How a Sustainable Maritime Traffic Can Shape the California's Kelp Forests

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Abstract

This article analyzes how the change in Californian maritime traffic in the ECA, after the trade collapse of 2008-2009, has affected one of the coast's most important marine ecosystems, the kelp forests. Using satellite data to locate kelp, tracking vessels using AIS signals, and using a difference-in-difference approach, we analyze how the canopy has evolved. We find that a reduction of maritime traffic and the enforcement of an Emission Control Area (ECA) are positively correlated to kelp forests, and may cause, an increase in kelp canopy and biomass growth. JEL: F18, R40, Q57

1 Introduction

Pollution is the bane of maritime transports, ships leaving both water and air pollution in their wake. Although the impact of air pollution has been extensively studied, analysis of the effects of maritime transport on marine ecosystems remains in comparison underdeveloped. We propose a new contribution in that vein that analyzes one of the Californian's most important marine habitats, the kelp forests.

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Kelp are large brown algae that live in cool, relatively shallow waters close to the shore in several parts of the world. They are important and complex biogenic habitats considered as a foundation species (Paine, 1969; Hale and Koprowski, 2018). The kelp canopy functions as a nursery and provides food sources for a multitude of fish, marine mammals, and invertebrates (Christie et al., 2009). Given their ecological importance and the ecosystem services provided, the conservation and sustainable management of these forests are essential for the general health and resilience of marine ecosystems. Taking an anthropocentrist measure of the value of kelp (which gives only a tiny fraction of the real value of these ecosystems),[1] these forests generate between \$465 and \$562 billion/year worldwide, due to their benefit on fisheries production (\$29,900,904 Kg/Ha/year) and nitrogen removal (\$73,800, 657 Kg N/Ha/year). These forests also act as crucial carbon sinks, absorbing and sequestering atmospheric CO2 (4.91 megatons per year).[2]

By studying the effect of the Ocean-Going Vessel Fuel Rule that set up an Emission Control Area (ECA) in California, at the height of the international collapse, our analysis goes to the heart of the issues at stake in the green transition of the blue economy. It enables to think about the impact of a maritime regulation during a period of trade recovery in one of the richest regions in the world. It also enables to study the restoration of marine forests. Indeed, kelp are one of the fastest growing foundation species (6 centimeters a day in optimal conditions),[3] and then provide an interesting case study to analyze natural restoration in oceans over a short period of time. Our contribution is twofold.

First, we exploit the timing of the trade crisis and the spatial delimitation of the ECA to define the canopy treated by this maritime regulation. To track change in the kelp forests we use satellite detection from Bell et al. (2023), which provides high spatial resolution data of the floating kelp canopy, in a quarterly time series, along the Pacific Coast from Oregon to Baja California (Mexico). These data, coming from the Landsat satellite program, provide imagery with continuous global coverage at a 30 meter resolution. The panel structure of our data allows us to capture all time-invariant characteristics of the kelp canopy over our short period of analysis. We also control for all available time-varying potential confounding fac-

[1] Assessing the value of ecosystems solely in terms of their impact on human life is ethically and philosophically dubious. Kelps, as all nonhuman organisms, have an intrinsic value. If we were only able to evaluate the value of kelp from the "point of view" of all living organisms that live there, we will start to approach a measure that makes sense. Philosophers and experts in welfare economics have begun to discuss these important and difficult questions (see Nussbaum, 2018; Fleurbaey and Leppanen, 2021).

[2] All these estimations comes from Eger et al. (2023).

[3] See Carr and Reed (2019) and Krumhansl et al., 2016 that describe the rapid recovery of kelp after catastrophic population losses due to frequent recruitment and fast individual growth rates.

tors, including temperatures, ocean currents, and economic activity at the coast. We find a significant relative restoration of the kelp forest in several different locations along the Californian coast (San Diego, Los Angeles and Long Beach, in Huemene, in the Rocks and Islands Wilderness, in Big Creek State Marine Reserve).

Second, we focus on the period of trade recovery (2009–2014) to analyze the effect of vessel traffic on kelp ecosystems. To conduct this analysis, we combine data on ship movements with satellite measurements of kelp canopy. We construct a detailed exposure indicator that accounts for both the number and the length of vessel passages in proximity to coastal kelp forests. Following the implementation of the first Emission Control Area (ECA) zone in 2009, we observe an initial adaptation in shipping behavior, with many vessels altering their routes to avoid the regulated zone. After the ECA was expanded in 2011, ships stopped avoiding the 2009 zone and started passing through it again. We exploit these successive changes in route patterns as a quasi-natural experiment to isolate the direct impact of vessel traffic on nearby kelp forests. Our findings reveal that in areas where ships return after 2011, both kelp canopy cover and biomass decline, suggesting a tangible ecological cost associated with increased marine traffic near coastal habitats.

Our analysis contributes to three different literature. First, the consequence of international trade on the environment has attracted much work, particularly on its negative effect on terrestrial forests (Berman et al., 2023; Abman and Lundberg, 2020; Carreira et al., 2024 and Nedoncelle et al., 2024). Surprisingly, however, its effect on underwater forests has never been addressed.

Second, the polluting impact of vessels on kelp is often carried out in the laboratory or at a specific site (Johansson et al., 2012)[4] but to our knowledge these analyzes are never related to maritime regulation and are analyzed as we do here.

Third, the effect of ECAs on human health has been analyzed in important articles (e.g. Klotz and Berazneva, 2022, Hansen-Lewis and Marcus, 2022) but their effect on the maritime environment is to date unknown.

The remainder of this article includes the following sections. In Section 2, the economic and environmental background is presented. Section 3 presents the data and the empirical strategy. Section 4 shows the results of this investigation. In Section 5, we study the movement of vessels to directly analyze their impact on kelp. Finally, Section 6 concludes with some avenues for future research and the policy implications of our research.

[4]We survey this literature in the next section.

2 Background

The coasts of California (US) and Baja California (MEX) are inhabited by two dominant kelp species, bull kelp (*Nereocystis luetkeana*) and giant kelp (*Macrocystis pyrifera*). Bull kelp are located mainly from Alaska to northern California, while giant kelp formed the majority of the canopy in central, southern California, and the Baja California Peninsula (MEX). We focus our analysis on these two types of kelp that are detected by satellites because they emerge at the surface (or nearly). Indeed, kelp can grow up to 150 feet (about 45 meters), forming dense underwater forests along the coast. These rich habitats offer shelter for invertebrates, feeding grounds for fish, and nursery areas for many juvenile marine species. Larger animals, such as sea otters and seals, also rely on them for both food and protection. Kelp forests are vital hotspots of biodiversity, playing a key role in sustaining coastal ecosystems. However, the canopy and the subcanopy are formed by other kelp that can also be affected by the maritime traffic that we document here.[5]

In this section, we present how kelp are affected by climatic conditions and human activities, in particular by maritime transportation. We then discuss how international trade has evolved during our analysis period.

2.1 Climatic conditions

Kelp forests are influenced by cooling water periods due to La Niña and to the North Pacific Gyre Oscillation, which sets the pace of ocean climate by fluctuations in sea surface temperatures, salinity and nutrient availability over a cycle of four to ten years (Castorani et al., 2022). The canopy is sensitive to warm water events and has been regularly decimated due to El Niño events during the period 1987-1988 and 1997-1998, and by the 2014-2016 heatwave (see Bell et al., 2023, Krumhansl et al., 2016). The preservation of kelp seems to be even more pressing as the forest has faced a dramatic decline since 2014 (Rogers-Bennett and Catton, 2019). The main culprits after 2014 are prolonged warm water conditions that threaten the kelp forest both directly and indirectly[6]

[5] Such elk kelp (*Pelagophycus porra*), the feather boa kelp (*Egregia menziesii*) and the dragon kelp (*Eualaria fistulosa* in Alaska). Several other kelp species form a subsurface canopy, such as the sea palm (*Pterygophora californica*) and the southern stiff-blade kelp (*Laminaria setchelli*). See Carr and Reed (2019) which provides an interesting map of the composition of these forests.

