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# Expansion of macroalgae forests and gains in Blue Carbon at Caleta Potter, Antarctica

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## Abstract

*In the western Antarctic Peninsula, glacier systems have retreated as a result of a temperature increase of approximately 2°C over the past 50 years. This process has led to the formation of "new ice-free areas" (NALH) which are suitable for the colonization of benthic marine algae, as observed in the case of Caleta Potter in response to the significant retreat of the Fourcade Glacier. Studies were conducted to estimate the expansion of macroalgae and gains in Blue Carbon in recently ice-free areas, focusing on the spatial and vertical distribution of macroalgal communities, colonization processes, and the succession in the NALH of Caleta Potter. The Fourcade Glacier has retreated ~1.5 km^2 since 1956 and our estimates indicate colonization and expansion of macroalgae in NALH of ~0.005-0.012 km^2 with a carbon storage of ~0.2-0.4 tons C per year. Beneath the Antarctic Sea lies a unique life adapted to extreme temperature and light conditions. Antarctic macroalgae are true ecosystem engineers, creating and modifying habitats whilst also providing shelter and protection to a variety of marine organisms. In the context of climate change, continued colonization and expansion of macroalgae is expected, leading to significant changes in primary productivity and trophic chains in Antarctic coastal systems.*

## Keywords

**Climate change, New ice-free areas, Coastal ecosystems, Antarctic Peninsula, Conservation.**

## Introduction

The Antarctic continent, located in the southern hemisphere, has remained isolated for over 40 million years. The formation of the Drake Passage definitively separated the Antarctic Peninsula from southern South America and favored the formation of the Antarctic Circumpolar Current (Scher and Martin, 2006). Since then, these events have contributed to the cooling of the region, with the lowest air temperatures recorded on Earth reaching -89.2°C in 1983 at Vostok Station (Peck et al., 2005), strong winds, and the formation of large glaciers. In these environments, unique ecosystems are found with a great diversity of organisms specially adapted to these extreme conditions. Antarctic macroalgae are an example of this, having evolved and being particularly adapted to living at very low temperatures (~0°C) and the marked seasonal light availability in the region, with many hours of darkness in the winter months, and extensive hours of daylight in the summer (Wiencke et al., 2014).

Antarctica is one of the regions most severely affected by phenomena associated with global climate change (Clarke et al., 2007; Hendry et al., 2018; IPCC, 2021; Chown et al., 2022). Over the past 50 years, the western Antarctic Peninsula (AP) has experienced a rapid increase in air temperature, significant glacier retreat, and a clear decrease in the duration and extent of sea ice cover (Meredith et al., 2005; Turner et al., 2009; Stammerjohn et al., 2012; Cook et al., 2016).

Glacier retreat and melting significantly affects the pelagic and benthic communities of coastal ecosystems in western AP (Barnes and Peck, 2008; Schofield et al., 2010; Torre et al., 2012; Ducklow et al., 2013; Sahade et al., 2015; Jerosch et al., 2019; Moon et al., 2015). Many of the environmental changes associated with the effects of climate change have already been detected and are expected to strongly influence the structure and function of benthic marine communities in the region (Barnes and Conlan, 2007; Smale and Barnes, 2008; Constable et al., 2014; Lagger et al., 2018). In many ways, the effects of global warming on macroalgal communities are and will be caused, not only by the temperature increase itself, but also by indirect changes it causes in the environment. The western Antarctic Peninsula has become a model area for studying glacier retreat on the effect of coastal biota in a climate change context (Smith et al., 2008).

Macroalgae play a crucial role in marine ecosystems and represent an ideal study subject due to their fundamental role in benthic biodiversity hotspots in western AP (Deregibus et al., 2017; Pellizzari et al., 2020). Additionally, they play an important role in oxygen production and carbon dioxide (CO2) absorption from the atmosphere (Runcie and Riddle, 2012; Wiencke and Amsler, 2012; Gómez and Huovinen, 2020). Macroalgae are true ecosystem engineers (Fig. 1), their presence creates and modifies underwater habitats and provides shelter and protection to a variety of organisms such as fish, crustaceans, and mollusks (Amsler et al., 2005; Constable et al., 2014; Moreira et al., 2014; Marina et al., 2018; Barrera Oro et al., 2019; Campana et al., 2020).

