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

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Abstract

This article analyses how California's Ocean-Going Vessel Fuel Rule implemented in 2009 impacts trade and marine ecosystem. By studying the implementation of this policy, we measure not only the consequences for ports activites but also for one of the most important maritime ecosystem of the California Coast: the Kelp forests. Using Difference in Difference (DiD) approach at the Californian ports level, we find that this policy has led to an significant decrease of trade volume at this period. As a result, we find a positive and significant effect of the policy on 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. While the impact of air pollution has been extensively studied, the analysis of the effects of maritime transport on marine ecosystems remains nascent. This study contributes to the existing literature by examining how an environmental regulation (the Ocean-Going Vessel Fuel rule) that has altered maritime traffic in California, may has influenced one of most vital marine habitats there, the kelp forests.

Kelp are large brown algae that live in cool, relatively shallow waters close to the shore in several parts of the world.[1] They are important and complex biogenic habitats considered as a foundation species (Paine, 1969; Hale and Koprowski, 2018). The California canopy of kelp[2] functions as a nursery and provides food sources for a multitude of fish, marine mammals and invertebrates (Christie et al., 2009, Teagle et al., 2017).[3] Given their ecological importance and the ecosystem services provided, the conservation and sustainable management of these forests are essential for the overall health and resilience of the region's marine ecosystems. This preservation seems all the more pressing that the forest has been severely decimated over the past half-century (Krumhansl et al., 2016) and has encountered a dramatic decline since 2014 (Rogers-Bennett and Catton, 2019). The main culprits are prolonged warm-water conditions that

[1] 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.

[2] 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.

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

threaten kelp forest both directly and indirectly[4], as well as eutrophication (due to discharge of untreated sewage, agricultural fertilizers, etc.) that fosters the replacement of kelp by turf algae (known to cause "dead zones", see Filbee-Dexter and Wernberg, 2018).

In this study, we examine the California Ocean-Going Vessel Fuel Rule established in 2009, which delineated an Emission Control Area (ECA) to regulate ship fuels and exhaust gases with the aim of limiting NOx, SOx, and PM emissions. The law was enacted purely in response to air pollution concerns and was not influenced by considerations about the marine ecosystem. However, given its negative impact on maritime traffic, it may have inadvertently affected the kelp environment.

There are several reasons to consider that less boat traffic can have a positive effect on water quality and then on kelp forests. To name a few, less traffic reduces the amount of anti-fouling paint dispersed, the risk of fuel spills and the greywater and blackwater discharges. 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. While ballast water discharge are known to cause biodiversity disruption and are then regulated, the California State Lands Commission that manage these discharges still consider that stricter standards are necessary (Wang et al., 2020). Finally the sulfur dioxide emissions of vessels contribute to increase the acidity of seawater in particular in coastal waters which is detrimental to kelp forest located there (Doney et al., 2007).

However to date, it is unknown whether a reduction of maritime traffics can restore kelp forest by reducing the water pollution. Some research are worisome, such as Johansson et al., 2012 which alerts of the potential irreversible damage of the maritime pollution on kelp. However several research in biology note that kelp is one of the most resillient and fast

[4] During and after the heat wave of 2014 that hits California, sunflower stars that are an important urchin predator (which consumes kelp) have been decimated and are considered by Rogers-Bennett and Catton (2019) as functionally extinct in the region.

growing foundation species. Krumhansl et al., 2016 for instance describe the rapid recovery of kelp following catastrophic population losses due to frequent recruitment and fast individual growth rates.[5] 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 (2007Q1-2012Q1).

We use standard and synthetic Difference-in-Differences techniques (DiD), at the ports level to study imports, and at the kelp level, to analyse the impact on this maritime ecosystem. Data on the kelp canopy biomass are derived from the relationship between satellite detection, defined at a 30 x 30 meters resolution, and empirical measurements of kelp canopy and biomass (Bell et al., 2023). We use 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.

Regarding the effect of ECAs, our work builds on and contributes to several literatures. First, 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, 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. Our work complement this analysis,[6] by showing a reduction of trade in the ECA and by analyzing

[5] In optimal conditions, kelp can grow by 65 centimeters by day

[6] 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. In this study, we utilize data that is less precise - focusing on imports at the port - but that nonetheless offers a complementary perspective. Indeed, avoidance of the ECA does not necessarily indicate a reduction in goods being unloaded at ports. Ships can exploit opportunities for avoidance, such as entering or exiting the ECA via maritime routes where the ECA is narrowest, while still maintaining their exports to California's ports.

the consequences of the ECA on a different topic, the kelp canopy.

