Bioecological analysis of *Asparagopsis taxiformis* (Delile) Trevisan de Saint-Léon, 1845: relationship between morphology, habitat characteristics, and water quality

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Abstract. Global warming is widely recognized as a humanitarian crisis that threatens life on Earth. Methane (CH_4) emissions from ruminant livestock are a significant contributor. The red sea plume, *Asparagopsis taxiformis (Delile) Trevisan de Saint-Léon, 1845,* has demonstrated potential as a natural method for reducing CH_4 emissions. However, large-scale cultivation of *A. taxiformis* remains constrained by a limited understanding of its bioecological requirements, particularly the interrelationships among morphology, habitat, and water quality. This study investigates the bioecological characteristics of *A. taxiformis* by analyzing the relationships between its morphological features, habitat, and water quality in natural environments. Fieldwork was conducted in the waters of Baluno and Somba, Majene Regency, West Sulawesi, Indonesia, from April to August 2024. Measurements included current speed, salinity, water temperature, depth, and nutrient concentrations, including nitrate (NO_3), phosphate (PO_4), and ammonia (NH_3). Canonical correspondence analysis (CCA) was employed to examine the physical traits of the algae stands. The results indicate that variations in the morphology and structure of *A. taxiformis* are primarily influenced by nutrient availability and water movement. Elevated concentrations of NO_3 and PO_4, as well as increased current velocity, are associated with greater thallus length and width. Salinity, temperature, NH_3, and depth also contribute to the adaptive responses and spatial arrangement of the algae. These findings suggest that *A. taxiformis* exhibits morphological plasticity in response to environmental conditions, potentially facilitating its proliferation in nutrient-rich waters. In summary, understanding the interactions between *A. taxiformis* and its environment is essential for developing sustainable cultivation strategies and managing coastal ecosystems amid climate change and nutrient pollution.

Key Words: environmental gradients, hydrodynamic forcing, nutrient enrichment, eutrophication pressure, physicochemical drivers.

Introduction. Currently, global warming is not just an environmental problem but has led to a humanitarian crisis that threatens life on Earth. When ruminant livestock became a major contributor to methane (CH_4) emissions, causing global warming (Haryuni 2018), the red sea plume, *Asparagopsis taxiformis* (Delile) Trevisan de Saint-Léon, 1845, emerged as a unique alternative from the seabed (Wasson et al 2022). Global warming is the impact of the increasing accumulation of carbon dioxide (CO_2), (Arbit et al 2018), CH_4, and other greenhouse gases in the atmosphere. These gases absorb sunlight and radiation reflected from the Earth's surface. Usually, this radiation will escape into space, but pollutants that can survive for centuries in the atmosphere generate heat and cause global warming. The increase in Earth's temperature triggers longer and hotter heat waves, more frequent droughts, heavier rainfall, and more severe storms. Increasingly frequent and prolonged droughts will endanger global food security (Tuwo et al 2022) and worsen people's welfare, especially in coastal and island areas due to crop failure (Tresnati et al 2022).

To mitigate CH_4 produced by ruminant livestock, it is recommended to use *A. taxiformis* as a supplement in ruminant feed to reduce the CH_4 content in ruminant manure (Jia et al 2022). The addition of *A. taxiformis* to ruminant livestock feed has been shown to reduce CH_4 content by up to 80 percent (Roque et al 2021). In addition to mitigating CH_4, *A. taxiformis* is also beneficial for aquaculture because it can be used as a supplement in fish feed to improve fish health and growth. *A. taxiformis*, used as a supplement in fish feed, can increase immune response, stress tolerance, pathogen tolerance, growth rate, and feed efficiency (Thépot et al 2021a). In Mottled spinefoot, *Siganus fuscescens*, bioactive compounds (bromoform, flavonoids, and sterols) from *A. taxiformis* have positive effects on the gastrointestinal microbiome, immune and endocrine cells, so that they can increase the growth and efficiency of fish feed (Thépot et al 2021b). Meanwhile, in Salmon, adding *A. taxiformis* (whole or extract) can increase growth and immune response (Thépot et al 2022).

