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Quo Vadimus

Identifying marine ecological production units in Vietnam

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Ecosystem-based management is generally viewed as one of the most promising avenues for addressing the various anthropogenic pressures facing the world's marine ecosystems. These approaches have been developed to varying degrees by individual countries or international organisations, but there remain a large proportion of marine ecosystems, particularly in developing regions, that have not yet been the subject of such research. In these areas, lack of effective regulation and the often high importance of the marine environment in providing food and economic opportunities, together create conditions where marine resources and habitats come under unsustainable levels of pressure. Here, we present a data-limited assessment approach to discern marine ecological patterns, in this case for the exclusive economic zone of Vietnam. By combining data from environmental and biological surveys from the Vietnamese national survey dataset and local oceanographic models, we have identified a series of 12 candidate ecological production units, delineated by their environmental characteristics, and the key commercial species that exist within them. These units are suggested as a possible foundation for a spatial management structure in the Vietnamese exclusive economic zone including considerations such as placement of marine protected areas, or ecological boundaries of key areas of socio-economic importance.

Keywords: ecosystem-based management, fisheries, Vietnam, integrated assessments

Introduction

It is increasingly acknowledged that ecosystem-based management (EBM), not just with respect to fisheries, is urgently needed to mitigate the wide range of pressures facing the marine environment (Morishita *et al.*, 2008; Link *et al.* 2011; Jennings *et al.*, 2014; Kenny *et al.*, 2018; Link and Marshak, 2018; Koen-Alonso *et al.*, 2019; Karnauskas *et al.*, 2021). This is particularly true where the marine environment provides locally important sources of food provision and economic opportunities. Historically, fisheries assessments have largely taken a less holistic approach, focusing upon single species, or specific habitats. For commercial species, single-species fish stock assessments still dominate management approaches (Skern-Mauritzen *et al.*, 2015). These assessments tend to implicitly overlook interactions between non-target species or their environments, such as the influence of population size changes amongst their predators, prey, and competitors (Plagányi *et al*, 2012; Donadi *et al.*, 2018).

The implementation of EBM continues to be debated in a number of countries (Karnauskas *et al.*, 2021) but is gradually becoming enshrined in national or international legislation (e.g. EU Marine Strategy Framework Directive, e.g. Pedreschi *et al.*, 2019) and adopted by regional fishery management organizations (like the Northwest Atlantic Fisheries Organisation; NAFO, 2017). Notable steps towards implementing EBM have been made in Europe and North America, usually in the form of regional environmental management plans, and the development of ecological indicators (Lockerbie *et al.*, 2020). However, EBM remains a frontier for marine environmental management, even in the most advanced nations, partly as a result of the lack of clear definitions and guidelines for implementation, and poor uptake of the multiple relevant factors (Pitcher *et al.*, 2009; Link and Browman, 2017; Porobic *et al.*, 2018; Townsend *et al.*, 2019; Link *et al.*, 2020). Establishing EBM is a multi-annual, iterative process, owing in part to the complexities of needing to address a myriad of conflicting stakeholder views, ecological variables, and political challenges (Link and Marshak, 2018). It is not yet clear how this approach may be fostered in a region with challenges facing international cooperation (e.g. the South China Sea, also called the East Sea) and governance, where the dominant anthropogenic pressures, socio-economic context, and political climate are very different to Europe or North America (Anh *et al.*, 2014; Suuronen *et al.*, 2020). Furthermore, the availability of historic data, and the capacity to conduct nationally coordinated, integrated surveys is also much reduced when compared with wealthier nations, meaning that management should, ideally, depend more heavily upon precautionary principles.

The central region of the South China Sea is contested between several countries including Vietnam, China, the Philippines, and Indonesia (Teh *et al.*, 2014). The exclusive economic zone of Vietnam (EEZ; ca. 751 000 km^2 Flanders Marine Institute, 2018) considered here stretches from the Chinese border in the Gulf of Tonkin to the Cambodian border in the Gulf of Thailand. A considerable part of this area is formed either of shallow shelf seas (53.6% of EEZ is shallower than 200 m) or deep-waters of the South China Sea Basin (35.7% of EEZ is deeper than 1000 m) (Ryan *et al.*, 2009). Marine activities in Vietnam are extensive, with multiple competing pressures upon resources and space, foremost among which, are the many and varied fisheries. There are around 100 000–120 000 active vessels in Vietnam, equating to direct employment of more than 1 million people, and no cap upon the number of vessels within a given fishery (Anh *et al.*, 2014; RIMF, pers. comm.). The vast majority of licences are issued for low or unpowered vessels that are at least semi-subsistence in nature (van Zwieten *et al.*, 2002), and only around 3% of the licenced vessels are thought to carry any kind of position indicator system (RIMF, pers. comm.). Tourism, energy needs, and waste disposal are also prominent pressures upon Vietnamese waters and the South China Sea more broadly, largely affecting coastal and inshore environments.

One of the facets of developing and adopting EBM is to consider a set of spatially explicit management units that bear meaningful relevance to coherent ecological production processes, such as those related to plankton, fish, and benthic invertebrates; collectively sometimes termed "Integrated Ecosystem Assessment" (Ojaveer and Kalejs, 2008; Kenny *et al.*, 2009; Montecino and Lange, 2009; Pepin *et al.*, 2010; Pérez-Rodrigues *et al.*, 2010; Fogarty *et al.*, 2011; Pepin *et al.*, 2012; Anh *et al.*, 2014; DePiper *et al.*, 2017; Belgrano and Villasante, 2020; Lauria *et al.*, 2020; Muffley *et al.*, 2020; Zottoli *et al.*, 2020). This set of spatial units, sometimes referred to as a meta-ecosystem, is preferable to geo-political or economic boundaries that have been historically imposed, often somewhat arbitrarily (ICES, 2016; Petitgas *et al.*, 2018).

Ecosystem-based management is necessarily spatially explicit and often expressed as divisions known as Ecological Production Units (EPUs), which allow management areas to reflect ecologically meaningful boundaries (Batten *et al.*, 2008; Ojaveer & Kalejs, 2008; Kenny *et al.*, 2009; Lucey & Nye, 2010; Pepin *et al.*, 2010; Fogarty *et al.*, 2011; Lucey *et al.*, 2013; Petitgas *et al.*, 2018; Koen-Alonso *et al.*, 2019; Lucia *et al.*, 2020). In this article, we use a combination of environmental and biological data to suggest a set of candidate EPUs for the Vietnam EEZ. These environmental and ecological gradients are considered in the context of the current fisheries management regime in Vietnam, as well as some of the ongoing limitations.

