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EDITED BY
Cornelia E. Nauen,
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REVIEWED BY
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State University of Zanzibar, Tanzania
Ilana Rosental Zalmon,
State University of the North Fluminense Darcy Ribeiro, Brazil

*CORRESPONDENCE
Nittya S. M. Simard
Nittya.simard@research.usc.edu.au

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Utilization of marine taxa within an artisanal shellcraft sector of the Indo-Pacific region

Nittya S. M. Simard[1]*, Thane A. Militz[1], Jeff Kinch[2] and Paul C. Southgate[1]

[1]School of Science, Technology & Engineering and Australian Centre for Pacific Islands Research, University of the Sunshine Coast, Sippy Downs, QLD, Australia, [2]National Fisheries College, National Fisheries Authority, Kavieng, Papua New Guinea

Sustainable utilization of marine taxa is critical for maximizing social and economic goals of livelihood development within the Indo-Pacific. Yet, despite an increasing importance of shellcraft as a livelihood activity within the Indo-Pacific, information on the taxa utilized within shellcraft sectors remains scant. To address this knowledge gap, our study examined diversity, in terms of composition and quantities, of marine taxa utilized by artisan households and, collectively, within an artisanal shellcraft sector of Papua New Guinea. For each taxon, critical source habitats were identified, and the geographic scale of exploitation established. Critically, presented data revealed 73 taxa, representing at least 77 species, were utilized within the studied sector. Many of the taxa utilized had not previously been linked to shellcraft sectors, demonstrating that a broader composition of taxa is utilized than previously acknowledged. In terms of quantity, annual utilization within the sector was close to 500,000 individuals, the majority being mollusks of either class Gastropoda (83.6%), represented by 37 genera, or class Bivalvia (9.6%), represented by four genera. There was a strong bias towards a particular species, *Chrysostoma paradoxum* (78.5% of all individuals), as indicated by indices for the diversity utilized (H' = 1.23; D = 0.38). However, substantial variation was evident in the diversity of taxa utilized among households (n = 36) engaged in shellcraft (H' = 1.09 $\pm$ 0.71; D = 0.43 $\pm$ 0.27), with each household utilizing a unique composition of 19.1 $\pm$ 10.6 taxa. Source habitats for taxa ranged from pelagic to benthic intertidal and subtidal substrates, with the geographic scale of exploitation extending to 34 discrete locations up to 417 km away. The array of sector, household, and taxon-specific information presented provides a basis for supporting greater sustainability within shellcraft sectors across the Indo-Pacific, which is discussed within a context of informing community-based resource management, further developing marine aquaculture, and strengthening existing governance.

KEYWORDS

artisanal fisheries, diversity, coastal communities, exploitation, livelihoods, mollusks (molluscs), Papua New Guinea (PNG)

Introduction

Shellcraft, an activity producing shell-handicrafts (Fröcklin et al., 2018) or shell-based handicrafts (Simard et al., 2019), encompasses production of ornamental and decorative items that utilize shells and other skeletal remains of marine taxa. Such items, hereafter referred to as shellcrafts, can be produced in remote locations using either traditional tools or modern equipment, and can offer much-needed livelihood opportunities, particularly in coastal areas with high marine biodiversity (Fröcklin et al., 2018; Simard et al., 2019; Southgate et al., 2019; Militz et al., 2021). Shellcraft has become an increasingly important means of income generation for coastal communities throughout the Indo-Pacific (Sulu et al., 2015; Barclay et al., 2018; Fröcklin et al., 2018; Simard et al., 2019) and, over recent years, demand for souvenirs made locally, by hand, and with natural materials, such as shellcrafts, has grown with the rise of tourism (Floren, 2003; Gössling et al., 2004; Dias et al., 2011; Chand et al., 2014; Naidu et al., 2014; Militz et al., 2021). Yet, despite an increasing importance of shellcraft, there has been limited research on this activity, within a contemporary context, with prior research focused primarily on anthropological perspectives (Lewis, 1939; Grulke, 2022).

To maximize social and economic goals of livelihood development in the Indo-Pacific, sustainable utilization of marine taxa is critical (Allison and Ellis, 2001), and this is particularly true for shellcraft sectors (Fröcklin et al., 2018). Within related and better studied curio sectors, over 5,000 species of marine mollusks, corals, and other taxa groups are reportedly traded (Wood and Wells, 1995). While a similar composition of taxa may be traded within shellcraft sectors, our knowledge of the taxa utilized to produce shellcrafts is scant (Floren, 2003; Fröcklin et al., 2018). Legally protected, and often larger taxa, such as sea turtles (Kinch and Burgess, 2009) and nautilus (Nijman and Lee, 2016; Nijman, 2019), are known to be utilized for shellcraft, however, the quantities involved along with other information relevant to their use is seldomly investigated. Moreover, efforts to document shellcraft within the Indo-Pacific have focused primarily on socio-economic impacts of this activity (e.g., Tiraa-Passfield, 1996; Chand et al., 2014; Sulu et al., 2015; Barclay et al., 2018; Fröcklin et al., 2018; Simard et al., 2019), rather than the taxa utilized.

Collecting information on taxa utilized for small-scale and artisanal livelihood activities is challenging but necessary to estimate potential socio-ecological impacts (Pita et al., 2019). While intact and unprocessed remains of marine taxa traded as curios may be easily identified and quantified, this is not necessarily the case for taxa utilized to produce shellcrafts (Nijman et al., 2015). Post-harvest processing, inherent in producing shellcrafts, may render the remains of taxa unidentifiable, limiting the feasibility of market surveys (e.g., Nijman and Lee, 2016; Nijman, 2019). Furthermore, available trade records tend to generate limited information on local exploitation for shellcraft and fail to adequately represent the diversity of taxa utilized (Wood and Wells, 1995; Floren, 2003; Simard et al., 2019; Simard et al., 2021). To overcome these and additional challenges in monitoring shellcraft sectors, including remoteness, geographic scale, and irregular frequencies of artisanal fishing (Simard et al., 2019), data collection through structured household interviews appears to be an effective approach to obtaining sector-specific information at a local scale (Kronen et al., 2007). This approach has been used to generate information for other artisanal fisheries sectors in the Indo-Pacific (Friedman et al., 2008; Purdy et al., 2017; Thaman et al., 2017), and has potential to afford a basic understanding of taxa utilized within shellcraft sectors.

Within the Indo-Pacific, the island nation of Papua New Guinea (PNG) has a long tradition of shellcraft with coastal communities producing shellcrafts for personal ornamentation and exchange (Lewis, 1939). More recently, shellcraft has taken a commercial focus, expanding rapidly in areas popular with tourists by adapting traditional knowledge to produce contemporary designs (Simard et al., 2019). While exploring socio-economic aspects of such development among the Tigak Islands of New Ireland Province in PNG, Simard et al. (2019) found that at least 17 marine species were utilized to produce shellcrafts. As a baseline study, however, Simard et al. (2019) only accounted for species deemed of critical importance from a socio-economic perspective and the study did not determine the diversity of taxa utilized. To address this knowledge gap, the aim of our study was to evaluate diversity, in terms of composition (i.e., number of taxonomic groups) and quantities (i.e., number of individuals per taxonomic group), of marine taxa utilized by individual artisan households and, collectively, within the shellcraft sector of the Tigak Islands. For each taxon, we identified critical source habitat(s), established the geographic scale of exploitation, and examined the relational structure among metrics representing various aspects of utilization.

