

Sessile invertebrate assemblages associated with natural and farmed kelp habitats in Lüderitz, Namibia: a baseline assessment of spatial and temporal patterns

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Abstract

Kelp aquaculture is expanding globally, yet its role in supporting sessile invertebrate biodiversity relative to natural kelp forests remains poorly understood. This study described sessile invertebrate assemblage in a natural kelp forest at Diaz Point and a kelp farm at Shearwater Bay in Namibia's Benguela upwelling system. Sampling was conducted across multiple months in 2024 using presence/absence data to quantify species richness, community composition, and temporal variation. A total of 30 sessile invertebrate taxa from eight phyla were recorded. Species richness was higher at the natural kelp forest (25 taxa) than at the kelp farm (19 taxa). Additionally, community composition differed significantly between sites and months (PERMANOVA), with site explaining more variation than temporal effects. Ordination (PCoA) indicated clear separation between assemblages, with the kelp farm showing more clustered and compositionally similar samples. The kelp farm assemblage was largely characterized by the frequent occurrence of Mytilida and Balanomorpha, whereas the natural kelp forest supported a broader assemblage including sponges, anemones, bryozoans, and polychaetes. Substrate use was stable and evenly distributed across artificial structures at the farm, while the native kelp forest showed greater temporal variability in substrate occupation. Results indicate that kelp aquaculture structures support distinct fouling communities but show lower taxonomic richness and compositional heterogeneity compared to natural kelp forests. Differences in assemblage patterns were primarily associated with habitat type and structural context.

1. INTRODUCTION

Kelp habitats, both natural and farmed, serve as biodiversity hotspots that support structurally complex sessile communities. Natural kelp forests typically host richer assemblages, with holdfast and frond size strongly influencing species diversity (Teagle et al. 2018; Velasco-Charpentier et al. 2021). Artificial substrates can also increase habitat complexity and diversity (Hauser et al. 2006), though kelp farms may not match the biodiversity of natural forests due to operational and temporal constraints (Forbes et al. 2022).

Sessile marine invertebrates such as mussels, barnacles, sponges and bryozoans play key roles in benthic ecosystems, contributing to nutrient cycling, habitat structure and ecosystem stability (Sarà 1986; Vaughn and Hoellein 2018). As filter feeders, many sessile taxa influence pelagic–benthic coupling and coastal productivity by regulating the flow of organic matter and suspended particles (Bracken 2003; Sardà et al. 2020). The diversity and composition of sessile assemblages can therefore have important implications for ecosystem functioning (Stachowicz et al. 1999, 2007).

The structure of sessile invertebrate assemblages is influenced by a range of factors, including substrate type, habitat complexity, and local environmental conditions. Increased structural complexity is generally associated with higher species diversity, as it provides more niches and refugia for colonizing organisms (McHenry et al. 2017). In addition, temporal variability in recruitment and colonization can lead to changes in assemblage composition over time (Vermeij and Sandin 2008; Lozano-Cortés and Zapata 2014; Shunatova et al. 2018). Understanding these patterns is important for characterizing the dynamics of benthic communities in both natural and modified habitats.

Globally, kelp (seaweed) aquaculture is expanding as a sustainable marine industry, contributing to food production, carbon sequestration, and the provision of ecosystem services such as nutrient cycling and habitat formation (Purcell-Meyerink et al. 2021; Yong et al. 2022; Forbes et al. 2022). In Africa, seaweed resources have long been recognized for their economic potential, with more recent development of seaweed farming occurring primarily in countries such as Tanzania and Kenya, where it has provided important socio-economic benefits to coastal communities (Msuya et al. 2014; Bolton et al. 2016). In Namibia, large-scale kelp farming by Kelp Blue® (Kelp Blue Namibia | Pioneering Ocean Farming in Africa) cultivates *Macrocystis pyrifera* on suspended artificial substrates offshore of Lüderitz, in proximity to natural kelp habitats dominated by *Laminaria pallida* and *Ecklonia maxima*. These farmed structures introduce additional habitat complexity into the marine environment, potentially supporting diverse assemblages of sessile organisms.

Kelp aquaculture in Namibia is a rapidly expanding sector, particularly in the Lüderitz region, where offshore cultivation of *Macrocystis pyrifera* is being developed at commercial scale. Despite this growth, there is currently a lack of baseline ecological data describing the communities associated with these artificial kelp farming structures. This represents a critical knowledge gap, as such information is necessary to evaluate ecological interactions, track changes over time, and inform sustainable management practices. This study therefore provides one of the first baseline datasets on sessile invertebrate assemblages associated with kelp aquaculture systems in Namibia, contributing to a foundation for future monitoring and ecosystem-based management.

Despite growing interest in kelp aquaculture, there is limited information on the composition of sessile invertebrate communities associated with farmed kelp systems, particularly in understudied regions such as Namibia. Existing research has largely focused on natural kelp forests, with comparatively few studies documenting assemblages associated with cultivated kelp habitats. For example, a recent review identified a limited number of studies addressing biodiversity in kelp aquaculture systems, many of which were not specifically focused on community-level responses (Forbes et al. 2022). This review highlighted a significant knowledge gap, which is particularly evident in understudied regions such as southern Africa, including Namibia. Therefore, this study aimed to characterize sessile invertebrate assemblages associated with kelp habitats in Lüderitz, Namibia, and to assess patterns of spatial and temporal variation in community composition.

2. MATERIALS AND METHODS

2.1. Study site

Field sampling was conducted at a kelp cultivation site at Shearwater Bay (26°38'48" S; 15°08'25" E) and a natural kelp habitat at Diaz Point (26°38'35.8" S; 15°05'22.4" E), near Lüderitz in the Karas region of Namibia (Fig. 1).