[6] To give an example of an indirect cascading effect, during and after the heat wave of 2014 that hits California, the iconic Californian sunflower stars that are an important urchin predator have been decimated and are considered by Rogers-Bennett and Catton (2019) as functionally extinct in the region.

2.2 Invasive species

Beyond these climatic conditions, international trade may have affected the canopy of kelp through several channels, such as by bringing invasive species detrimental to kelp.

Maritime traffic regularly brought many invasive species in California on the hull of vessels and in their ballast water,[7] and their impacts on kelp are unclear to date. For example Ambrose and Nelson (1982) and Britton-Simmons (2004) that have analyzed eradication of the brown seaweed *S. Muticum* (established from Asia in California in the 1970s), have observed an increase in the growth and density of native kelps (*Macrocystis* and *Laminaria*). However, more recent studies do not find an impact (Smith, 2015). Similarly, the effect of the *Undaria pinnatifida* (henceforth referred to as Undaria) which is a kelp from northeast Asia, established in California in the 2000s, and classified as one the ”100 of the world's worst invasive alien species” (in the UCN's list) is not fully understood (see McHaskell (2024)). This invasion may have an effect on the native sub-canopy (e.g. on *Pyrifera* and *Pterygophora californica*) but not on the kelp studied here that are not located in the same areas.

Maritime traffic also brings in ballast water grazers that, if too numerous, can harm the canopy, such as sea urchin larvae. However, ballast water also contains pathogens detrimental to these species. For example, the 1983–1984 mass mortality of sea urchins in the Caribbean appears to have been caused by this ballast water exchange (Phinney et al., 2001).

Furthermore, several laws have been implemented to reduce these invasion, however, almost at the end of our period of analysis. Indeed, the real fight against invasive species started in 2012 with the US Ballast Water Management Act. This law implemented throughout the US marine area makes it mandatory to replace ballast water with seawater in mid-ocean. Oceanographers consider that invasive species are decimated by this discharge into the open sea.[8]

[7] Ballast water comes from the following mechanism: once the cargo has been unloaded, the ships must carry an equivalent weight of water in their ballast to ensure stability until the next load. Thousands of organisms such as bacteria, algae and plankton, but also small fish and invertebrates are then transported over long distances and then discharged into different ecosystems.

[8] Based on interviews we led to better understand the environmental impact of these laws. We thank in particular Christophe Maes for his time and explanations. The US Ballast Water Management Act also mandates the use of ballast water treatments which eradicate invasive species inside the ballast (and then make relax the exchange in the ocean), but this technology have been adopted by vessels only in 2015. However, this law on ballasts does not affect invasive species coming from hull fouling, which is a vector of seaweed introduction (Williams and Smith, 2007).

2.3 Eutrophication

Human activities may destabilize the kelp by their impact on eutrophication. First, through urban and agricultural activities (discharge of untreated sewage, agricultural fertilizers, etc.) leading to the replacement of kelp by turf algae (known to cause 'dead zones', see Filbee-Dexter and Wernberg, 2018). Second, through maritime transport through the discharge of greywater with chemical products (from sinks, showers, and kitchens) and blackwater with nutrients (sewage). These discharges, due to their high content of nutrients, can participate in oxygen depletion and algae bloom. [9]

2.4 Noxious paints

As the algae and mollusks that attach themselves to the hull slow down the ship and increase fuel consumption, ships have long been using anti-fouling paints to coat their underwater surfaces. These anti-fouling paints that contains biocide (copper and tributyltin) ends in water and are harmfull for the environment (Dafforn et al., 2011, Cima and Varello, 2022), including for kelps.[10] Even if this pollution has been reduced since the International Convention on the Control of Harmful Anti-Fouling Systems on Ships in 2008 (which prohibits the use of biocides), the real effect of this agreement remains uncertain over the period we are studying (and probably very weak, as it only concerns new boats and not those in circulation).

2.5 Air Pollution and the Emission Control Area

Lastly, there are other sources of pollution, such as sulfur dioxide emissions from vessels that contribute to increasing the acidity of seawater (Doney et al., 2007) with a potential detrimental effect on kelp. Since this air pollution is dangerous for the health of the population, the State of California implemented an Emission Control Area (ECA) of 24 nautical miles off the California coast in 2009 through its Ocean-Going Vessel Fuel Rule. The area of the ECA was slightly extended in 2011 in southern California to protect (by 24 additional nautical miles) the Channel Islands. It is also designed to better channel traffic onto a particular lane and reduce it elsewhere (in the south of the Channel Islands)

[9] See Lindgren et al. (2016) for a review.

[10] Johansson et al. (2012) study in laboratory sugar kelp *Saccharina latissima* (Linnaeus) collected in Sweden and observe that six out of seven antifouling compounds had a detrimental effect on kelp photosynthesis and growth.

The Ocean-Going Vessel Fuel Rule imposes the use of low sulfur fuel in the ECA which is more expensive (but less polluting) than the heavy fuel used by ships and incurs investment on engines for ship owners. Due to this legislation, Klotz and Berazneva (2022) have detected a change in the maritime route taken by the ships. Whereas ships sailed along the coast before the law, after its implementation, ships navigate outside and enter the zone by heading towards the port using the shortest distance. This strategy minimizes the use of low-sulfur fuel, which is used only in the ECA (outside it, ships are still using heavy fuel). This law, by reducing traffic along the coast, may have reduced water pollution with a beneficial impact on the canopy.

2.6 Economic Background

The financial crisis of 2007-2008 led to a significant decrease in international trade that reached its lowest point in 2009, known as the Great Trade Collapse (Levchenko et al., 2010; Bricongne et al., 2012; Eaton et al., 2016).

Figure (7) shows the sharp and parallel decline in imports in American ports on the Atlantic coast, of the Gulf of Mexico, and in California. Interestingly, the recovery of international trade is smaller in California than in other US ports. Total import even in ports of the Gulf Coast overpass import in California in the last quarter of 2011. Another interesting stylized fact is that while all other ports recover their level of trade around 2011-2012, Californian ports remain during that period twice less underutilized than in 2007.

This slower growth can be explained by several factors. The cost of complying with the ECA for vessel owners (e.g., investment in new engines that use low sulfur fuel) increases the costs of trading goods and may lead to avoidance of Californian ports. Furthermore, the demand-side mechanism of the financial crisis may be at play in this relative decline of traffic in Californian ports. In fact, California was one of the regions in the world that has been the most severely affected by the burst of the housing bubble (Bardhan and Walker, 2011), which limited the consumption and import of goods there.

3 Empirical strategy

The previous section presents several facts that guide our empirical study.

First, kelp along the California coast has been treated twice by the ECA, in 2009 at its enforcement, and in 2011 by its extension. In this section, we focus on our analysis over the period 2007-2011 with quarterly data (we study the extension of 2011 in the last section).

