USING LANDSAT-DERIVED WATER QUALITY DATA TO SELECT AQUACULTURE SITES IN TONGOY BAY, CHILE

Carlos Lara[1], Amalia Detoni[2], Felipe Torres[1], Bernardo R. Broitman[3], Aline De Matos Valerio[4]

[1]Departamento de Ecología, Universidad Católica de la Santísima Concepción, carlos.lara@ucsc.cl, ftorres@doctorado.ucsc.cl; [2]Instituto Milenio en Socio-Ecología Costera (SECOS), Santiago, Chile, amaliadetoni@gmail.com, [3] Departamento de Ecología, Facultad de Artes liberales, Universidad Adolfo Ibañez, campus Viña del Mar, Chile, bernardo.broitman@uai.cl; [4]National Institute for Space Research, Av. dos Astronautas, 1758, São José dos Campos - SP, Brazil, aline.valerio@inpe.br

ABSTRACT

Coastal shellfish aquaculture in Tongoy Bay, Chile, experiences significant interannual variability in scallop larval supply, with the underlying drivers remaining unclear. This study uses Landsat-8 and Landsat-9 imagery from 2023, corrected atmospherically using Acolite and derived water quality parameters such as sea surface temperature, turbidity and chlorophyll-*a* concentration (Chl-*a*). These parameters were used as inputs for the Oyster Suitability Index (OSI). Additionally, OSI images were classified into quartiles, identifying pixels consistently within the highest-value quartile to assess the stability of potential aquaculture areas over time. Results reveal high OSI values near zones with elevated phytoplankton biomass, suggesting temperature as a primary driver affecting both OSI and larval development. These findings highlight remote sensing potential as a powerful tool to assess aquaculture conditions in real-time. However, further studies are needed to understand the long-term impacts on larval supply and overall productivity in these ecosystems.

Key words: Aquaculture; oyster; shellfish; Chile; productivity; ocean color remote sensing.

1. INTRODUCTION

Shellfish aquaculture currently accounts for approximately 45% of global aquaculture production, and it is projected to increase to 53% by 2050 [1]. Rapid population growth, the constraints on terrestrial food production systems, CO_2 emissions constraints, and the increasing demand for high-quality foods, such as protein and fatty acids, are set to challenge current production systems [2–4]. In this context, understanding the impacts of climate change on biological resources is crucial for aquaculture [5].

In mid- and high-latitude ecosystems, rising sea surface temperatures (SST) and chlorophyll-*a* concentrations (Chl-*a*) significantly affect the physiological performance (e.g., growth and survival) and recruitment (e.g., reduced reproductive output) of bivalves [6,7]. Over time, these changes may alter the suitability of bivalve habitats [8].

In Chile, the production of scallops and mussels relies on the capture of wild seed [9,10], with Tongoy Bay being the country's main producer of *Argopecten purpuratus*. However, fluctuations in scallop supply have led to the collapse of this fishery [10,11]. Multiple processes have been associated with the decline of *A. purpuratus* production. Scallop cultivation, for instance, depends on multiple ecosystem services (i.e., spat and food supply from the natural environment), synchronized with local environmental processes (e.g., Chl-*a* and SST) over seasonal and inter-annual scales, including El Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) forcing [12]. These combined drivers complicate efforts to distinguish the effects of climatic and local environmental factors on larval supply at different time scales.

The selection of seed collection sites and cultivation areas within optically complex coastal marine systems is essential for sustainable oyster farming [12]. Ocean color remote sensing can effectively be employed to characterize key water-quality parameters (e.g., Chl-*a*, colored dissolved organic matter, and suspended particulate matter), facilitating the mapping and selection of suitable shellfish farming sites at a local scale [13–15]. In this study, we explore the potential use of OSI (Oyster Suitability Index) based on Landsat-8 and Landsat-9 imagery. We hypothesize that the suitability index varies spatially and temporally in Tongoy Bay, northern Chile during 2023.

2. MATERIAL AND METHODS

Tongoy Bay is situated along the semi-arid coast of northern--central Chile (Figure 1). This small equatorward-facing bay is sheltered from upwelling favorable winds, which are intensified by the large headland center of Punta Lengua de Vaca (PLV) that closes the bay to the west. The PLV headland is the largest upwelling center in the northern-central section of the coastline and is associated with high coastal productivity [11,16]. Aquaculture in Tongoy Bay primarily focuses on the Peruvian bay scallop, *Argopecten purpuratus*, which accounts for 90% of the total scallop production in Chile [17].