Materials and methods

Data availability

During a workshop held in Hai Phong at the Vietnamese Research Institute for Marine Fisheries (RIMF) in June 2018, the availability and distribution of a range of data sources held by RIMF for the full extent of the Vietnam EEZ were reviewed. Oceanographic data (including the distribution and abundance of planktonic organisms) included a combination of direct observations (e.g. from CTD casts; Tuân *et al.*, in prep.) and modelled data (CLS, (2012) using $1/12^{\circ 2}$ NEMO model). Faunal abundance data (survey catch-per-unit-effort) from the Vietnam national fisheries survey programmes for benthic/demersal and pelagic species was used as a basis for identifying the areas of the Vietnamese EEZ that are characterized by different assemblages (primarily of commercial species). Catchability was necessarily assumed to have negligible variation across the survey period. Data for species not covered by either of these surveys were patchy and generally related to small-scale sampling programmes of particular coastal regions, and not considered further.

The highest resolution considered is that of the pre-existing 0.5° rectangles used in Vietnam's official register of catch data. Though this information may be still quite coarsely resolved in terms of local-scale processes (e.g. distribution of particular habitat types), it was assumed that finer-scale spatial resolution would be difficult to achieve, given the historic inconsistencies in survey design and data availability and could create unrealistic expectations for future standards of reporting by users of the marine environment in Vietnam.

Also included were data on the distribution of fishing effort by vessels using the eight most common gear classes, to provide contextual information on the distribution of human activities with respect to the different EPUs described from the environmental and oceanographic data discussed below. These gear classes were: line-based methods (bottom longline and handlines); purse seines (with or without lights); gillnets (surface drifting and bottom fixed); and demersal trawls (pair and otter trawls). These data cover the majority of gear classes used in Vietnam. Number of active vessels per gear type per 1 × 1 degree cell (annual mean, between 2016 and 2019) were available for the whole Vietnamese EEZ from the RIMF fisheries biology database. Since the aim here was to describe ecological variability, rather than patterns in fisher behaviour, these data were not included within the analyses described below but presented to aid discussion on how the EPUs identified match with spatial differences in fishing activity.

Filtering and statistical analyses

A total of 21 separate environmental variables were used in the subsequent analyses (Table 1), from a candidate set of 25 variables that were spatially representative of the assessed area and covered a period between 1997 and 2017. The remaining variables were excluded from the analysis either because they

Table 1. Summary of data supplied by RIMF for inclusion in the integrated assessment

Variable	Time period	Source	Notes	Justification
Depth	N/A	Global Multi-Resolution Topography (GMRT; Ryan *et al*., 2009)	Subset of 100 m gridded global digital elevation model.	Average depth, as well as specific seafloor features strongly influence the availability of suitable environment for different ecosystems.
Seafloor substrata	N/A	Viet Nam National Atlas, (Viet Nam National Atlas Programme, 1996)	Modal seafloor substratum type per 0.5° grid cell.	Seafloor substratum type (e.g. rock, sand, and mud) is often a strong driver of benthic assemblage composition.
NO_X content	1997–2010	RIMF Survey data	Surface and bottom layers of NO_2 and NO_3^- (downscaled to 0.5° resolution).	Nutrient availability for primary productivity, and proxy for influence of riverine inputs or localized upwelling.
NH_4 content	1997–2010	RIMF Survey data	Surface and bottom layers (downscaled to 0.5° resolution).	
PO_4 content	1963–2010	RIMF Survey data	Surface and bottom layers (downscaled to 0.5° resolution).	
SiO_3 content	1963–2010	RIMF Survey data	Surface and bottom measurements. Rejected: High interpolation error	
Chlorophyll	2011–2017	VIIRS, via THEMIS (CLS, 2012)	Surface layer. Full EEZ coverage (downscaled to 0.5° resolution).	Proxy for primary productivity potential.
Temperature	2011–2017	MODIS + NEMO, via THEMIS (CLS, 2012)	Surface and bottom layers. Full EEZ coverage (downscaled to 0.5° resolution)	Physical variable that is key in structuring the distribution of most species, both migratory and non-migratory
Thermocline depth	2011–2017	NEMO, via THEMIS (CLS, 2012)	Full EEZ coverage at 0.5° resolution	Mixed layer depth, proxy for stratification and near-surface overturning. Generally absent in shallower regions
Current speed	2011–2017	MODIS + NEMO, via THEMIS (CLS, 2012)	Surface and bottom layers. Full EEZ coverage (downscaled to 0.5° resolution)	Surface currents: relate to position and intensity of eddies/frontal systems—driver of distribution for migratory species. Bottom currents: driver of habitat suitability for suspension feeding benthos.
Salinity	2011–2017	MODIS + NEMO, via THEMIS (CLS, 2012)	Surface and bottom layers. Full EEZ coverage (downscaled to 0.5° resolution)	
Phytoplankton	1959–2009, variable interval	RIMF Survey data	Biomass density from RIMF field surveys Rejected: co-linear with, and superseded by, modelled chlorophyll content surface.	Biomass density of phytoplankton, a proxy for primary production potential.
Zooplankton	1959–2009, variable interval	RIMF Survey data	Density and biomass from RIMF field surveys.	Index of food availability for higher trophic levels. Non-linear relationship with observed primary production potential.
Pelagic fish	1997–2016	Vietnam fisheries survey programme	Large pelagic fish abundance (standardized catch-per-unit effort) from pelagic surveys.	Semi-standardized index of spatial variation species assemblage composition, used as the basis for biological classifications.
Benthic fish and invertebrates	1997–2016	Vietnam fisheries survey programme	Fish and large invertebrate abundance (standardized catch-per-unit effort) from benthic surveys.	

Also includes small pelagic fishes in the Tonkin Gulf and Gulf of Thailand.

exhibited significant co-variance (e.g. chlorophyll and phytoplankton biomass) or because residual error in their interpolated surfaces was >5% (e.g.SiO_3) (Table 1). Other attributes of these variables were also considered (e.g. minimum and maximum values of temperature, current velocities, chlorophyll concentration, etc.), but not included, usually because they accounted for only very small proportions of variance. Additionally, some sources of data were rejected because of a lack of information regarding their provenance or derivation, such as spatial data on benthic biomass (Viet Nam National Atlas Programme, 1996).