Materials and methods

Study area

Papua New Guinea comprises the eastern part of the island of New Guinea and numerous smaller islands in the southwestern Pacific region. Domestic and international tourism greatly expanded at coastal destinations in PNG prior to the COVID-19 pandemic (PNGTPA, 2020; Militz et al., 2021). The influx of tourists brought demand for a new range of goods and services, presenting coastal communities with novel income generating opportunities (IFC, 2016). An unmet demand for souvenirs (IFC, 2016) coupled with a loss of critical income sources, such as bêche-de-mer fisheries (Purdy et al., 2017), appears to have catalyzed local expansion of shellcraft (Simard et al., 2019; Militz et al., 2021). This is particularly true among the Tigak Islands of New Ireland Province where households rely on marine resources for subsistence and income (Kaly et al., 2005; Purdy et al., 2017). Over a span of twenty years, participation in shellcraft among the Tigak Islands expanded from a single household to become an income source supporting at least 6% of residents by 2017 (Simard et al., 2019). The shellcraft sector of the Tigak Islands is now well-established and presents a unique opportunity to evaluate utilization of marine taxa for this increasingly important livelihood activity. With resumption of international tourism to PNG now underway (PNGTPA, 2022), such information comes at an opportune time to provide a basis for future development plans supporting sustainability within this sector.

Data collection

Past research on the shellcraft sector of the Tigak Islands (Simard et al., 2019) found that artisans concentrated at the Nusa Islands. We conducted a survey at these islands in July 2019 to identify households producing shellcrafts. Households with at least one member that had routinely produced shellcrafts during the previous year were asked to participate in an interview. No household refused participation, and all households (n = 36) that met the inclusion criteria were interviewed.

Interviews were conducted verbally in either English or Tok Pisin, depending on the preference of the participants, and followed a semi-structured format with a questionnaire to guide the interview. Participants were asked to identify all marine taxa their household utilized in the production of shellcrafts. Since it was unreasonable to expect participants to identify taxa by internationally recognized (i.e., scientific) names (Moesinger, 2018), taxa were identified to the lowest taxonomic rank possible using a photographic reference guide and voucher specimens. Nomenclature was based on the World Register of Marine Species (Horton et al., 2022). For each taxon identified, participants were asked to indicate the quantity utilized during the previous year. Additionally, participants were asked to list all locations from where they had obtained (either purchased, traded, or fished) each taxon identified and, if obtained through their own fishing activities, to identify source habitat(s).

Where identified taxa were phenotypically and functionally (as a material) similar, participants were unable to provide species-specific information. Instead, information was provided for a group of taxa. This applied to the black corals *Antipathes* spp. and *Cirrhipathes* spp. (hereafter Antipathidae), the cowries *Monetaria annulus* and *Monetaria moneta* (hereafter *Monetaria annulus/moneta*), the nautilus *Allonautilus scrobiculatus* and *Nautilus pompilius* (hereafter Nautilidae), and the sea turtles *Chelonia mydas* and *Eretmochelys imbricata* (hereafter Cheloniidae). We considered each group as a 'taxon' in our study to accommodate the integration of local and traditional knowledge systems with contemporary fisheries science (Moesinger, 2018).

For each taxon utilized, information obtained from interviews was supplemented with biological data gleaned from SeaLifeBase (Palomares and Pauly, 2020). Specifically, 'common length' was used as an indicator of the typical size of a given taxon. In cases where data were not available, an appropriate metric of size (antero-posterior measurement, dorso-ventral measurement, carapace width, or colony height, depending on the taxon) was measured from a voucher specimen using either a vernier caliper (for taxa ≤ 15 cm) or measuring tape (for taxa > 15 cm).

Data standardization

Varying systems of measurement were used by participants to indicate the quantities of taxa utilized during the previous year. Quantities were reported as the number of individuals, 'bottles', or pieces of a taxon utilized on a weekly, monthly, or annual basis. As these measures were not directly comparable, quantities were standardized as the number of individuals utilized annually. For some measures (i.e., bottles and pieces), this required establishing appropriate conversion factors.

Quantities reported in terms of 'bottles' refers to a local practice of storing and trading smaller taxa in 330 mL glass bottles (Figure 1). To establish an appropriate conversion factor for each of the 20 taxa quantified in this manner, the number of individuals within a representative bottle was determined. An appropriate conversion factor was then applied to express the quantity of individuals utilized annually.

Quantities of sea turtles (Cheloniidae), reef sharks (*Carcharhinus melanopterus*), and black corals (Antipathidae) were commonly reported in terms of taxon-specific pieces. For sea turtles, participants reported the number of carapace scutes utilized (Figure 1), which is a typical measure of sea turtle utilization for shellcraft (Kinch and Burgess, 2009). Since *Chelonia mydas* and *Eretmochelys imbricata* were the only sea turtles identified by participants, a conversion factor of 13 scutes to one carapace (i.e., individual) was adopted (Wyneken, 2001). For reef sharks, participants reported the cumulative length, in centimeters, of cartilaginous vertebrae utilized. Since only vertebrae of immature sharks were reportedly utilized, a conversion factor of 42.5 cm to one individual was adopted (White et al., 2017). For black corals, participants reported the cumulative length, in centimeters, of branches utilized. A conversion factor of 100 cm to one individual was adopted, representing a typical *Cirrhipathes* spp. colony (pers. obs.).

Source habitats were standardized broadly as intertidal benthic, subtidal benthic, or subtidal pelagic. The local ecological knowledge of participants, however, permitted further differentiation of