The reminding part of this article includes the following sections. In Section 2, the ECA is explained as well as the empirical strategy to estimate its effects and the data used. In Section 3 the trade reduction due to the California regulation is presented. In Section 4 we describe the result on the kelp. Finally, Section 5 concludes with some avenues for future research and the policy implications of our research.

2 Background, Data and the 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. In January 2014, California ECA is deepened by reducing the content of low sulfur fuels to 0.1% of SO_x.

Compliance with the law

To comply with the law, vessels do not have many solutions, while in Europe (in the Baltic Sea and North Sea) it is possible to invest in scrubbers that remove sulphur from the exhaust,[7] in North America vessels have to

[7]However even in Europe this technology seems to have not been massively adopted due to its cost (between 2 and 8 million of Euros per ship according to OECD, 2018) and moreover this increases the fuel consumption.

switch to low sulphur fuels (Klotz and Berazneva, 2022). The use of liquefied natural gas (LNG) is a possible way to comply but represents the most expensive solution and has not been adopted at that time (Carr and Corbett, 2015).

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.

2.2 Data and descriptive statistics

Trade at the ports level (monthly data)

To analyse trade at the ports level we rely on the U.S. Import and Export Merchandise trade statistics, compiled by the U.S. Census Bureau (Economic Indicators Division USA Trade Online). We use the volume of import in each port over the period 2007-2012 on a monthly basis. Eight ports are in the treated area, controls are ports of the Gulf Coast and of the U.S. Atlantic Coast (see appendix for details).

These data concern total goods but also trade in container. Focusing on contenainerized trade is particulary interesting for California which is the hub of a substantial containerized seaborne trade, and then this trade captures the majority of manufactured goods traded (Heiland et al., 2019). Total trade includes in addition agricultural goods that are traded by bulkers.

Local Economic Conditions of Trade

To study how the local economic conditions in the hinterland of each port 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. Department of Commerce (for employment).[8]

[8] More precisely the Quarterly Worforce Indicator

To approximate the supply capacity,[9] we use data on workers productivity by functional area from the OECD.

Finally, 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).

Kelp canopy and biomass

Data on kelp comes from Bell et al. (2023)[10] which provides an impressive amount of data on the growth and coverage of kelp forests on the Californian coast. The location 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.[11]

Temperature

Water temperature has a significant impact on kelp, especially warm water destroys the canopy. Hence, it matters to take into account temperature change for both treated and untreated groups to identify the effect of ECA. Data on temperature come from the National Oceanic and Atmospheric Administration (NOAA) Climate.gov website. Sea surface temperature

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

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

[11]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

are measured by satellites which analyze how much energy comes off the ocean at different wavelengths. These data are then merge with sea surface temperatures from ships and buoys. See Reynolds et al. (2007) for a full description. Here sea surface temperature is the average of a week taken in the middle of each month at the quarter level between 2004 and 2014. We also use data temperature anomaly that are usually taken to consider heatwave (Kennedy et al., 2019). These data comes from the Met Office Hadley Centre and are expressed relative to the 1961-1990 average. They are available on an equi-rectangular 5° latitude by 5° longitude monthly grid, we take the average at the qarter level over our period of analysis.

Ocean acidification

Ocean acidification, caused by the increased absorption of atmospheric carbon dioxide (CO2) by seawater, has an ambiguous effect of kelp which depends on various factors, including the specific kelp species, the environmental conditions, the broader ecosystem dynamics and cascading effects along the food chain up to fish and marine mammals (Terhaar et al., 2020). For instance, ocean acidification could negatively affect animals that eat kelp predators, resulting in a population increase of these predators and thus more pressure on kelp populations. To give a simplified example, many types of shellfish and starfish are negatively impacted by ocean acidification because it makes it more difficult for them to form their shells or to maintain their skeletal structure (for starfish). These shellfish are a significant food source for many animals, including sea otters. Sea otters are fundamental for kelp forest because they are a natural predator of sea urchins (as well as starfish, such as the famous Californian Sunfower star, now potentially extinct, see Rogers-Bennett and Catton, 2019). Because sea urchins are the major grazers of kelp, they can devastate kelp forests if their populations are unchecked.