Several datasets had incomplete spatial coverage and required interpolation. Three interpolation methods were tested [Inversedistance weighting (IDW); thin-point spline and nearest neighbour], IDW was found to have the lowest residual mean standard error (RMSE), relative to a null model, in 9 out of 12 surfaces interpolated. Retained surfaces had a mean RMSE of 0.9% and a maximum of 5%. The retained, complete surfaces were used to create a principal components ordination (R package "Vegan" v2.5-2; Oksanen *et al.*, 2018) to examine groupings between different cells and the spatial autocorrelation between cells. Seasonal variation was also considered in a subset of environmental variables that had sufficient temporal resolution.

Biological survey data were not gridded or interpolated; within their designated coverage, this was unnecessary and outside of these areas, the inference was considered inappropriate. Thus, some of the final EPU categorisations were informed by a subset of the data streams (e.g. there were no benthic/demersal survey data from areas deeper than 200 m). This is representative of current fishing activity in the Vietnamese EEZ, but if for instance, the potential for a deep-water demersal fishery were to be investigated, then these results would not be appropriate.

Dissimilarity matrices were computed for each of the data streams. Biological survey data were transformed (square root for pelagic; fourth root for benthic) and dissimilarity matrices created using the Bray–Curtis distance method. Environmental data dissimilarity was computed using the Euclidean distance method (Oksanen *et al.*, 2018). Multivariate structure with each data set was assessed using principal components analysis (PCA) of the respective distance matrices, taking account of the potential for issues with their interpretation noted by Planque and Arneberg (2018), such as methodological artefacts that can arise from autocorrelation. PCAs with primary and secondary components that accounted for only a low proportion of explained variance were rejected (<30% cumulatively). Several different PCA iterations were considered for the environmental data, using several measures of the data listed in Table 1. PCAs that incorporated minimum and maximum values of data, where available, generally did not perform better than models based on mean values only (the direction and length of the eigenvectors were similar for all measures of the same dataset, usually even when compared to the "simpler" PCA). This indicated a strong element of spatial autocorrelation within the season/sub-annual variability for temperature, salinity, chlorophyll content, and other variables, as has been observed within other IEA applications in north-western Europe (Planque and Arneberg, 2018).

In sufficiently large ecological datasets, the significant structure will tend to exist at varying scales of discrimination, but it is necessary to find a compromise that represents a useful amount of variation, whilst not being overly detailed or resolved. This analysis takes the form of attempting to ascertain the inherent structure within the different datasets, rather than testing specific hypotheses (e.g. to ask *where is the rate of change spatially most pronounced*, rather than *does a particular variable drive system-level difference*). As the aim was to detect emergent structure, rather than to test against an *a priori* structure, multivariate methods, such as PERMANOVA (Anderson, 2017), were deemed inappropriate. To determine an optimal number of clusters within each of the datasets, an ensemble approach comparing 30 different indices of k-means clustering (R package 'NbClust' v3.0, Charrad *et al.*, 2014) was implemented, using the dissimilarity matrices. In each case, the modal number of clusters was taken as the optimal fit.

Interpretation of ecological production unit boundaries

Since each of the three determinant layers did not fully overlap (e.g. because the pelagic and benthic species assemblage data were confined to the spatial limits of their respective surveys), the final interpretation of the boundaries between adjacent EPUs was considered through a qualitative, expert assessment of each of the underpinning layers, including their seasonal variability if appropriate. The resultant EPUs were therefore defined at a spatial scale different from the scale that would have resulted from considering the individual data layers separately.

Results

Clustering

A total of four clusters were identified within the environmental data (Figure 1), two each in shallow- and deep-waters, separated approximately by the 200 m isobath as well as by latitude. The major drivers of environmental differences were found to be factors such as depth, depth of the thermocline, surface and bottom water temperature, although several of these factors do covary to an extent (e.g. depth and bottom temperature), making depth likely the strongest single driver of differences between the environmental clusters identified (Figure 2). Bottom temperature, although somewhat co-linear with depth, was still relevant in driving differences between clusters because of its latitudinal variability (e.g. between clusters 1 and 4—Figures 1 and 2). Several factors had low variability throughout the region, including sea surface temperature, and were of relatively minor importance.

The optimal number of clusters for the biological survey data was determined to be two and three for the pelagic and benthic survey data respectively (Table 2). Of the 249 cells that fall mostly or wholly within the Vietnam EEZ, 78 and 86 were not sampled for large pelagic or bentho-pelagic fish species composition respectively, at any point in the history of the surveys (Figure 1).

A total of 970 species, morphotypes, or discrete higher taxa, were enumerated in the collation of the benthic/demersal survey data, the coverage of which extends into waters of up to ~160 m depth. Benthic/demersal commercial assemblages had clear differences between regions within the EEZ, with only ponyfishes (*Leiognathidae*) consistently being amongst the top five most abundant taxa. Accordingly, three clusters of grid cells were identified (Figure 1): a northern cluster extending southwards to around 11°N; and two southern clusters. The nearshore benthic cluster was focussed off the Mekong Delta but also reached to the Cambodian border (Divisions V and VI; Figure 3). Demersal reef and soft-bottom species [e.g. filefishes (*Paramonacanthus* spp.), lizardfishes (*Saurida* spp.), and goatfishes (*Upeneus* spp.)] tended to dominate these assemblages, except in southern inshore areas that were dominated by crustaceans (e.g. *Charybdis* spp. and Portunidae), comprising five of the top ten most abundant genera compared with one to three elsewhere.