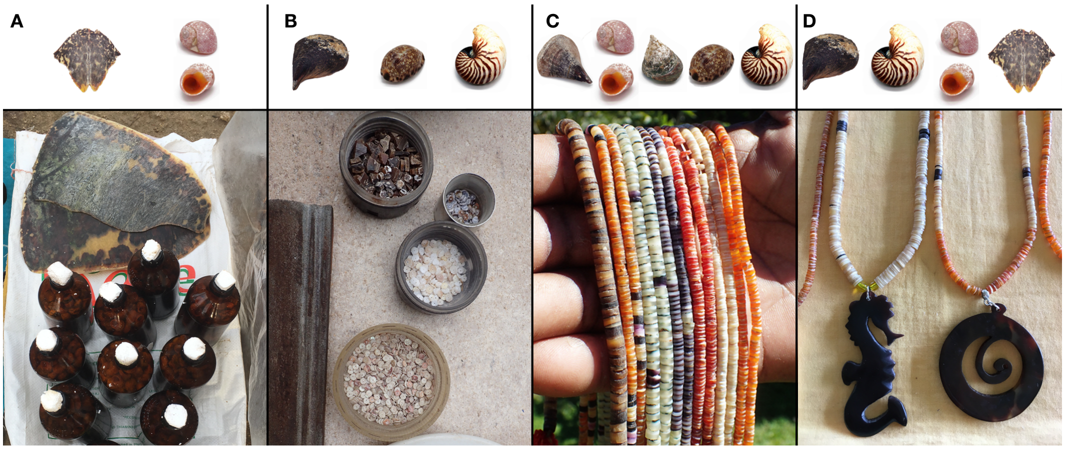

FIGURE 1
Examples of marine taxa utilized within the shellcraft sector of the Tigak Islands at various stages of production. **(A)** Bottles containing gastropod (*Chrysostoma paradoxum*) shells and pieces (i.e., scutes) of sea turtle (Cheloniidae) carapace being sold at a local market. **(B)** Shell fragments produced from (top to bottom) *Atrina vexillum*, *Mauritia arabica*, and Nautilidae, separated by color, which will be further processed into beads. **(C)** Strands of beads made from *Atrina pectinata* (brown), *C. paradoxum* (orange or red), *Turbo maculatus* (green), *M. arabica* (purple), and Nautilidae (white). **(D)** Shellcrafts at a local market (left: pendant made from *A. vexillum*, beads made from Nautilidae and A. *vexillum*; right: pendant made from Cheloniidae, beads made from Nautilidae, C. *paradoxum*, and *A. vexillum*) for which enumerating the number of individuals of each taxon utilized is exceedingly difficult. Photos by Nittya S.M. Simard.

intertidal benthic habitats based on substrates that the taxon was associated with, and a distinction was made between hard substrates (i.e., rock, wood, or sedimentary hardgrounds) and soft substrates (i.e., unconsolidated sediments).

In addition to source habitats, it was also necessary to standardize locations that were identified using vernacular place names. Coordinates from the World Geodetic System 1984 (WGS84) were attributed to all referenced locations from where taxa were obtained. Where the referenced location was not discrete but referred to an island or region, the center of referenced area was used when attributing coordinates.

Data analysis

All statistical computing was performed using *R* programming (version: 4.1.3), with the *stats* (R Core Team, 2021), *geosphere* (Hijmans, 2021), *corrplot* (Wei and Simko, 2021), and *vegan* (Oksanen et al., 2020) packages. For all analyses, statistical significance was accepted as $P < 0.05$ and summaries of data are presented in-text as the mean ± standard deviation.

Diversity, in terms of composition and quantities of taxa utilized, was further represented by two compound indices: Shannon-Wiener index (H') and Simpson's index (D). The Shannon-Wiener index was calculated as

$$H' = -\sum p_i \ln(p_i)$$

where p_i is the proportional quantity of taxon i that was utilized for shellcraft (function: *diversity*). Simpson's index was calculated as

$$D = 1 - \frac{\sum n_i(n_i - 1)}{N(N-1)}$$

where N is the total quantity of all taxa utilized and n is the quantity of taxon i that was utilized for shellcraft (function: *diversity*). These indices were calculated to express diversity within the shellcraft sector (based on simple-pooling of data from all households) and among artisan households (based on data from each household), the latter being summarized by measures of central tendency and variation (mean ± standard deviation and range). Additionally, multivariate statistics were used to investigate whether composition and quantities utilized differed among artisan households. Specifically, non-metric multidimensional scaling (nMDS) was used to visualize differences in the probability that households utilized a non-identical composition of taxa, based on a Raup-Crick dissimilarity matrix, and to visualize differences in the quantities of taxa utilized, based on a Bray-Curtis dissimilarity matrix (function: *metaMDS*). A taxa-accumulation curve was also constructed from random permutations of the data to estimate the proportional composition of taxa that were utilized by a random sample of artisan households (function: *specaccum*).

To examine whether both the composition and quantities of taxa originating from the four source habitats differed, χ^2-tests with Yates' continuity correction were used (function: *prop.test*). Since the broadly defined source habitats led to an absence of variation in the number of habitats from which a taxon was obtained, this metric was excluded from further analyses describing utilization. In contrast, metrics representing the geographic scale of exploitation (i.e., the number and distance [based on Haversine distances; function: *distHaversine*] of locations from which a taxon was obtained) had sufficient variation to merit further analysis.

To examine the relational structure among metrics representing various aspects of utilization, a correlation matrix was constructed comparing the number of households utilizing each taxon, the quantity of each taxon utilized, the typical size of each taxon, the number of locations from where each taxon was obtained, and the furthest location from where each taxon was obtained. Kendall's correlation tests (function: *cor.mtest*) were used to construct the correlation matrix, controlling for the false discovery rate with the Benjamini and Hochberg (1995) procedure.

Research activities associated with this study were reviewed and approved by University of the Sunshine Coast's Human Research Ethics Committee (approval number: S191337). Authorization to conduct research activities in PNG was obtained through a Memorandum of Subsidiary Agreement (approval number: FIS/2014/060) between the Australian Centre for International Agricultural Research and the PNG National Fisheries Authority. Permissions to engage with residents of the Nusa Islands were obtained from elected and traditional community leaders prior to obtaining informed consent from households for their participation in this study.

Results

Diversity of taxa utilized within the shellcraft sector

Seventy-three marine taxa from seven classes were utilized within the shellcraft sector of the Tigak Islands (Figure 2). The majority (93.2%) of taxa utilized were mollusks of either class Gastropoda (83.6%), represented by 37 genera, or class Bivalvia (9.6%), represented by four genera. All taxa representing these classes are presented in Figure 2 and Table S1. Each of the other classes were represented by only a single taxon: for Cephalopoda this was Nautilidae, for Chondrichthyes this was *Carcharhinus melanopterus*, for Hexacorallia this was Antipathidae, for Malacostraca this was *Carpilus maculatus*, and for Reptilia this was Cheloniidae.

Annual utilization within the sector was close to 500,000 individuals (Table 1). Gastropoda was the most utilized class (98.7%), followed by Bivalvia (1.0%). Critically, most (90.4%) of the 73 taxa accounted for less than 1.0% of individuals, while a single gastropod, *Chrysostoma paradoxum*, accounted for 78.5% of all individuals utilized (Figure 2). By comparison, the next most utilized taxa, *Euplica scripta*, which is also a gastropod, accounted for only 3.0% of all individuals utilized. Among the other classes, the most utilized bivalve was *Pinctada margaritifera* of which 1,090 individuals (0.2%) were utilized, while 899 (0.2%) Nautilidae, 97 (< 0.1%) Antipathidae, 55 (< 0.1%) Cheloniidae, and 40 (< 0.1%) *Carpilus maculatus* individuals were utilized (Figure 2). Additional data, pertaining to the quantity of each taxon utilized within the shellcraft sector, are presented in Table S1.

When considering both the composition and quantities of taxa utilized, a Shannon-Wiener index (H') of 1.23 and a Simpson's index (D) of 0.38 was calculated for the shellcraft sector of the Tigak Islands. Excluding *Chrysostoma paradoxum*, however, showed a more even utilization ($H' = 3.27$; $D = 0.94$) of the remaining taxa.

