

## Long term natural and human perturbations and current status of Clipperton Atoll, a remote island of the Eastern Pacific

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### Abstract

Clipperton Atoll is one of the most isolated tropical island in the world and the only atoll of the eastern Pacific. Its outer slopes also make the largest coral reef of this region. Clipperton is a remarkable site for the geochemistry of its closed eutrophic stratified lagoon, the influence of both tropical eastern Pacific and Oceania gene pool on coral reef communities, the low diversity of the marine and land fauna, and for the equilibrium of its land ecosystem. The three components of the Clipperton Atoll seascape (coral reef-lagoon- land) all appear to have remarkable properties and history. All components experienced important changes in the last century due to anthropogenic (importation of exogenous species) or natural perturbations (closing of passes, coral bleaching). Here, we review the history of these three systems (land-lagoon-coral reef) and provide new insights of the current status of the atoll based on recent surveys and high resolution IKONOS satellite imagery. Most dramatic changes occurring in the last decades include explosion in crab *Gecarcinus planatus* population, almost-complete desertification of the island and increase in Masked Boobies *Sula dactylatra* population, making Clipperton Atoll one of the most important sites for this specie in the world. This review intends to provide a sound basis to discuss the future of Clipperton balanced between conservation and development priorities, and to raise awareness on the future of a delicate ecosystem.

**Keywords:** changing ecosystem – desertification – satellite imagery – IKONOS – coral reef – remote sensing – Clipperton atoll – seabirds - feral pig – *Sula dactylatra* – *Sula leucogaster* – *Gecarcinus planatus*

## Introduction

Clipperton Island (10°18N and 109°13W), also known as Ile de la Passion, is the only atoll of the North-East Pacific (Fig. 1) and the largest coral reef of the Eastern Pacific (Glynn *et al.* 1996). Clipperton is the fourth French possession in the Pacific Ocean (with French Polynesia, Wallis and Futuna, and New Caledonia), providing a large 435,000 km<sup>2</sup> Economic Exclusive Zone that is the subject of discussion between France and Mexico to control the access to the important pelagic fishery resources living in the area. In addition to its economic interest, Clipperton is a unique target for scientific research. It is located in a unique location and is a critical stepping stone to assess the spread of marine and land species between Oceania and the Tropical Eastern Pacific, as well as their endemism and evolution (Robertson & Allen 1996). It also provides coral cores from which paleoclimate of the Central Eastern Pacific can be reconstructed to understand El Niño Southern Oscillation patterns (Linsley and al. 2000). In addition, the closed lagoon offers a unique geochemistry due to its marked stratification (Bourrouilh-Le Jan *et al.* 1985a). Finally, because of its remoteness and discontinuous human settlement history, Clipperton is a unique laboratory to assess the long-term consequences of short-term human actions on a remote seascape.

The land and marine ocean and lagoon environment of Clipperton has been studied since 1935/1937 at the occasion of several international short surveys. There are no continuous biological data sets, and the data are unfortunately disparate, yet there is evidence that the atoll went through drastic changes in its natural equilibrium following natural or human-induced perturbations, despite its remoteness. Here, we review the changes that have occurred along the three components of the Clipperton seascape, namely the land, lagoon and coral reef ecosystems. We combine previous data with an IKONOS satellite image and *in situ* data acquired during scientific trips in 1997 and 2001 to evaluate the vegetation cover and seabird community status. We also update knowledge of the shallow marine systems of Clipperton, with a classification of the benthic communities of the lagoon and a re-evaluation of the extent of the outer reef flats and outer coral reef slopes.

Our goal is to provide a complete view of the status of the seascape, at a time where Clipperton's future is discussed. Two options are possible: limited development and conservation. Both have merits and drawbacks that need to be discussed.

## Material and methods

### Short review on Clipperton Atoll natural environment

The atoll is 4287 km away from the closest atoll of Pukapuka in the Tuamotu Archipelago, (French Polynesia), 4018 km away from the Marquesas Archipelago (French Polynesia), 4930 km from the Hawaiian Archipelago and 1280 km in the west of Acapulco (Mexico). The closest island is Socorro (Mexico) 945 km away in the North (Fig. 1). The basement of the atoll is a seamount rising 3000m above the seafloor. Clipperton also presents volcanic remnants in the form of a conspicuous 29 meter-high rock, called "Le Rocher". This volcanic relic explains why Clipperton is also referred as an almost-atoll (Sachet 1962), a true atoll presents only carbonate facieses (Battistini *et al.* 1975).

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Fig. 1 : Location of Clipperton Atoll (from Jost 2003).

The regional oceanography and current regime of the area is detailed in Glynn *et al.* (1996). Briefly, the atoll lies in the path of the North Equatorial Current or North Equatorial Countercurrent depending on the season. Clipperton is subject to hurricanes (Glynn *et al.* 1996). Connectivity between Clipperton and the coast of Central America or Pacific Island is an important issue to explain the population of the atoll and biogeography patterns in the Pacific and is discussed in Emerson (1994), Glynn *et al.* (1996), and Robertson and Allen (1996).

The now closed lagoon of Clipperton is a unique eutrophic and productive lagoon. Its chemistry is detailed in Bourrouilh-Le Jan *et al.* (1985). The turbid waters are stratified with surface salinities ranging 3.5-5.3 ‰ and reaching 34 ‰ in the deeper areas encountered in several enclosed lagoon basins (Ehrhardt 1971b, Niauxat 1986). Surface and deep waters do not mix and the deeper (>14m) anoxic waters are saturated with hydrogen-sulphide.