In the last decade, there has been an emphasis on studying the carbon cycle (fixation, storage, and sequestration) leading to the emergence of the concept of Blue Carbon. In this context, macroalgae not only play an essential role as CO2 fixers, but also in carbon storage in their biomass and subsequent sequestration in phytodetritus present in sediment. Glacier retreat in Antarctica has created new areas available for colonization by benthic organisms such as macroalgae and invertebrates (Sahade et al., 2015; Lagger et al., 2017, 2018; Quartino et al., 2020; Barnes et al., 2020; Fig. 1). Benthic colonization leads to increased uptake of atmospheric carbon and negative feedback to the process of climate change, making it important to study the diversity, biomass, and primary production of Antarctic macroalgae. Although our understanding of carbon sequestration processes by seaweed remains limited, it has been identified that macroalgae are globally important in both carbon capture and exportation (Krause-Jensen and Duarte, 2016).

**Figure 1.** *Macroalgae and invertebrates in the benthic marine ecosystem of Caleta Potter, Antarctica.*

**Caleta Potter: a natural lab**

In Caleta Potter (25 de Mayo Island, South Shetland Islands, Fig. 2), where the Carlini Scientific Base is located, a marked retreat of the Fourcade Glacier surrounding the inlet has been observed (Rückamp et al., 2011) exposing rocky areas without ice potentially suitable for colonization by macroalgae, but also affected by meltwater and sedimentation (Neder et al., 2022). There, the "Antarctic Macroalgae" research group of the Argentine Antarctic Institute carries out various studies to describe and quantify the effect of disturbances associated with glacier retreat on the macroalgae community. Initial observations showed a remarkable presence of algae in sites where they were not previously present, and they were even recorded growing in highly disturbed areas near the glacier (Quartino et al., 2013). Macroalgae mainly depend on hard substrate and favorable light conditions to settle, grow, and develop (Zacher et al., 2009; Wiencke and Amsler, 2012; Campana et al., 2020). In these recently ice-free areas, a negative relationship between light penetration and the complexity of macroalgae assemblages present has been documented (Quartino et al., 2020). Caleta Potter, with its constantly changing ecosystem, serves as an invaluable natural laboratory for investigating how macroalgae face the challenges of climate change.


**Figure 2.** *Fourcade Glacier surrounding Caleta Potter, where its melting during the summer of 2023 can be observed, contributing sediments and freshwater to the water column. Photograph by SIGMA Project.*

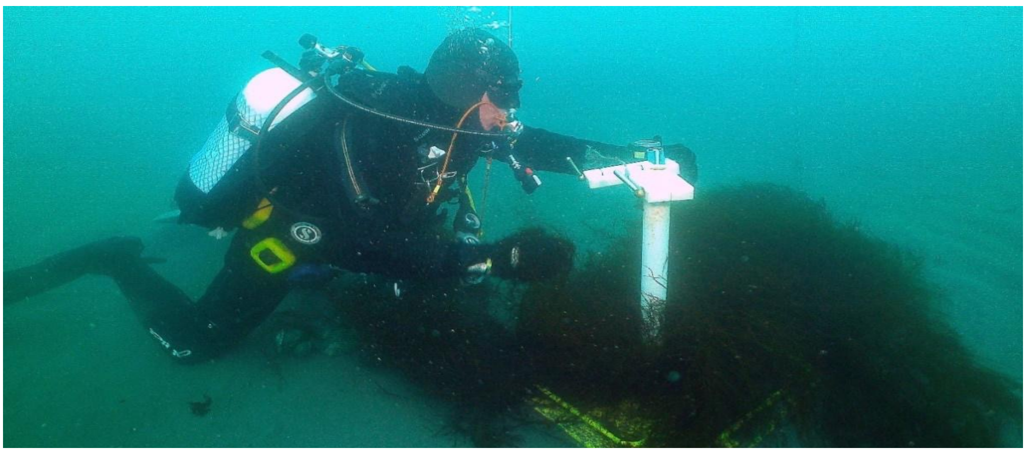

**Figure 3.** *Diver performing underwater light sensor check in Caleta Potter.*

One of the recent objectives in Caleta Potter has been to estimate the expansion of macroalgae and gains in Blue Carbon in NALH (Deregibus et al., 2023). To this end, some of the research lines developed involve (1) measuring environmental variables in the water column, especially the measurement of photosynthetically active light which is fundamental for macroalgae to perform photosynthesis, and thus grow and survive (Fig. 3), (2) characterizing macroalgae assemblages in terms of diversity and biomass at different sites in Caleta Potter with varying glacial influence, (3) conducting experiments on colonization and succession of Antarctic macroalgae, (4) calculating the loss of marine area from the Fourcade Glacier over the last decades, and (5) estimating the colonization and potential expansion of macroalgae in NALH using species distribution models.