The current challenge is that the production of *A. taxiformis* still relies on minimal natural production because *A. taxiformis* is a rare seaweed. To increase production and market supply, commercial-scale cultivation is needed. Until now, *A. taxiformis* cultivation has not been on a commercial scale due to limited knowledge and technology about *A. taxiformis* cultivation. From the previous research results, 4340 scientific publications were found on *A. taxiformis*. Of that number, 1,020 scientific publications were related to the ability of *A. taxiformis* to reduce CH_4 content in ruminant animal waste. Scientific publications related to water's physical, chemical, and biological parameters related to *A. taxiformis* cultivation are very few. Only four scientific publications were found describing light intensity (Goldman 2021), one on temperature (Mata et al 2017), two on habitat (Padilla-Gamino & Carpenter 2007; Mancuso et al 2022), one on morphometric characteristics (Andreakis et al 2004), one on growth (Torres et al 2024), and one on nitrate (NO_3) (Thorsteinsson et al 2023). From the results of previous studies, no scientific publications were found related to environmental parameters (pH, salinity, dissolved oxygen, CO_2, phosphate (PO_4), and water chlorophyll) that were good for the life of *A. taxiformis* in cultivation media and its natural habitat. There were also no scientific publications on the morphometric characteristics and growth parameters of *A. taxiformis* in cultivation media and its natural habitat.

This study aims to evaluate the bioecological aspects of *A. taxiformis* through an analysis of the relationship between morphology, habitat characteristics, and water quality in order to understand the complex interactions between *A. taxiformis* and its environment, including how environmental factors influence growth and morphological development.

The research was conducted in Baluno Waters and Somba Waters, where *A. taxiformis* was found throughout the year. Both research locations were chosen because they are natural habitats and are overgrown with *A. taxiformis*, a rare seaweed. *A. taxiformis* is very rarely found in nature

Material and Method

Study area. Field observations were conducted from April to August 2024 in Majene Regency, West Sulawesi, Indonesia. Observations were conducted in three water locations, namely in Baluno Waters, which consists of three stations (Station 1, 2, and 3) (Figure 1d). Snorkeling was needed at Somba 1 (Stations 4, 5, and 6) and Somba 2 (Stations 7, 8, and 9) (Figure 1e) during high tide, when the water reaches 90-100 cm deep. At low tide, these stations were 50-60 cm deep, so snorkeling was not required. At Baluno (Stations 1, 2, and 3), the depth was 30-50 cm, so snorkels were not needed. The selection of the three locations was based on the abundance of *A. taxiformis*. At Stations 1 to 6, the abundance of *A. taxiformis* was low, and at Stations 7 to 9, the density of *A. taxiformis* was moderate.