Due to the small area of Tongoy Bay, we decided to use Landsat-8 and Landsat-9 imagery, which have a spatial resolution of 30 m, making them suitable for our study area. We downloaded images from the United States Geological Survey (USGS) portal (https://earthexplorer.usgs.gov/) and selected those with less than 25% of cloud cover, resulting in a total of 14 images from 2023. These images were atmospherically corrected using the standard ACOLITE processor, that is indicated for coastal waters [18].

Water quality parameters such as SST, Chl-*a*, and turbidity were obtained from the Operational Land Imager sensor (OLI) and thermal infrared sensor (TIRS) aboard Landsat-8 and Landsat-9. For SST retrieval, we used the thermal Band 10 as recommended by Snyder et al. [13]. Chl-*a* was retrieved using the empirical OC3 model [19] and turbidity was estimated according to Nechad et al. [20].

Before calculating the Oyster Suitability Index (OSI), the three parameters were normalized between 0 and 1. The OSI was calculated using the following Equation 1 [13]:

$$OSI = SST * 0.8 + chla * 0.15 + turbidity * 0.05$$

The resulting OSI images from the 14 evaluated images were classified into quartiles, identifying pixels consistently within the highest-value quartile to assess the stability of potential aquaculture areas over time. Finally, spatial data on aquaculture concessions for scallop farms were sourced from the Chilean Undersecretariat for Fisheries and Aquaculture (SUBPESCA). The data was accessed via the SUBPESCA Map Viewer platform (https://mapas.subpesca.cl/ideviewer) and subsequently processed for accurate cartographic representation.

3. RESULTS

In Tongoy Bay, the SST mean during 2023 varies between 10.5 and 13°C. The northern sector of Tongoy Bay is characterized by a consistent presence of colder water masses (below 11°C). In contrast, the southern sector, Punta Lengua de Vaca (PLV), experienced consistently warmer water temperatures throughout 2023 (Figura 1A and C). Turbidity for the same period shows high spatial heterogeneity, with low turbidity values (< 2 NTU) observed in the coastal zone, while high values observed in the PLV waters (> 2.5 NTU) (Figure 1D). Surface chlorophyll-*a* concentration shows high values associated with the coastal region, mainly in Tongoy Bay (Figure 1E), indicating high primary productivity. However, these factors appear secondary in influence compared to temperature, underscoring temperature as the predominant environmental parameter driving successful *Argopecten purpuratus* aquaculture in Tongoy Bay. In the oceanic regions, Chl-*a* values are below < 1 mg m^{-3}.

Figure 1F shows an average map of the Oyster Suitability Index (OSI) for 2023 in Tongoy Bay. The scallop farming areas (white stars in Figure 1F) are located in areas with the highest suitability index, i.e., the coastal strip with high phytoplankton biomass concentration (measured as Chl-*a*).

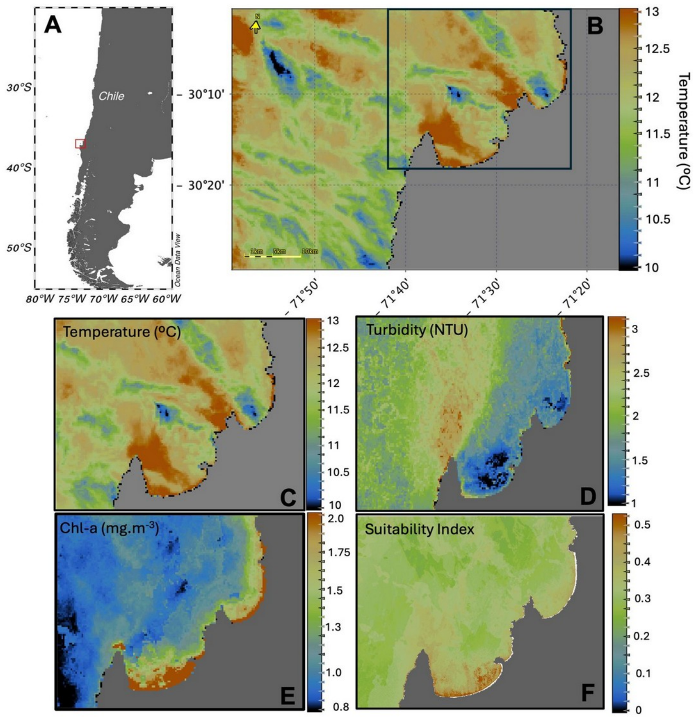

Figure 1. (A) Map of the Chilean coast, with the red rectangle indicating the study area, the Tongoy Bay, north-central Chile. Average values of Landsat-9 retrieved products for the study area (A) sea surface temperature, (B) Turbidity, and (C) Chlorophyll-*a* concentration. White stars represent scallop aquaculture sites.

