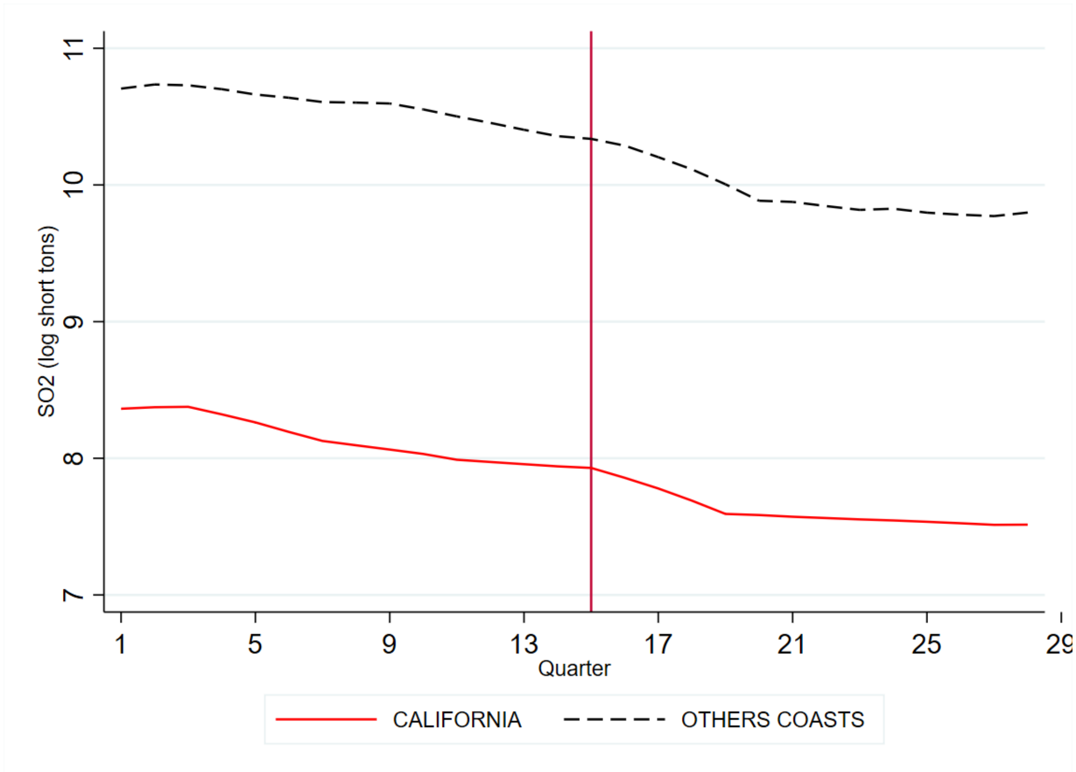


Figure 15: Change in Chl-a

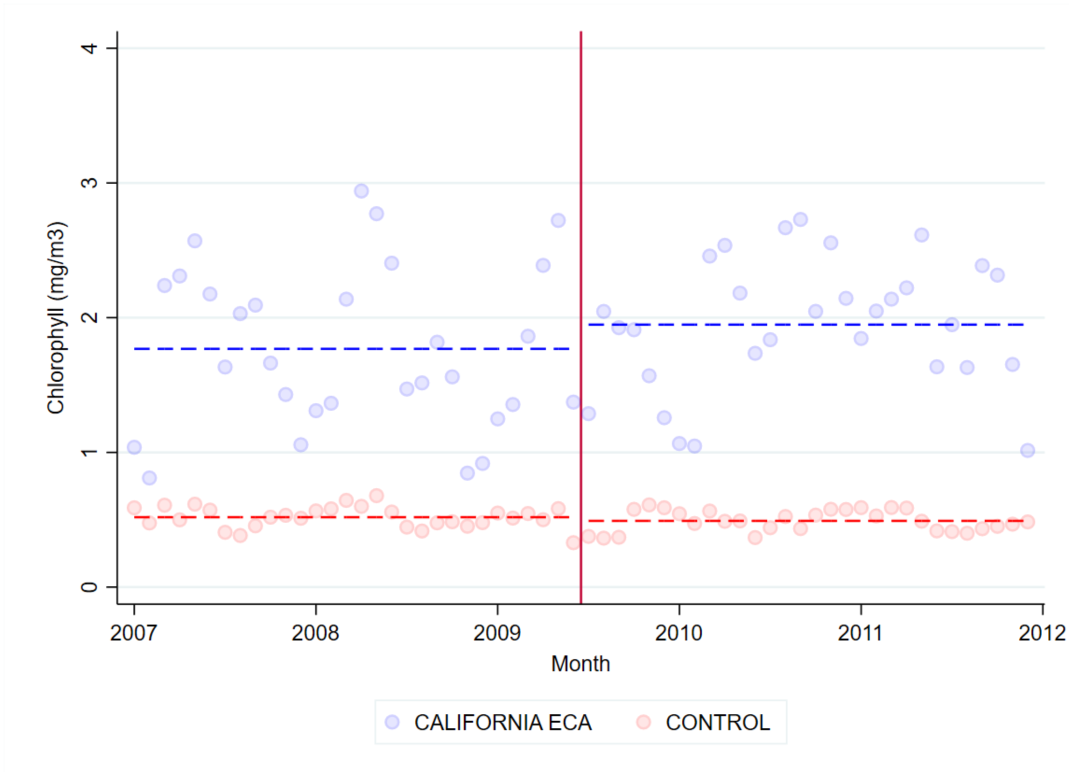