Fish diversity is low in the lagoon, with four species reported in 1968 (Ehrhardt 1971b). The benthic flora was reported as equally poor in species with seagrass (*Rupia maritima*) and green algae of the family Characeae (Bourrouilh Le Jan *et al.* 1985). Algal communities are abundant and productive (Murphy and Kremer 1983) and permanently fertilized by the release of phosphate and nitrate coming with the dejections of a large bird population (~1.8 tons/day for 35,000 birds in 1968, according to Bourrouilh Le Jan *et al.* 1985). It was previously estimated that these macrophytes covered 45% of the lagoon, mostly on the shallow and intertidal terraces bordering the rim (Ehrhardt 1971b).

The coral reef zones lie on the oceanic slopes of the atoll from 0 down to 70 meters (Glynn *et al.* 1996), including 6 major zonations with different degrees of coral cover and

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various coral communities. These are, by increasing depth: reef flat, spurs and grooves, coral *Pocillopora* spp. thicket, *Porites* spp. zone, a slope and a 60-m terrace where *Agaricia* sp. is dominant. Reef-building coral diversity is low with 18 species reported (Carricart-Ganivet and Reyes-Bonilla 1999).

Fauna is also characterized by a low diversity, even for Pacific Ocean remote atoll standards, and high endemism (Robertson 1996, Glynn *et al.* 1996, Allen & Robertson 1997, Lessios *et al.* 1996). Paucity of species is generally explained by Clipperton isolation, small size, reduced habitat diversity and oceanic environment controlling the physical connectivity between western Pacific Islands and the coast of America (Robertson and Allen 1996).

### History of Clipperton

Sachet (1960) provides an overview of human visits to the atoll between its discovery and 1958. Table 1 presents the era before 1958, when the first modern scientific expedition reached Clipperton. Despite several discrepancies in the grey literature, the consensus on the modern history of Clipperton is the following.

Table 1: Summary of the history of Clipperton island before 1958, which marks the beginning of modern scientific expedition.

cerca 1705	John Clipperton, is said to have approached the island, yet no text has ever been found confirming this assertion
1711	Discovery by French Martin de Chassairon and Michel du Bocage, first map established.
1839	New map established, showing two narrow and shallow passes
1858	French officer Le Coat de Kerveguen reports lack of passes and saline lagoonal waters suggesting the lagoon was closed by natural events between 1839 and 1858, (tsunamis or hurricanes).
1861	US officer Griswold report brackish lagoonal waters.
1892-1897	U.S. phosphate mining. First pigs and coconut trees brought to the island.
1897-1917:	Occupation by Mexicans. This ended the longest period of human settlement on the island. Various reports emphasize that the island was totally deserted with no vegetation cover, along with a huge abundance of crabs.
1931	Clipperton is internationally recognized as a French Territory
1935	First bathymetric chart (published 1937) of the lagoon by French hydrographers on-board the vessel Jeanne D'Arc. Aerial photographs were also acquired at this occasion highlighting increased vegetation cover. 58 pigs roam the island (in Sachet 1960).
1941	Opening of a narrow artificial passage on the eastern side of the atoll by US Navy, closed one year after. Construction of a small base and airstrip.

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The modern era of scientific investigation brought a new series of quantitative data and cartographic products, and some short periods of human settlement. To the best of our knowledge, there are 334 articles on Clipperton Atoll on land and lagoon aspects, although land reports are far more numerous (Jost 2005). These publications follow the few scientific missions that investigated the island. Four periods can be described. First, the results of the ornithological and vegetation-oriented Doldrums expedition of the Scripps Institution were released in 1958 and subsequent years (Sachet 1960, 1962a, 1962b, 1962c). Members of this expedition decided to eradicate the population of pigs to stop egg predation (Ehrhardt 1976). Bushy low vegetation was present on the island, with the exception of the north-eastern rim, wiped out by a hurricane in late 1957 (Sachet 1960). During the first nuclear tests in French Polynesia, the French Navy established the Bougainville settlement and a team of scientists studied the hydrobiology and the fauna of the atoll from late 1966 to 1969 (Niaussat *et al.* 1968 ; Ehrhardt & Niaussat, 1970; Ehrhardt 1971b). A conspicuous population of 11 million crabs *Gecarcinus planatus Stimpson* was reported (Ehrhardt 1968). In 1980, the Cousteau Society investigated various aspects of the atoll (Taxit 1981; Carsin 1987a, 1987b, Bourrouilh-LeJan *et al.* 1985a, 1985b). Finally, from the nineties to present, American and Mexican scientific investigations produced several publications (Glynn *et al.* 1996; Allen and Robertson 1997; Carricart-Ganivet and Reyes-Bonilla 1999a, Carricart-Ganivet and Reyes-Bonilla 1999b).

### “SURPACLIP” and “PASSION 2001” cruises

Two scientific trips occurred in 1997 and 2001. The Mexican cruise “SURPACLIP” on R/V Puma occurred in November 1997 to collect data on ecological and oceanographic conditions of the atoll (Carricart-Ganivet and Reyes-Bonilla 1999a) and along transects to the Revillagigedo islands and the Mexican coast. Assessment of bird populations during nesting periods and vegetation cover were carried out by one of us (CJ).