Pelagic survey assemblages comprised 80 genera characterized by both assemblages occupying shallow-water (<200 m) and deep-water (>200 m) areas, with the deeper-water assemblages extending to more coastal regions only in areas where the continental shelf is narrowest, on the central coastline (11–14°N). Although the abundance index varies substantially between several of the more dominant genera (e.g. Skipjack tuna; *Katsuwonus pelamis* or Marlin; *Makaira* spp.), there was a less obvious distinction between clusters in the most abundant genera/species in

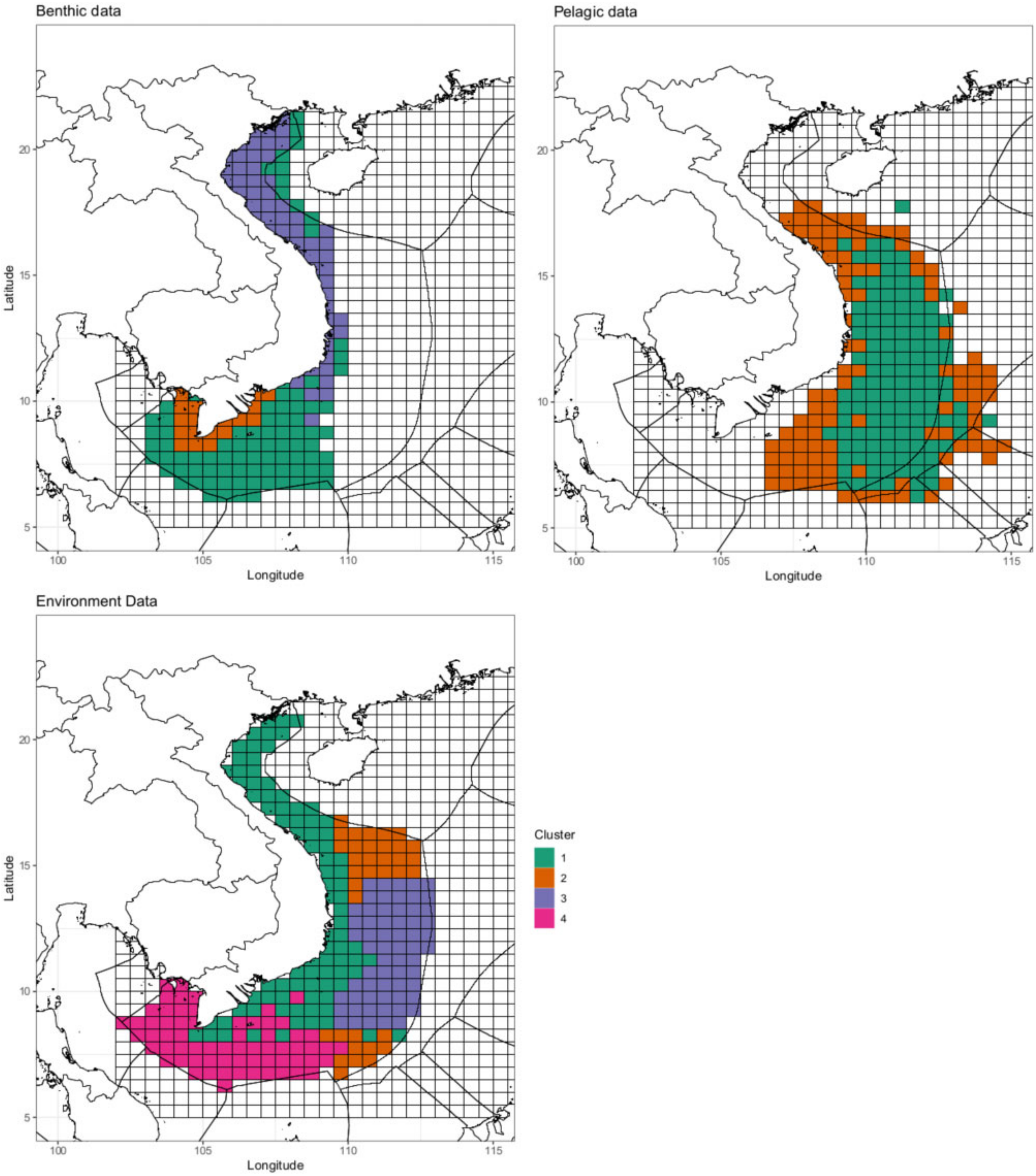

Figure 1. Cluster assignations for each of the data streams. 'Static' model presented for environmental data (averaged over seasons).

these data than between benthic assemblages. This indicated that the patterns were more strongly driven by less abundant species, such as other sharks (*Isistius* spp. or *Carcharhinus* spp.) or pomfret (*Brama* spp.). There were also instances of the predominately 'inshore' cluster occurring on the periphery of the Vietnam EEZ, associated primarily with the Spratly and Paracel Islands, in the disputed regions of the central South China Sea, and relating to the northern- and southernmost of the three deep-water EPUs identified.

A total of 12 discrete broad-scale candidate ecosystem production units were defined (Figure 3) which are variously similar to the management units currently used by RIMF (Figure 3). In some areas, the EPU analysis suggested larger areas than currently used (Figure 3; two EPU areas, I and II, covering the current sub-