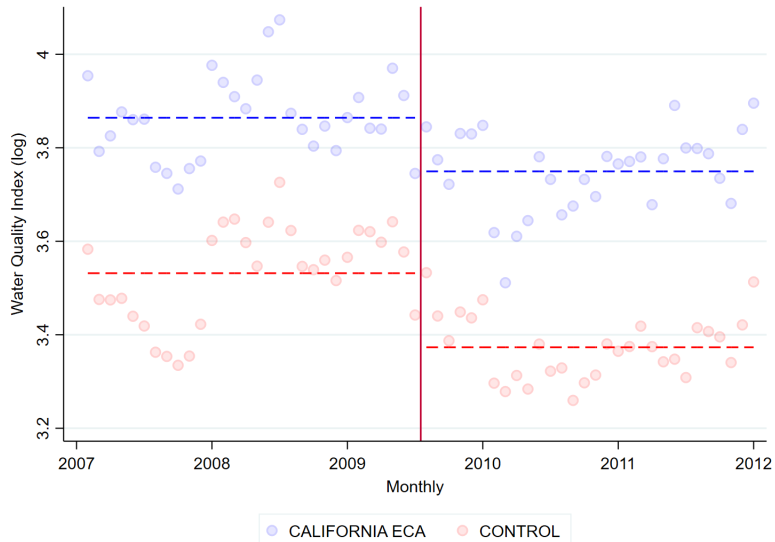
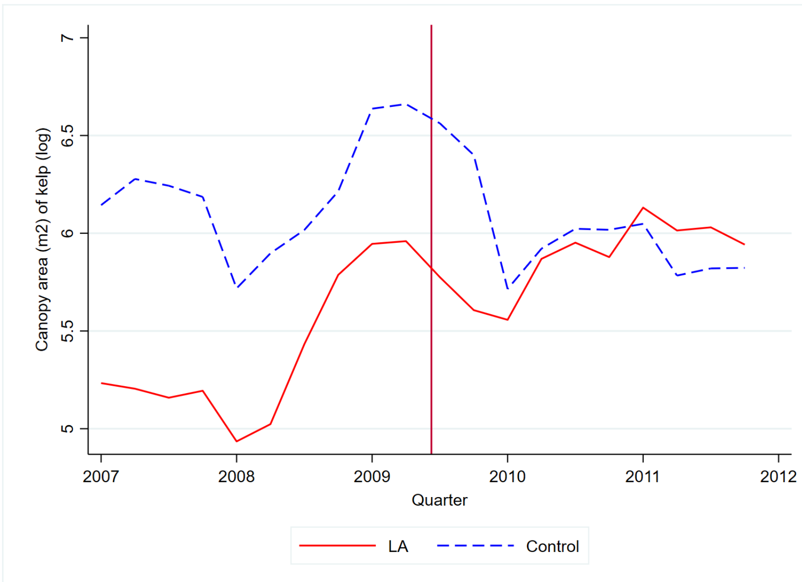