Second, the financial crisis has been so severe that parallel trends in the collapse of trade are being detected in all ports. In contrast, trade recovery has been slower in Californian ports and greener due to the implementation of a specific maritime zone. In other words, the kelp forests in the ECA have been treated by environmental regulations and by a relative reduction of traffic compared to the kelp in other regions. Therefore, we consider the implementation of the ECA in California that accidentally coincides with trade recovery as the date of treatment.

3.1 Empirical strategy and data

3.1.1 Empirical strategy

The previous analysis makes clear that we have to control for as many changes in unobservables as possible. We thus estimate a difference-in-differences model with two time periods and with times fixed effects f_t, individual fixed effects f_i and location-time varying characteristics Z_{it} as follows:

$$Kelp_{it} = \alpha + \beta California_i Recovery_t + Z_{it} + f_i + f_t + \varepsilon_{it}, \tag{1}$$

where $Kelp_{it}$ represents successively the kelp canopies (in m²) and biomass (in kg) at the cell level i on a quarter dimension t (see data description for more details). $California_i$ is a dummy variable equal to one for kelp groups located within the area defined by the 2009 ECA, and zero otherwise (control kelp, see section below). Indeed, to exploit the geographical variation introduced by the 2009 ECA, we select several groups of kelp located within the regulated zone and compare them to untreated kelp situated further south, in Mexican waters. $Recovery_t$ is a time dummy equal to one from 2009 Q3 onward—marking both the trough of the trade crisis and the start of the ECA implementation—and zero for earlier periods. We use the Poisson pseudo-maximum likelihood estimator (PPML) (e.g., Santos Silva and Tenreyro, 2006) to account for areas (pixels) where there is no kelp during the entire period or where the kelp have disappeared. We cluster the standard errors at the cell level for kelp.

The coefficient of interest, β, is the interaction term between the time and location of the treatment. It captures the treatment effect on the kelp canopy.

Finally, to go beyond the average monthly impact over the whole pre and post treatment period, we present the dynamic effects year after year for the L.A area, using a standard event-study regression:

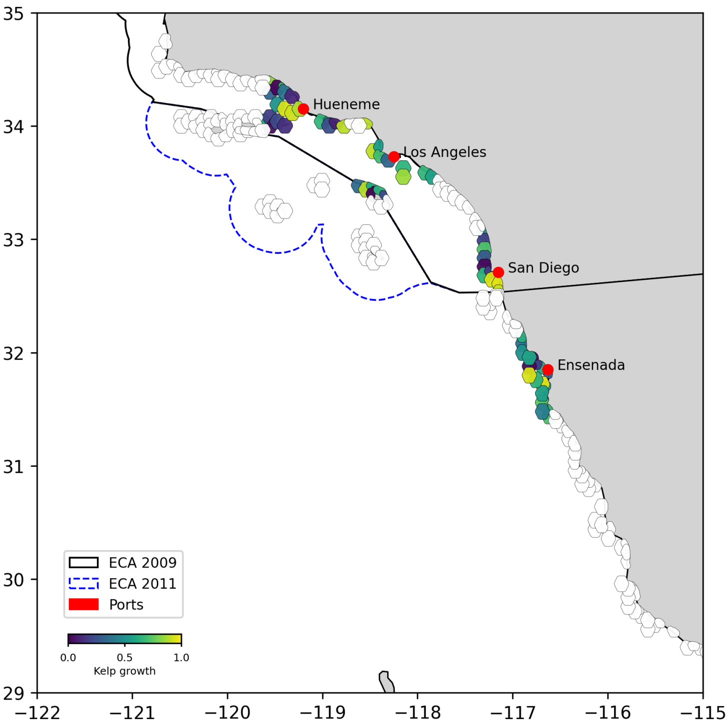
$$Kelp_{it} = \alpha + \sum_{\ell} \beta_{\ell} Area_{i,t-\ell} + Z_{it} + f_i + f_t + \varepsilon_{it}, \tag{2}$$

where ℓ is the time-since-event, we take seven periods before and after, and the enforcement of the policy occurs at $\ell = 0$. Thus, we measure the dynamic effect via coefficients β_ℓ for $\ell > 0$, while coefficient β_ℓ for $\ell < 0$ provides a falsification test (with no anticipation effects, no misspecification and no omitted confounding variables).

To verify by a different methodology whether our results are robust, we then use a Synthetic Control approach. We focus our analysis on kelp in a large area around Los Angeles and Long Beach. The SDID has several advantages, such as a good validation of the pretreatment parallel trend assumption due to the weighted control group that better aligns with the treated group's pretreatment trends.

3.2 Sample

Map 1 presents the different group of kelp studied in the treated groups and in the control group.



Note: The different hexagons represent the aggregated kelp canopy. The black line represents the limit of the ECA enforced in 2009. The blue dashed line represents the 2011 extension (studied in the last section). Projections are under EPSG:4326 - WGS 84 coordinate reference system.

Figure 1: Kelp in the ECA and in Baja California

We first consider kelp around the ports of Los Angeles and Long Beach, which are among the largest ports in North America. These ports are the entry door for Pacific trade with Asian countries and form the largest seaport complex in the US accounting for 28% of the total value of U.S. maritime trade in 2010 (US, 2010). As a result, we focus our analysis on the kelp forests near the Greater Los Angeles metropolitan area using a buffer of 50 km from the L.A. ports. The 50 km buffer is chosen because it is large enough to reduce the local-scale dynamics related to sedimentation and recruitment.

Then we consider treated kelps that grow near San Diego and Hueneme in the ECA. The relevance of these groups comes from their strategic locations along major maritime routes, which implies that the effect of treatment may have been more pronounced in these regions. San Diego, the southernmost ECA port, located near the Mexican border, provides a useful point of comparison with our control group. It is far enough (approximately 200 km) to avoid direct contamination effects, yet close enough to share a relatively homogeneous marine environment.

Port Hueneme, on the other hand, is located within a central maritime trade corridor — the Channel Islands Passage. This area serves as a true maritime highway, concentrating heavy shipping traffic and exposing the region to significant maritime pressure.

In Appendix A, we also consider two very different treated regions in the ECA that are marine protected areas (Big Creek and Rock Islands). We find similar results.