Finally, the frequency of occurrence of pixels associated with high OSI values in the processed satellite images (Figure 2A) indicates that the northern region of the study area (Guanaqueros Bay) (Figure 2B) shows a higher temporal occurrence of pixels associated with high OSI during the analyzed period (greater than 7 images for the study year), while in the southern section (Tongoy Bay), a lower temporal frequency of suitable area pixels for scallop farming is observed. These results reveal that the potential areas for scallop farming are highly variable in time and space throughout the investigated area, as shown in Figure 2.

4. DISCUSSION

Over the past 10 years, ocean color space-based sensors have operationally generated water quality products freely available online [15], greatly enhancing our understanding of key oceanographic processes and enabling the mapping of biological potential for various aquaculture sectors at
been especially beneficial for bivalve

aquaculture, which is heavily influenced by environmental parameters in the water column [12,21].

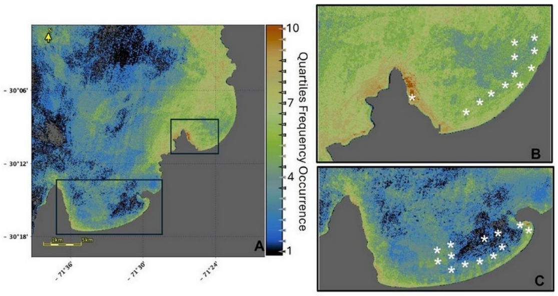

Figure 2. (A) Frequency of occurrence of the highest OSI quartiles. Regions with the greatest potential for oyster cultivation in the (B) northern and (A) southern areas of Tongoy Bay. White stars represent scallop aquaculture sites.

More recent advances in optical sensor technology have improved our ability to quantify variability in coastal waters over large spatial areas and across multiple temporal scales. These advancements in ocean color remote sensing now allow us to evaluate sensor performance, leverage their distinct optical properties, and test hypotheses about biogeophysical processes in coastal waters. For example, the use of *in situ* data in conjunction with the higher spatial resolution and frequent revisit times as found in Landsat-9 (OLI) and Sentinel-2 (MultiSpectral Imagery - MSI) enable detailed study of surface waters with varying optical uncertainties [22,23]. In this context, multiple studies have demonstrated the effectiveness of ocean color remote sensing products (e.g., SST, Chl-*a*, turbidity) in aquaculture site selection and production monitoring over time [13,14].

The spatial characterization of relevant environmental parameters from our analysis demonstrates a strong association between satellite-derived environmental patterns and larval arrival dynamics in Tongoy Bay [12], which is key for the successful collection of wild seed stock obtained through passive collection of planktonic larvae that settle on collecting surfaces [10].

5. CONCLUSIONS

Analysis of Landsat-8 and Landsat-9 imagery throughout 2023 revealed a detailed spatial characterization of the Tongoy Bay coastal area, indicating that the southern sector exhibited higher OSI values, primarily due to elevated water temperatures, increased Chl-*a* concentrations near the coast, and slightly elevated turbidity levels. In contrast, temperature emerged as the critical factor for creating conditions favorable for oyster cultivation, while the northern sector, characterized by persistent cold-water masses, demonstrated a more favorable temporal frequency for cultivation despite its lower OSI values. These findings ssuggest that the northern sector of Tongoy bay offers optimal conditions for larval settlement and oyster development. For future studies, we plan to first validate SST, turbidity, and Chl-a data. Regarding the OSI validation, we can consider the locations of aquaculture farms and their productivity as reference points. Finally, we will consider implementing TACT in future studies for achieving higher accuracy in SST images

6. REFERENCES

[1] FAO-Fishstat 2020 FAO-Fisheries and Aquaculture Information and Statistics *FAO-Fishstat.*

[2] Ezgeta-Balić D, Najdek M, Peharda M and Blažina M 2012 Seasonal fatty acid profile analysis to trace origin of food sources of four commercially important bivalves *Aquaculture* 334–337.

[3] Ottinger M, Clauss K and Kuenzer C 2016 Aquaculture: Relevance, distribution, impacts and spatial assessments - A review *Ocean Coast Manag* 119.

[4] Boyd C E, McNevin A A and Davis R P 2022 The contribution of fisheries and aquaculture to the global protein supply *Food Secur* 14.

[5] Reid G K, Gurney-Smith H J, Flaherty M, Garber A F, Forster I, Brewer-Dalton K, Knowler D, Marcogliese D J, Chopin T, Moccia R D, Smith C T and De Silva S 2019 Climate change and aquaculture: Considering adaptation potential *Aquac Environ Interact* 11.

[6] Philippart C J M, Van Aken H M, Beukema J J, Bos O G, Cadée G C and Dekker R 2003 Climate-related changes in recruitment of the bivalve Macoma balthica *Limnol Oceanogr* 48.