The French cruise “Passion 2001” occurred in February 2001 with the support of the French Navy vessel *Latouche Tréville*. The same observations as during SURPACLIP were repeated on vegetation cover and on birds’ population at the end of the nesting period (Jost 2003). Finally, geodetic first mark equipment and geopositioning measurements, collection of volcanic rocks and coral samples for dating were carried out.

Bird population was estimated during these two cruises during short periods of three days each. On several sections of the rim, such as the north-western part of the atoll, booby nests clearly appear as white dots on the IKONOS satellite panchromatic image. However, this data source was not used for validation because of the lag time between census and image acquisition. Census was made during day time by two teams of three persons. They focused on Masked Boobies and did not report systematically on other species. Census occurred using 20 x 20 meters quadrats in areas of high nest density, and 50 x 50 meters elsewhere. A total of fifteen quadrats has been established on the ring. Out of two to three quadrates per area of same apparent density, visually estimated, extrapolation to the whole sector of similar density was made. In late November 1997, during the plain nesting period without youths, only adults were counted, while in February 2001, adults and youths were counted separately. Under the hypothesis that during day time, one bird of the couple was at sea searching for food, the number of

adults was multiplied by two, and, in 2001, the youths were then added, providing the final figures in Table 3.

### **Satellite imagery and processing**

In the course of a program aimed at evaluating the potential of the IKONOS sensor launched in late 1999 for coral reef studies (Andréfouët *et al.* 2003), the Scientific Data Purchase Program (SDP) of the National Space and Aeronautics Administration (NASA) had Space Imaging Inc. acquire an image of Clipperton Atoll. It was collected the 7<sup>th</sup> July 2001, 4 months after the “Passion 2001” cruise.

An IKONOS image comprises a multispectral 4-band image at 4-meter resolution (blue, green, red and near infra-red, or NIR, bands) and a spectrally-wide Panchromatic band at 1 meter resolution. Geodetic accuracy (i.e. precision in latitude and longitude ) specification was  $\pm 12\text{m}$  providing excellent accuracy for mapping or planimetry work (Helder *et al.* 2003).

The image collected was not fully optimal. It included  $0.68 \text{ km}^2$  of clouds and cloud shadows that hide some of the lagoon and rim features. At the time of the acquisition, sea surface was rough around the island, with wind blowing and wave breaking around the outer reef flats, resulting in a poor visibility of the outer slope features. Many reports (e.g., Glynn *et al.* 1996) emphasize that waves almost continuously hit the atoll in every direction. The same patterns are visible on the IKONOS image.

The image was filtered according to the method described in Hochberg *et al.* (2003) to remove sea surface effects as much as possible. Since the analysis uses the NIR band to examine the sea surface state, the resulting image does not have a corrected NIR band, and all land or intertidal areas appear black on the corrected image (Fig. 2).

Segmentation of the blue and green filtered bands provided the limit and extent of the forereef. Outer reef flat limits were manually drawn following the outer limit of the breaking waves, thus at the upper limit of the spur and grooves (Glynn *et al.* 1996). Land limit was identified by thresholding the near-infra red band which provided the highest contrast between submerged and land targets..

After sea surface effects filtering, the features of the shallow lagoon were more visible. Supervised classification and segmentation were carried out to isolate the main different zones based on color and texture (Fig. 2). Ground-truthing of the main zones was conducted in January 2005 at the occasion of a survey dedicated to marine flora.

## **Results**

### **Atoll morphometry, reef geomorphology and benthic zonations**

The morphology of the rim corresponds almost entirely to a type of rim (named “Rim 9”) also identified on Tuamotu Archipelago (Andréfouët *et al.* 2001). This corresponds to a closed rim (i.e., no connections between lagoon and ocean, except possible interstitial exchanges through the carbonate basement of the atoll), without significant vegetation, dominated by carbonate material (coral rubble, mollusc shells and other skeletal debris),

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and with a narrow outer reef flat. According to the IKONOS image, the emerged part of the rim is 1.69 km<sup>2</sup>. Its outer perimeter is 11.8 km. Maximal rim width is 360 m (north-west) and minimum is 40m (north-east). Lagoon waters cover 7.84 km<sup>2</sup>, including the intertidal terraces covered by algae which provides a strong NIR signal (Fig. 2). The cloud free deep enclosed basins represent 3.04 km<sup>2</sup>. It seems that 0.09 km<sup>2</sup> cloudy on the image on the North of the largest basin, can be added to that surface without ambiguity.

A true color composite image based on the blue, green and red bands filtered for surface effects (glint) removal show different benthic zonations previously undescribed (Fig. 2). The interpretation of the image suggest that seven main different habitat occur (Fig. 2), in addition to the habitat made of intertidal marine flora that runs along two-third of the lagoon's shore (Fig. 2) and the deep areas (>5 meters) where no details were visible. Fifteen ground-truthing sites clarified the benthic community structure of Clipperton lagoon. The Table 1 provides a short description and the area of these seven classes. Algal, seagrass and cyanobacterial mats are dominant, among with remnants of coral colonies located especially in the G habitat class (Table 2, Fig.2). Shell debris cover the floor of classes A and G. The class I (Fig. 2) comprises a deeper platform too deep to see details and the intertidal algal terrace (1.69 km<sup>2</sup>).