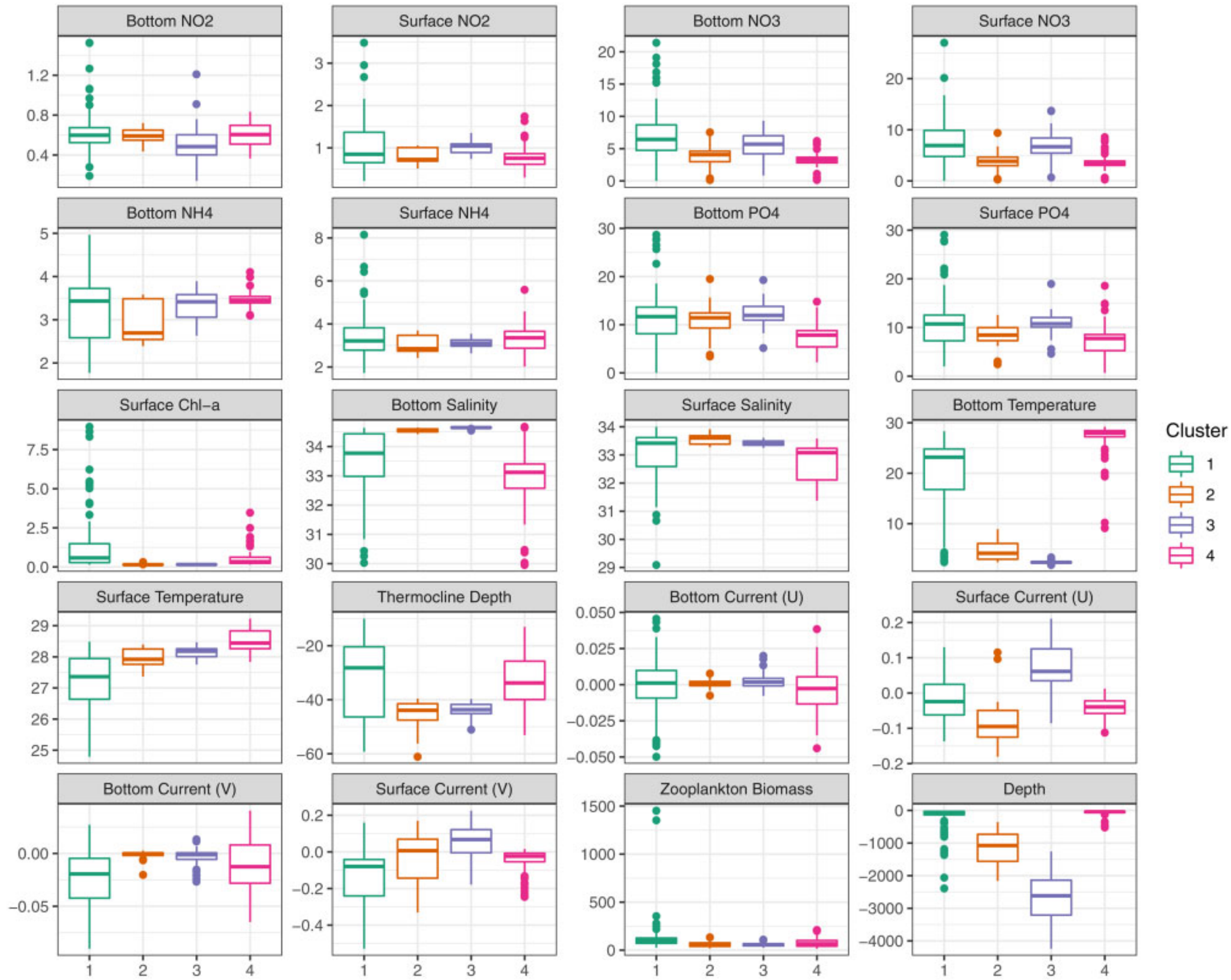

Figure 2. Distribution of environmental variables (mean per 0.5° cell) within each of the four clusters identified in the environmental data. Cluster numbers as per the environment panel in Figure 1.

Table 2. Number of clusters and summary statistics

Dataset	No. of clusters	Cells per group	% of total area (750 998 km^2)	Dominant characteristic attributes or taxa (with median value)
Environment	4	1: 87	1: 34.9%	Lowest SST (27°C); shallow (50 m); shallow thermocline depth (25 m).
		2: 35	2: 14.1%	Low bottom temperature (4°C); moderately deep (1 200 m) with a deep thermocline (45 m); weak bottom currents.
		3: 62	3: 24.9%	Deepest (2 500 m) with lowest bottom temperature (2°C); weak bottom currents.
		4: 65	4: 26.1%	Warmest surface and bottom temperatures (28.5 and 27°C respectively); shallow (50 m).
		NA: 0	NA: 0.0%	
Large pelagic fish	2	1: 104	1: 41.8%	*Katsuwonus pelamis*; *Mobula* spp.; *Thunnus* spp.; *Makaira* spp.
		2: 67	2: 27.0%	*K. pelamis*; Istiophoridae (particularly *Makaira* spp.); *Auxis* spp.; *Thunnus* spp.;
		NA: 78	NA: 31.3%	
Demersal fish and invertebrates	3	1: 85	1: 34.3%	*Leiognathus* spp.; *Nemipterus* spp.; *Paramonacanthus* spp.; *Saurida* spp.
		2: 18	2: 7.2%	*Charybdis* spp.; *Leiognathus* spp; Portunidae; *Dasyatis* spp.
		3: 60	3: 24.0%	*Arius* spp.; *Leiognathus* spp.; Dasyatidae; *Acropoma* spp.
		NA: 86	NA: 34.5%	

NA, no assignation, due to missing data. Only the 249 cells within the EEZ counted, but the pelagic survey data coverage exceeds the extent of the territory (see Figure 2).