Figure 16: Change in the Water Quality Index



Appendic E: Kelps parallel trend

Figure 17: Change in Kelp biomass (Ensenada)



Appendix F: Other treated groups

In the text we have chosen to focus our attention on kelps that are near the L.A. maritime hub, since the effect of the ECA is certainly heterogenous inside the ECA. However, such a focus may raise questions about the generalization of our results. Then, we lead here some additionnal analysis by considering different other treated areas. To simply the analysis we use in this appendix only kelps that are on the coast of Valle de los Cirios as a control.

Firstly, we consider as treated kelps that grow near San Diego and Hueneme in the ECA. The relevance of these groups stems from their strategic locations along major maritime routes, implying that the treatment effect of the ECA may have been more pronounced in these regions compared to less trafficked areas within the ECA. For example, if a significant volume of trade has been rerouted to Mexico, then the kelp populations in these regions may have experienced a genuine improvement in their conditions. A limitation is that these areas have characteristics that diverge from the control group, which is not located near a port.

Secondly, we consider two other treated groups at the other extreme of the conditions of life in an human environment, that are kelp populations growing within protected areas. Like our control in the coast of the Valle de los Cicios (which is also a protected area) in Baja California, theses areas are not directly located on a maritime route.

In that case, these kelp populations may have gained from a traffic displacement attributed to the ECA. Indeed, while these kelp reside in a protected area, currents may still introduce pollution. Therefore, the avoidance of the ECA (see Klotz and Berazneva, 2022) may have been beneficial by moving the traffics further away. As a consequence of the ECA, the amount of pollution transported to these areas by currents may have been reduced.

More precisely, we have selected the Rocks and Islands Wilderness in Northern California, which in 2006 (a year before our analysis), has been incorporated into the National Wilderness Preservation System. Federal law prohibits motorized transport, including vessels, within areas designated as wilderness. The fact that this area is protected during all the period implies that Rocks and Islands Wilderness is less affected than other zones by anthropogenic factors. This makes it relatively straightforward to isolate the ECA's effect in this context. However, one potential issue with this group is that they do not belong to the same biogeographic regions as the other areas discussed thus far, including Baja California. Indeed, the region from north of San Francisco to Oregon not only hosts the Giant Kelp seen everywhere else, but also another type of kelp, the Bull Kelp (Nereocystis luetkeana). This variety may be more susceptible to warm water (Rogers-Bennett and Catton, 2019) and could benefit more in this area from the cold California Current. We however control for temperature and currents but certainly not perfectly.

Finally the last treated group considered, is kelp that grow in the Big Creek State Marine Reserve (SMR) and in Big Creek State Marine Conservation Area (SMCA) that are located on the offshore of Big Sur in the California's central coast. This area shares various characteristics with the control, it is not on a significant maritime route, benefit of relatively similar environment and has a canopy essentially composed of Giant Kelp .

As shown in Map (9) where treated areas are represented in green, we have taken zones that are relatively well/uniformy distributed along the coast. For each zone, we define a buffer of 30 km in proximity to the coast and within the ECA boundaries.

Results

Table (8) displays the results of the difference-in-differences analysis of the ECA's impact on kelp canopies, taking into account various treatment groups. The primary observation is that the ECA has consistently led to an expansion of the kelp area, regardless of the treated group considered. Firstly, as previously discussed, the results from Column 1 for Rocks and Islands Wilderness may overestimate the impact of the ECA in this area, due in part to both the chosen control and the treated group. Conversely, when considering the largest ports (Columns 4-5), the effect of the ECA is subject to two opposing biases, and we indeed observe a smaller coefficient for San diego and L.A.[24] compared to the Rocks and Islands Wilderness. It possible in particular that kelp in the control grow faster than the counterfactual of kelp in these ports if not treated, since damage on the canopy is relatively important there, than in our control group.

Finally, kelp in Big Creek (Column 2) may be the most appropriate for a DiD analysis since they share significant characteristics with the control (there are relatively isolated and grow in a similar biogeographic environment). The coefficient obtained indicates that, in comparison to kelp in Baja California, the ECA has fostered the growth of the canopy by 11,6%

[24]The pH indicator is dropped during the estimation, certainly due to not enought variation concerning this variable that is then colinear with fixed effects.