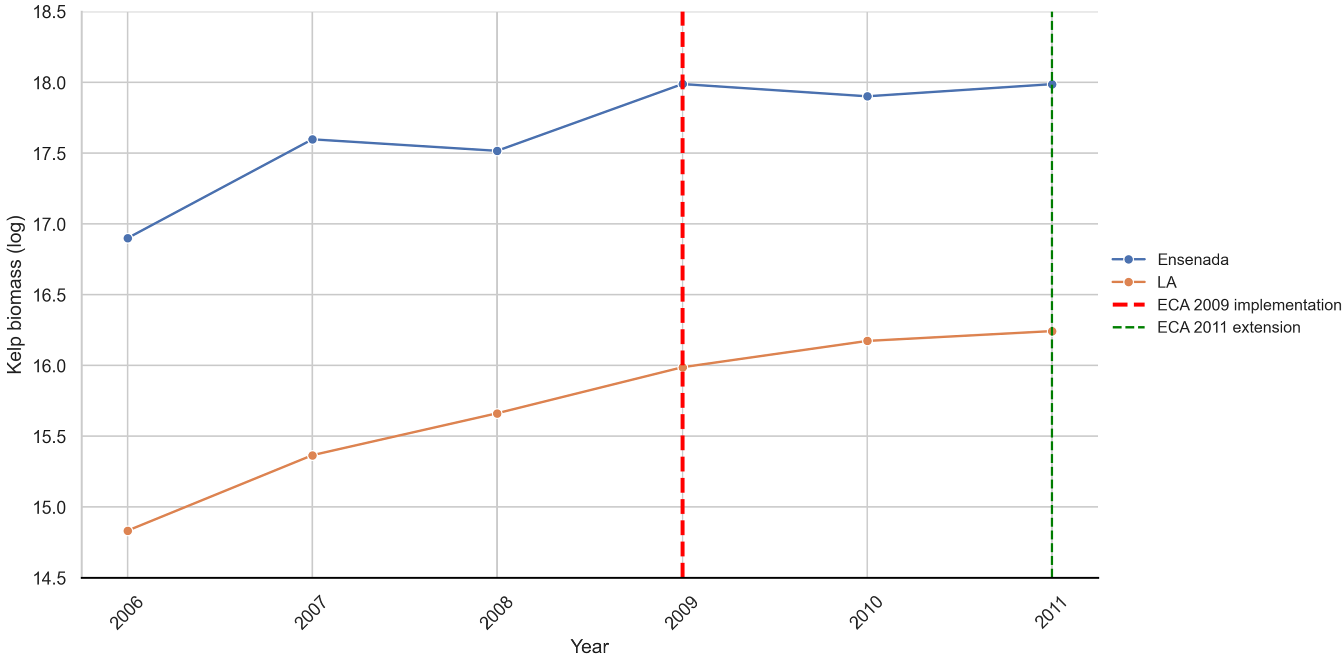
3.3 Controls

As a control group, we took the canopy around the port of Ensenada in Baja California. 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. Ensenada shares several key characteristics with our Californian ports. It is the second busiest port in Mexico after Veracruz (located on the Gulf of Mexico) and the only deep-water port in the state of Baja California. Moreover, changes in shipping patterns follow a similar trend 7, particularly in terms of shipping-related emissions — highlighting the broader impact of global trade dynamics during the period.

Kelp forests near Californian ports and those around Ensenada are part of the same coastal ecosystem. Indeed, these kelps don't recognize political borders — they form a continuous stretch from Southern California into Baja California, with no natural barrier separating them.

When considering the raw data in Figure (2), without any estimation or controls, the pretrends between the kelp treated around LA and the control groups in

Ensenada are quite similar.



Note: This graph shows the evolution of kelp biomass (log scale) between our control group (Ensenada) and our treated group (Los Angeles) up to the extension of the ECA in 2011.

Figure 2: Change in biomass in treated (LA) and control groups (Ensenada)

3.4 Data

3.4.1 Kelp canopy and biomass

Data on kelp comes from Bell et al. (2023)[11] which provides the growth and coverage of bull and giant kelp on the California 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 provides a time series of cloud-free imagery. Estimates of kelp canopy biomass are derived from the relationship between satellite surface reflectance and

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

empirical measurements of kelp canopy and biomass.[12] Machine learning is also used to treat these data.

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 approximates the total mass of living kelp (in kg) within each pixel. Although these data have major advantages, in particular that they provide a historical series of kelp, they also have limitations. The most important drawback is linked to the use of satellite technology, which does not allow us to identify the sub-canopy. Only emerging kelp appears in this dataset, leading Bell et al. (2023) to consider that only giant kelp and bull kelp are observed.

3.4.2 Variables of control

Kelp are affected by several factors such as temperature, water acidity, water motion, light, nutrients, salinity, substrata and sedimentation (see the section on the environmental background). We cannot take into account all these variables due to multicolinearity problems (e.g. correlation with temperature) or due to the non-availability of them. Note, however, that all the determinants that vary exclusively across space are captured by fixed effects, and those that vary over time by temporal effects (e.g. common shocks).

Temperature

The 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 surface. SST is an important variable that helps to explain the variability in ocean activity (including frequency, density, and strength) and chlorophyll concentration (Yang et al., 2023; Dunstan et al., 2018).

SST data are extracted from NASA's Terra and Aqua satellites and used at the monthly level.

Sea Surface Weight

Wave and current can have a very different effect on the marine environment depending on their intensity. Moderate wave and water currents disperse spores and are thus essential to the expansion of species. They also bring nutrients from deeper waters, and finally by removing sediment and epiphytes from the plant

[12] 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

blades, they favor photosynthesis. However, strong intense waves and currents cause physical damage, breaking off fronds or dislodging whole plants from the substrate, leading to a reduction in biomass.

The intensity of current waves is approximated by "the average height of the highest third of the ocean / sea surface 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 wind-sea waves (due to local winds) and swell (due to wind at a different location and time). We refer to this variable in our results tables as the sea surface weight.

Economic activity

As discussed above, eutrophication due to economic discharge (e.g. untreated sewage, fertilizers) can also affect the growth of kelp. To proxy for these human activities, we use the nighttime light data captured by satellite on the coast that are the closest to the observations analyzed (based on the dataset of Li et al. (2020)).

4 Results

4.1 Restoration of the Kelp forest

Table (1) presents our first results for the growth of the canopy surface (in m^2). Whatever the location of the kelp along the California coast, we find a significant positive coefficient after 2009, namely during the period when the trade recovery has been smaller in California than in the control group. The restoration of kelp seems to have been effective after the implementation of the ECA.

Control variables show expected signs; for example, 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 probably due to the quarter fixed effects absorbing the impact of these variables when their variability is small.

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 our Equation (1) again, but this time by considering this indicator.

	LA	San Diego	Hueneme
Diff-in-Diff Effect	0.351***	0.43***	0.231***
	(0.0871)	(0.0479)	(0.06)
Sea surface temperature	-0.0258	-0.474***	0.275***
	(0.0507)	(0.0378)	(0.0906)
Sea surface weight	-4.093***	-2.615***	-6.828***
	(0.149)	(0.221)	(0.823)
Economic Activity	0.0000225	-0.000464***	-0.000404***
	(0.0000259)	(0.0000220)	(0.0000662)
Constant	10.03***	21.55***	11.63***
	(0.815)	(0.663)	(2.437)
Time FE	✓	✓	✓
Kelp FE	✓	✓	✓
Observations	105423	180743	44625
Log-Likelihood	-5372934.8	-8840835.4	-3129865.0
Pseudo R2	0.518	0.503	0.516

Notes: Standard errors in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.
This table shows the result of our DID specification with severals treated groups (Los Angeles, San Diego and Hueneme) and Ensenada control group. The dependent variable is the canopy in each reported kelp pixel. We add time and kelp individual fixed effect.
The period concerned is 2007-2011. Estimator is PPML. All covariates are in log.

Table 1: Kelp biomass growth after 2009

The results are presented in Table (2), where we observe that the biomass has also increased significantly after 2009.

	LA	San Diego	Hueneme
Diff-in-Diff Effect	0.381***	0.45***	0.22***
	(0.0858)	(0.0476)	(0.06)
Sea surface temperature	-0.0298	-0.502***	0.295***
	(0.0501)	(0.0374)	(0.0906)
Sea surface weight	-4.150***	-2.631***	-6.653***
	(0.148)	(0.219)	(0.826)
Economic Activity	0.0000302	-0.000480***	-0.000410***
	(0.0000259)	(0.0000213)	(0.0000663)
Constant	12.07***	24.24***	13.08***
	(0.808)	(0.652)	(2.439)
Time FE	✓	✓	✓
Kelp FE	✓	✓	✓
Observations	105423	180743	44625
Log-Likelihood	-39124235.0	-63920371.9	-22690642.8
Pseudo R2	0.519	0.503	0.522

Notes: Standard errors in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.
This table shows the result of our DID specification with severals treated groups (Los Angeles, San Diego and Hueneme) and Ensenada control group. The dependent variable is the biomass in each reported kelp pixel. We add time and kelp individual fixed effect.
The period concerned is 2007-2011. Estimator is PPML. All covariates are in log.