Diversity of taxa utilized among artisan households

Composition of taxa utilized for shellcraft varied among artisan households (Figure 3), with 19.1 ± 10.6 (range: 3 – 56) taxa utilized per household. No household utilized the full composition of taxa within the sector (n = 73), and only two of the 36 households (5.6%) utilized more than half ($n \geq 37$). The taxa-accumulation curve (Figure 4) shows that with a random sample of 10 (27.7%) households, an estimated 80.3 ± 12.2% of taxa within the sector would be represented, whereas a sample of half the households would represent 92.0 ± 7.3% of taxa. No taxon, or class of taxa, was utilized by all households, with an average of 10.0 ± 9.0 (range: 1 – 33) households utilizing a given taxon (Table 1 and Figure 2). The number of households utilizing each taxon is presented in Table S1, while the composition of taxa utilized by each household is presented in Table S2.

Quantities of taxa utilized annually for shellcraft also varied among households, in both absolute and relative terms (Figure 3). A combined 12,744.1 ± 9,289.7 (range: 36 – 31,229) individuals were utilized per household, with taxon-specific utilization spanning from 9,999.3 ± 9,465.6 (range: 0 – 29,400) individuals per household for *Chrysostoma paradoxum* down to 0.1 ± 0.3 (range: 0 – 2) individuals per household for *Ovula ovum*. The combined quantity of taxa utilized by each household is presented in Table S2, while taxon-specific quantities utilized by each household are summarized in Table S1 as the mean ± standard deviation of all households.

A Shannon-Wiener index (H') of 1.09 ± 0.71 (range: 0.17 – 2.57) and a Simpson's index (D) of 0.43 ± 0.27 (range: 0.06 – 0.88) represented the composition and quantities of taxa utilized among households. Additional data, pertaining to the H' and D indices for each household, are presented in Table S2.

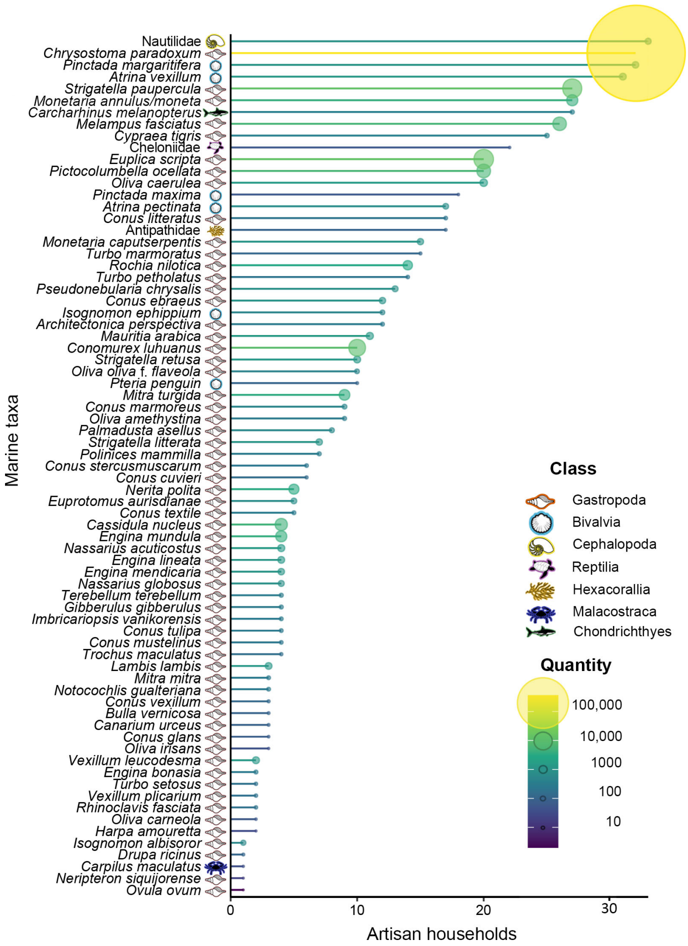

FIGURE 2
Utilization of marine taxa within the shellcraft sector of the Tigak Islands, Papua New Guinea between July 2018 and July 2019. Utilization is represented by the number of artisan households (*n* = 36) utilizing each taxon and the quantity of each taxon utilized by all households.

Source habitats

Each taxon was attributed to only one of the four broadly defined source habitats, amongst which the composition of taxa differed significantly (χ^2 = 68.4, P< 0.001; Figure 5). Intertidal benthic habitats accounted for 91.8% of all taxa, with a similar number of taxa being sourced from hard (n = 35) and soft (n = 32) substrates (χ^2< 0.01, P = 1.0). By comparison, subtidal

TABLE 1 Summary of marine taxa utilization, by taxonomic class, within the shellcraft sector of the Tigak Islands, Papua New Guinea between July 2018 and July 2019.

Class	Taxa		Households		Quantity	
	n	%	*n*	%	*n*	%
Gastropoda	61	83.6	35	97.2	453,023	98.7
Bivalvia	7	9.6	35	97.2	4,336	1.0
Cephalopoda	1	1.4	33	91.7	899	0.2
Reptilia	1	1.4	22	61.1	55	< 0.1
Hexacorallia	1	1.4	17	47.2	97	< 0.1
Malacostraca	1	1.4	1	2.8	40	< 0.1
Chondrichthyes	1	1.4	27	75.0	338	< 0.1

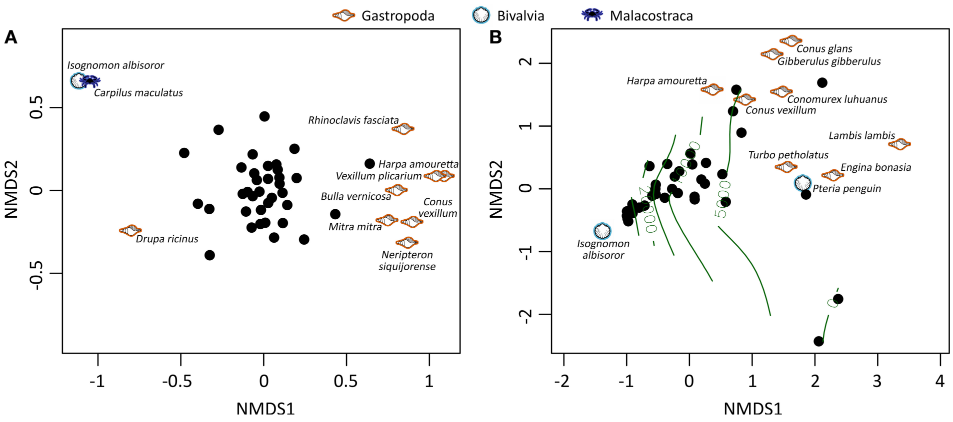

FIGURE 3
Differences in marine taxa utilization among artisan households (n = 36) within the shellcraft sector of the Tigak Islands, Papua New Guinea between July 2018 and July 2019. **(A)** nMDS biplot based on the probability that households utilized a non-identical composition of taxa (Raup-Crick dissimilarity). **(B)** nMDS biplot based on differences in the quantities of taxa utilized (Bray-Curtis dissimilarity), where green contour lines illustrate a significant ($F_{1,35}$ = 14.0, P< 0.001) association between ordination structure and the quantity of all taxa utilized by a household. Positioning of taxa reflects associations with the ordination structure; the ten most influential taxa are shown.

habitats accounted for only 8.2% of taxa, with the number of taxa sourced from benthic substrates (n = 4) similar to those sourced from the water column (i.e., pelagic; n = 2; χ^2 = 0.17, P = 0.68). Notably, gastropods and bivalves were sourced from all benthic habitats. Data pertaining to the source habitat for each taxon are presented in Table S1.