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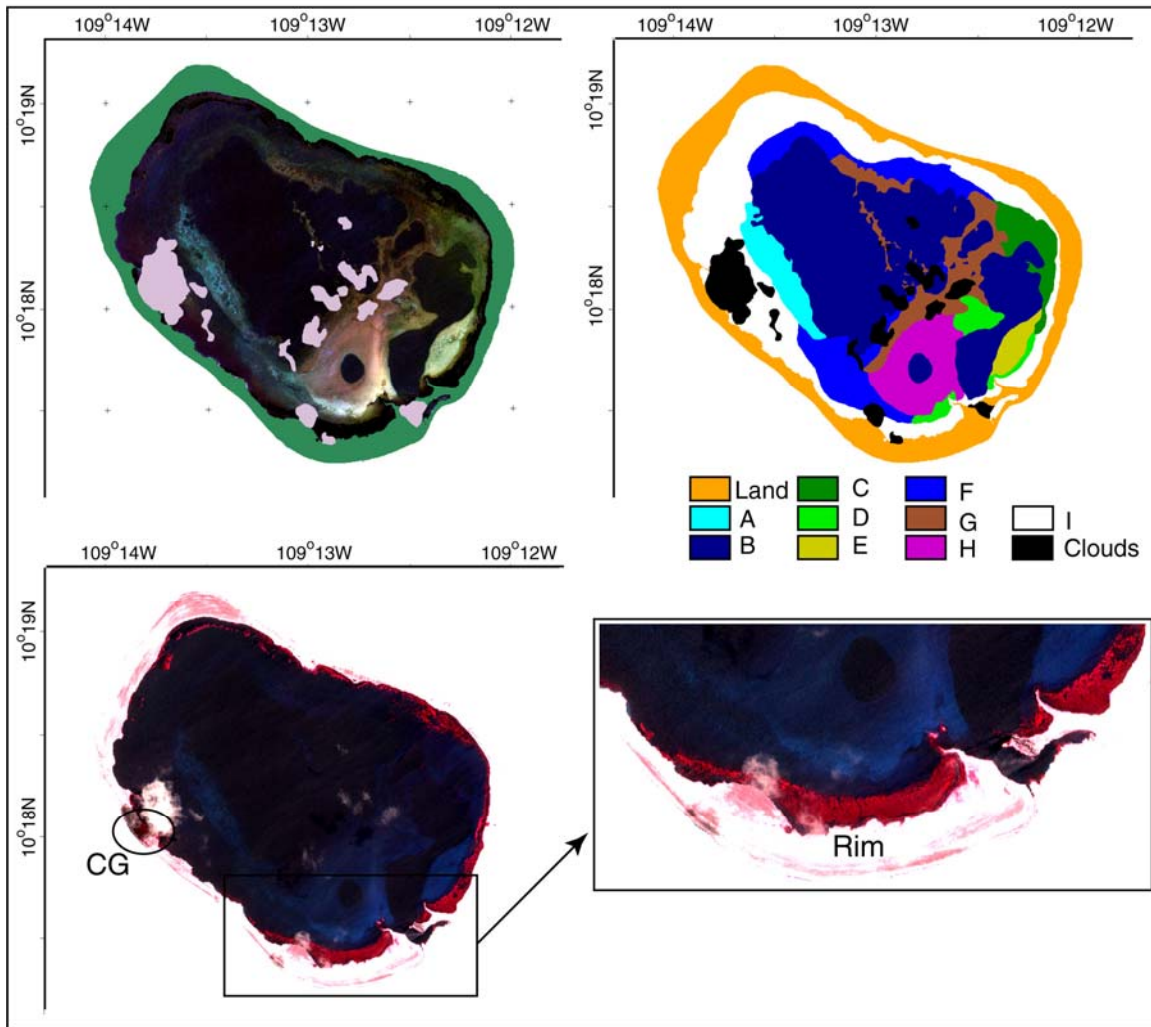


Fig. 2 : Lagoon features. Upper left, a composite of the glint-corrected Red, Green and Blue IKONOS bands. Land and clouds are masked. Upper-right: classification and segmentation of the main areas and habitats of the lagoon. See Table 2 for detailed caption of the classes. Lower left and lower right: composite of the original NIR, Green and Blue IKONOS bands. The intertidal terrace covered by algae have a strong response in the NIR due to the chlorophyll pigments (appearing red on the image). In contrast, the land NIR response is weak, highlighting the almost complete absence of vegetation, except around the coconut groove (CG) area (even partially obscured by cloud shadows).

On the oceanic side of the atoll, the outer reef flat covered 2.40 km<sup>2</sup>. The width and structure of the flats varied along the atoll. Cover is crustose coralline algae and <1% coral cover according to two transects reported by Glynn *et al.* (1996). Flats were wider (145m max.) on the southwestern side, with a structure similar to Tuamotu atolls, i.e. a well-developed crest separating flats and spurs and grooves. Conversely, the eastern rim, despite being the most exposed side of the atoll to waves and winds (Glynn *et al.* 1996), had virtually no outer reef flat, with waves breaking very close to the rim at high tide. The western tip of the atoll also lacked flats and crest, but presented a gentle-slope

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forereef. The northeast rim had intermediate features with a crest, but narrow flat (55m width max).