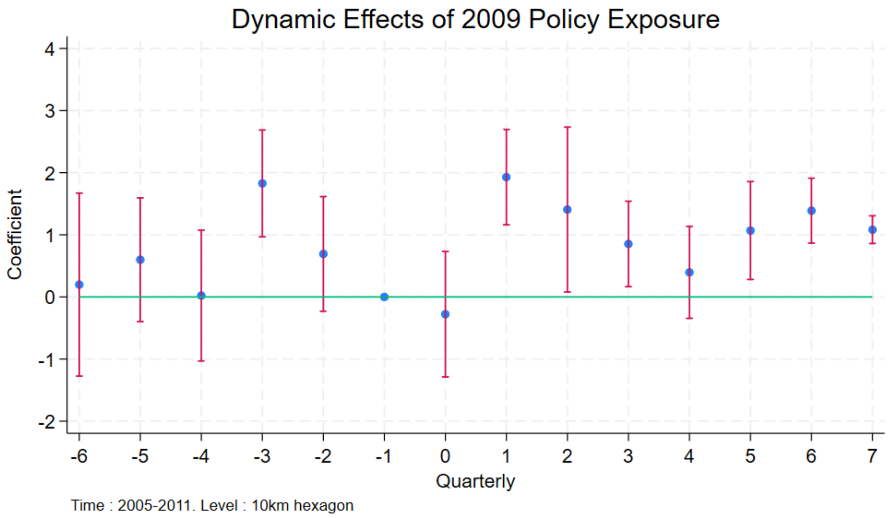
Table 2: Kelp biomass growth after 2009

In contrast to standard analysis in economics, the current study on kelp has a distinct advantage: Kelp do not consider the different potential outcomes, and thus, there is no selection bias (as we usually understood it) or anticipation. However, several other challenges persist because of the unknown heterogeneous effects of vessels traffic on kelp, due to a possible lack of control, and because of the possible violation of the parallel trend assumptions. For instance, when considering raw data, without any estimation or controls, the parallel pretrends between the treated and the control groups are never perfect. For example, the most convincing figure is obtained for LA (see Figure 2), while for other treated groups several discrepancies are observed before the treatment (not reported).

We thus test the robustness of our results by considering different areas and methodologies in the next two subsections (and in Appendix A).

4.2 Dynamic effects

We present here a dynamic Difference-in-Differences approach to evaluate whether the previous results appear just after 2009, or are delayed, and/or persistent over our period of analysis. We focus on kelp around L.A. which provides the best pre-trend parallel plot as discussed in the previous section. The results of the estimation of Equation 2 for the parameters β_ℓ are reported in Figure (3).



Note: This graph shows the quarterly dynamic effects on kelp biomass (log scale) in the treated group (Los Angeles) compared to the control group (Ensenada), using the DID method. All covariates are included in the model.

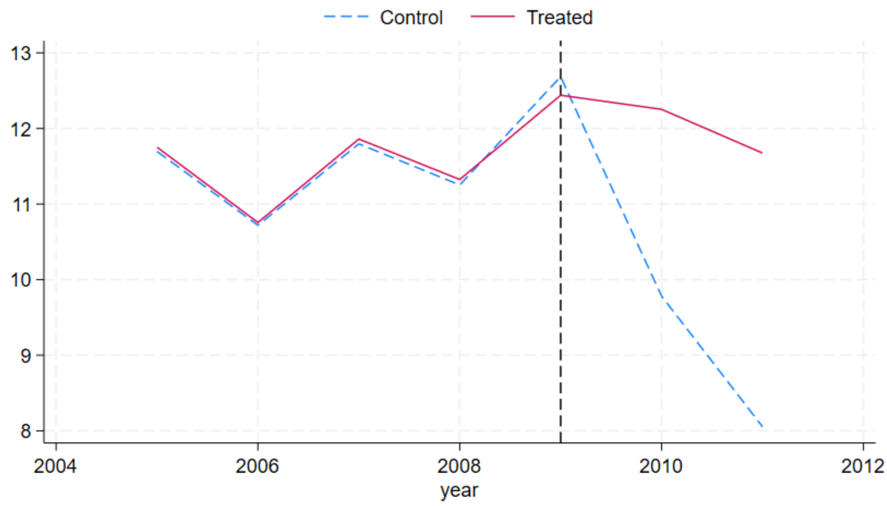
Figure 3: Dynamic effect for kelp in L.A.

In the pretreatment period, the coefficients are almost always not significant, confirming the parallel trend presented in the raw data. After 2009, when California is treated by a slower and greener recovery of international trade, the biomass growth is significantly positive until the end of the period.

The two exceptions observed in quarters -3 and 4 are certainly explained by seasonal variations. Indeed, despite the several controls introduced and the time-fixed effect on quarter, we do not control enough for natural and seasonal variations that are strong in the life cycle of kelp. The significant positive coefficient obtained before the shock in quarter -3 corresponds to the seasonal period of kelp growth (April, May, June). Similarly, a seasonal reduction in the kelp canopy is generally observed toward the end of summer and into early fall due to warmer water temperatures (Cavanaugh et al., 2019). Then, during the treatment period, the decreasing and finally not significant effect during quarter 4, which corresponds to this period (July to September), can be explained by these cyclical changes.

4.3 Synthetic Control

We also implement a synthetic control strategy to recreate a counterfactual Californian coastline based on untreated Mexican hexagons, as shown in Figure 4, in order to provide a broader view of kelp dynamics over the study period.



Note: This figure displays the kelp biomass trends (summed by hexagon and quarter) for the treated hexagons located within the 2009 ECA zone—excluding those already analyzed—compared to a set of untreated hexagons on the Mexican coast. These spatial units correspond to the transparent hexagons shown in Figure 1.

Figure 4: Synthetic Control for unstudied kelp area

As expected with this methodology, prior to the implementation of the treatment, both the treated and control groups followed a similar trajectory. Any post difference may be attributed to the shocks rather than by pre-existing trends. The observed increase in kelp growth in the treated area after 2009 suggests the implementation of conditions conducive to canopy growth. The decrease in the control group indicates that without these conditions implemented after the trade collapse in California, kelp growth may have faced unfavorable conditions due to trade recovery.

5 The Trade Recovery Period (2009-2014)

In this section, we focus on the period 2009-2014 to better understand how the recovery of international trade has affected the canopy. More precisely, our aim is to directly analyze the effect of vessels by tracking their location and then to better measure the exposure of kelp to traffic. [13]

5.1 Exposure of kelp to vessels

To reconstruct the full set of vessel trajectories, we first use a uniform grid of 10-kilometer hexagonal cells that cover both the original 2009 Emission Control Area (ECA) and its 2011 expansion. Trajectory data are derived from georeferenced ship positions recorded by the Automated Identification System (AIS), made available by the U.S. Coast Guard [14] The data are processed across a 10-kilometer hexagonal grid. We focus on four major cargo vessel classes—tankers, container ships, general cargo ships, and bulk carriers which represent the dominant commercial fleet in the region. For each hexagon and quarter, we calculate two measures of shipping intensity: (i) the number of unique vessels traversing the cell (named "count"), and (ii) the total distance traveled within it (named "length"). These metrics capture both the frequency and intensity of shipping activity at a fine spatial and temporal resolution.