Shearwater Bay is a relatively sheltered embayment surrounded by rocky cliffs, with a predominantly muddy seabed at the cultivation site and no natural rocky substrate. In contrast, Diaz Point is a semi-exposed coastal area characterized by a rocky substrate that supports natural kelp communities dominated by *Ecklonia maxima*. These two locations represent distinct kelp-associated habitats within the Lüderitz coastal system. This study does not represent a controlled comparison between habitat types, as the two sampling locations differ in several environmental and structural characteristics, including kelp species composition, wave exposure, and underlying substrate. The cultivated site consists of suspended artificial structures supporting *Macrocystis pyrifera* over a predominantly soft (muddy) seabed, whereas the natural site is characterized by rocky substrate supporting *Ecklonia maxima* and *Laminaria pallida*. Consequently, observed differences in assemblage structure should be interpreted as patterns associated with distinct habitat contexts rather than as direct effects of habitat type.

2.2. Sampling procedures

This study employed an observational survey design to characterise sessile invertebrate assemblages associated with kelp habitats. Sampling was conducted during three periods in 2024, corresponding to the second (April–May), third (August–September), and fourth (November–December) quarters. Due to logistical and weather constraints, sampling within each period was conducted once, with the specific month varying depending on field conditions. No experimental manipulation of substrates or deployment times was undertaken.

At the kelp cultivation site, bottom-based units consisting of polyurethane (PU) floats, breeze blocks, and polysteel rope uplines supporting *Macrocystis pyrifera* (Fig. 2) were sampled. These units had been deployed at different times during 2023 and early 2024 as part of routine farm operations, resulting in variable submersion durations. During each sampling period, five units were retrieved by divers and transported to the laboratory. As sampled units were permanently removed, each was treated as an independent replicate.

Figure 2 Bottom-based structures used for kelp cultivation deployed at 9 m depth at the study site. (A) Schematic drawing of the bottom-based block design; (B) Photograph of the deployed bottom-based blocks

At the natural kelp habitat, sampling was conducted along a 10 m transect. Substrates collected included *Ecklonia maxima* thalli ($n = 5$), rocks ($n = 20$), and shells ($n = 20$) per sampling period. Rocks and shells were selected opportunistically but constrained to representative sizes (rocks $\geq$ hand-sized; shells spanning naturally occurring size ranges). All samples were transported to the laboratory for processing.

In total, 15 bottom-based units were collected from the cultivation site. At the natural site, 135 sampling units were collected, comprising 15 *Ecklonia maxima* thalli, 60 rocks, and 60 shells. Each unit or substrate was treated as an independent sampling unit for analysis. In the laboratory, sessile invertebrates were removed manually using forceps or by hand for larger organisms and identified to the lowest possible taxonomic level. Most specimens were preserved in 70–99.9% ethanol for later identification. Delicate taxa (e.g. sponges, hydroids, bryozoans, and sea anemones) were identified on the day of collection prior to preservation to minimize degradation.

2.3. Data Analysis

Species identification used Field Guide to the Offshore Marine Invertebrates of South Africa (Atkinson and Sink 2018), supported by Two Oceans (Branch et al. 2022), and Living Shores of Southern Africa (Branch 2018). Mussel samples were verified via DNA sequencing at the African Centre for DNA Barcoding, University of Johannesburg. Data were cleaned and organized and Shapiro–Wilk tests in SPSS v29 assessed normality prior to statistical analyses.

Although abundance related data were recorded, these consisted of two different metrics (individual counts and percentage cover) depending on the taxon. Because these measures are not directly comparable or convertible into a single standardised abundance metric across all species, a consistent abundance matrix could not be constructed. Consequently, diversity indices that require comparable abundance data (e.g. Shannon index) were not appropriate for this dataset. Instead, analyses were based on presence-absence data, and community similarity and composition were assessed using the Jaccard dissimilarity index and Sørensen similarity coefficient, which are suitable for binary data. This approach avoids introducing bias associated with combining fundamentally different measures of abundance

Data analyses were conducted in R (version 4.3.2). Sessile invertebrate communities were quantified using presence/absence data, with species occurrence on each sampled unit or substrate recorded as 1 (present) or 0 (absent). Species richness (the total number of taxa per structure) was calculated for each sample as a measure of taxonomic diversity.

Community composition was examined using the Jaccard dissimilarity index, which quantifies differences in species composition between samples based on presence/absence data. Principal Coordinates Analysis (PCoA) was used to visualize community dissimilarities and summarize assemblage patterns in multivariate space.

Statistical testing of differences in community composition between sites and months employed PERMANOVA (permutational multivariate analysis of variance) via the *adonis2* function in the *vegan* package (999 permutations) with Jaccard distances. Models included site and month as fixed factors. All species were retained, with no frequency-based filtering, to preserve rare taxa that may influence patterns in presence–absence data. Because PERMANOVA and PCoA rely on dissimilarity measures, no assumptions of normality were required. Results are presented in terms of species richness, community composition, and significant differences in assemblage structure across sites and sampling periods.

Pairwise similarity among samples was quantified using the Sørensen similarity coefficient, which measures species overlap between sampling units on a scale from 0 (no shared species) to 1 (identical composition). Mean Sørensen similarity was calculated across all pairwise comparisons to summarize overall community overlap across sites, sampling periods, substrates, and taxonomic groupings.

Community structure was further described by species occupancy across substrates, sites, and time. For each grouping factor (site, quarter, substrate, and taxonomic order), the number of species recorded as present (Presence = 1) was expressed as a proportion of the total species pool observed for that grouping. This metric, referred to as “frequency of occurrence,” reflects occupancy patterns rather than abundance or density.