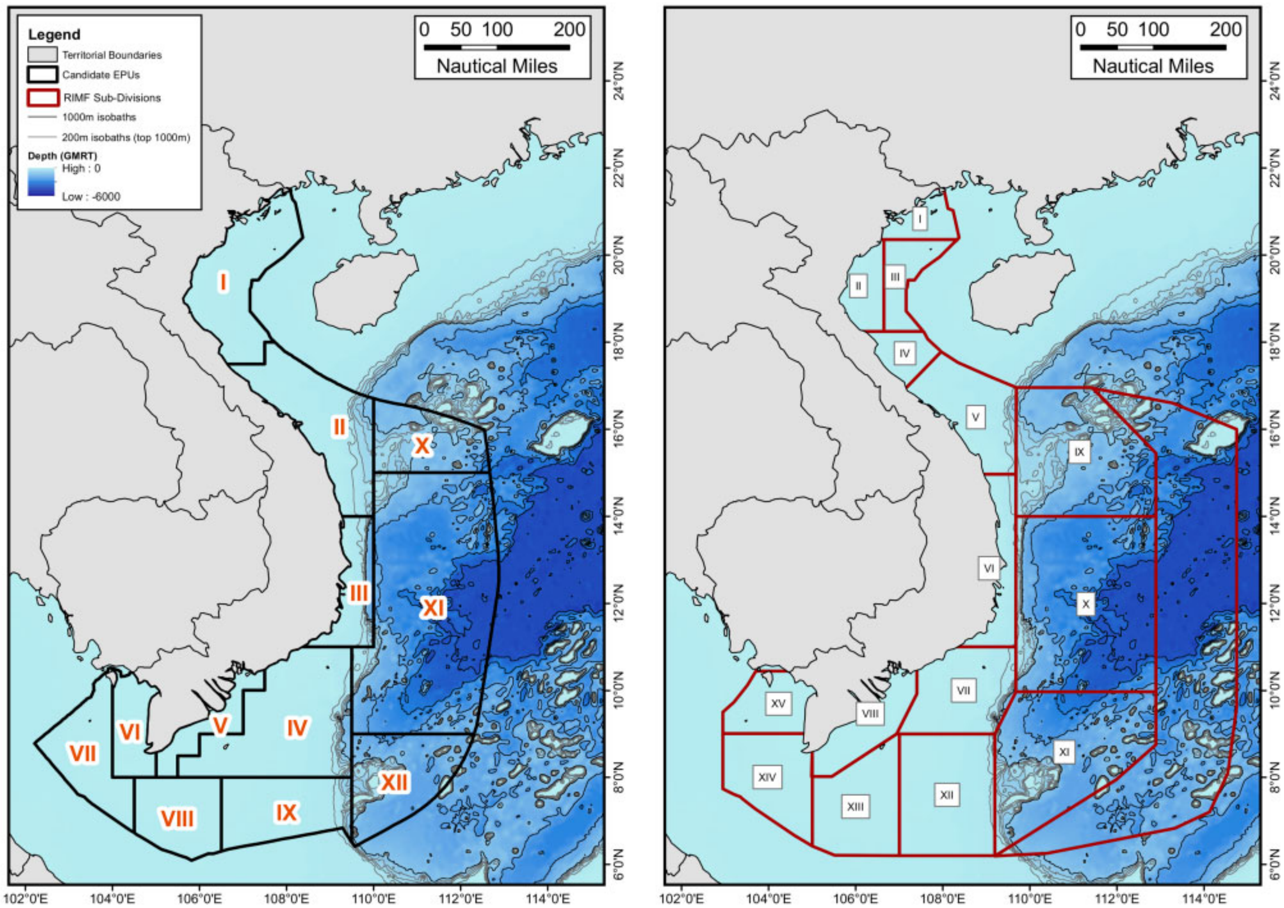

Figure 3. Candidate EPU areas (left) and current management units (right) for the Vietnamese EEZ. Bathymetry from GMRT database (Ryan *et al.*, 2009). EEZ boundary according to Flanders Marine Institute (2018). Current management units supplied by RIMF. Also used, but not displayed here, are five broad fishery management areas: Tonkin Gulf, Central, South-East, South-West, and Offshore. The eastern-most area of the right-hand side figure is the contested region of the East/South China Sea. Catch and survey data were not available from this area.

Divisions I–V). Other areas had the same number of units, but with the EPU analysis suggesting a modification to the position of their boundaries (e.g. offshore regions; Figure 3).

Discussion

Synthesising EPUs

To generate a unified set of candidate ecosystem production units, an additive model averaging approach was applied, designed to incorporate the spatial structure determined by each of the separate data streams. Each of the clusters was characterized by a different complement of environmental and biological parameters, with large areas having poor or no coverage from either benthic or pelagic survey data (Figure 1). Therefore, the influence of each data stream upon a given cell depends upon its position within the EEZ, with only those cells between 107 and 110°E having assignations informed by all three data sources.

In some cases, a single set of clusters was overwhelmingly responsible for the delineation between two adjacent candidate EPU areas. For instance, the boundary between EPU areas IV & V and VI & VII (Figure 3) was determined by the strong disparity in the benthic/demersal assemblage structure (Figure 1). Other boundaries were more evident across multiple sets of clusters [e.g. between the 'shallow' (I–IX) and 'deep' (X–XII) EPU areas]. This corresponded closely to environmental and biological differences occurring broadly between the 100 m and 200 m depth isobaths. Although demersal data were limited in these areas, and absent from deeper water, it is certainly plausible that considerable assemblage composition differences would be evident on either side of the shelf-break (as has been noted in the NE Atlantic region by Mangi *et al.*, 2016) although, as discussed elsewhere in this paper, the EPUs delineated are not informative for demersal or benthic species in deeper waters. Finally, seasonal variation in environmental parameters (e.g. sea surface temperature or thermocline depth) was found to affect the position of boundaries between different clusters. Rather than proposing impractical, seasonally shifting management units, the scale of these differences was encapsulated by ensuring that the EPUs were more spatially explicit than would otherwise have been necessary. For instance, only one EPU was required in the northern-most regions, as defined by the benthic survey, and mean environmental model results in the Gulf of Tonkin. However, given the seasonal shift of environmental clustering (chiefly driven by changes in SST), two EPUs were selected (EPU areas I and II; Figure 3), to adequately reflect important seasonal differences due to spring and winter positions of 'fronts' between the clusters. This boundary also, perhaps coincidentally, corresponded closely to differences in fisher activity, EPU area II being the main region where