To assess maritime exposure in ecologically sensitive areas, we assign these indicators to kelp forest aggregation hexagons located along the California coast. Specifically, for each kelp cell, we compute shipping intensity measure from the nearest hexagon(s) with significant vessel traffic and scale the exposure metrics by the inverse of their geographic distance. This procedure yields a continuous measure of exposure that reflects the proximity and magnitude of nearby maritime operations for each kelp zone.

[13] The choice of our analysis period (2009-2014) is also constrained by the data on ship movements (using the AIS signal) that are only available to us from 2009. Furthermore, as discussed in the background section, the literature has clearly indicated that the 2014 heat wave was so strong that it was the main driver of the kelp decline after this period. We therefore stop our analysis in 2014.

[14] AIS data accessed via MarineCadastre.gov, jointly maintained by the U.S. BOEM and NOAA.

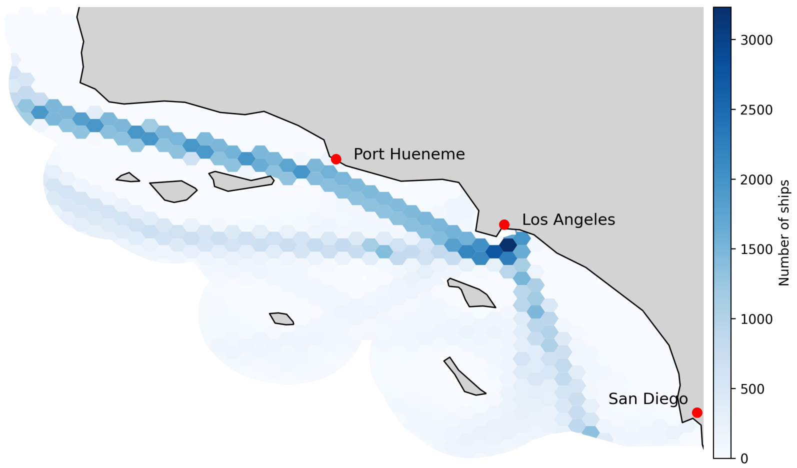
5.2 Extension of the ECA in 2011

We have the opportunity to directly analyze the relationship between traffic and kelp by analyzing the 2011 expansion of the ECA, since this reform implies a change in traffic around the Channel Islands.

Figure 1 presents the extension of 2011. Notice that the new boundary adds three areas with a circular border in order to attract traffic at the intersection of the different circles. These points represent the shortest distance for vessels to travel to ports.

In particular, the limit has been changed at the entrance to the Santa Barbara Channel to encourage vessels to use a shipping lane there and to reduce traffic elsewhere (for example at the Point Mugu. See Klotz and Berazneva, 2022).

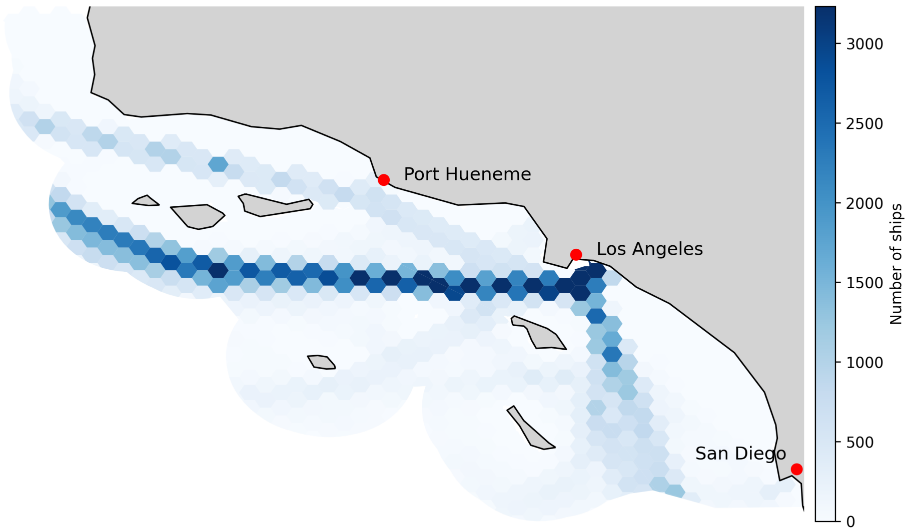
In that lane, traffic (which have been drastically reduced by the 2009 law) suddenly increases after 2011. The comparison between the exposure in 2009 and 2011 then shows a significant change in the route taken by vessels as reported in Figure (5) and (6).



Note: We create a measure showing the number of ships passing through each hexagonal cell in Southern California in 2009, to reflect shipping patterns before the 2009 ECA was implemented.

Figure 5: Exposure of Kelp to Maritime Traffic in 2009

It is quite clear from these maps that until 2009, ships navigated along the coast while they avoided this route after the 2011 extension.



Note: This map shows the number of ships crossing each hexagonal cell in 2011, just before the ECA extension.

Figure 6: Exposure of Kelp to Maritime Traffic in 2009

This offers a natural experiment to assess how changes in vessel traffic directly impact sensitive coastal habitats that are the kelp forests located there.

5.3 Empirical strategy

To measure the effect vessel traffic on kelp after the change due to the 2011 extension of the ECA, we put in interactions a dummy $Policy_t$ that takes one after 2011 (zero otherwise) and our variable of $Exposure_{it}$. More precisely, we estimate the following equation:

$$Kelp_{it} = \alpha + \beta Exposure_{it} + \gamma Policy_t Exposure_{it} + Z_{it} + f_i + f_t + \varepsilon_{it}, \tag{3}$$

The coefficient of interest here is γ, a significant negative coefficient indicates that the 2011 extension modifies the relationship between $Exposure_{it}$ and $Kelp_{it}$.

5.4 Results

Table (3) presents the results. We first observe a negative coefficient for exposure alone. This can be explained by the fact that the vessel traffic has been reduced in the previous period (before 2011) and then the kelp continue to growth in general. This indicates that the ECA of 2009 has been beneficial. However, after 2011, when the traffic in canalized in the lane of Chanel Islands, kelp in this area starts to decrease again. To have the global of effect of the 2011 extension in this area, we have to add the estimates of γ and β and since the coefficient of the interaction term is negative and higher in absolute term ($\gamma > \beta$), the effect of interest is negative. Hence the 2011 extension, in the area where traffic has strongly increased, is correlated with a decrease in the kelp canopy.

	2009 zone		2011 zone	
	Biomass	Canopy	Biomass	Canopy
Length exposure (ln)	-0.0359	-0.0380	-0.107	-0.104
	(0.0520)	(0.0530)	(0.0684)	(0.0696)
Policy * Length exposure (ln)	-0.0744**	-0.0747**	0.142**	0.145**
	(0.0338)	(0.0345)	(0.0654)	(0.0664)
Sea surface temperature (ln)	-0.490	-0.418	-24.46***	-24.57***
	(1.516)	(1.552)	(3.347)	(3.392)
Sea weight intensity (ln)	-2.665**	-2.705**	2.465	2.688
	(1.132)	(1.149)	(4.266)	(4.334)
Economic activity (ln)	0.105	0.106	-0.412**	-0.421**
	(0.145)	(0.147)	(0.169)	(0.171)
Constant	16.04***	13.86***	84.94***	83.20***
	(4.456)	(4.555)	(8.997)	(9.121)
Time FE	✓	✓	✓	✓
kelp FE	✓	✓	✓	✓
Observations	702	702	535	535
Log-Likelihood	-74977217.3	-10229451.1	-39866122.0	-5441001.7
Pseudo R2	0.831	0.829	0.881	0.881

Notes: Standard errors in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.
The dependent variable is the sum of kelp biomass (in kg) and area (in m^2) within each hexagonal cell located in the 2009 ECA and the 2011 ECA extension zones, measured quarterly from 2009 to 2018. Exposure is defined as the total distance (in meters) traveled by ships within each hexagonal cell in proximity to kelp forests. All covariates are expressed in logarithmic form. Sea Surface Temperature and Wave Intensity are included as quarterly averages, calculated from monthly observations. Economic Activity is measured annually. The model includes both time fixed effects and kelp cell fixed effects. Regressions are estimated using a Poisson Pseudo Maximum Likelihood (PPML) approach.