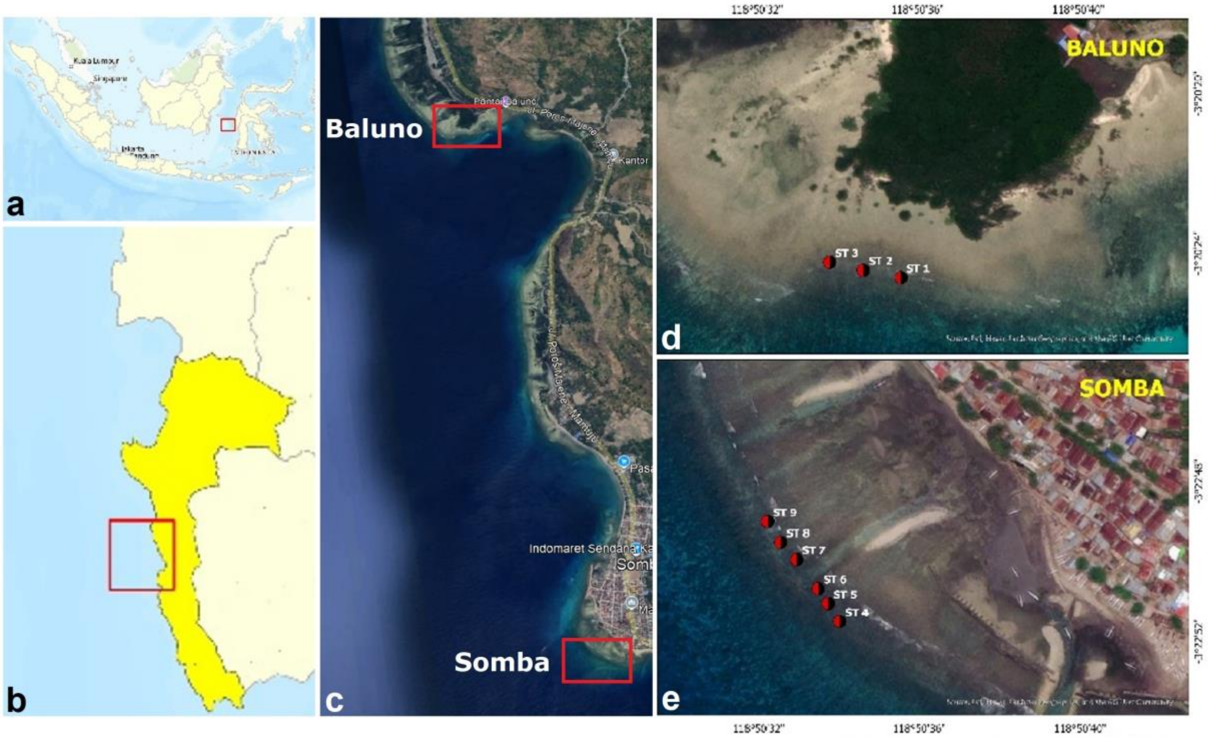

Figure 1. Map of the research location of the *Asparagopsis taxiformis* red sea plume in the coastal waters of Baluno, Binanga Village, and the coastal waters of Somba, Mosso Village, Sendana District, Majene Regency, West Sulawesi, Indonesia. Source: Base Map of Indonesia (a, b), Google Map (c, d, and e).

Water quality and morphometric analysis. Field observations and sampling were conducted every month for five months. Samples were put into labeled plastic. Habitat and water quality parameters measured directly in the field were current speed, water salinity, water surface temperature, depth, and exposed water. Parameters analyzed in the laboratory were PO_4, NO_3, and ammonia (NH_3). During transportation from the field to the laboratory, samples are stored in a coolbox filled with ice crystals. The equipment used in this study was a current meter, refractometer, and digital thermometer.

Measurement of morphometric characteristics using a digital caliper with an accuracy of 0.01 mm. Measurements were conducted in the laboratory. During transport from the field to the laboratory, samples were stored in a coolbox filled with seawater and aeration. The morphometric parameters to be measured include distance between stands (DBS), stand thallus length (STL), stand length without leaves (SLWL), stand diameter (SD), lower thallus width (LTW), center thallus width (CTW), upper thallus width (UTW) (Figure 2).

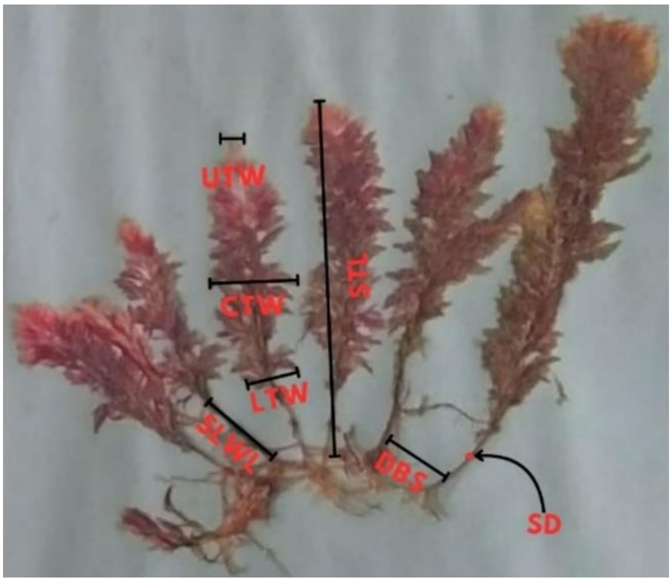

Figure 2. Morphometrics of red sea plume *Asparagopsis taxiformis*. DBS: distance between stands, STL: stand thallus length, SLWL: stand length without leaves, SD: stand diameter, LTW: lower thallus width, CTW: center thallus width, UTW: upper thallus width.

Data processing. A multivariate ecological approach was used to analyze the relationship between aquatic environmental variables and stand morphological characteristics at multiple observation stations. Data came from three research stations. All data were verified for completeness before analysis. Because all variables showed strong ecological relevance and fell within reasonable value ranges, data were kept in their original units. This preserved ecological interpretability. Canonical correspondence analysis (CCA) was used to evaluate the direct relationship between environmental gradients and stand morphological characteristics. The CCA method is well-suited for ecological data expected to show a unimodal response to environmental gradients.

CCA is a widely used method in ecology for directly linking changes in biotic structure to environmental gradients (ter Braak 1986; ter Braak & Šmilauer 2012). CCA is particularly valuable because it assumes that organisms respond to environmental gradients in a unimodal fashion, a pattern commonly observed among benthic aquatic organisms and macroalgae in diverse environments. In the present study, CCA was employed to identify the primary environmental factors influencing morphological variation in *A. taxiformis* stands. This approach aligns with established practices in coastal aquatic ecology, where complex interactions among nutrients, water movement, and other variables are often not adequately captured by simpler analytical methods (Legendre & Legendre 2012; Borcard et al 2018).