[7] Maulu S, Hasimuna O J, Haambiya L H, Monde C, Musuka C G, Makorwa T H, Munganga B P, Phiri K J and Nsekanabo J D M 2021 Climate Change Effects on Aquaculture Production: Sustainability Implications, Mitigation, and Adaptations *Front Sustain Food Syst* 5.

ntry R R and Halpern B S 2018 Global

change in marine aquaculture production potential under climate change *Nat Ecol Evol* 2.

[9] Molinet C, Astorga M, Cares L, Diaz M, Hueicha K, Marín S, Matamala T and Soto D 2021 Vertical distribution patterns of larval supply and spatfall of three species of Mytilidae in a Chilean fjord used for mussel farming: Insights for mussel spatfall efficiency *Aquaculture* 535.

[10] von Brand E, Abarca A, Merino G E and Stotz W 2016 Scallop Fishery and Aquaculture in Chile: A History of Developments and Declines *Developments in Aquaculture and Fisheries Science* vol 40.

[11] Lagos N A, Benítez S, Duarte C, Lardies M A, Broitman B R, Tapia C, Tapia P, Widdicombe S and Vargas C A 2016 Effects of temperature and ocean acidification on shell characteristics of Argopecten purpuratus: Implications for scallop aquaculture in an upwelling-influenced area *Aquac Environ Interact* 8.

[12] Broitman B R, Lara C, Flores R P, Saldías G S, Piñones A, Pinochet A, Galán Mejía A and Navarrete S A 2022 Environmental variability and larval supply to wild and cultured shellfish populations *Aquaculture* 548.

[13] Snyder J, Boss E, Weatherbee R, Thomas A C, Brady D and Newell C 2017 Oyster aquaculture site selection using landsat 8-derived sea surface temperature, turbidity, and chlorophyll a *Front Mar Sci* 4.

[14] Gernez P, Doxaran D and Barillé L 2017 Shellfish aquaculture from Space: Potential of Sentinel2 to monitor tide-driven changes in turbidity, chlorophyll concentration and oyster physiological response at the scale of an oyster farm *Front Mar Sci* 4.

[15] Jiang B, Boss E, Kiffney T, Hesketh G, Bourdin G, Fan D and Brady D C 2022 Oyster Aquaculture Site Selection Using High-Resolution Remote Sensing: A Case Study in the Gulf of Maine, United States *Front Mar Sci* 9.

[16] Bravo L, Ramos M, Astudillo O, Dewitte B and Goubanova K 2016 Seasonal variability of the Ekman transport and pumping in the upwelling system off central- northern Chile (∼ 30° S) based on a high-resolution atmospheric regional model (WRF) *Ocean Science* 12.

[17] Bakit J, Burgos-Fuster V, Abarca A, Etchepare I, Illanes J E, Villasante S, Bonilla E, Rojas R, Dudouet B and Cortés N 2024 Scallop aquaculture growth: Four decades of economic policy in Chile *Mar Policy* 163 106139.

[18] Vanhellemont Q and Ruddick K 2016 Acolite for Sentinel-2: Aquatic applications of MSI imagery *European Space Agency, (Special Publication) ESA SP*.

[19] O'Reilly J E, Maritorena S, Mitchell B G, Siegel D A, Carder K L, Garver S A, Kahru M and McClain C R 1998 Ocean Color Chlorophyll algorithms for SeaWiFS *J Geophys Res* 103 24.937-24.953.

[20] Nechad B, Ruddick K G and Park Y 2010 Calibration and validation of a generic multisensor algorithm for mapping of total suspended matter in turbid waters *Remote Sens Environ* 114 854–66.

[21] Palmer S C J, Gernez P M, Thomas Y, Simis S, Miller P I, Glize P and Barillé L 2020 Remote Sensing-Driven Pacific Oyster (Crassostrea gigas) Growth Modeling to Inform Offshore Aquaculture Site Selection *Front Mar Sci* 6 1–19.

[22] Warren M A, Simis S G H, Martinez-Vicente V, Poser K, Bresciani M, Alikas K, Spyrakos E, Giardino C and Ansper A 2019 Assessment of atmospheric correction algorithms for the Sentinel-2A MultiSpectral Imager over coastal and inland waters *Remote Sens Environ.*

[23] Pereira-Sandoval M, Ruescas A, Urrego P, Ruiz-Verdú A, Delegido J, Tenjo C, Soria-Perpinyà X, Vicente E, Soria J and Moreno J 2019 Evaluation of atmospheric correction algorithms over spanish inland waters for sentinel-2 multi spectral imagery data *Remote Sens (Basel)* 11 1–23.