## EXPANSION OF MACROALGAE FORESTS IN NEW ICE-FREE AREAS

Among the most important results highlighted in this study is the retreat of the Fourcade Glacier by ~1.5 km^2 since 1956, altering the landscape of one of the most studied fjords in Antarctica, Caleta Potter (Fig. 4). Through in-situ colonization studies and univariate spatial analysis for species distribution, a potential expansion of macroalgae of 0.45 ± 0.06 km^2 since 1956 was estimated (Fig. 5). Specifically, in the new ice-free areas, an expansion and colonization of macroalgae of ~0.005–0.012 km^2 with an annual carbon storage in their biomass of ~0.2–0.4 tons C was estimated (Deregibus et al., 2023).

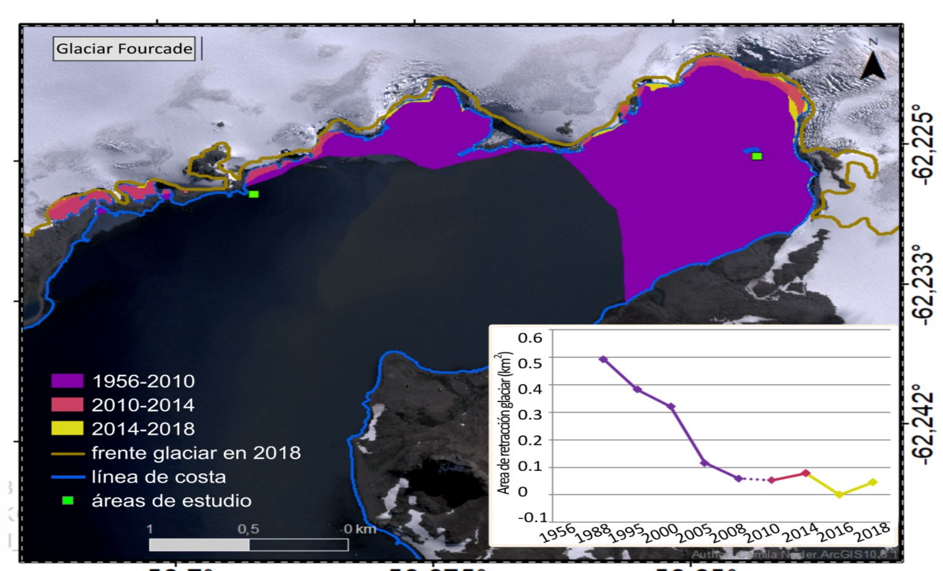


**Figure 4.** *Retreat of the Fourcade Glacier in Caleta Potter, 25 de Mayo Island/King George Island, Antarctica. The colored lines indicate the glacier retreat during three different stages between 1956 and 2018 (represented in purple, pink, and yellow areas).*

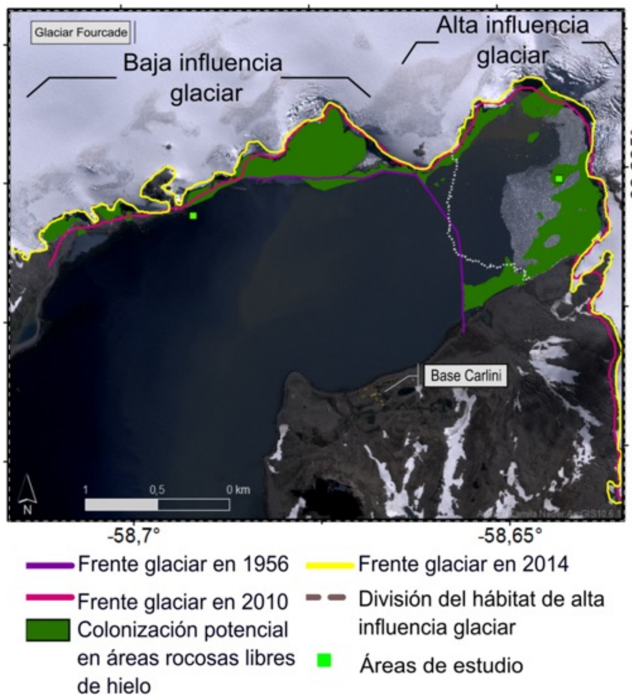


**Figure 5.** *The green region in the image represents the potential area for colonization and expansion of macroalgae following glacier retreat (modified from Deregibus et al., 2023).*