The outer slopes visible on the filtered image represented 1.17 km<sup>2</sup> (horizontal projection). It is not certain whether or not our limit reach the break of the “20-m terrace” described by Glynn *et al.* (1996). According to the six profiles and width of reef slopes given by Glynn *et al.* (1996), our limit captures mostly three zones. By order of increasing depth, these are the spurs and grooves, the pocilloporid and the first half of the poritid zone, around the 15m depth isobath. Deeper slopes (20-70m) and the agariciid coral zones on the “60-m terrace” are not visible on the IKONOS image.

The Table 2 summarizes the main geomorphologic and benthic surface areas.

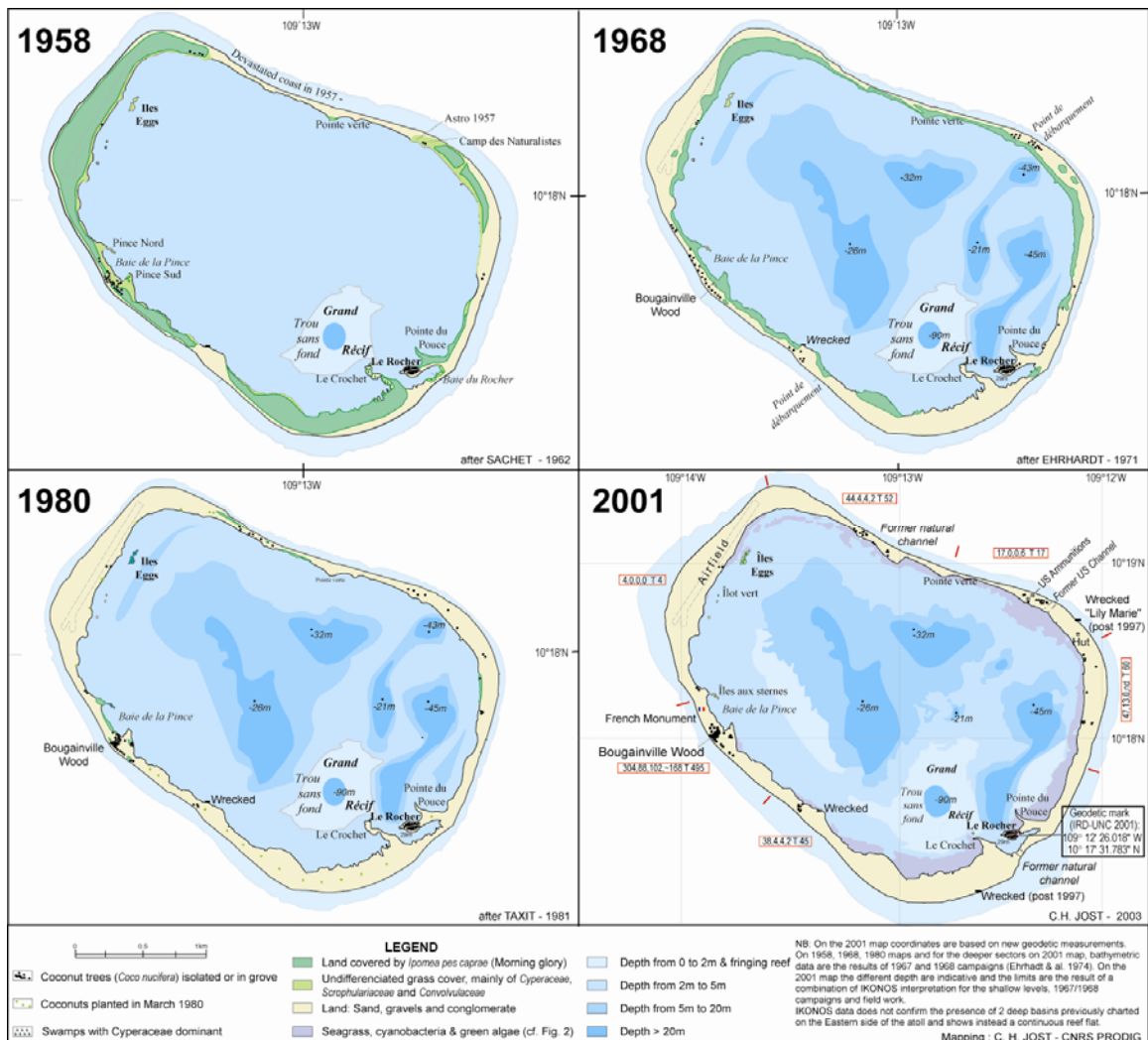
Table 2: Summary of the surface areas for the main marine geomorphological units and lagoon habitat.