Table 3: 2011 expansion impacts on zone affected in 2009 and 2011

We observe that kelp forests located within the 2009 ECA (Emission Control Area) experienced a decline in growth after 2011. More specifically, the return of maritime traffic—reflected by an increase in the exposure variable measuring ship passage intensity—particularly in the Channel Islands corridor, which had previously seen reduced activity due to the ECA policy, had a detrimental effect on these kelp ecosystems. In contrast, kelp forests within the area designated in the 2011 ECA benefited from a continued decrease in shipping pressure, leading to the opposite outcome: improved growth rates and increased biomass.

Similar results are obtained for biomass as a dependent variable. The robustness of the results are also obtained for change in the explanatory variable for traffic exposure (e.g. number of vessels or the duration of the exposure measured by the distance covered by vessel near the kelp). The relationship between kelp and vessel traffic appears to be negative.

6 Conclusion

> 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 benefit of kelp for human date from pre-historic time; Erlandson et al. (2007) even propose a 'Kelp Highway Hypothesis' explaining that human migration 20'000 years ago depended on this resource. However, the "highway of kelp" is now taken by giant vessels that leave in their wake maritime pollution. We have shown in this article that when traffic is relatively decreasing, the growth of the kelp canopy increases in the California ECA, while when it increases, the kelp canopy and biomass decrease.

This indicates that the Ocean-Going Vessel Fuel Rule has succeeded not only in protecting human health, as shown by Klotz and Berazneva, 2022, but also in protecting the underwater environment in places where traffic has decreased. Our analysis is obviously limited to a particular area and period, but it has implications for both economic analysis and maritime policy.

First, the cost-benefit analysis of international trade, which is beginning to take into account the effect of global trade on deforestation, should also consider its effect on marine forests. Perhaps by starting to take into account the negative impact of maritime traffic from fishing to alginate, food, medical, and bioengineering additives, as well as the reduction in carbon sequestration in the oceans that are directly linked to kelp forests.

Second, the International Maritime Organization (IMO), which has been pivotal in enforcing essential regulations over the past decade, could have a role to play in the future in promoting sustainable international trade that respects the underwater canopy. In that respect, emission control areas are a good policy to promote.

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Appendic A: Kelps in maritime protected areas

We consider here 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 but still inside the ECA. More precisely, we consider the canopy in Rocks and Islands Wilderness in Northern California and in the Big Creek State Marine Reserve (SMR) on the offshore of Big Sur in the California's central coast. The effect of treatment may have been smaller in these areas, but still not null because these kelp populations may have gained from a traffic displacement attributed to the ECA. Indeed, while these kelp reside in a protected area, currents can still introduce pollution. Therefore, avoiding the ECA (see Klotz and Berazneva, 2022) may have been beneficial by moving the traffic farther away. As a consequence of the ECA, the amount of pollution transported to these areas by currents may have been reduced. As a control group, one cannot use the one chosen in the text, namely kelps in Ensenada which are too different to verify the parallel trend assumption. Indeed as stated in the text, Ensenada is important port and then kelp located there certainly does not have the same environment than kelp located in the U.S. protected areas. We then consider a control zone that is far from maritime lanes and about 250 km from the nearest Mexican port of Ensenada, on the coast of the Valle de los Cirios, which is a protected area for wildlife. This control group is chosen because it shares some characteristics with the treated units in the protected area inside the ECA in California, it is a wildlife protected area like in Rocks and Islands and Big Creek. However, we agree that these controls are far from perfect, kelp in Valled de los Cirios does not have the same characteristic and climatic conditions. However, we expect that these differences are partially controlled by fixed effects and control variables.

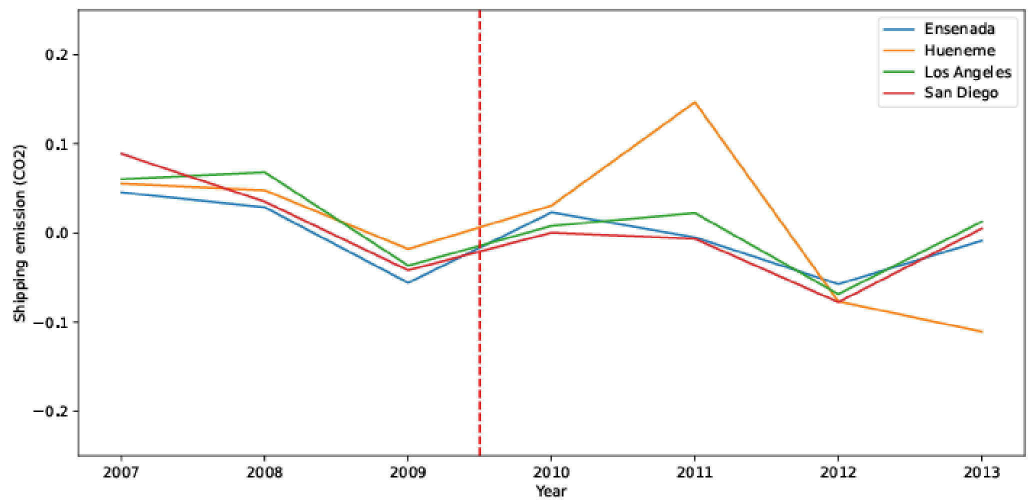
All the results presented in the text are verified here. The canopy and biomass of kelp in Big Creek and Rock Island have increased after 2009.

	Canopy		Biomass	
	Big Creek	Rock Island	Big Creek	Rock Island
Diff-in-Diff Effect	3.32***	1.08***	3.152***	1.05***
	(0.0335)	(0.708)	(0.0136)	(0.35)
Sea surface temp	0.238***	0.262***	0.0110*	0.0111*
	(0.0267)	(0.0264)	(0.00594)	(0.00594)
Sea surface weight	8.331***	4.730***	-4.093***	-2.615***
	(0.851)	(1.007)	(0.149)	(0.221)
Economic Activity	0.00765***	0.00722***	0.0000225	-0.000464***
	(0.000790)	(0.000843)	(0.0000259)	(0.0000220)
Constant	-10.42***	-5.657***	10.03***	21.55***
	(1.264)	(1.409)	(0.815)	(0.663)
Observations	468146	474512	105423	180743
Log-Likelihood	-30214177.2	-30398078.5	-5372934.8	-8840835.4
Pseudo R2	0.520	0.521	0.518	0.503

Notes: Standard errors in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.
Estimation: 2007–2011. Control: kelp near Valle de Los Cirios.

Table 4: Impact of shipping exposure on kelp biomass and area

Appendic B: Shipping patterns within groups



Note: This graph shows the yearly change in shipping CO emissions within a 20 km buffer around each treated or control port between 2007 and 2013. The measure represents the year-over-year variation compared to the previous year.