3. RESULTS

3.1. Species richness and community composition

A total of 30 sessile marine invertebrate species, representing eight phyla and 13 taxonomic orders, were recorded across both sites. These included Cnidaria (Actiniaria, Leptothecata), Mollusca (e.g., Mytilida, Siphonariida), Porifera (Suberitida, Trachycladida), Arthropoda (Balanomorpha), Annelida (Sabellida), Bryozoa (Cheilostomatida), Chordata (Stolidobranchia), and Brachiopoda (Lingulida). Species richness was higher at the native kelp forest at Diaz Point (25 species) compared to the artificial kelp farm at Shearwater Bay (19 species) (Table 1), with only nine species (30%) shared between sites.

Table 1
Presence (1) and absence (0) of sessile invertebrate taxa recorded in natural and farmed kelp habitats in Lüderitz, Namibia.

Species name	Common name	Natural kelp habitat	Farmed kelp habitat
<i>Anthopleura michaelseni</i>	Crevice anemone	1	1
<i>Anthothoe stimpsonii</i>	Stripped anemone	0	1
<i>Aulacomya atra</i>	Ribbed mussel	1	1
<i>Austromegabalanus cylindricus</i>	Giant barnacle	1	1
<i>Bunodactis reynaudi</i>	Sandy anemone	1	1
<i>Bunodosoma capense</i>	knobbly anemone	1	1
<i>Calyptraeidae spp.</i>		1	0
<i>Choromytilus meridionalis</i>	Black mussel	0	1
<i>Chthamalus dentatus</i>	Tooth barnacle	1	0
<i>Crepidula porcellana</i>	Slipper limpet	1	0
<i>Cymbula compressa</i>	Kelp limpet	1	0
<i>Dendrofissurella scutellum</i>	Saddled keyhole	1	0
<i>Discinisca tenuis</i>	Disc lamp shell	1	1
<i>Electra Pilosa</i>	Hairy lace animal	0	1
<i>Hymeniacidon perlevis</i>	Crumb of bread sponge	1	0
<i>Isanthus capensis</i>	Ring tentacle anemone	1	1
<i>Membranipora rustica</i>	Rustic lace animal	1	1
<i>Menipea crispa</i>	Curled moss animal	1	0
<i>Menipea triseriata</i>	Spiral moss animal	0	1
<i>Mytilus galloprovincialis</i>	Mediterranean mussel	1	1
<i>Notomegabalanus algicola</i>	White dwarf barnacle	1	1
<i>Obelia geticulata</i>	knotted thread hydroid	1	1
<i>Plumalaria setacea</i>	Plumed hydroid	1	1
<i>Pseudactinia infecunda</i>	False plum anemone	1	1
<i>Serpula vermicularis</i>	Operculate fanworm	0	1
<i>Siphonaria capensis</i>	Cape False limpet	1	0
<i>Siphoria spp.</i>		1	0
<i>Spirorbis spirorbis</i>	Coil worm	1	0
<i>Styela angularis</i>	Angular ascidian	0	1
<i>Trachycladus spinispirulifer</i>	vented sponge	1	0
Total		25	19

Species richness differed significantly between sites (Kruskal-Wallis $\chi^2 = 76.92$, $df = 1$, $p < 0.001$), and pairwise comparisons confirmed that Diaz Point supported significantly higher richness than Shearwater Bay ($p < 0.001$). This pattern was also observed in the ordination results, where the native kelp forest at Diaz Point exhibited higher taxonomic diversity and greater dispersion of taxa, including groups such as sea anemones and sponges that were not recorded at the kelp farm. In contrast, the kelp farm at Shearwater Bay was characterised by a higher frequency of occurrence of a limited number of filter-feeding species, particularly *Notomegabalanus algicola* and *Aulacomya atra*.

The PCoA ordination showed separation of sessile invertebrate communities by site (Fig. 3). Samples from Shearwater Bay and Diaz Point formed largely distinct clusters along the primary ordination axis (PCoA1). Shearwater Bay samples were more tightly clustered, while Diaz

Point samples were more widely dispersed across the ordination space. This visual separation corresponds to high dissimilarity among samples (Jaccard mean = 0.86). Analysis using the Sørensen similarity coefficient, appropriate for presence–absence data, indicated moderate overlap among samples, with a mean similarity of 0.46.

Permutational multivariate analysis of variance (PERMANOVA) confirmed that both site and month significantly influenced community composition. Site explained 13% of the variation ($R^2 = 0.13$, $F = 24.51$, $p < 0.001$), while month explained 12% ($R^2 = 0.12$, $F = 4.43$, $p < 0.001$). The combined model (Site + Month) accounted for 21% of the total variation ($R^2 = 0.21$, $F = 7.42$, $p < 0.001$).

3.2. Substrate utilisation across sites and time

All frequency of occurrence values presented in the results are derived from presence/absence data and represent the proportion of species recorded as present within each site, substrate, taxonomic order, and sampling period. These values reflect species occupancy patterns rather than abundance or individual counts.

The frequency of occurrence for sessile invertebrates across different substrate type was analysed for Diaz Point and Shearwater Bay from Quarter 2 through Quarter 4 visualised in Fig. 4. The data reveals differences in both total substrate utilization and the specific materials occupied at each site. A marked difference in the total frequency of occurrence was observed between the two study locations. Shearwater Bay consistently exhibited higher species occupancy across sampling periods, with a greater proportion of recorded species present across sampling units. In contrast, Diaz Point showed lower species occupancy, which increased from Quarter 2 to Quarter 3 and showed little change in Quarter 4.