We use the National Oceanic and Atmospheric Administration (NOAA) OceanSODA-ETHZ dataset (Gregor and Gruber, 2020). This dataset contains a global gridded dataset of the surface ocean carbonate system (the total scale for pH is used). This indicator pH acidity/alkalinity indicator is given on a monthly basis. We average it by semester and we consider the deviation in each pixel from the whole California coast in order to control for difference in environment. An increase in value corresponds to a relative decrease in pH (increase in alkalinity, not acidity in fact). In the absence of georeferenced data for some kelps, the closest value (in term of distance) is assigned.

Wave and Current Intensity

Wave and current intensity can have very different effect on the growth of kelp. On the one hand, moderate wave and water currents disperses kelp spores, and are thus essential to the expansion of the canopy. They also bring up nutrients from the deeper waters and finally by removing sediment and epiphytes from the kelp blades, they favor the photosynthesis. However, on the other end, strong intense wave and currents cause physical damage to the kelp, breaking off fronds or dislodging whole plants from the substrate, leading to a reduction in biomass. Dayton et al. (1992) for instance document how entire kelp forests can be dislodged from the reef during a single large storm, while the recovery of the canopy occur within a few months under good conditions.

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).[12] Appendix A shows an example of these data.

2.3 Empirical strategy

The standard difference-in-differences model with two time periods fits our research question. The number of ports, and even more the number of

[12] 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.

kelps concerned by the ECA, as well as the timing of the implementation of the ECA (trade data are available on a quarterly basis) invite us to use a standard DID. 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 two differents variables, in Section 3 we consider the importation in the port j in volume, at time t (defined by month-year), while Section 4 analyzes the kelp canopies (in m²) and biomass (in kg) in j on a quarter dimension t.

$Area_j$ takes one when a port (in Section 3) or a kelp area (in Section 4) is affected by the ECA and zero otherwise. The ECA_t is a dummy that takes one after the implementation of an ECA and zero before.

To interpret the result of our analysis as causal, 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 month (for trade) or quarter (for kelps) fixed effects f_t, individual fixed effects f_j and location-time varying characteristics Z_{jy} described in the data section.

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 kelp forest in Section 4.

Due to the presence of zero in the data, we use the Poisson Pseudo-Maximum Likelihood (PPML) estimator which is widely used in trade analysis (e.g., Santos Silva and Tenreyro, 2006). The analysis of kelp also employs the PPML estimator to account for areas (pixels) where there is no kelp during all the period or where kelp have disappeared.

Because it is likely that two ports i and j in the same state are exposed to the same economical environment and law, or simply have similar background characteristics for historical or geographical reasons, we cluster the standard errors at the States level to take into account these intra-group correlation (we also use cluster at the port level and obtained the similar results, but due to the limited number of treated ports, a cluster at the state level might be more relevant, see Abadie et al., 2022 for a discussion). Concerning the analysis of kelp, we clusterize at the level of kelp.

Finally, we also pursue a different approach by using the Synthetic Difference-in-Differences estimation of 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.