Clouds		
(over lagoon area)	Lagoon habitat	0.68 km <sup>2</sup>
Lagoon habitats		
	60% of carbonate soft bottom (coral and shell debris), 40% of , fragmented patch of <i>Chara</i> spp and <i>Najas marina</i> var. <i>latifolia</i> ,	
A	1m<z<2 m	0.27 km <sup>2</sup>
B	Deep enclosed basins Hard bottom with <i>N. marina</i> and <i>Potamogeton pectinatus</i>	3.04 km <sup>2</sup>
C	beds, z<1.5m	0.24 km <sup>2</sup>
D	Transition zones between dense algae cover (90% <i>Chara</i> spp) and sediments, with cyanobacterial mat, z<1m	0.16 km <sup>2</sup>
E	Sediments with small patches of rock with <i>N. marina</i> , z=1m	0.11 km <sup>2</sup>
F	Heterogeneous cover, <i>N. marina</i> dominant and isolated small dead coral colonies, z>2m	0.70 km <sup>2</sup>
G	Micro-basins with shell debris, and dead coral framework covered by <i>N. marina</i> , <i>Chara</i> spp, <i>P. pectinatus</i> , 1m<z<2m	0.48 km <sup>2</sup>
H	Sediment floor with continuous mid-density <i>Chara</i> , z<1m	0.47 km <sup>2</sup>
I	(no data: too deep or post-glint filtering) Deep terraces (z>2m) and intertidal terrace covered by dense continuous algae beds ( <i>Zostera maritime</i> var. <i>latifolia</i> , <i>N. marina</i> ), z<1m	1.69 km <sup>2</sup>
Total lagoon		7.84 km <sup>2</sup>
Land		1.70 km <sup>2</sup>
Outer reef flats		2.40 km <sup>2</sup>
Outer slope (0-20m)		1.17 km <sup>2</sup>

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### Changes in vegetation

According to the previous reports, the two coconut trees imported in 1897 provided around 40 trees in three groves by 1935 (Gauthier 1949). During these decades, shrub and grass vegetation was abundant and covered the rim of the atoll almost entirely, as evidenced by aerial photographs (not shown) and ground photographs from Taylor (1948). In 1958, the vegetation cover appeared as dense as in 1935, and may have been slightly more abundant, with as much as 80% cover in the South and West of the atoll (Fig. 3) (Sachet 1962c). Sachet (1962c) report mostly *Ipomoea pes-caprae*, plants of the Convolvulaceae family. Conversely the northern rim of the atoll is depleted from any vegetation, likely due to a 1957 storm impact (Sachet 1960). In 1967-1968, there was a drastic reduction in vegetation cover around the atoll (Fig. 3) (Ehrhardt 1971b). The main coconut grove (named Bougainville Wood) was healthy with as much a 150 trees, for a grand total of 590 trees inventoried around the atoll. In 1980, Taxit (1981) identified only few patches of shrub and a few coconut trees in the eastern rim and around Baie de la Pince. Attempts in 1980 to regenerate the coconut grove between Bougainville Wood and Le Rocher failed since most of the new plants were not visible by 1982 (Fig. 3).



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Fig. 3 : Bathymetry and vegetation cover in 1958, 1968, 1980 and 2001 compiled from various publications and from in situ observations (see text for details). The 1958 map shows a healthy vegetation cover except where hurricane-generated waves struck in 1957. The 2001 shows a rim completely depleted of any vegetation except 674 coconut trees. The red boxes detail the census per sector according to the size and status of the trees (>5m, 2-5m, <2m, dead, T:total alive). For the entire atoll, we report: 454, 109, 111, 168, T=674. Note also the discrepancy in isobaths, with previous reports of two 21m and 43m deep basins in the East of the atoll. The 43m basin was not found in the 1997-2001 surveys, neither on the IKONOS image. The 21m basin was mis-located.

In November 1997, with SURPACLIP expedition, Jost (2003) reveal a rim totally depleted of any vegetation except coconut trees. In February 2001, 674 coconut trees (454 taller than 4 meters high, 110 between 2m and 4m, 111 smaller than 1m; 479 in Bougainville Wood alone) were counted. No other species on the rim occurred (Jost 2003) (Fig. 3). Only six of the ten lagoon islets were still covered by some vegetation, mostly Cyperaceae, some Scrophulariaceae, and some Convolvulaceae such as *Ipomoea littoralis* but no more *Ipomoea pes-caprae*. In 2001, changes were not drastic compared to 1997, yet we noticed in the dry period the reduction of the vegetation cover in one of the two Sterne islets. Flora observations on Eggs Islands only revealed half a dozen species on these islets. Patterns during the rainy season may be slightly different and some patches of Convolvulaceae may reappear around the Bois de Bougainville as seen in March 2005.

Field observations are confirmed by the IKONOS image acquired in July 2001. The NIR band, or a Normalized Difference Vegetation Index (NDVI) computed with the multispectral original image, indicates that dense vegetation along the rim is limited to the coconut grove (CG, in Fig. 2).

### Changes in bird population

Avian survey in 1958 (Stager 1964), 1968 (Ehrhardt 1971a and 1976), 1980 (Taxit and Ehrhardt 1981) and 1997-2001 (Jost 2003) are disparate. Only Ehrhardt (1971a and 1976) reported clearly the July 1968 census method, by counting the total bird population simultaneously at sunset (to limit the number of birds fishing at sea) on 8 sections of the atoll. In 1997-2001, surveys were not exhaustive throughout the atoll, but stratified by nest densities since the time allowed on the atoll was short. Ehrhardt (1971a and 1976) reported that the 1968 census raised to 40 the number of species known on Clipperton, out of which only 11 lived there permanently. Howell et al. (1993) report 80 species of migrants for the island, not including breeding birds. The observations of the various boobies' population suggest changes in bird community structure (Table 3), with shift to dominance of one specie, and increase of the total bird population.