3.2.1. Diaz Point: Substrate composition across sampling periods

At Diaz Point, substrate use in Quarter 2 was primarily associated with shells, rocks, and holdfasts, which showed similar levels of species occupancy across these substrate types. From Quarter 3 onwards, fronds were additionally recorded as a substrate category. This composition remained relatively stable through Quarter 4, with shells, rocks, holdfasts, and fronds all showing consistent representation in species presence across sampling periods.

3.2.2. Shearwater Bay: Substrate composition across sampling periods

Shearwater Bay exhibited a broader range of substrate categories with similar species occupancy across sampling periods throughout the study period. Species occupancy was evenly distributed across five substrate categories, including ropes, holdfasts, fronds, floats, and breeze blocks. Unlike Diaz Point, Shearwater Bay showed similar distributions of species occupancy across substrates and sampling periods.

3.3. Taxonomic shifts and temporal trends

Figure 5 illustrates the distribution of species occupancy across taxonomic orders at Diaz Point and Shearwater Bay over three consecutive quarters (Quarters 2–4). Overall, Shearwater Bay consistently exhibited higher species occupancy compared to Diaz Point, with both sites showing an overall increase in occupancy patterns from Quarter 2 through Quarter 4. Diaz Point showed a lower but similarly increasing trend in species occupancy over time. These values represent changes in the proportion of species recorded as present across taxonomic orders rather than absolute abundance or individual counts.

3.3.1. Taxonomic composition trends

The community composition differed between the two sites and across time. The community in Quarter 2 at Diaz Point included a high proportion of Mytilida and Siphonariida. However, by Quarter 4, there was an increase in Suberitida (lime) and Actiniaria (dark purple). Shearwater Bay most frequently recorded Mytilida (teal) in Quarter 2. As the year progressed into Quarter 3 and 4, there was an increase in the proportion of Actiniaria and Balanomorpha, which collectively accounted for more than half the total occurrences by the final quarter. In terms of the minor taxa, orders such as Lingulida and Trachycladida were recorded at low frequencies to the overall frequency at both sites throughout the study period.

4. DISCUSSION

4.1. Species richness and community composition

A total of 30 sessile marine invertebrate species, spanning eight phyla and 13 taxonomic orders, were recorded across the two study sites, reflecting a moderately diverse assemblage within the context of the sampled habitats and study design. The study area, located in Lüderitz within the northern Benguela upwelling system, is characterised by cold, nutrient-rich waters and high primary productivity, conditions that are widely recognised to support productive and dynamic marine communities (Hutchings et al. 2009). In such systems, elevated nutrient

availability enhances phytoplankton production, which in turn supports higher trophic levels, including filter-feeding and suspension-feeding invertebrates (Verheye et al. 2016). The observed species richness is consistent with patterns reported for highly productive upwelling systems such as the Benguela region, where elevated nutrient availability supports high benthic productivity and diverse sessile assemblages (Hutchings et al. 2009; Kremer et al. 2025). However, differences in richness between sites are more likely associated with local habitat structure and substrate complexity.

The separation of samples revealed in the Principal Coordinates Analysis (PCoA) indicates that sessile invertebrate communities differ between sites. The tighter clustering of Shearwater Bay samples suggests more similar community composition within this site, while the greater dispersion at Diaz Point indicates higher variability among samples. This pattern aligns with the Jaccard dissimilarity, suggesting that communities share relatively few species overall. This reflects a high degree of compositional heterogeneity across the study area. Complementary analysis using the Sørensen similarity coefficient further highlights that less than half of the species pool was shared across sites and sampling units, reinforcing the high degree of compositional heterogeneity observed across the study area.

PERMANOVA revealed a stronger effect of site compared to month, suggesting that spatial variation exceeds temporal variation in community composition. This pattern is widely reported in benthic systems, where local environmental conditions and substrate characteristics often outweigh short-term temporal variability (Underwood and Chapman 1996; Morton and Anderson 2013). This reflects a high degree of compositional heterogeneity (beta diversity) across the study area, a common feature of benthic communities where species turnover is associated with small-scale environmental differences and habitat discontinuities (Anderson et al. 2011). Additionally, the higher species richness observed at Diaz Point is consistent with its greater dispersion in the ordination space which corresponds to higher variability among samples, often associated with more heterogeneous habitats that support a wider range of ecological niches (Stein et al. 2014).

4.2. Substrate utilisation across sites and time

The frequency of occurrence data revealed clear differences in substrate utilisation between sites. Shearwater Bay exhibited consistently higher total frequencies of occurrence and a stable distribution across multiple substrate types, including ropes, floats, holdfasts, fronds, and breeze blocks. The relatively even distribution of occurrences across these substrates, maintained throughout all quarters, suggests that sessile invertebrates utilised the full range of available artificial and natural surfaces without pronounced temporal shifts. This consistency may reflect the continuous availability in providing consistent and suitable settlement surfaces under relatively stable hydrodynamic conditions (Shunatova et al. 2018).

In contrast, Diaz Point showed lower overall frequencies of occurrence and greater temporal variability in substrate use. Substrate utilisation was initially concentrated on shells, rocks, and holdfasts, with fronds becoming more prominent in later quarters. This pattern indicates a more variable use of available substrates over time, with shifts in the relative contribution of different substrate types rather than a consistent distribution. Unlike Diaz Point, Shearwater Bay showed little variation in both total frequency of occurrence and proportional substrate use across the three quarters, indicating a relatively stable pattern of substrate utilisation. This consistency may reflect the continuous availability of artificial structures at the kelp farm, in contrast to the more dynamic and potentially transient nature of natural substrates at Diaz Point.