3 Trade redux

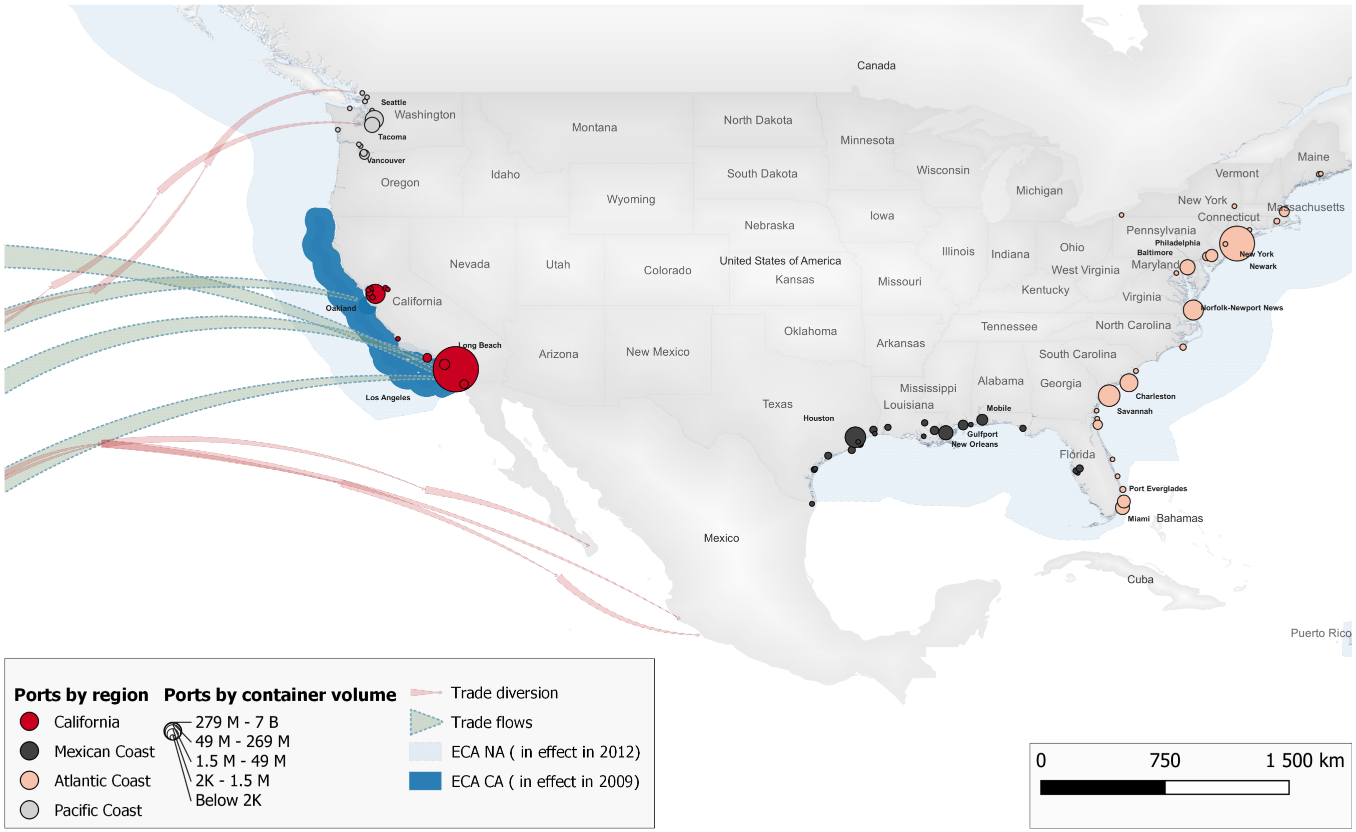
3.1 Treatment and control groups

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.

3.2 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.

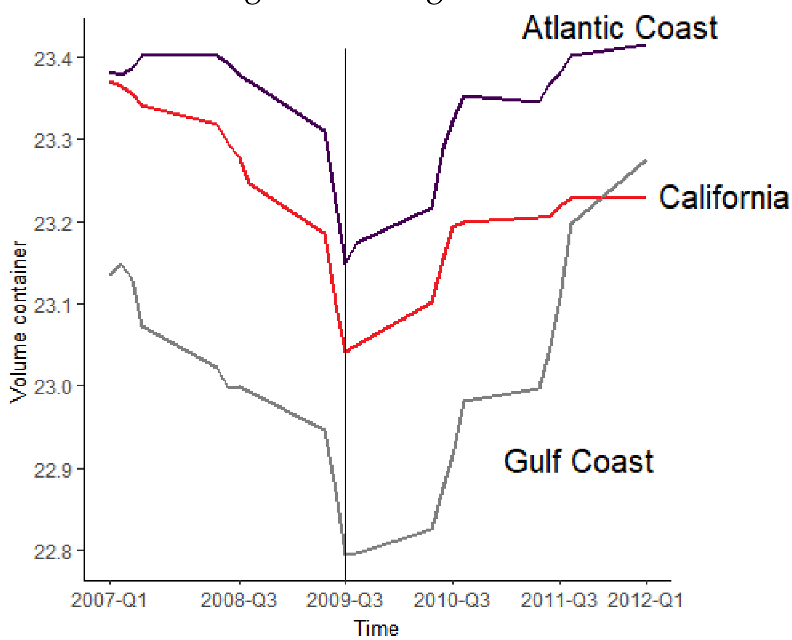
Lastly, to explain that the ECA implemented in 2009 has an effect in the year that follows (and not immediatly), we have to keep in mind precisely that the traffics was in a period of recovery at that time. This indeed implies that the entry of vessels has been progressive, then the choice to comply 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).