In this analysis, environmental variables served as explanatory variables, while stand morphological variables were designated as response variables. The ordination axes represented linear combinations of environmental variables that best accounted for differences in stand morphology among stations. Multivariate analysis was conducted using PAST software version 4.0b, a Windows-based program for quantitative ecological analysis. CCA was performed via the Ordination and CCA menu. Eigenvalues, correlations between axes and environmental variables, and the percentage of cumulative variation were used to assess the strength and ecological significance of the axes. The influence of each environmental variable on stand structure was inferred from the lengths and directions of vectors in the ordination diagram (biplot). CCA results were presented using symmetric scaling, which facilitated the simultaneous interpretation of station positions, environmental variables, and stand morphological characteristics. Stations located in close proximity within the ordination space were interpreted as having similar environmental conditions and stand structures. To interpret the CCA results, the relationship between environmental gradients and stand morphological responses was examined, identifying morphological variables closely associated with specific environmental gradients as key indicators of factors influencing stand structure. This approach enabled the identification of the primary environmental factors driving spatial variation in stand structure and provided a robust ecological basis for explaining differences among the study stations.

Results

Morphometrics. At all stations in Baluno and Somba, *A. taxiformis* was attached to live coral. *A. taxiformis* was also attached to dead coral, macroalgae, and marine animals, such as Clam Shells.

The average test of the morphometric size of *A. taxiformis* showed that there was no significant difference for DBS and STL size in Somba 2 and Baluno, SLWL and SD size in Somba 1 and Baluno, and LTW, CTW, and UTW size in Baluno and Somba. Meanwhile, the morphometric size of *A. taxiformis* showed significant differences for STL size in Somba 2 and Somba 1, STL size in Somba 1 and Baluno, SD size in Somba 2 and Somba 1, and SD size in Somba 2 and Baluno (Table 1).

Table 1
Morphometric measurements of *Asparagopsis taxiformis* in the coastal waters of Baluno, Binanga Village, and the coastal waters of Somba, Mosso Village, Sendana District, Majene Regency, West Sulawesi, Indonesia

Morphometric measurements	*Location*		
	Baluno	*Somba 1*	*Somba 2*
DBS (mm)	3.02-4.75 (3.80±0.64)	2.74-6.64 (4.14±1.52)	3.14-4.09 (3.60±0.39)
STL (mm)	20.25-59.24 (36.66±14.83)	24.32-56.35 (35.93±12.89)	37.33-55.70 (43.94±7.19)
SLWL (mm)	4.59-12.31 (6.83±3.12)	2.49-6.88 (5.00±1.63)	5.60-10.32 (7.56±1.91)
SD (mm)	0.43-0.74 (0.59±0.14)	0.48-0.67 (0.56±0.08)	0.44-0.77 (0.59±0.13)
LTW (mm)	2.54-4.66 (3.40±0.94)	2.38-4.66 (3.40±0.94)	2.51-4.23 (3.28±0.70)
CTW (mm)	5.84-11.42 (8.52±2.31)	6.49-11.09 (7.86±1.96)	7.34-9.84 (8.49±0.96)
UTW (mm)	1.22-2.17 (1.52±0.42)	1.13-1.84 (1.49±0.28)	1.33-1.49 (1.41±0.07)

Note: DBS: distance between stands, STL: stand thallus length, SLWL: stand length without leaves, SD: stand diameter, LTW: lower thallus width, CTW: center thallus width, UTW: upper thallus width.

Habitat characteristics and water quality. The results of water quality parameter measurements showed that the average values of CS in Baluno and Somba 1, CS in Baluno and Somba 2, WS and WST in Baluno and Somba 1, WST in Baluno and Somba 2, PO_4, NO_3, AE, and NH_3 in Baluno and Somba were not significantly different. The water quality parameters that showed significant differences were CS in Somba 1 and Somba 2, WST in Somba 1 and Somba 2, and DP in the three locations (Table 2).

Tabel 2
Water quality in the natural habitat of *Asparagopsis taxiformis* in the coastal waters of Baluno, Binanga Village, and the coastal waters of Somba, Mosso Village, Sendana District, Majene Regency, West Sulawesi, Indonesia