In terms of quantity, the vast majority (91.4%) of all individuals (n = 458,788) utilized were sourced from intertidal benthic hard substrates (Figure 5). Far fewer individuals were sourced from intertidal benthic soft substrates (8.1%), subtidal benthic (0.4%), or subtidal pelagic (< 0.1%) habitats (χ^2 = 1.45×10^6, P< 0.001).

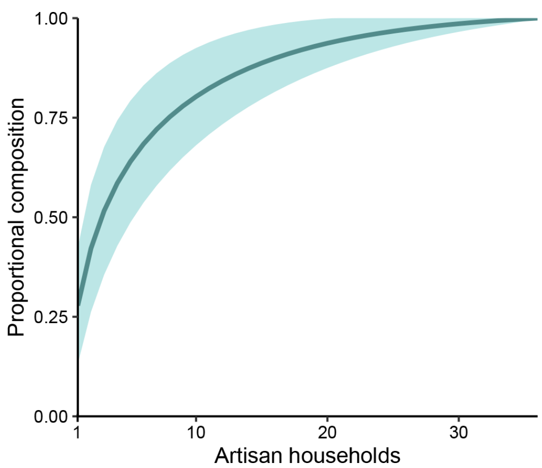

FIGURE 4
Taxa-accumulation curve for proportional composition of marine taxa utilized among artisan households (n = 36) within the shellcraft sector of the Tigak Islands, Papua New Guinea between July 2018 and July 2019. Shading represents standard deviations of the mean composition.

Geographic scale of exploitation

Taxa were obtained from at least 34 unique locations across three provinces: New Ireland, Manus, and East New Britain (Figure 6). The number of locations from which a given taxon was obtained ranged from one to thirteen (2.3 ± 2.1). Most taxa (94.5%) were obtained from the Nusa Islands and 54.8% of taxa were only obtained from the Nusa Islands. Less than half (45.2%) were obtained from 33 other locations that were, on average, 55.5 ± 84.5 km from the Nusa Islands. Three taxa (Nautilidae, *Oliva irisans* and *Pinctada margaritifera*) were obtained from interprovincial locations (Manus and East New Britain) and five taxa (Antipathidae, Cheloniidae, Nautilidae, *Pinctada maxima*, and *Pteria penguin*) were obtained from intraprovincial locations (Mussau and Tingwon Islands) more than 100 km from the Nusa Islands, but all locations were within a 500 km radius of the Nusa Islands. Table S1 summarizes the number of locations, distance of furthest location, and the mean ± standard deviation of distances for all locations from which each taxon was obtained.

Relational structure among metrics

There were eight significant associations among the metrics selected to represent aspects of taxa utilization within the

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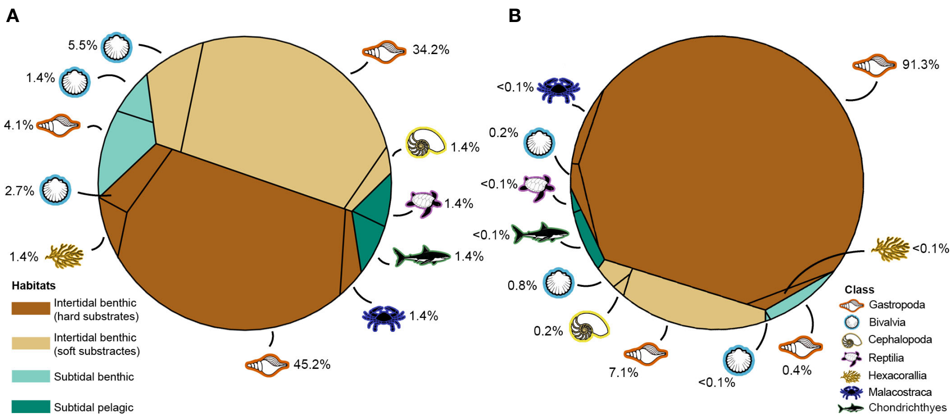

FIGURE 5
Source habitats for marine taxa utilized within the shellcraft sector of the Tigak Islands, Papua New Guinea. **(A)** Relative composition by class and habitat. **(B)** Relative quantities by class and habitat.

shellcraft sector of the Tigak Islands (Figure 7). The strongest association (τ_b = 0.74, P< 0.001) occurred between the number of locations and furthest location from which a taxon was obtained, such that taxa obtained from more locations were likely to be obtained further from the Nusa Islands. Taxa utilized by a greater number of artisan households were also likely to be obtained at increasing distances from the Nusa Islands (τ_b = 0.44, P< 0.001), as were taxa utilized in greater quantities (τ_b = 0.36, P< 0.001). The number of locations from which a taxon was obtained was positively associated with the number the

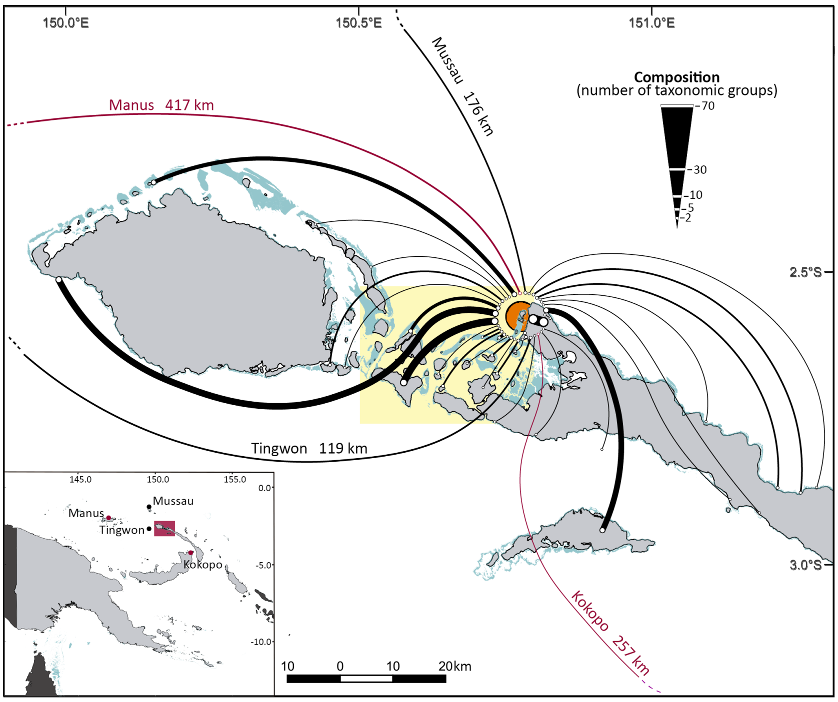

FIGURE 6
Map of the Tigak Islands (*shaded yellow*) illustrating locations from where marine taxa utilized for shellcraft were obtained by artisan households at the Nusa Islands (*center of orange point*). Line widths and point diameters indicate the composition of taxa obtained from a given location. Black lines denote intra-provincial locations while red lines denote inter-provincial locations. Bottom left insert places the map and peripheral locations in geographic context within Papua New Guinea.