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

3.3 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 verify that the very high volume of imports in this port does not biaised

[14]see Appendix B for similar results concerning containers

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 3.1, 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, implying that the ECA has led to a decrease in imports going from 16 % ($\mid e^{-0.18} - 1 \mid = 0.16$) to 20% on average.

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

Table 1: Trade reduction

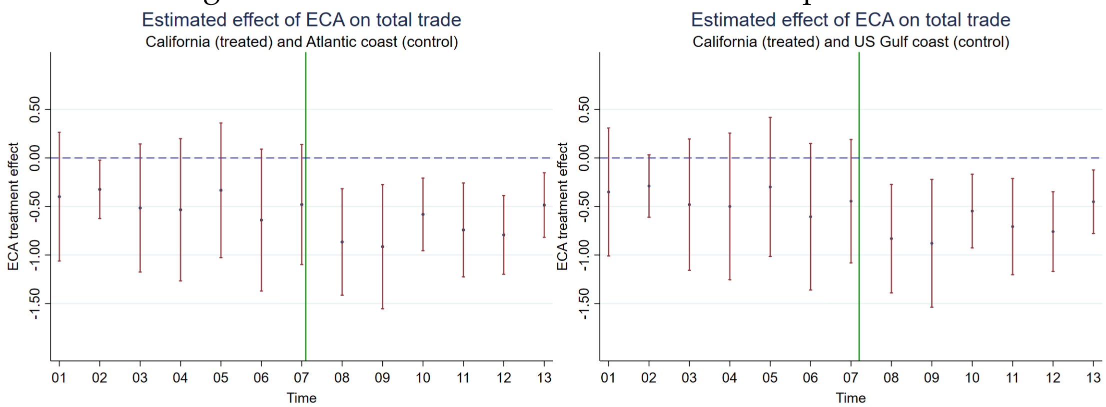
Treated	California		Without L.A.		Placebo: N. Pacific	
Control	Gulf	Atlantic	Gulf	Atlantic	Gulf	Atlantic
DiD effect	-0.188***	-0.233**	-0.203***	-0.253***	-0.278	-0.382
	(0.0737)	(0.0948)	(0.084)	(0.106)	(0.215)	(0.259)
Timetrend	-0.199	-1.641	0.505***	-1.669	0.282***	-0.145
	(0.733)	(1.296)	(0.087)	(1.308)	(0.0845)	(0.521)
Night light	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: Standard errors are clusterized at the state level. Upper-script ***: p<0.01, **: p<0.05, *: p<0.1. The dependent variable is the volume of trade between 2007-2012 on a monthly basis. All the regressions include quaterly-year effects, f_t and port fixed effects f_j.

Column 5 and 6 provide the same estimation but now consider as treated other ports of the Pacific Coast, which 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 Figure (3) the dynamic effects of this policy year after year.

Figure 3: Difference in Difference coefficient plot



Obviously, 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).

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

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

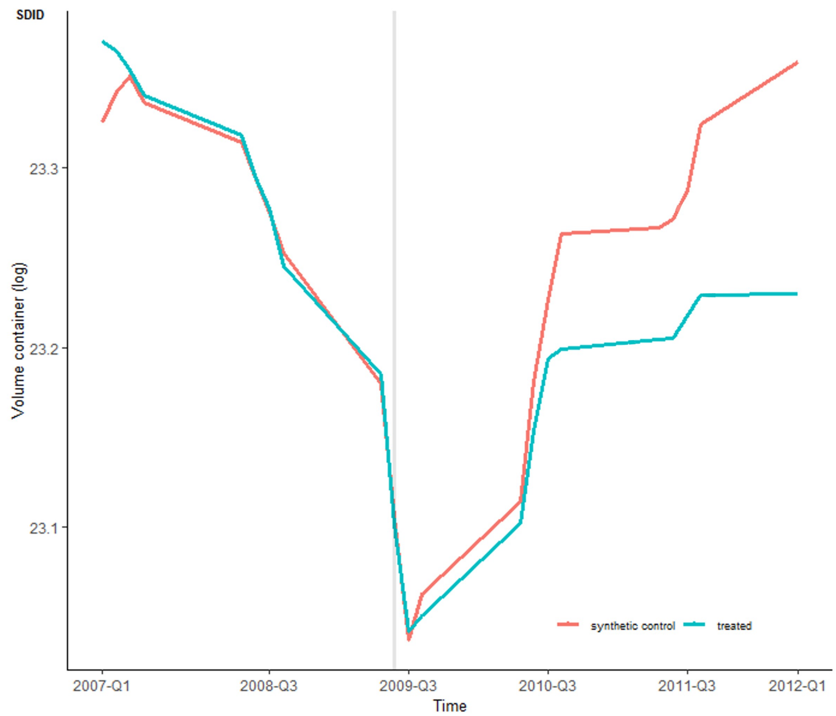
[15] In particular, the drawback of night light pictures are well known, they poorly detect low density areas and are not enough acurate for developed countries (see Gibson et al., 2021).