(exp(0.115)-1). The policy effect is stronger around areas with high ship traffic, such as Los Angeles or San Diego. As extensively discussed, we cannot interpret this coefficient as a clean elasticity of the ECA's impact within the ECA itself (ATT), indeed this coefficient is quite high and may includes the negative effect of trade diversion on the control. However, these results do highlight the significant influence of the ECA on the kelp canopy either on the treated and/or on the control.

Table 8: Impact of the ECA on the Canopy Area (m2) of Kelp

	Rock Islands	Big Creek	Huemene	San Diego	Los Angeles
DiD effect	0.277***	0.115***	0.155***	0.179***	1.05***
	(0.0809)	(0.0139)	(0.0176)	(0.0109)	(0.0156)
Temperature	8.811***	5.914***	8.939***	6.547	8.826***
	(0.146)	(0.154)	(0.136)	(0.113)	(0.134)
pH indicator	0.431***	0.275***	0.412***	0.0914***	0.370***
	(0.00365)	(0.00489)	(0.00339)	(0.00182)	(0.00350)
Current	0.10***	0.455***	-0.111***	1.078***	-0.359***
	(0.0184)	(0.0209)	(0.0181)	(0.0153)	(0.0186)
Obs	619966	652185	683652	1021165	737394
Log-Likelihood	-45122989.0	-49590441.2	-48507181.7	-68697508.1	-51318963.5
Pseudo R2	0.453	0.409	0.423	0.363	0.403

Notes: Standard errors are clusterized at the state level. ***: p<0.01, **: p<0.05, *: p<0.1. The dependent variable is the area of kelp in m^2. Each column presents a different treated group in the ECA area. For all groups, the control group is in Baja California, outside the ECA (see Map 2 to locate these treated and control groups).

The biomass, which is the total mass of living kelp within a given area, is another important indicator of the health and productivity of the kelp forest ecosystem. We thus estimate again our Equation (1) but this time by considering this indicator. Rocks and Islands Wilderness is not analyzed because we do not have the data on biomass for the kelp in this area.

Results are presented in Table (9), where we observe that kelp biomass has significantly increased in the treated group in comparison to the control group, due to the implementation of the ECA. Naturally, the same constraints outlined in the context of the previous table preclude a simplistic interpretation of these coefficients as causal elasticities.

The fact that a reduction of traffics helps to improve this biomass, is a good news and may indicate that the reduction of vessels passage contributes to reduce the nutrient overload from maritime activities (discharge of untreated sewage or ballast water). Indeed while nutrients are essential for kelp growth, excessive amounts cause harmful algal blooms. These algae can outcompete kelp for light, leading to reduced kelp growth rates and lower kelp biomass. Another chanel of diffusion of this effect may be that the diminution of vessels has reduced the chemical pollutants that inhibite photosynthesis and limit biomass growth.

Table 9: Impact of the ECA on the biomass of Kelp

	Big Creek	Huemene	San Diego	Los Angeles
Diff-in-diff effect	0.00991	0.118***	0.178***	1.041***
	(0.0144)	(0.0174)	(0.0109)	(0.0154)
Temperature	8.701***	6.392***	8.635***	0.328**
	(0.156)	(0.136)	(0.113)	(0.134)
pH indicator	0.259***	0.412***	0.0905***	0.370**
	(0.00532)	(0.00350)	(0.00182)	(0.00359)
Current	0.412***	-0.132***	1.072***	-0.385***
	(0.0205)	(0.0182)	(0.0150)	(0.0187)
Observations	652185	683652	1021165	737394
Log-Likelihood	-366031138.5	-355065193.6	-503116300.2	-376178680.1
Pseudo R2	0.416	0.426	0.365	0.406

Notes: Standard errors are clusterized at the state level. ***: p<0.01, **: p<0.05, *: p<0.1. The dependent variable is the biomass of kelp. Each column presents a different treated group in the ECA area. For all groups, the control group is in Baja California, outside the ECA (see Map 2 to locate these treated and control groups).