These differences may be associated with the contrasting structural environments between the two sites. The kelp farm provides a range of persistent artificial substrates that remain available throughout the sampling period, whereas the native kelp forest is characterised by more variable natural substrates, which may influence how frequently different surfaces are occupied over time (Connell 2001; Bulleri and Chapman 2010). An additional contextual difference between the sites is their degree of hydrodynamic exposure. The native kelp forest at Diaz Point is situated along a semi-exposed rocky shoreline, whereas the kelp farm at Shearwater Bay is located within a relatively sheltered embayment above a muddy bottom. Differences in exposure are known to influence sessile invertebrate colonisation by influencing larval delivery, settlement success, substrate stability, and post-settlement survival (Denny 1988; Menge 2000; Pineda et al. 2009).

4.3. Taxonomic occurrence patterns across sites and time

Differences in taxonomic composition between sites were also evident in species occupancy patterns. Shearwater Bay consistently showed higher species occupancy, associated with the high occurrence of Mytilida across sampling periods. Mytilids are well known for their high occupancy in artificial and fouling environments due to rapid colonisation and persistence on hard substrates (Harms and Anger 1983; Borthagaray and Carranza 2007). According to Harms & Anger (1983), mytilids can overgrow earlier colonisers such as barnacles (Balanomorpha) in fouling assemblages. Balanomorpha exhibited an increased frequency of occurrence over time, peaking during the second and third quarters before declining in the fourth, consistent with patterns typically reported for early colonising taxa in fouling communities (Harms and Anger 1983; Toledo et al. 2020). Increasing contributions from Actiniaria in later quarters were associated with a broader taxonomic representation over time. Cheilostomatida (bryozoans) declined mid-year before recovering in the fourth quarter, indicating temporal variation in occupancy patterns that may be associated with seasonal processes (McKinney and Jackson 1989). In contrast to their relatively high occupancy at the natural kelp forest at Diaz Point, Sabellida were nearly absent from the kelp farm, consistent with differences in structural and habitat complexity between natural and artificial environments (Connell 1978).

At Diaz Point, taxonomic composition showed greater temporal variability. Early quarters were characterised by higher frequencies of occurrence of Mytilida and Siphonariida, whereas later quarters showed increased representation of Suberitida and Actiniaria. These shifts indicate temporal turnover in taxonomic presence patterns. Seasonal variation in benthic invertebrate occurrence is widely documented and is associated with larval supply, environmental conditions, and post-settlement mortality (Menge 2000; Pineda et al. 2015).

Minor taxa, including Lingulida and Trachycladida, consistently exhibited low frequencies of occurrence at both sites throughout the study period. Despite their low representation, their repeated presence indicate they form a persistent background component of the assemblage. Overall, the kelp farm exhibited more temporally stable taxonomic occurrence patterns than the native kelp forest, which may be associated with reduced habitat heterogeneity and greater environmental consistency associated with artificial structures. Such systems are often characterised by simplified assemblages dominated by a small number of opportunistic or competitively dominant taxa, particularly mussels and barnacles (Harms and Anger 1983; Toledo et al. 2020). In contrast, natural habitats tend to support more variable assemblages due to greater habitat complexity and environmental heterogeneity. Similarly, natural kelp forest environments typically support higher temporal variability due to increased structural complexity and microhabitat diversity, which enhance species turnover and coexistence (Connell 1978).

This study is based on observations from a single kelp aquaculture site and a single natural kelp forest site and therefore does not represent a spatially replicated experimental comparison. The two sites differ in several co-varying environmental and structural characteristics, including kelp species composition, substrate type, and hydrodynamic exposure. As a result, the observed differences in species richness, community composition, and substrate utilisation may reflect a combination of these factors rather than any single underlying driver. Consequently, findings should be interpreted as indicative patterns associated with contrasting habitat contexts rather than causal relationships. Future studies should incorporate spatial replication across multiple sites and more controlled sampling designs to better isolate the influence of individual environmental variables on sessile invertebrate assemblages. In addition, the use of presence-absence data limits the ability to detect changes in species dominance, relative abundance, and evenness, which may influence interpretations of community structure.

In conclusion, this study demonstrates consistent differences within the study sites in sessile invertebrate assemblages between natural and farmed kelp habitats in the Benguela upwelling system. The natural kelp forest at Diaz Point supported higher species richness and greater community heterogeneity than the kelp farm at Shearwater Bay, which was characterised by lower richness and dominance of a few opportunistic fouling taxa. Across all analyses, spatial variation exceeded temporal variation, with patterns of community structure differing among habitat contexts and substrate types. Artificial farming structures provided persistent, homogeneous substrates that supported relatively stable but simplified assemblages dominated by mussels and barnacles. In contrast, natural kelp forests exhibited more variable and diverse assemblages, reflecting greater structural complexity and environmental heterogeneity.

While kelp aquaculture structures do contribute additional habitat for sessile organisms, they did not replicate the biodiversity or community complexity observed at the natural kelp forest within this study. These findings are particularly relevant in the context of the ongoing expansion of kelp aquaculture in the region, where ecological outcomes remain insufficiently documented. This study provides the first dataset of its kind for Namibia describing sessile invertebrate assemblages associated with both natural kelp forests and kelp aquaculture structures. As such, it establishes a critical baseline for future ecological monitoring and long-term assessment of biodiversity change, ecosystem functioning, and the ecological role of kelp aquaculture within southern African coastal systems.