building of this synthetic California.

Figure (4) presents 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 most evident 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 4: SDID on Trade



4 Effect on the kelp forests

To analyze the effect of the ECA on the kelp forests, we follow the same empirical strategy than in the previous section 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.

4.1 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 have not opted to be affected by an ECA by considering 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.

4.1.1 Control group

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 one area in the South (see Map 4.1.2), on the Baja California peninsula in Mexico. 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 Baja California. On the other hand, the condition of externality might be compromised for this group that is located both near the Californian ports and on the Mexican coast. However, we have chosen a zone that is relatively far from maritime lanes (see Map 4.1.2) and about 250 km from the nearest Mexican port (Ensenada), on the coast of the Valle de los Cirios, which is a wildlife protected area. One could further contend that even if the ECA has resulted in a trade diversion towards Ensenada, and even if this pollution has detrimental effects over such a long distance, the North Equatorial Current, which flows southwards along the Baja coast, may have dispersed the pollution changes away from our control group.

Still, given the absence of comprehensive studies that accurately quantify water pollution from vessels and its dispersal, it remains plausible that the kelp in this area have been impacted by a shift in the trade route due the ECA. Ensenada, even if located at a relatively far distance, is the second busiest port in the country after Veracruz on the Gulf of Mexico and the only deep-water port in the state of Baja California, so a trade diversion there is plausible and a contamination of our control also. We should then consider the implication of this external effect. If this area experience negative effects (due to the dispersed pollution of an influx of vessels circumventing Californian ports and rerouting towards Mexico), the derived results would amalgamate the positive influence of the ECA on the treated areas with the negative repercussions on the kelp in Baja California. Put differently, the impact of the ECA on California's kelp population is not properly identified and and may well be overstated *for* the treated groups (but not for treated *and* control groups). This estimation remains of interest, as it underscores the detrimental effects of maritime transport on kelp, not confined solely to the ECA-designated area but extended to Baja California. 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 is only affected by the externality (e.g. no anticipation) we have: $E[Y^0(1,1)] - E[Y^0(1,0)] = E[Y^0(0,1)] - E[Y^0(0,0)]$. This gives:

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

where ATT is the Average Treatment on the Treated. In conclusion we overestimate the effect of the ECA on the treated due to the addition of $E[p]$, but we rightly estimate the global effect of the ECA on the treated and control which is what matter from an ecological point of view.

4.1.2 Treated Groups

Kelp that grow along the California coast do not benefit of exactly the same conditions and more importantly, the treatment can have a different effects depending of their locations. Indeed kelp located on maritime routes may be much more affected by the ECA in comparison to kelp that are in area relatively isolated. This implies that we cannot pull all these observation in the sample and directly compare them with the control without introducing the so called heterogeneous treatment effect bias. The simplest way to deal with this is to understand the distribution of the treatment effects by analyzing separately the different treated groups. We have then chosen several distinct groups along the California coast within the ECA. As shown in Map (5) where these 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.

Firstly, we have considered kelp that grow near Los Angeles-Long Beach, San Diego and Hueneme. 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 in Baja California, which is not located near a port. Therefore, if kelp in Baja California grow at a faster rate than the unobserved counterfactual of ECA's ports if untreated, the effect of the ECA could be underestimated.