Water quality	*Location*		
	Baluno	*Somba 1*	*Somba 2*
CS (m s^{-1})	0.20-1.40 (0.56±0.48)	0.20-0.60 (0.36±0.15)	0.30-0.70 (0.50±0.16)
WS (ppt)	35.00-36.00 (35.40±0.55)	34.50-35.50 (34.90±0.42)	34.00-35.50 (34.90±0.65)
WST (^{o}C)	27.00-29.10 (27.96±0.83)	27.00-29.50 (28.28±0.96)	26.50-29.00 (27.94±0.94)
PO_4 (mg L^{-1})	0.00-0.07 (0.03±0.04)	0.01-0.01 (0.01±0.00)	0.01-0.06 (0.02±0.03)
$N0_3$ (mg L^{-1})	0.06-1.11 (0.47±0.55)	0.08-0.14 (0.10±0.02)	0.06-1.50 (0.38±0.63)
AE (cm)	0.0	0.0	0.0
NH_3 (mg L^{-1})	0.00-0.22 (0.08±0.11)	0.00-0.00 (0.00±0.00)	0.00-0.00 (0.00±0.00)
DP (cm)	30.00-50.00 (43.80±8.20)	50.00-90.00 (67.20±17.30)	55.00-95.00 (72.20±16.87)

Note: CS: current speed, WS: water salinity, WST: water surface temperature, PO_4: phosphate, NO_3: nitrate, AE: water exposure, NH_3: ammonia, DP: depth.

Relationship between morphometric and water quality. CCA shows that variations in stand morphological characteristics among research stations are mainly determined by aquatic environmental gradients. The first two axes of the CCA account for most of the variation in the morphological data. This supports their use for ecological interpretation. Axis 1 represents the main gradients in water movement and nutrient conditions. Axis 2 captures differences in stand structure linked to thallus size and spatial arrangement (Figure 3).

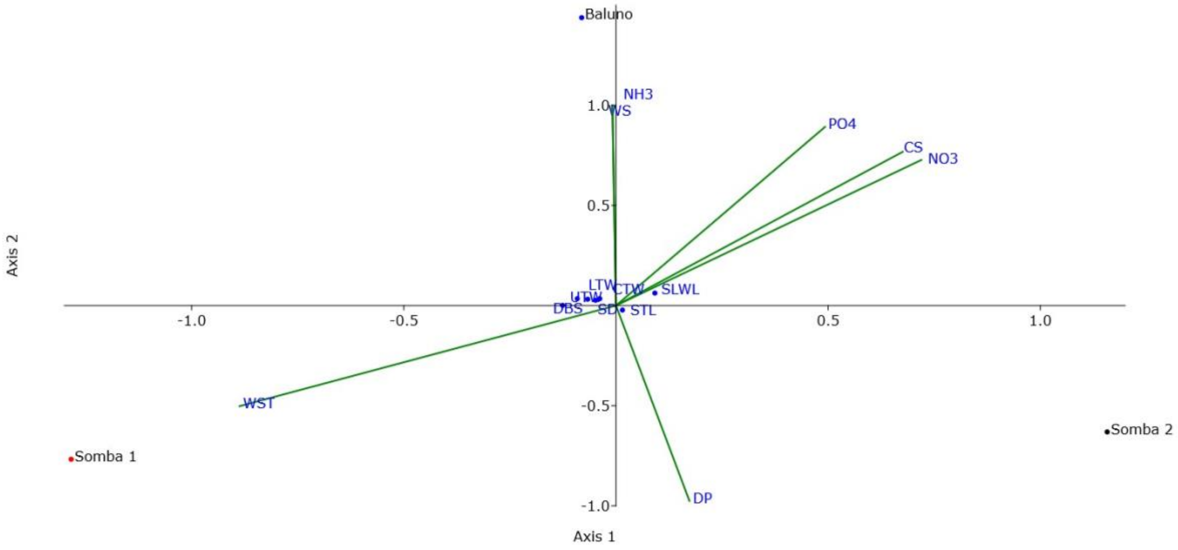

Figure 3. Results of Canonical correspondence analysis in three habitats of *Asparagopsis taxiformis* in the coastal waters of Baluno and Somba beaches, Mosso Village, Sendana District, Majene Regency, West Sulawesi, Indonesia.

Axis 1 is mainly influenced by variations in CS, DP, and concentrations of dissolved nutrients (NO_3 and PO_4). Stations on the positive side of Axis 1 have greater water depth. They also have higher current velocity and higher nutrient availability. This environmental gradient corresponds to increased STL, greater CTW, and greater UTW. Thus, higher nutrient concentrations and stronger water movement are associated with the development of larger and more structurally complex stands.

In contrast, stations on the negative side of Axis 1 have shallower water, lower current velocity, and lower nutrient concentrations. These are associated with smaller stand morphological dimensions. Axis 2 mainly reflects changes in WS, WST, and DBS. Higher salinity and temperature along this axis are linked to greater spacing between individuals and smaller stand diameters. This pattern suggests adaptation to environmental stress, especially fluctuations in temperature and salinity.