Declarations

This study was funded by the Kelp Forest Foundation. The authors declare that they have no known competing financial or non-financial interests that could have appeared to influence the work reported in this paper. The research was conducted at the Kelp Blue facility with logistical support from Kelp Blue employees, including divers and the marine monitoring team; however, the funders and supporting personnel had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

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Author Contribution

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by D. N.K.H. The first draft of the manuscript was written by D.N.K.H. L.K. provided co-supervision, academic guidance throughout the study and conceptual development of the overall study design. T.N. provided the main supervision, mentorship, and academic guidance throughout the study and manuscript preparation. D.N.K.H. and T.N. contributed to manuscript review and editing, and both authors read and approved the final manuscript.

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Data Availability

The datasets generated and analyzed during the current study are not publicly available but are available from the corresponding author on reasonable request.

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Figures

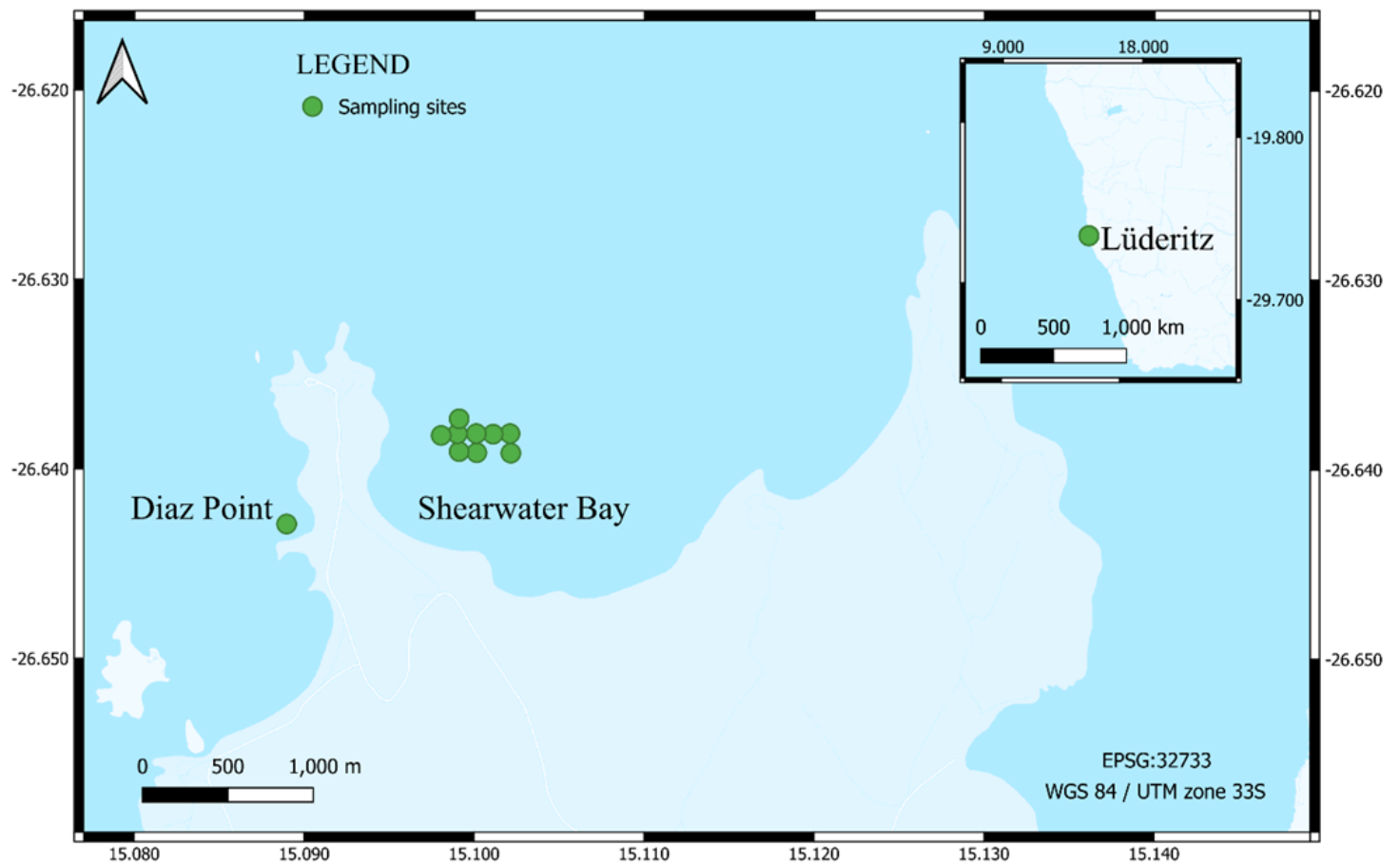


Figure 1

Study area map showing sampling sites in Lüderitz, Namibia, created using Quantum Geographic Information System (QGIS) (Spatial without Compromise · QGIS)

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Figure 2

Fig. 2 Bottom-based structures used for kelp cultivation deployed at 9 m depth at the study site. (A) Schematic drawing of the bottom-based block design; (B) Photograph of the deployed bottom-based blocks

PCoA of Sessile Invertebrate Composition (Jaccard Distance)