## BLUE CARBON, CLIMATE CHANGE, AND CONSERVATION

Climate change is one of the most pressing challenges facing our planet today and its effects impact countless places on Earth. A wide variety of biological responses are expected in relation to the loss of ice and snow in polar regions, both in terrestrial and marine environments.

Among some of the effects, changes in the primary production of Antarctic coastal ecosystems are highlighted not only in phytoplankton (Schloss et al., 2002), but also in macroalgae (Deregibus et al., 2016) in response to glacier melting, resulting in lower benthic primary production (Braeckman et al., 2021). Conversely, other studies have revealed significant phytoplankton blooms (Schloss et al., 2014) and increased productivity by macroalgae, as these organisms are rapidly colonizing newly ice-free areas (Quartino et al., 2013). Additionally, it is likely that the decrease in the extent and duration of sea ice will lead to an increase in light availability, causing ecosystems to transition from predominantly heterotrophic to autotrophic states (Clark et al., 2013). With the increase in macroalgae and microalgae production, herbivores would have no restrictions on their food sources (Amsler et al., 2019). These studies, combined with research that includes the effect of other factors such as substrate, ice disturbance and sedimentation, duration of frozen sea, species competition, life cycle, and herbivory among others, are crucial for predicting the evolution of Antarctic coastal ecosystems in the context of global change.

Coastal areas play a fundamental role in providing highly valuable ecosystem services (Barbier et al., 2001) including Blue Carbon which is captured and stored as biomass. This carbon is ultimately sequestered in sediments emerging as a crucial service for climate regulation (Laffoley and Grimsditch, 2009; Chung et al., 2011; Krause-Jensen and Duarte, 2016; Krause-Jensen et al., 2018; Queirós et al., 2019; Barnes et al., 2020; Zwerschke et al., 2021). Macroalgae, with remarkable responsiveness to environmental changes and high productivity, could be colonizing new ice-free areas in fjords located at higher latitudes of the AP, both currently and in the future. The decrease in the duration and extent of frozen sea in polar regions has driven the expansion of macroalgae forests (Bartsch et al., 2016; Clark et al., 2013; Clark et al., 2017; Deregibus et al., 2020), potentially increasing their contribution to carbon sinks in Antarctic coastal zones (Quartino et al., 2020). However, the fact that we still have a limited understanding of carbon sequestration processes by macroalgae and their associated species (e.g., how much is likely to be sequestered, where this would happen, etc.), leads us to continue these investigations to achieve a better understanding of the effects of Blue Carbon and climate change mitigation (Gogarty et al., 2019; Dolliver and O'Connor, 2022).

Consequently, our research serves as a tool that can contribute to decision-making in conservation and management spaces of ecosystems in this unique region in the world. This type of data and results are very useful for informing processes within the framework of the Antarctic Treaty (e.g., projects of international scientific cooperation in Antarctica; processes for the establishment of protected areas); Scientific Committee for Antarctic Research (SCAR); The Southern Ocean Observing System (SOOS), etc.), and beyond this (e.g., Intergovernmental Panel on Climate Change (IPCC)). The conservation of Antarctic benthos is necessary due to its unique and high biodiversity, and because it provides solid Blue Carbon ecosystem services that potentially play a role in mitigating CO2 emissions (Chown et al., 2022; Morley et al., 2022). These studies indicate that the effects of climate change continue to stress and impact coastal ecosystems in the AP. This underscores the importance of protecting AP ecosystems, reinforcing the importance of adopting the proposal of the Marine Protected Area in the so-called Domain 1 (MPA1) (CCAMLR-42/26), which includes the Western Antarctic Peninsula and South of the Scotia Arc, led by Argentina and Chile under these scenarios of environmental changes and increased human activity in that region.

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