Stations on the negative side of Axis 2 display denser stands with larger diameters. This indicates that more stable environmental conditions promote increased lateral growth. Taken together, the CCA biplot illustrates how environmental factors relate to changes in stand structure. The longer the vector for an environmental variable, the greater its contribution to differences in stand structure.

CS and nutrients (NO_3, PO_4) exhibit the longest vectors. These are oriented parallel to the thallus length and width. This finding confirms that water movement and nutrient availability are the primary factors influencing both vertical and horizontal stand growth. WS and WST form large angles relative to the nutrient vector. This indicates that these variables primarily influence stand arrangement and adaptive responses rather than principal size characteristics.

The positions of the Baluno, Somba 1, and Somba 2 stations within their ordination space indicate the degree of similarity and difference in the environment, which are directly reflected in the stand structure. Stations that are spatially adjacent in the biplot share similar environmental and morphological characteristics. Those that are separated exhibit different ecological responses.

Discussion. This study shows that NO_3, PO_4, and current velocity mainly influence *A. taxiformis*. This pattern matches past macroalgal research. Those studies show that red algal thalli depend on dissolved nutrients, especially inorganic nitrogen, which is vital for metabolism and tissue formation (Lobban & Harrison 1994). In *A. taxiformis*, more nutrients speed up growth, elongate the thalli, and increase branching complexity. These changes are most apparent in areas with strong currents (Schaffelke & Klumpp 1998). Water currents help deliver nutrients and thin the boundary layer around the thallus. This boosts nutrient uptake and aids robust structural development (Hurd 2000). Moreover, the biplot reveals a positive association between nutrient concentrations and morphological traits (STL, SLWL, CTW, UTW). This indicates that *A. taxiformis* capitalizes on productive water conditions to develop more complex and robust thallus structures. Such adaptive responses are characteristic of opportunistic macroalgae, which exhibit enhanced growth given favorable environmental conditions.

Beyond nutrients and current velocity, the analysis demonstrates that salinity, NH_3, water temperature, and depth also influence the structure of *A. taxiformis*. While this species tolerates a broad range of temperatures and salinities, exposure to extremes prompts morphological and functional adjustments to mitigate stress (Chualáin et al 2004; Zanolla et al 2018). NH_3 can serve as nitrogen. High concentrations, though, cause stress. This affects both biomass distribution and thallus morphology (Britto et al 2001). Water depth controls light and water-column stability. These factors shape vertical growth and the spacing of algal stands. These findings support the statement that the structural organization of *A. taxiformis* results from the interplay of primary and secondary environmental factors, which collectively respond to local habitat conditions. *A. taxiformis* is recognized globally for its adaptability and significant invasive potential in tropical and subtropical waters (Andreakis et al 2007, Zanolla-Balbuena et al 2018). The results indicate that this species alters its morphology and growth patterns in response to nutrient availability and water movement, a characteristic common among organisms capable of rapid adaptation to novel environments.

A. taxiformis demonstrates a high capacity for colonization, especially in coastal habitats subject to disturbance or elevated nutrient levels. Molecular and biogeographic research indicates that this species can disperse across biogeographic boundaries and establish persistent populations in non-native environments (Andreakis et al 2007; Zanolla et al 2022). This study reveals a strong association between nutrient concentrations, such as NO_3 and PO_4, and the morphology of *A. taxiformis*, as measured by STL, CTW, and UTW. These findings suggest that eutrophication may enhance the competitive advantage of *A. taxiformis* over native macroalgae. Its increased size and structural complexity enable it to occupy more substrate, thereby reducing available space for other species and modifying the composition of the benthic community. Eutrophication represents a significant anthropogenic issue in coastal aquatic ecosystems globally. The present study demonstrates that elevated dissolved nutrient concentrations, particularly nitrogen and phosphorus, are directly associated with the growth and development of *A. taxiformis*.

These findings support the hypothesis that opportunistic macroalgae proliferate in nutrient-enriched environments, where abundant resources facilitate rapid growth and spatial dominance (Valiela et al 1997; Cloern 2001). Specifically, *A. taxiformis* exhibits accelerated growth rates and increased biomass under elevated nutrient conditions, as observed in both field and laboratory studies (Schaffelke & Klumpp 1998). These results support the idea that eutrophication not only boosts primary productivity but can also shift the community toward species such as *A. taxiformis*, which have opportunistic life strategies. Global climate change continues to alter the physical and chemical conditions of coastal waters by increasing temperatures, modifying currents, and intensifying extreme events. In line with these broader changes, this study found that water temperature and depth emerged as primary factors influencing the distribution and growth of *A. taxiformis*. Building on these findings, previous research demonstrates that *A. taxiformis* can tolerate a broad range of temperatures, facilitating its survival and growth under warming conditions (Chualáin et al 2004; Zanolla et al 2018). Its thermal tolerance, combined with a positive response to increased nutrient availability, may enhance its future prevalence in coastal waters experiencing both warming and nutrient enrichment.