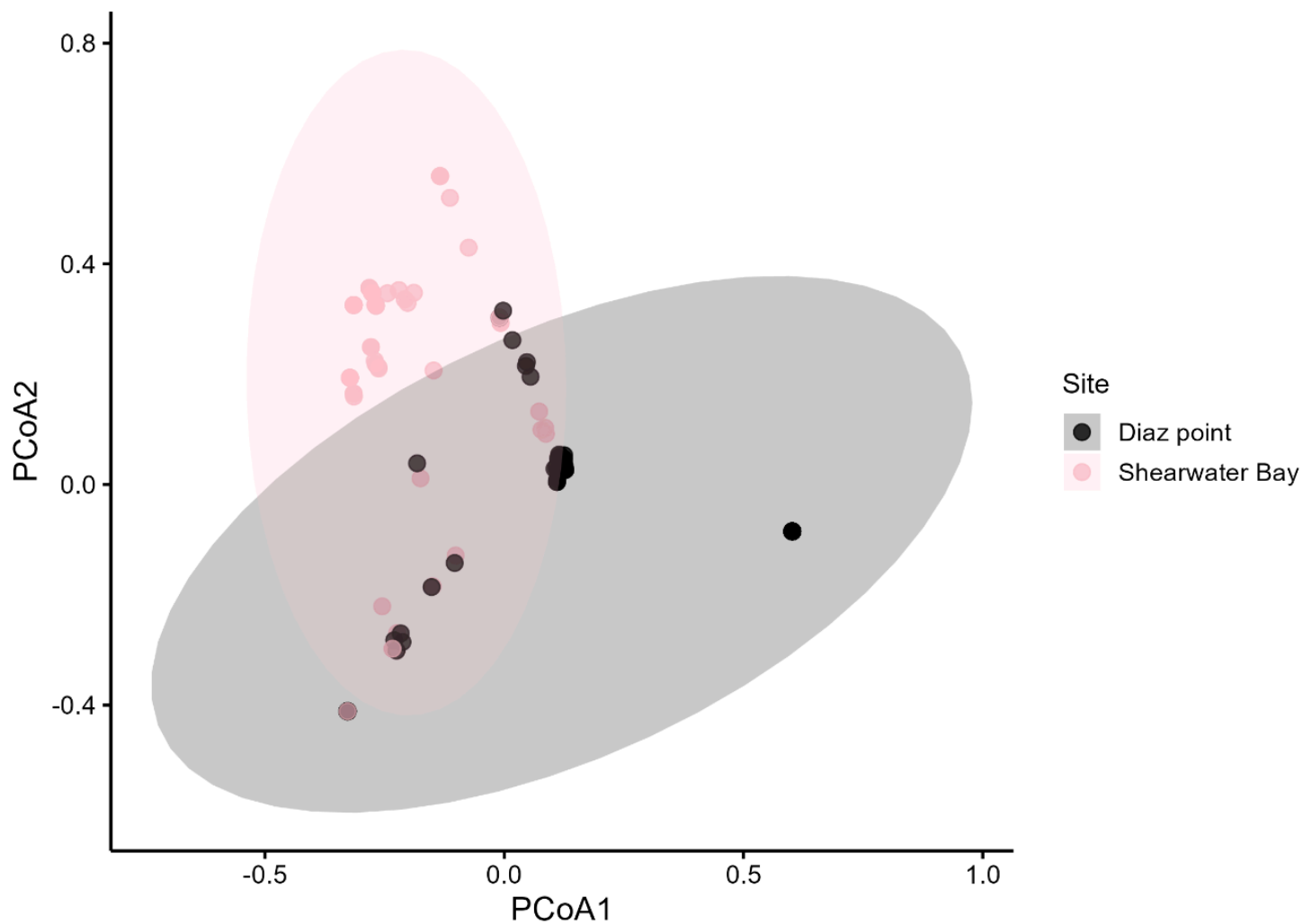


Figure 3

Principal Coordinates Analysis (PCoA) of sessile invertebrate communities based on Jaccard dissimilarity