Figure 7: International trade dynamics across groups

Figure 7 illustrates the evolution of international maritime trade over time by tracking CO2 pollutant emissions by shipping sector, using data from the EDGAR database (Centre. and IEA., 2024). The figure focuses on our treated Californian port areas (Los Angeles, San Diego, Hueneme) and our control port in Mexico (Ensenada). We observe similar temporal patterns across the different port zones: prior to the implementation of the Emission Control Area (ECA), vessel emissions appear to follow a comparable trajectory, including a marked decline during the 2009 global financial crisis.

Thus, the comparability between our treatment and control groups appears to be validated with respect to their exposure to international trade fluctuations.

Appendix C: Synthetic Control Approach

To complement our Difference-in-Differences strategy, we apply a Synthetic Control Method. Specifically, for each treated hexagon around the Californian ports, we identify its synthetic counterpart along the Mexican coast.

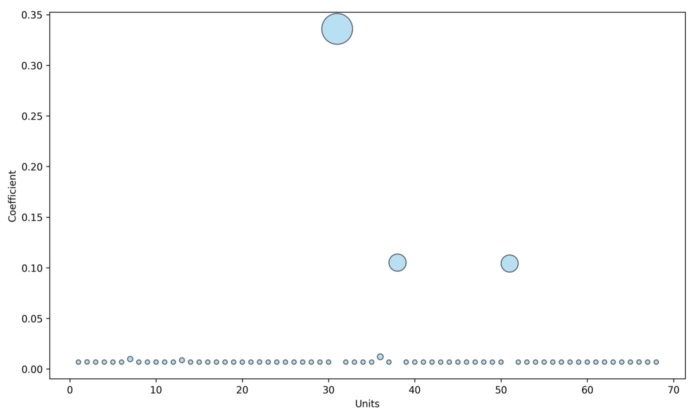
	(1)	(2)
	Biomass (ln)	
Synthetic Control	1.391**	1.911**
	(0.642)	(0.753)
N	819	721

Standard errors in parentheses
* p¡0.10, ** p¡0.05, *** p¡0.01

Table 5: Synthetic control results

Treated units correspond to all hexagons located within the 2009 ECA boundaries, while control units are hexagons on the Mexican coastline (excluding Ensenada). Results indicate a positive impact of the ECA policy on Californian kelp forests when compared to their synthetic counterparts, suggesting that the ECA played a role in preserving these marine ecosystems.

The contribution weights used to construct the synthetic California are shown below in Figures 8:



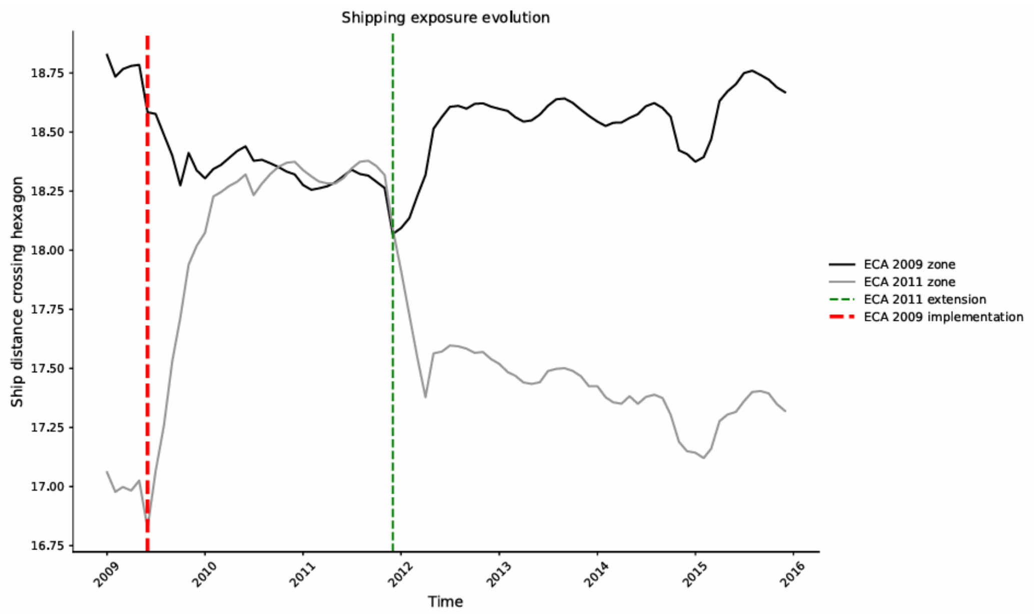
Note: The dependent variable is the sum of biomass in each hexagon's cells.

Figure 8: Synthetic control (weight)

Appendix D: After 2011 extension

This chart (9) quantifies the total distance traveled by vessels within each hexagonal cell, between the 2009 ECA zone and the area corresponding to the 2011 ECA expansion. It complements the patterns previously observed on the 2009 (**??**) and 2011 (**??**) traffic maps. The data clearly illustrate a shift in vessel behavior: ships increasingly avoided the 2009 ECA zone and instead transited through the area that would later be included in the 2011 extension.

Between 2009 and 2011, a reduction in shipping activity is observed within the 2009 ECA, while traffic increased in the (future) 2011 zone. This redistribution suggests a strategic rerouting by ship operators. Following the extension of the ECA in 2011, the shift becomes even more pronounced.



Note: This graph shows the distance traveled by ships in each hexagonal cell near kelp forests, distinguishing between cells located in the 2009 ECA zone and those in the 2011 ECA extension. The data is presented monthly from 2009 to 2016.

Figure 9: Evolution of shipping patterns

Appendix E: robustness exposure measure

We perform a robustness check by replacing our exposure measure with the number of ships crossing each hexagonal cell, instead of the total distance traveled. The results are very similar and support the conclusions presented in the main analysis.

	2009 zone		2011 zone	
	Biomass	Area	Biomass	Area
Policy * Count exposure (ln)	-0.0894**	-0.0908**	0.154**	0.158**
	(0.0371)	(0.0379)	(0.0719)	(0.0732)
Count exposure (ln)	-0.0623	-0.0655	-0.106	-0.108
	(0.0761)	(0.0770)	(0.0847)	(0.0872)
Sea surface temperature (ln)	-0.442	-0.365	-24.44***	-24.54***
	(1.535)	(1.572)	(3.313)	(3.359)
Sea weight intensity (ln)	-2.766**	-2.811**	2.473	2.700
	(1.130)	(1.146)	(4.215)	(4.285)
Economic activity (ln)	0.125	0.127	-0.410**	-0.420**
	(0.144)	(0.146)	(0.165)	(0.168)
Constant	15.23***	13.02***	84.44***	82.72***
	(4.547)	(4.647)	(8.907)	(9.033)
Time FE	✓	✓	✓	✓
kelp FE	✓	✓	✓	✓
Observations	702	702	535	535
Log-Likelihood	-74892022.1	-10211572.1	-39931439.8	-5448420.9
Pseudo R2	0.831	0.829	0.881	0.881

Notes: Standard errors in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.
The dependent variable is the sum of kelp biomass (in kg) and area (in m^2) within each hexagonal cell located in the 2009 ECA and the 2011 ECA extension zones, measured quarterly from 2009 to 2018. Exposure is defined as the total number of ships within each hexagonal cell in proximity to kelp forests. All covariates are expressed in logarithmic form. Sea Surface Temperature and Wave Intensity are included as quarterly averages, calculated from monthly observations. Economic Activity is measured annually. The model includes both time fixed effects and kelp cell fixed effects. Regressions are estimated using a Poisson Pseudo Maximum Likelihood (PPML) approach..

Table 6: Shipping exposure (cunt sum) impact on kelp : 2009 and 2011 zone