Furthermore, rising sea levels and altered currents are outcomes of climate change that may facilitate the dispersal of *A. taxiformis* by transporting its fragments and propagules over greater distances, thereby expanding its geographic range. The results presented in this study provide robust evidence for predicting the species' responses to various climate change scenarios, further reinforcing the importance of understanding current environmental patterns. Given these projected changes, from an ecosystem management perspective, the findings indicate that controlling nutrient inputs is essential to limit the spread and dominance of *A. taxiformis*. Effective water quality management, particularly through reductions in terrestrial nutrient runoff, may help prevent alterations in benthic community structure.

This management approach highlights that this analysis is useful for identifying key environmental factors. It can be incorporated into monitoring programs to detect early changes that promote the spread of opportunistic or invasive species, thus supporting informed management decisions.

Conclusions. The study showed that dissolved nutrients and water movement mainly shaped differences in stand structure among stations. Nitrate, phosphate, and current speed were key to increasing thallus length and width. Salinity, ammonia, temperature, and water depth also affected how stands were arranged and adapted. These findings demonstrate that both primary and secondary environmental factors determine the distribution of stand structures.

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Conflict of interest. The authors declare that there is no conflict of interest.

References

Andreakis N., Procaccini G., Kooistra W. H., 2004 *Asparagopsis taxiformis* and Asparagopsis armata (Bonnemaisoniales, Rhodophyta): genetic and morphological identification of Mediterranean populations. European Journal of Phycology 39(3):273-283.

Andreakis N., Procaccini G., Maggs C., Kooistra W. H., 2007 Phylogeography of the invasive seaweed *Asparagopsis* (Bonnemaisoniales, Rhodophyta) reveals cryptic diversity. Molecular Ecology 16(11):2285-2299.

Arbit N. I. S., Omar S. B., Tuwo A., Soekendarsi E., 2018 Effect of global warming scenarios on carotenoid pigments *Gracilaria changii*. International Journal of Environment, Agriculture and Biotechnology 3(6):268287.

Borcard D., Gillet F., Legendre P., 2018 Spatial analysis of ecological data Numerical ecology with R. Springer, New York, USA. pp. 299-367.

Britto D. T., Siddiqi M. Y., Glass A. D., Kronzucker H. J., 2001 Futile transmembrane NH4+ cycling: a cellular hypothesis to explain ammonium toxicity in plants. Proceedings of the National Academy of Sciences 98(7):4255-4258.

Chualáin F. N., Maggs C. A., Saunders G. W., Guiry M. D., 2004 The invasive genus *Asparagopsis* (Bonnemaisoniaceae, Rhodophyta): molecular systematics, morphology, and ecophysiology of *falkenbergia* isolates 1. Journal of Phycology 40(6):1112-1126.

Cloern J. E., 2001 Our evolving conceptual model of the coastal eutrophication problem. Marine Ecology Progress Series 210:223-253.

Goldman J., 2021 Optimizing the growth of the red seaweed *Asparagopsis taxiformis* by managing light quality and intensity. Mestrado em Aquacultura e Pescaria, Universidade do Algarve, 26 p.

Haryuni N., 2018 Methane mitigation technology in ruminants to reduce the negative impacts of global warming. Journal of Development Research 2(2):55-58.

Hurd C. L., 2000 Water motion, marine macroalgal physiology, and production. Journal of Phycology 36(3):453-472.

Jia Y., Quack B., Kinley R. D., Pisso I., Tegtmeier S., 2022 Potential environmental impact of bromoform from *Asparagopsis farming* in Australia. Atmospheric Chemistry and Physics 22(11):7631-7646.

Legendre P., Legendre L., 2012 Numerical ecology. Elsevier, Amsterdam, 419 p.

Lobban C. S., Harrison P. J., 1994 Seaweed ecology and physiology. Cambridge University Press, Cambridge, UK, 384 p.

Mancuso F. P., D'Agostaro R., Milazzo M., Badalamenti F., Musco L., Mikac B., Brutto S. L., Chemello R., 2022 The invasive seaweed *Asparagopsis taxiformis* erodes the habitat structure and biodiversity of native algal forests in the Mediterranean Sea. Marine Environmental Research 173:105515.