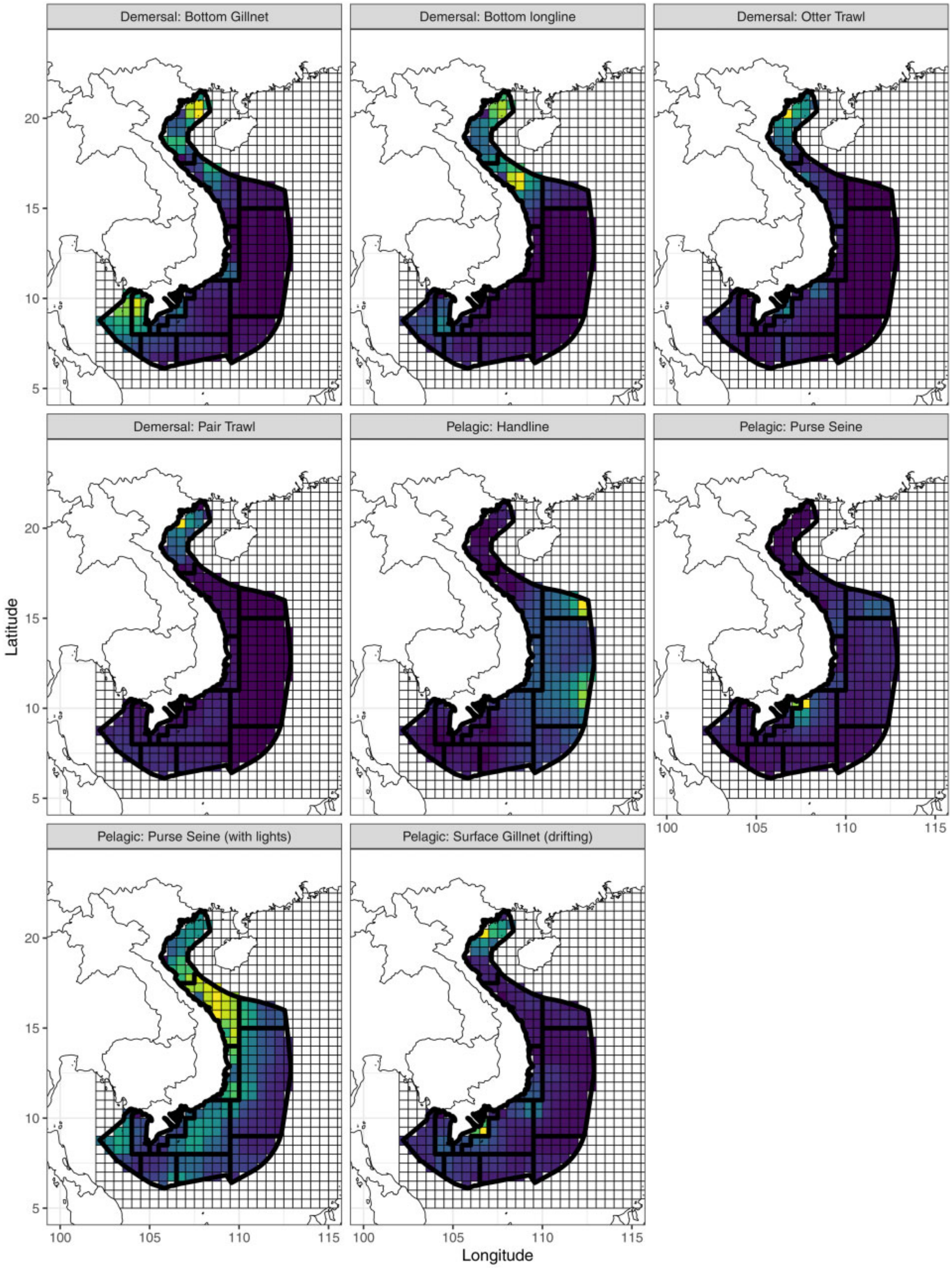

Figure 4. Relative distribution of fishing activity in the Vietnamese EEZ (mean annual vessels per cell, 2016–2019) with the candidate EPU areas overlaid. N.B. Absolute values normalized for comparison between gear types (i.e. the cell with the maximum number of days normalized to 1).

purse seine effort occurs (Figure 4). The relatively short period over which most of the environmental data were available (Table 1), means the approach detailed here does not capture non-linear effects of inter-decadal oscillations or climate change. Adaptation to climate change is another key feature of successful ecosystem-based management (Nguyen *et al.*, 2017; Wolf *et al.*, 2020), and future iterations of related work should seek to consider climate forecasts, distributional range shifts of key species, and the vulnerability or wellbeing of coastal communities (Lucey and Nye, 2010; Townhill *et al.*, 2020; Spooner *et al.*, 2021). Like Lucey and Fogarty (2013), we do not consider the EPUs proposed here as static, isolated systems, rather dynamic compartments of a broader, spatial approach to ecosystem-based management.

Consequently, the confidence in the suggested boundaries will ultimately depend upon their application, and it is possible that future boundary revisions will be required as more data become available or as environmental conditions change (e.g. through climate or land-use changes). Nevertheless, it is important to consider that, although survey coverage for certain parameters in some areas may be limited, this was primarily due to such areas not being important for certain fisheries. For instance, there are no demersal surveys in deeper water (>200 m), since there are no or limited demersal fisheries operating at these depths. To make suggestions about spatial management of extant human activities therefore does not currently require a consideration of demersal fish or invertebrate species living in deep-water.

Considerations for particular species or functional groups

For highly migratory species (e.g. tunas, pelagic sharks, and billfishes), the proposed EPU boundaries may, in particular, be more explicit than is necessary as differences between these units are largely a product of deep-water environmental characteristics, particularly depth and bottom temperature, and also surface currents (Figure 2). These differences are mainly driven by the presence of seamounts and atolls associated with the Spratly and Paracel islands, which influenced the composition of pelagic survey catches (Figure 1), and the distribution of handline fishing effort targeting tunas (Figure 4). The pelagic survey data formed two clusters only; deep-water and shallow-water, and consequently, it should not be assumed that catches within EPU areas X–XII can be considered separate for more widely ranging species. The analysis presented here takes a more holistic view of the environmental variability than may be relevant to a single stock, and although it may provide a starting point, it is not a substitute for determining the actual stock boundaries of a given species (Ojaveer and Kalejs, 2008). For instance, in fisheries targeting large pelagic species, it might be more appropriate to consider catches in EPU areas X–XII together, whereas for the reef- or shellfishes that have a much more limited range, the EPUs presented here are more likely to be an overestimate of their stock distribution. The present analysis considers a more holistic concept of EPUs based upon an assemblage of species and therefore may not be an accurate spatial representation for a single species or stock. Ojaveer and Kalejs (2008) suggested, using herrings (*Clupea* spp.) as an example, that fisheries in separate EPUs should be assessed and managed independently, provided that life-history characteristics are significantly different between EPUs. Depending on the species, this may involve aggregating two or more EPU areas.

The fishery-independent survey data also includes a number of species that feature on the IUCN red list of threatened or endangered species, including pelagic species such as devil rays (*Mobula mobular*, Bonnaterre, 1788) and demersal or reef-associated species such as the whitecheek shark (*Carcharhinus dussumieri*, Müller and Henle, 1839), both of which are currently considered endangered. If such species were to be targeted for specific management measures, then the EPUs described here may provide a more rapid assessment of their potential spatial distribution, *in lieu* of dedicated species distribution maps or targeted surveys. The presence of such species in national survey databases also demonstrates that such data may be useful as a previously untapped resource for future conservation efforts.

Distribution of fishing activity

The available data on fishing activity (as the number of vessels that reported fishing within a given 1 degree grid cell per year) demonstrated strong regional differences in the application of different gear types (Figure 4). Demersal gears, particularly towed gears and gillnets are used most heavily in the north (Gulf of Tonkin; candidate EPU area I) and south-west (Gulf of Thailand; candidate EPU areas VI and VII), with purse seining and bottom longlining tending to be the most common method along the central coast (candidate EPU areas II–IV). Handlines, being the favoured method for tuna fisheries, were most used in offshore regions, focused on the areas around the Spratly and Paracel Islands (EPU areas X and XI) on the borders of the Vietnamese EEZ. In terms of the absolute effort, demersal trawls (otter and paired) were by far the most common gear types, comprising almost 52% of the total reported fishing days (120 921 of the total mean 233 166 records). Purse seines and drifting gillnets were also very common (19 and 14% of records, respectively). From the data available, it is not possible to ascertain the extent to which the dominance of towed gears is driven by a numerical advantage or if vessels using towed gears simply cover more of the grid cells than others and thereby have more records overall.