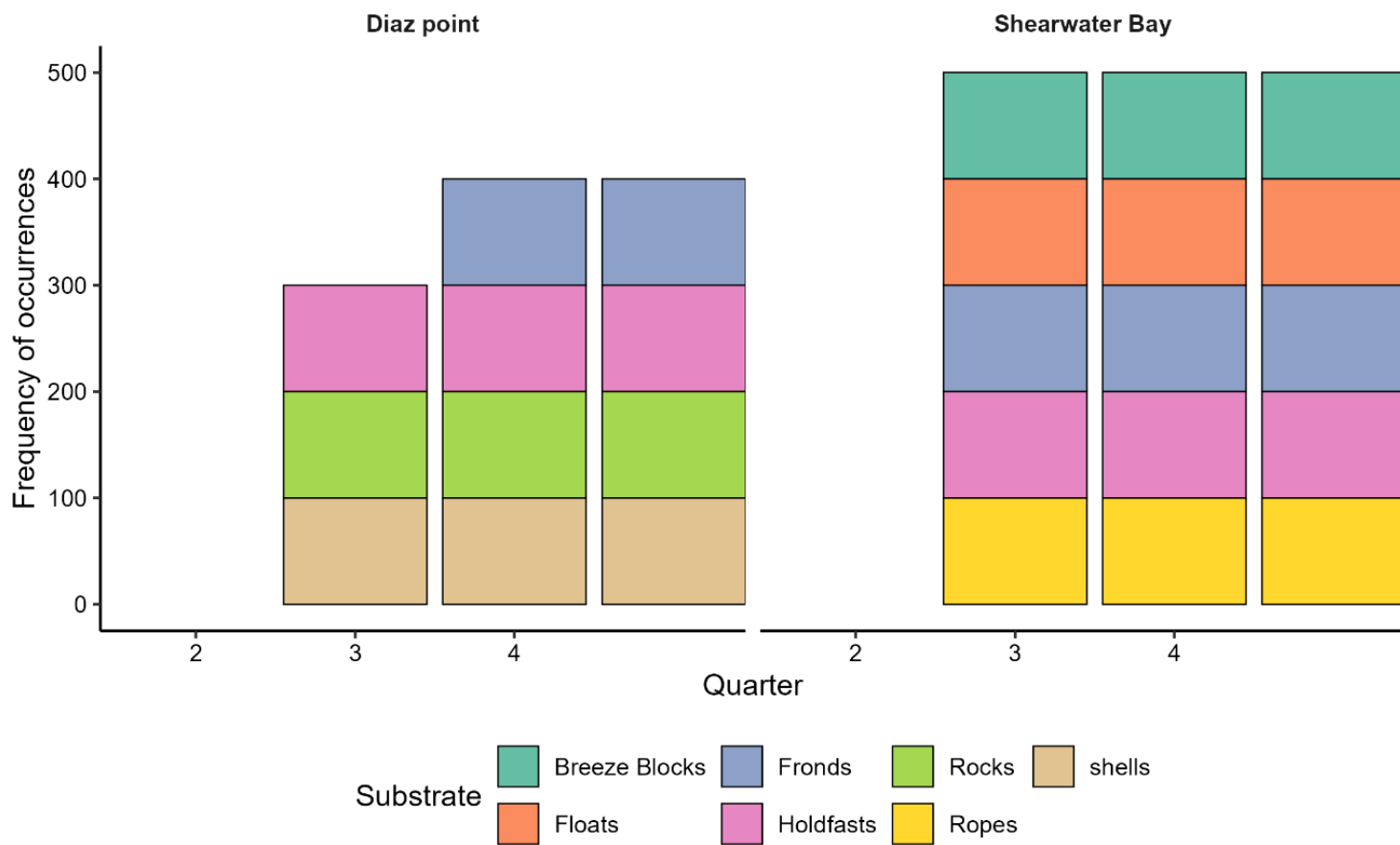


Figure 4

Frequency of occurrence of sessile invertebrates across substrate types, sampling quarters, and sites, illustrating temporal and spatial variation in community distribution

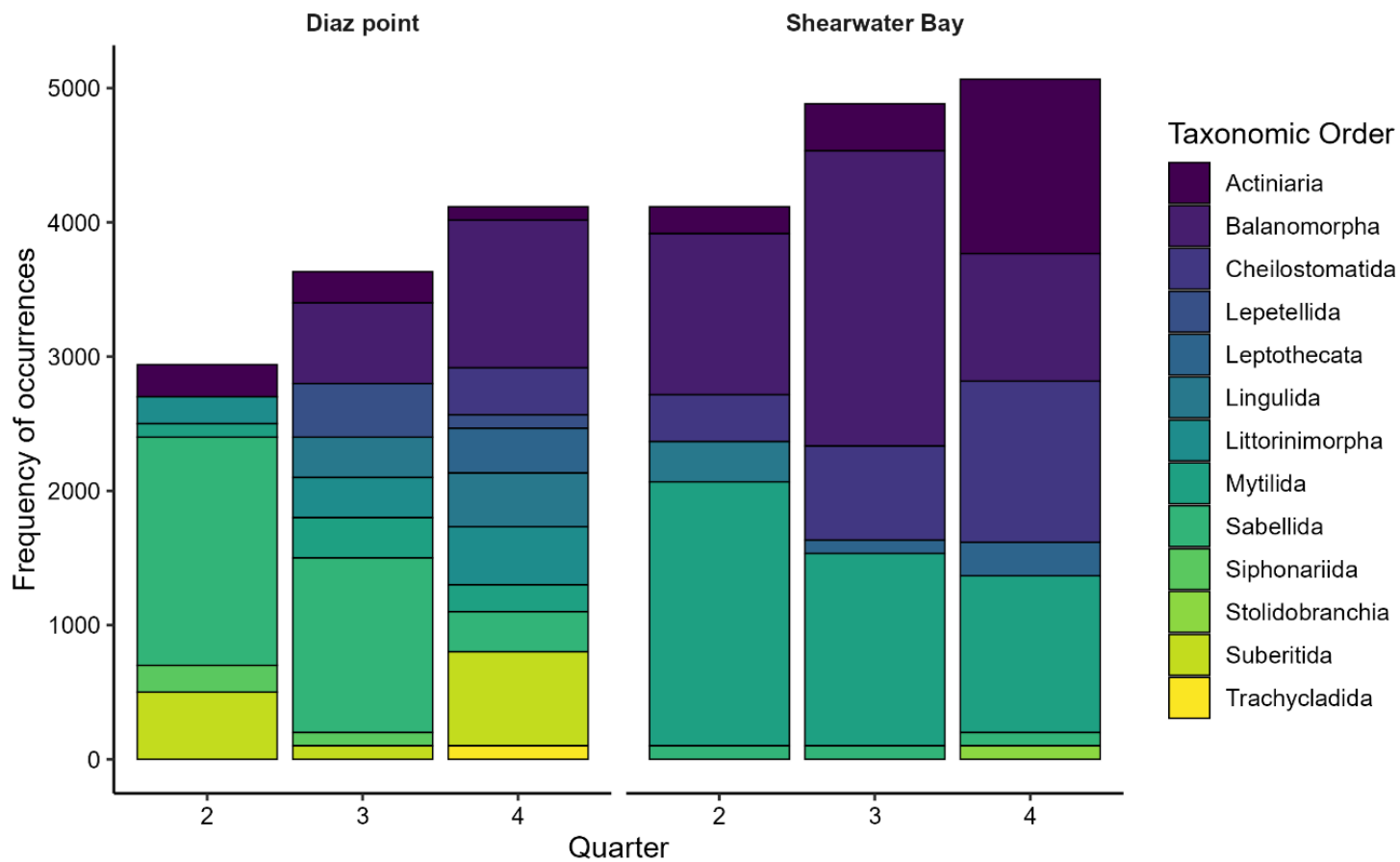


Figure 5

Frequency of occurrence of sessile invertebrate taxonomic orders across sites and quarters, showing spatial and temporal variation in taxonomic composition