Mata L., Lawton R. J., Magnusson M., Andreakis N., de Nys R., Paul N. A., 2017 Within-species and temperature-related variation in the growth and natural products of the red alga *Asparagopsis taxiformis*. Journal of Applied Phycology 29(3):1437-1447.

Padilla-Gamino J. L., Carpenter R. C., 2007 Seasonal acclimatization of *Asparagopsis taxiformis* (Rhodophyta) from different biogeographic regions. Limnology Oceanography 52(2):833-842.

Roque B. M., Venegas M., Kinley R. D., de Nys R., Duarte T. L., Yang X., Kebreab E., 2021 Red seaweed (*Asparagopsis taxiformis*) supplementation reduces enteric methane by over 80 percent in beef steers. Plos ONE 16(3):e0247820.

Schaffelke B., Klumpp D. W., 1998 Nutrient-limited growth of the coral reef macroalga *Sargassum baccularia* and experimental growth enhancement by nutrient addition in continuous flow culture. Marine Ecology Progress Series 164:199-211.

ter Braak C. J., 1986 Canonical correspondence analysis: a new eigenvector technique for multivariate direct gradient analysis. Ecology 67(5):1167-1179.

ter Braak C. J., S̆milauer P., 2012 Canoco reference manual and user's guide: software for ordination, version 5.0. Microcomputer Power, Ithaca, USA, 496 p.

Thépot V., Campbell A. H., Paul N. A., Rimmer M. A., 2021a Seaweed dietary supplements enhance the innate immune response of the mottled rabbitfish, *Siganus fuscescens*. Fish & Shellfish Immunology 113:176-184.

Thépot V., Campbell A. H., Rimmer M. A., Paul N. A., 2021b Effects of a seaweed feed inclusion on different life stages of the mottled rabbitfish *Siganus fuscescens*. Aquaculture Research 52(12):6626-6640.

Thépot V., Campbell A. H., Rimmer M. A., Jelocnik M., Johnston C., Evans B., Paul N. A., 2022 Dietary inclusion of the red seaweed *Asparagopsis taxiformis* boosts production, stimulates immune response and modulates gut microbiota in Atlantic salmon, Salmo salar. Aquaculture 546:737286.

Thorsteinsson M., Maigaard M., Lund P., Weisbjerg M., Nielsen M., 2023 Effect of fumaric acid in combination with *Asparagopsis taxiformis* or nitrate on in vitro gas production, pH, and redox potential. JDS Communications 4(5):335-339.

Torres R., Campos A. M., Goldman J., Barrote I., Mata L., Silva J., 2024 Effects of light quality and intensity on growth and bromoform content of the red seaweed *Asparagopsis taxiformis*. Journal of Applied Phycology 36(2):627-637.

Tresnati J., Kiyokazu U., Yasir I., Melanie H., Aprianto R., Tuwo A., 2022 Seaweed cultivation for community welfare in coastal areas and small islands. In Seaweed Biotechnology. Apple Academic Press. pp. 15-45.

Tuwo A., Nakajima M., Tresnati J., Yasir I., Melanie H., Aprianto R., 2022 Seaweeds for food security and environmental mitigation seaweed biotechnology. Apple Academic Press. pp. 15-45.

Valiela I., McClelland J., Hauxwell J., Behr P. J., Hersh D., Foreman K., 1997 Macroalgal blooms in shallow estuaries: controls and ecophysiological and ecosystem consequences. Limnology and Oceanography 42(5part2):1105-1118.

Wasson D. E., Yarish C., Hristov A. N., 2022 Enteric methane mitigation through *Asparagopsis taxiformis* supplementation and potential algal alternatives. Frontiers in Animal Science 3:999338.

Zanolla M., Altamirano M., Carmona R., De la Rosa J., Souza-Egipsy V., Sherwood A., Tsiamis K., Barbosa A. M., Muñoz A. R., Andreakis N., 2018 Assessing global range expansion in a cryptic species complex: insights from the red seaweed genus *Asparagopsis* (Florideophyceae). Journal of Phycology 54(1):12-24.

Zanolla M., Carmona R., Mata L., De la Rosa J., Sherwood A., Barranco C. N., Muñoz A. R., Altamirano M., 2022 Concise review of the genus *Asparagopsis Montagne*, 1840. Journal of Applied Phycology 34(1):1-17.

Zanolla-Balbuena M. F., Carmona-Fernández R., De la Rosa J., Altamirano-Jeschke M., 2018 Structure and temporal dynamics of a seaweed assemblage dominated bythe invasive lineage 2 of *Asparagopsis taxiformis* (Bonnemaisoniaceae, Rhodophyta) in the Alboran Sea. Mediterranean Marine Science 19(1):147-234.

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