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Table 3: Evolution of bird population according to historical data and 1997, 2001 *in situ* partial observations

Family	Species	Nov. 1901	Aug. 1958	July 1968	Mar.1980	Nov. 1997	Feb. 2001
		Beck	Stager	Ehrhardt	Taxit & Ehrhardt	Jost	Jost
<b>Sula</b>	Masked Booby ( <i>Sula dactylatra</i> )	several thousands	<150	4 239	8 000	~ 100 000	~ 110 000
	Brown Booby ( <i>Sula leucogaster nesiotus</i> )		<500	15 300	25 500		
	Red foot Booby ( <i>Sula sula</i> )		occasional	293	450		
<b>Anous</b>	Brown Noddy ( <i>Anous stolidus ridwayi</i> )		abundant	3 374	150-200		
	Lesser Noddy ( <i>Anous tenuirostris diamesus</i> )		abundant	1 374	0		
<b>Tern</b>	Sooty Tern ( <i>Sterna fuscata crissalis</i> )		~1000	200	0		
	Common White Tern ( <i>Gygis alba candida</i> )		50	10	4		
<b>Fregata</b>	Great Frigate bird ( <i>Fregata minor minor ridwayi</i> )		~250	642	1000-1300		
<b>Coot</b>	American Coot ( <i>Fulica americana americana</i> )		-	200	-		
<b>Tringa</b>	Lesser Yellow legs ( <i>Tringa flavipes</i> )		-	14	-		
	Greater Yellow legs ( <i>Tringa melanoleuca</i> )		-	6	-		
<b>Phaeton</b>	Red-tailed Tropic Bird ( <i>Phaeton rubricauda melanorhynchos</i> )		occasional	6	0		
<b>Puffinus</b>	Wedgee-Tailed Shearwater ( <i>Puffinus pacificus</i> )		-	4	0		
<b>TOTAL</b>		<b>thousands</b>	<b>2 000</b>	<b>25 662</b>	<b>33 954</b>	<b>N/A</b>	<b>N/A</b>

Between 1958 and 1968, bird population seemed to increase for each permanent species. For instance Brown Booby *Sula leucogaster* went from ~500 in 1958 to 15,300 individuals in 1968. At that time *S. leucogaster* was the dominant species. In 1997 and 2001, Masked Booby largely dominated the bird population. Red Footed Booby, *Sula*

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*sula*, reported in expansion by Ehrhardt (1976) was not observed in 1997-2001 but this specie may have been overlooked during our census. Both 1997 and 2001 observations suggested more than 50,000 Masked Booby individuals on ground, while Taxit and Ehrhardt (1981) reported only 8,000 individuals (Table 3). If we correct our census data by a factor two to compensate for the bird population fishing at sea as suggested by Pitman (1995), the total population in 1997-2001 could be as high as ~100,000 Masked Boobies. These estimates are confirmed by census performed on aerial photographs making the Clipperton atoll population the most important in the world (Pitman pers. comm.).

### **Discussion: Clipperton Atoll, a changing low diversity ecosystem**

Clipperton is characterized by low floral and faunal diversity. From 1997-2001, land fauna was characterized by high abundance of only two dominant species: Masked Boobies and the crabs *Gecarcinus planatus Stimpson*. These two species colonize a rim where only coconut trees were present in 2001. Dominance of these few species can be explained by a series of events, both natural and human-induced, even though the cumulated time of human settlement is low during the last century.

In terms of vegetation cover, the most likely sequence of events leading to the return to the current barren state is the following. In 1968, ten years after the last pigs were killed, the crab population was estimated to be 11 million individuals (Ehrhardt, 1968) or ~6.5 individuals/m<sup>2</sup> of land over the entire rim. With pigs gone, the population of seabirds increased as suggested by Ehrhardt (1968), explaining the differences between 1958 and 1968 bird census. But eliminating pigs from the island also eliminated the only crab predator. After 1958, the bird and the crab population increased. The crab first fed on the resources easily available, i.e. vegetation, coconuts, young coconut shoot, algae and phanerogames from the lagoon, while the Convolvulaceae *Ipomea pes caprae* seemed not to be touched by them (Niaussat, 1986). They also fed on eggs, young isolated birds, dead animals and even on each others (Niaussat, 1986). With the vegetation gone, crabs feed on the fallen coconuts, dead birds and bird eggs. Otherwise, they survive by grazing seagrasses and algae on the intertidal terraces bordering the lagoon. The high productivity of the lagoon and continuous renewal of the intertidal macrophyte biomass is an easy and abundant food source to maintain the crab population. Under the crab feeding pressure the land ecosystem returned to a desertic stage similar to what was reported before 1935.

The eradication of the pig population clearly benefited the seabird population, with steady increase of booby population since. In addition to the overall rise in bird population, census data suggest a shift of dominance from Brown Boobies to Masked Boobies in the post-pig years. Unlike Masked Booby, Brown Booby population seems stagnant, with 25,500 individuals in 1980 (Taxit and Ehrhardt 1981), to ~20,000 in 2001 (Pitman, pers. com.). First, different feeding behaviors (off-shore vs onshore) and extent of available feeding grounds around Clipperton favor Masked Boobies (Pitman, pers. comm.). Second, we suggest that bare soils and desertification favor the ground-nesters Masked Booby. Finally, though this needs to be quantified, another reason for this shift can be the differential behaviors of each species when confronted to voracious crabs. It is reported, and confirmed by our own observations, that Masked Booby behaves far more aggressively in front of crab attacks (or human visits) compared to Brown Boobies.

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Taylor (1948) reported Masked Booby attacking pigs on ground and from air, showing the defensive capacity of this species. Conversely, Brown Booby seems more prone to abandon his nest and chicks. With the constant pressure of the crab population, we suggest that this behavior may partly explain the shift in bird community structure.