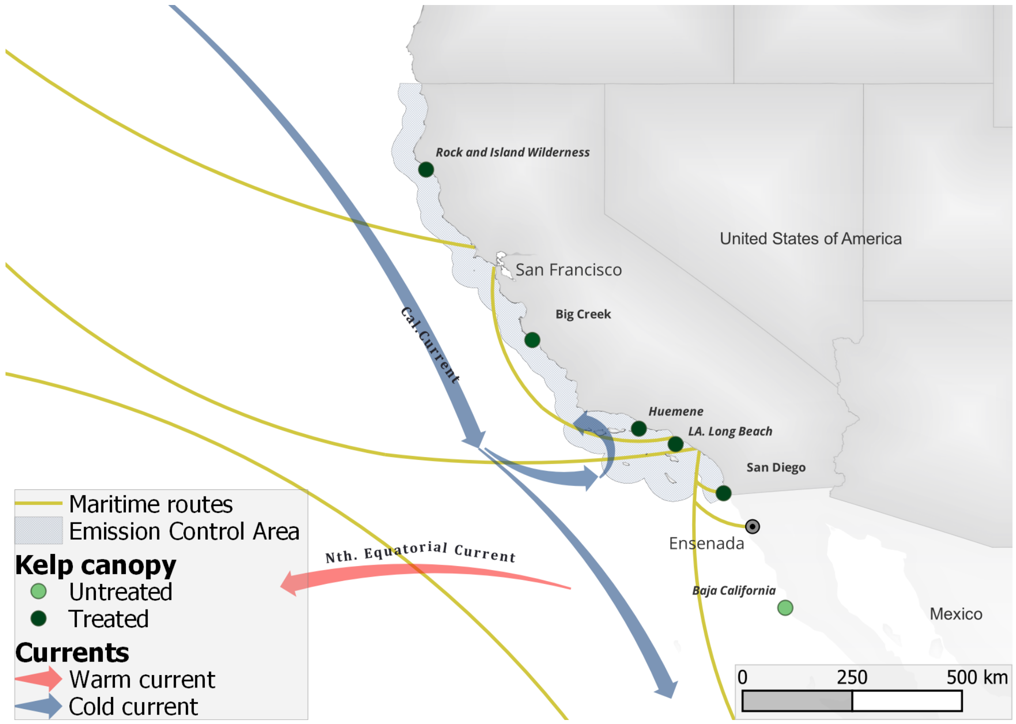
Secondly, we consider two other treated groups at the other extreme of the conditions of life in an human environment, that are kelp populations growing within protected areas. Like our control in the *Valle de los Cicios* (which is also a protected area) in Baja California, theses areas are not directly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

Figure 5: Kelp in California and beyond



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 SOx 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.

4.2 Results

Table (2) 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.[16] 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 25% (exp(0.23)-1). 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.

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

Table 2: Impact of the ECA on the Canopy Area (m2) of Kelp

	Rock Islands	Big Creek	Huemene	San Diego	Los Angeles
DiD effect	0.504***	0.232***	0.365***	0.215***	0.155***
	(0.0812)	(0.0147)	(0.0180)	(0.0109)	(0.0106)
Temperature	3.863***	0.721***	3.810***	-0.0277	-0.967***
	(0.137)	(0.143)	(0.125)	(0.109)	(0.111)
pH indicator	0.649***	0.444***	0.605***	0.146***	.
	(0.00371)	(0.00578)	(0.00365)	(0.00228)	.
Current	-0.140***	0.415***	-0.368***	1.868***	1.501***
	(0.0251)	(0.0264)	(0.0239)	(0.0188)	(0.019)
Obs	619966	652185	683652	737394	1025923
LLikelihood	-42377201	-47276078	-45758644	-67025255	-67495052
Pseudo R2	0.453	0.436	0.456	0.381	0.376

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 m². 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 (3), 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 3: Impact of the ECA on the biomass of Kelp

	Big Creek	Huemene	San Diego	Los Angeles
Diff-in-diff effect	0.118***	0.381***	0.213***	0.154***
	(0.0154)	(0.0178)	(0.0109)	(0.00718)
Temperature	0.328**	3.566***	-0.255**	-1.190***
	(0.145)	(0.126)	(0.110)	(0.0993)
pH indicator	0.419***	0.603***	0.144***	.
	(0.00645)	(0.00373)	0.00227)	.
Current	0.347***	-0.375***	1.873***	1.505***
	(0.0258)	(0.0239)	(0.0186)	(0.0233)
Observations	652185	683652	737394	1025923
Log-Likelihood	-349111391	-334396358	-490258814	493716190
Pseudo R2	0.443	0.460	0.383	0.379

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).