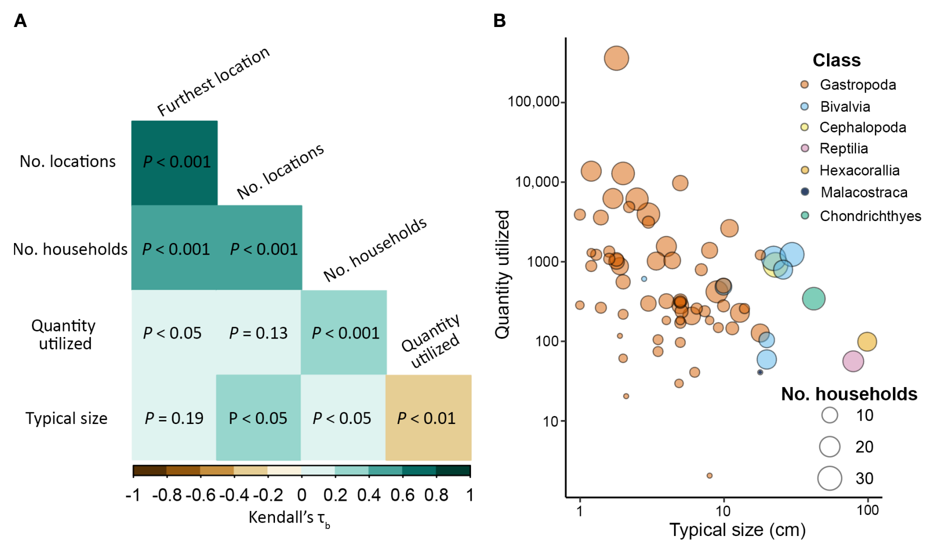

FIGURE 7
Relational structure among metrics representing aspects of marine taxa utilization within the shellcraft sector of the Tigak Islands, Papua New Guinea. **(A)** Correlation matrix of all metrics. **(B)** Bi-plot illustrating relationships among quantities utilized, typical size, and number of artisan households utilizing each taxon.

artisans utilizing it (τ_b = 0.56, P< 0.001), but unrelated to the quantities utilized (τ_b = 0.14, P = 0.13).

The typical size of a taxon (Table S1), which ranged from 1.0 cm (*Engina bonasia* and *Engina mundula*) to 100.0 cm (Antipathidae), had a significant positive association with the number of households (τ_b = 0.19, P< 0.05) and number of locations (τ_b = 0.23, P< 0.05) suggesting that larger taxa were utilized by a greater number of artisan households and obtained from a greater number of locations than smaller taxa (Figure 7). Despite this, typical size had a significant negative association with quantities utilized (τ_b = -0.27, P< 0.01) suggesting that larger taxa were used in lower quantities than smaller taxa (Figure 7).

Discussion

Located within a global center of marine biodiversity, known as the 'Coral Triangle', a wide selection of marine taxa is theoretically available to artisans among the Tigak Islands for producing shellcrafts. Whilst knowledge of species richness is superficial, a popular field guide to mollusks of PNG depicts shells of 950 species (Hinton, 1979) and, among the Tigak Islands alone, at least 26 different *Conus* spp. are known (Muttenthaler et al., 2012). In this context, the shellcraft sector of the Tigak Islands selectively utilized 73 taxa representing at least 77 species (incl. 10 *Conus* spp.). This included all species known to be utilized within the sector, such as *Eretmochelys imbricata* (Kinch and Burgess, 2009) and the 17 species that Simard et al. (2019) reported, and at least 59 additional species, confirming that a broader composition of taxa is utilized for shellcraft than previously acknowledged. The composition was also substantially broader than that of other shellcraft sectors within the Indo-Pacific where shellcraft integrates with aquaculture of *Rochia nilotica* (Lee et al., 2004), *Pteria penguin* (Teitelbaum and Fale, 2008; Southgate et al., 2016) or *Pinctada* spp. (Southgate et al., 2019). These sectors typically rely on one or two species (Lee et al., 2004; Southgate et al., 2019), and while the same species were utilized within the shellcraft sector of the Tigak Islands, their use occurs with that of numerous other taxa. The broad composition observed in our study likely reflects a reliance on artisanal fisheries, rather than aquaculture, but a clearer picture of how this composition compares to other fisheries-dependent shellcraft sectors (e.g., Floren, 2003; Dias et al., 2011; Fröcklin et al., 2018) is presently hindered by an absence of information. Excluding a few taxa, such as *Eretmochelys imbricata* (Kinch and Burgess, 2009), Nautilidae (Nijman et al., 2015; Freitas and Krishnasamy, 2016; Nijman and Lee, 2016; Nijman, 2019), and Antipathidae (Grigg, 2001), known to be utilized for shellcraft throughout the Indo-Pacific, artisanal fisheries for many of the taxa utilized by households among the Tigak Islands had not previously been linked to shellcraft sectors. When looking at related sectors reliant on artisanal fisheries, such as local trade of whole taxa as curios, analogous compositions of taxa are utilized. Curio sectors in Zanzibar (Gössling et al., 2004), Madagascar (Gibbons and Remaneva, 2011), and northeastern Brazil (Dias et al., 2011), for example, utilized 55, 122, and 126 species of mollusks, respectively. Whilst the species utilized in these sectors largely differed from those utilized for shellcraft among the Tigak

Islands, reflecting sector-specific demands (Wood and Wells, 1995) and local diversity (Sekhran and Miller, 1996), gastropods and bivalves were consistently among the most utilized taxa. Also, much like the curio sectors (Marshall and Barnett, 1997; Gibbons and Remaneva, 2011), our results demonstrate that not only mollusks, but a broader composition of marine taxa including corals (Antipathidae), crustaceans (*Carpilus maculatus*), sea turtles (Cheloniidae), and sharks (*Carcharhinus melanopterus*) are utilized to produce shellcrafts.

Noting that shellcraft sectors established elsewhere rely on one or two species (Lee et al., 2004; Teitelbaum and Fale, 2008; Southgate et al., 2016; Southgate et al., 2019), the broad composition of taxa utilized within the shellcraft sector of the Tigak Islands merits discussion. Utilization of all 73 taxa appears unnecessary for a given household to succeed in deriving satisfactory income from shellcraft (Simard et al., 2019) because each household utilized a unique composition of far fewer taxa than were collectively utilized within the sector. Factors influencing a household's access to a given taxon, their ability to process a given taxon, and desire to do so are presumably responsible for differentiating composition among households. For example, small gastropods, such as *Engina scripta*, are generally unsuited for use as pendants, whereas the shell valves of larger bivalves, like *Atrina vexillum* and *Pinctada margaritifera*, can be cut to produce pendants (Figure 1) provided an artisan has required tools (e.g., coping or jewelry saws) and proficiencies (Simard, 2019). Similarly, certain taxa, tools, and skills are more amenable to the production of beads (Figure 1) just as other unique combinations of taxa, tools, and skills are better suited for other components of shellcrafts. Since a broad range of shellcrafts appeal to consumers, with personal aesthetic preferences in design and color influencing purchase decisions (Militz et al., 2021), heterogenous demand is potentially encouraging households to specialize in specific products to best capture a particular market niche in this increasingly competitive sector (Simard et al., 2019). Specialization, in turn, would influence the composition of taxa utilized. Certainly, tool ownership, shellcrafts produced, and importance of taxa are known to vary among households (Simard et al., 2019), with our study now confirming that taxa composition also varies. Further exploring the human dimensions influencing utilization of taxa among artisan households is required to confirm these suppositions, and necessary for ensuring that taxa utilization is compatible with both resource conservation and the social and economic goals of livelihood development (Allison and Ellis, 2001).