In the case of Clipperton, the role of the pigs was both beneficial and negative. The positive side was the control of the crab population, resulting in healthier vegetation cover also due to limited bird population. In contrast, the impact of pig predation on bird nests was high (Sachet 1962, Taylor 1948) and is a main factor explaining the low bird population density reported in 1958, before the pig eradication (Pitman 1996).

Low diversity is reported by Glynn *et al.* (1996) for the outer coral reef slopes and by Bourrouilh-LeJan *et al.* (1985) for the lagoon. Molluscs and fish population were surveyed by Salvat and Ehrhardt (1970) and Robertson and Allen (1996) respectively. The marine environment of the lagoon is very poor. Even if we have detected much more lagoon habitats in Clipperton than what was previously described, the composition of these habitats is made of the same limited number of previously reported benthic species (Table 2). Only the floral density, type of substrate and vertical architectural structure due to fossil coral framework differentiate the habitats. Many other isolated and/or closed atoll lagoons also present a low lagoonal diversity (Salvat, 1971; Adjeroud *et al.* 2000). For example, in Fangatau atoll, French Polynesia, and several other Eastern Tuamotu Archipelago atolls, one species of clam (*Tridacna maxima*) also dominates and carpets the lagoon floor (Andréfouët *et al.* 2005). However, the analysis of 20 years of benthic changes in the uninhabited Taiaro Atoll in French Polynesia, noted that the low diversity did not imply stability since the dominant mollusc species changed over 20 years, from *Crassostrea cucullata* to *Pinctada maculata* (Adjeroud, 1997). In Taiaro, the natural mechanisms explaining the changes remain unknown. In Clipperton, changes in lagoon communities likely occurred after the closing of the passes and stratification of the waters, which were natural events.

In Clipperton, the oceanic slopes are covered by 18 reef-building corals, while other isolated atolls of the Pacific can reach higher numbers (e.g., 33 species at Johnston Atoll, Maragos and Jokiell 1986). To the best of our knowledge, no direct human perturbations, except possible unreported destructive fishing practices, could cause significant impacts on the outer slopes reef communities. There is no reported evidence that this is the case. Only offshore fish resources (tuna, sharks, etc...) seem to be targeted by authorized and unauthorized fishing vessels. The literature review suggests that the biodiversity inventory of the oceanic slopes of Clipperton is not exhaustive, since each new investigation reports new species (Carricart-Ganivet and Reyes-Bonilla 1999b). Therefore, it is difficult to discuss quantitatively any changes for the oceanic component of the Clipperton seascape. Coral bleaching, which has been devastating in coral reefs worldwide in 1998 and 2000 may have partially impacted the local communities. Coral bleaching is a global phenomenon, qualified as natural since it is mostly explained by the elevation of Sea Surface Temperature (SST), a global change process (Hoegh-Guldberg 1999). Coral bleaching in 1987 and 1991 have been pointed out as the likely explanation for mortalities observed in Clipperton outer slopes (Glynn *et al.* 1996). The most recent

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report (Carricart-Ganivet and Reyes-Bonilla 1999b) did not discuss recent mortality patterns, thus it remains unknown if the 1998 or 2000 ENSO events and elevated SST had an impact or not on Clipperton. However, if massive mortality had occurred, it is likely that the SURPACLIP investigators would have observed and reported it.

### **Conclusion: the future of Clipperton Atoll ?**

One goal of this brief review and reexamination of Clipperton ecosystems is to provide a sound basis to discuss the future of Clipperton and raise awareness on the future of a delicate ecosystem. Accurate values of surface areas, as provided here, are necessary to estimate the value of the ecosystems and the carrying capacity of the atoll in case of “restoration” of the lagoon. Indeed, mostly because of the economic pressure due to fisheries, France has authorized in August 2005 the EEZ exploitation, and there have been several proposals to re-establish a permanent human presence on the island (Aubert and Revillon 1984, Auger 1988, Jost 2003). The logistical aspects of such initiative also imply the re-opening of the lagoon to allow easier access to safe lagoonal waters and moorings. In fact a natural reopening of the eastern ancient pass seems to be slowly occurring and could be accelerated in case of rising sea level. Clearly, the natural or human-induced reopening of a pass would mean the destruction of the current ecosystem, which is unique on Earth. For scientific and conservation reasons, human settlement and lagoon reopening would destroy an ecosystem that is returned to pre-settlement conditions, even if one may argue that studying the change due to the reopening would be scientifically enlightening, and the results more aesthetic. But the cost would be the quick loss of a unique ecosystem, and, regarding the lagoon component, it would be the termination of an isolated ecosystem only modified by natural phenomenon thus far. On the other hand, strategic and economic aspects may dictate a permanent human presence which will provide its own benefits, including a better control of the offshore pelagic fishery resources, land vegetation and fauna.

A temporary solution may be the establishment of a scientific observatory of the environment, designed to impact the ecosystem as little as possible, and provide long-term time-series of information on the land, lagoon and oceanic environments. Many of the processes that we have suggested here (e.g. crabs and bird species interaction, coral bleaching occurrences) need to be tested experimentally or validated by long-term observations. The data we have compiled are uneven but indicate dramatic ecological changes. We can not go back in time to make consistent time-series, but it is still possible to initiate new ones to help understanding better the equilibrium of this unique atoll.

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