5 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 de-

struction 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 kelp forests. The significance of kelp forests as abundant sources of life has been recognized since at least Darwin (1839); however, the extent of human activity's influence on this critical ecosystem remains understudied.

Our study confirms that the California ECA has effectively reduced the region's trade volume. Moreover, we discovered that the ECA has played a significant role in the restoration of kelp canopies. 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 indirect. We use the exogeneity of the ECA with respect to kelp to study its effects, but we do not directly test the impact of traffic. Secondly, our analysis provides a point estimate that ignores all the nonlinear effects of the regulation on kelp. We do not investigate, for instance, whether kelp growth was immediate after the implementation of the law or took time, whether it was a temporary and fragile restoration or a more robust one. Answering these questions is crucial for determining policies that promote the resilience of ecosystems.

While the ECA was not originally designed to protect marine life, our findings reveal that it has made a substantial, positive impact on kelp. This underscores the need for targeted legislation to preserve these 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.

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: SDID

Figure (6) 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 6: California SDID weight

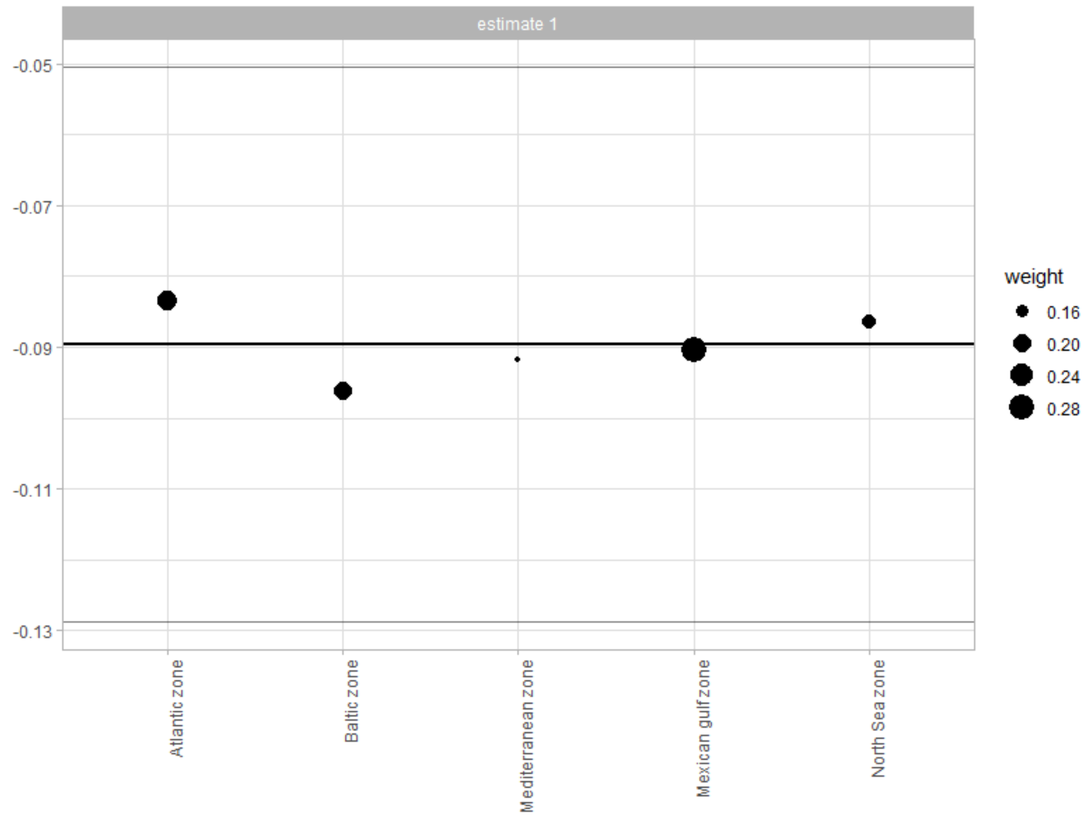


Table (7) present the SDID estimation, the ECA implementation in California has led to a decrease in trade of 7% which is smaller than the result obtained with the DiD but still significant at the 0.1 level. In contrast, when we consider regions where the ECA has not been implemented as treated (Columns 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)

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