Despite utilizing a broad composition of taxa, the shellcraft sector of the Tigak Islands utilized one species, *Chrysostoma paradoxum*, substantially more than any other. Not only aesthetics (Opitz, 2011), but also local cultural significance (Lewis, 1939), potentially impact market dynamics that govern production of shellcrafts incorporating *Chrysostoma paradoxum*. A similar bias towards particular, but different, species is anticipated for other shellcraft sectors of PNG given variability in how local cultures attribute value to specific mollusks (Lewis, 1939; Kinch, 2003). Excluding *Chrysostoma paradoxum*, a more even utilization of the remaining 72 taxa accounted for nearly 100,000 individuals annually. In relation to other sectors in PNG, however, quantities at which most taxa were utilized are largely insignificant. For example, the mother-of-pearl fishery in PNG exported around 249 tonnes of *Rochia nilotica* and 3 tonnes of *Turbo marmoratus* as unworked shell in 2019 (Simard et al., 2021); whereas only 2,604 and 125 individuals, respectively, were utilized annually by artisans among the Tigak Islands. As another example, several tonnes of Antipathidae from PNG are purchased by jewelers each year (Kailola, 1995) whereas only 97 colonies were utilized annually within the shellcraft sector of the Tigak Islands. While such comparisons help contextualize current utilization, they do not reflect the rapid growth of this sector (Simard et al., 2019) or growing demand for shellcrafts in PNG (Militz et al., 2021), which may lead to far greater quantities of taxa being utilized than at present. For example, annual utilization of sea turtles among the Tigak Islands over the last decade has expanded from a single family utilizing three to four carapaces (Kinch and Burgess, 2009) to 22 households utilizing 55 carapaces. Similar growth within the shellcraft sector of the Tigak Islands and, more broadly across PNG, could see utilization approaching the more industrial levels of shellcraft sectors in India (Shyam et al., 2017) and the Philippines (Floren, 2003). Within this context, the future role of shellcraft in marine taxa exploitation, particularly for taxa jointly exploited by other sectors (Kailola, 1995; Simard et al., 2021), merits continued monitoring and consideration as part of future development plans supporting greater sustainability within this sector.

Unevenness in quantities at which taxa are utilized is a trait shared with curio sectors (Gössling et al., 2004; Dias et al., 2011). As previously mentioned, market feedback likely influences which taxa are utilized, and this would also apply to their quantities (Gibbons and Remaneva, 2011). Unlike curios, where taxa are generally traded as individuals (i.e., whole shells or equivalent), a single shellcraft can represent multiple taxa in unequal proportions (Figure 1). For example, greater quantities of smaller taxa (e.g., *Mauritia arabica*) is required to produce an equivalent number of shell beads to those obtained from larger taxa (e.g., *Atrina vexillum*) (Figure 1). This aspect of a taxon's utility, combined with market feedback, are necessary considerations in explaining the unevenness in quantities utilized. Additionally, the reduced quantities at which larger taxa were utilized could be related to their scarcity (Dias et al., 2011). Many of the larger taxa utilized for shellcraft are presumably less abundant (White et al., 2007) and have histories of exploitation for subsistence (Swadling, 1994; Kailola, 1995) or other commercial activities (Simard et al., 2022). Without knowledge of current population trends, there is potential for current quantities, particularly for larger taxa of known importance (e.g., *Pinctada margaritifera, Pinctada maxima*, *Pteria penguin*, *Rochia nilotica*; Simard et al., 2019), to underestimate the demand for these species. An expansion of regional aquaculture activities could address supply limitations by providing a renewable source of shell material and should also be considered as part of future development plans for this sector.

Implications for monitoring shellcraft sectors

An absence of information pertaining to taxa utilized within shellcraft sectors, particularly those reliant on artisanal fisheries (Kailola, 1995; Wood and Wells, 1995; Dias et al., 2011), begets value in discussing how the approach taken in our study can be adapted for monitoring shellcraft sectors more broadly. Past studies with a single-species (Kinch and Burgess, 2009) or socio-economic focus (Simard et al., 2019) greatly understated the composition of taxa utilized within the shellcraft sector of the Tigak Islands. Thus, dedicated study on fisheries-dependent shellcraft sectors seems necessary to canvass diversity in its entirety.

Interviewing artisan households was an effective approach to obtaining information on the diversity of taxa utilized within the shellcraft sector of the Tigak Islands as it overcame challenges of geographic scale. Interviewing fishers directly, as opposed to artisan households, would have required a far greater investment in terms of both the number of interviews required and geographic scale over which interviews were conducted. Artisan households obtained taxa from more than 30 locations, up to 417 km away, indicating a dispersal of fishing effort, with monitoring further complicated by the fact that multiple fishers at each location may supply these taxa. A dispersal of fishing effort around a central hub of artisanal activity (either production or sales) is a common aspect of shellcraft sectors as, for example, artisans in Tuvalu, the Philippines, and Indonesia have been reported to source marine taxa from as far as 100, 400, and 500 km away, respectively (Tiraa-Passfield, 1996; Floren, 2003; Nijman et al., 2015). Identifying and targeting these hubs of activity is a recommended approach for monitoring the diversity of taxa utilized within shellcraft sectors, where fishing is potentially extended over a broad geographic scale and across a range of habitats.

Whilst artisan households among the Tigak Islands were highly concentrated, facilitating interviews, this may not be the case with other sectors. Our results suggest that a large proportional composition of taxa utilized can be identified even without sampling all households. Randomly sampling a quarter of households (n = 9) was predicted to identify around 80% of the composition utilized within the sector, which increased to 90% when involving half the households (n = 18). Given the positive association between the number of households utilizing a particular taxon and the quantity utilized within the sector, a subset of all households should help identify the more heavily exploited taxa in addition to those utilized by a large proportion of artisans. Thus, a reasonable account of both composition and relative quantities at which taxa are utilized is likely to be obtained even if not all participants within a sector can be interviewed.

Relevance for future development plans

Tourism is widely perceived as a central element of development among island nations of the Indo-Pacific (Connell and Rugendyke, 2008; Connell, 2018) and, through the purchase of souvenirs, tourism and shellcraft sectors are intrinsically linked (Chand et al., 2014; Militz et al., 2021). Prior to the COVID-19 pandemic, tourism expanded rapidly throughout the Indo-Pacific (UNWTO, 2022a). At many coastal destinations, including Madagascar (Gibbons and Remaneva, 2011), Fiji (Chand et al., 2014), and Brazil (Dias et al., 2011), growth in tourism coincided with increasing demand for shellcrafts and, in the case of PNG, local expansion of shellcraft (Simard et al., 2019). Detrimental impacts, such as overfishing of utilized taxa, could arise from such expansion (e.g., Dias et al, 2011). The cessation of tourism attributed to COVID-19 (UNWTO, 2022b) has allowed critical reconsideration of tourism-related development and provides opportunities to accelerate transformation towards more sustainable approaches (Connell, 2018; Gössling et al., 2020). Such opportunities could include implementing community-based resource management, expanding marine aquaculture activities, and strengthening existing governance as part of future development plans supporting greater sustainability within shellcraft sectors.

Within PNG, the existing top-down governance framework for managing fisheries is unlikely to sufficiently mitigate overexploitation of most taxa utilized within shellcraft sectors. Attempts to match resource extraction with productivity through a combination of government-imposed output and technical control measures have a high failure rate at a community level (Wilson et al., 1994) and are largely impractical for shellcraft sectors given the broad composition of taxa for which limited biological data are available (Kailola, 1995; Dias et al., 2011). Whilst existing regulations prevent harvesting 'sedentary' taxa (*viz.* 93.2% of taxa utilized) at night with aid of a torch and establish size restrictions for some species (*Pinctada margaritifera Pinctada maxima*, *Rochia nilotica*, and *Turbo marmoratus*), national and provincial governments often lack adequate funding and personnel for enforcement at a community level (Govan, 2015). Given such challenges, an alternative management framework, such as community-based, centrally governed, and co-managed marine protected areas (MPAs) (Smallhorn-West et al., 2019), are more likely to yield positive ecological and socio-economic impacts within shellcraft sectors. While poaching aggression and a lack of compliance have limited the effectiveness of MPAs for high-value taxa in PNG (Hair et al., 2020), most of the taxa utilized for shellcraft have negligible value as an unworked resource (Kailola, 1995). No-take MPAs appear particularly well-suited for shellcraft sectors, because most positive ecological impacts are associated with rapid recovery of benthic invertebrates following reduced fishing efforts (Thaman et al., 2017; Smallhorn-West et al., 2019). Targeting intertidal and subtidal benthic habitats, specifically, during MPA establishment would best ensure recovery of a large proportion of taxa utilized by artisans.

In addition to community-based resource management, an expansion of aquaculture activities could offer a renewable source of shell material while simultaneously creating additional income-generating opportunities. Several nations, such Fiji, Tanzania, and Tonga, already benefit from community-based farming of pearl oysters to provide a sustainable supply of shell and opportunity for additional income through pearl culture (Southgate et al., 2006; Jiddawi, 2008; Fröcklin et al., 2018; Johnston et al., 2019; Southgate et al., 2019; Saucedo et al., 2022). Whilst similar developments existed in PNG (George, 1978), production has greatly diminished in recent years (Simard et al., 2022) with current operations of marginal relevance to shellcraft sectors. For example, current operations are limited to the production of *Pinctada maxima* in Milne Bay Province (IPA 2021), to which the shellcraft sector of the Tigak Islands had no direct links (Figure 6). Establishing linkage between shellcraft sectors and existing aquaculture operations should be seen as a priority given that shellcraft can generate 5-10 times more income than the export of unprocessed shell (Friedman et al., 2008; Simard et al., 2019). Beyond this, reinvigorating community-based aquaculture in areas presently producing shellcrafts should be considered, given the apparent importance of pearl oysters within shellcraft sectors (Simard et al., 2019).

Studies have shown that marine taxa threatened with overexploitation, such as Antipathidae, Cheloniidae, and Nautilidae, are heavily trafficked as curios and shellcrafts (Nijman et al., 2015; Nijman and Lee, 2016; Nijman, 2019). Our study found all these taxa utilized within the shellcraft sector of the Tigak Islands. Papua New Guinea, as a Party to the Convention on International Trade in Endangered Species (CITES) since 1976, has acknowledged that international cooperation is essential for the protection of these taxa and is committed to ensuring their utilization is compatible with their survival. Under CITES regulations, transport of shellcrafts comprised of Antipathidae, Cheloniidae, or Nautilidae out of PNG requires a government-issued export permit. Despite this, such regulations have a history of being minimally promoted or policed, as evident from items containing *Eretmochelys imbricata* being offered for sale within Jackson's International Airport in Port Moresby (Kinch and Burgess, 2009). Current quantities of Antipathidae, Cheloniidae, and Nautilidae leaving PNG as shellcrafts are unclear, although conservative estimates can be made by examining their utilization within shellcraft sectors. In our study, an estimated 899 shells of Nautilidae, 55 carapaces of Cheloniidae, and 97 colonies of Antipathidae were utilized annually. For Nautilidae, current utilization represents no imminent threat to their survival as the shellcraft sector of the Tigak Islands exclusively utilized drift shells collected from intertidal benthic habitats (Kailola, 1995; Simard et al., 2019). Similarly, with Cheloniidae, scutes and carapaces used in shellcraft are mainly obtained from subsistence or opportunistic catches (Kinch and Burgess, 2009) with the quantity utilized comparatively low compared to other areas of PNG. For example, annual utilization across all households among the Tigak Islands was roughly half that reportedly utilized by a single household based at Hula village, Central Province (Kinch and Burgess, 2009). Given the relatively small quantities utilized for shellcraft, draconian measures to reduce utilization of these taxa within the sector would seem unnecessary. Rather, educating consumers, particularly foreign tourists (Militz et al., 2021), retailers, and relevant authorities would greatly strengthen existing governance to protect these taxa against unregulated international trade. Routine monitoring of shellcraft sectors would also help to detect a change in practices (such as targeted fishing of Nautilidae spp.; Dunstan et al., 2011) that may present a potential threat to the sustainability of both these taxa and the sectors they support.

Conclusion

For a fisheries-dependent shellcraft sector, our study demonstrated how data collection through structured household interviews was an effective approach to obtaining sector-specific information at a local scale. Information pertaining to marine taxa utilization within a shellcraft sector of PNG revealed a greater diversity, in terms of both composition and quantities, than previously reported. Knowledge generated on the taxa utilized, their quantities, source habitats, and geographic scales of exploitation can now provide a basis for developing greater sustainability within shellcraft sectors across the Indo-Pacific by informing community-based resource management, further developing of marine aquaculture, and existing governance arrangements. Given the socio-economic benefits that shellcraft provides to coastal communities of developing island nations (Tiraa-Passfield, 1996; Chand et al., 2014; Barclay et al., 2018; Fröcklin et al., 2018; Simard et al., 2019; Southgate et al., 2019), further research on social, economic, and ecological links of this livelihood activity is warranted.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving human participants were reviewed and approved by University of the Sunshine Coast's Human Research Ethics Committee. The participants provided their informed consent to participate in this study.

Author contributions

All authors contributed to the conception of the project, read manuscript revisions, and approved the submitted version. NSMS collected data and performed statistical analysis with TAM. NSMS wrote the manuscript with support from TAM, JK, and PCS.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2022.1074996/full#supplementary-material

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