Given the spatial patterns in gear/fleet activity, we argue that the candidate EPUs are for the most part defined at an appropriate scale, in the sense that there are clear differences in fishing activity between EPUs and minimal spatially arbitrary partitioning of fleets (e.g. separation of clearly distinct "patches" of bottom longlines in EPU areas I, and II; Figures 3 and 4). Data linking the distribution of effort by gear with their respective catches were not available. This is an important next step for contextualizing an ecosystem approach to marine fisheries management in Vietnam within the present system of single- and mixed-species assessments, as has been evaluated elsewhere (Lucey and Fogarty, 2013; Lauria *et al.*, 2020). These data represent a relatively coarse (or low) spatial resolution, which is appropriate for the analyses described here, but undoubtedly overlooks the finer-scale distribution of different gear usage, since each EPU area will contain many different habitat or assemblage types that are variously suited for different fishing methods (van Zwieten *et al.*, 2002; Lauria *et al.*, 2020).

Given a particular policy goal, the implications of the spatial variability of fishing effort are clear. For instance, if the goal is to improve the status of benthic ecosystems then the present candidate EPU areas, coupled with the distribution of fishing effort define the target area, and its spatial extent, for establishing bottom fishery closures (EPU area I in particular). Unlike finer-scale resolution information (e.g. van Zwieten *et al.*, 2002), these data are however, inadequate for delimiting a specific area closure but may provide some indication of the resulting effects upon fleet displacement. Such decisions also raise the important questions of trade-offs between and within different sectors (DePiper *et al.*, 2017). Addressing such questions is best served through extensive cooperation, transparency, and trust between key organisations (DePiper *et al.*, 2017; Link and Marshak, 2018; Spooner *et al.*, 2021), but it is another important consideration that affects different countries in varied ways; in a society like Vietnam where communication between Government departments is usually limited to very high level, hierarchy-driven interactions, this will pose a significant challenge for integrated ecosystem assessments.

Oversights and limitations of this approach

Given the relatively low spatial resolution, and the lack of cross-sectoral human use data, these results are considered only as a national-level guide for assessing ecological boundaries, and not a substitute for considering what management approaches are necessary within each EPU. The method also does not address which ecological indicators may be most useful to set goals and assess progress in the marine environment of Vietnam (Lockerbie *et al.*, 2021).

A significant gap in the analysis presented here is the lack of more detailed data on the distribution of human activities, including activities other than fishing (Falco *et al.*, 2019; Methratta *et al.*, 2020), and one common to many other countries (e.g. Breen *et al.*, 2015). This was in no small part owing to the very limited means for the collection of such data, including the tiny (and non-representative) fraction of licenced fishing vessels that carry positioning systems. An important future refinement of the present analysis would be to include these data, as has happened in more data-rich areas like the North Atlantic (Kenny *et al.*, 2009; Lucey and Fogarty, 2013; ICES, 2019). Spatial and temporal patterns in anthropogenic pressures are critical drivers in delineating management units, though the extent to which any spatial management regime can incorporate this is limited by how variable these patterns are (e.g. Solvang and Planque, 2020), and the potential influence of tipping points or decadal scale oscillations between states (Kenny *et al.*, 2009; Tam *et al.*, 2017). The dominant schema for addressing this in other countries has often been spatially explicit, sectoral management authorities (e.g. the Inshore Fisheries and Conservation Authorities in the UK, or the NOAA regional fisheries management offices in the USA) (Terry *et al.*, 2019). A similar approach could be considered in Vietnam, guided by the preliminary ecological boundaries described here, and subject to better information regarding the habits and distribution of the different fleets.

A large proportion of the licenced vessels are low-powered (<20 HP; RIMF licensing data, pers. comm.) and so generally are considered to have a limited range, focusing on near-shore areas (van Zwieten *et al.*, 2002; Pomeroy *et al.*, 2009). The different activity rates and potential for ecosystem impacts between such small scale and artisanal fisheries, and those of other, larger vessels complicates spatial patterns of effort distribution but also provides opportunities for management. Options for mitigating the areas of most intense anthropogenic pressure include fleet rationalisation (Pomeroy *et al.*, 2009; Nguyen, 2011) and the creation of areas that are set aside for specific fleets. In Ghana for instance, areas inshore of the 30 m depth contour are designated exclusively for artisanal vessels, which provide the majority of the employment opportunities in fisheries and the associated value chain. A similar measure could be considered in Vietnam, though it is clear that such measures in themselves will have little consequence without effective communication with fisher communities (the *van chai*; Ruddle, 1998), and a considerable degree of enforcement capability (Campbell *et al.*, 2012; Ha and van Dijk, 2013; Anh *et al.*, 2014).

This initial assessment could be further developed by the addition of new or refined data sources, particularly the distribution of human activities and seafloor habitat types, or the role of terrestrial influences (e.g. outflow of heavy metal pollution from rivers). For instance, although some information on the distribution of fishing effort is available within the Vietnamese national statistics, the key variables that are lacking are those which determine the relative use of different gear types, and their associated metrics. In terms of their impacts upon sensitive habitats, fishing gears are not made equal, and the future inclusion of much more detailed human activity data (e.g. trawl swept area) would be vital in identifying and prioritising areas in greatest need of preventative or restorative measures.

Introduction of any new data should be accompanied by further sensitivity testing, to ensure that spurious associations are not derived from the outputs of PCAs or similar analyses, particularly when considering longer-term time-series data such as the use of hindcasts from global ocean models to consider factors such as decadal-scale state shifts (Kenny *et al.*, 2009; Planque and Arneberg, 2018). More in-depth applications could also consider more novel statistical approaches, such as deep learning to examine patterns both for individual species/functional groups, and with respect to their broader communities (Frelat *et al.*, 2018).

Applications of the EPU method

Although the approach presented here would not be informative for making decisions about the size and shape of individual spatial management measures, such as marine protected areas (MPAs), it provides a reference for informing how the network of such measures could be applied at a regional level. A representative network of marine protected areas would ideally be distributed according to the different ecological boundaries. Taking the 2020 CBD target of 10% of marine area established as reserves as an example, these EPU areas could be used as a (data-limited) means to assess where a representative network of reserves should be implemented, to help (among other things) connectivity between individual MPAs (Kenchington *et al.*, 2019). From a fisheries management perspective, another potential application would be to inform the boundary limits of sub-national management authorities, similar to the NOAA regional fisheries centres in the US, or the Inshore Fisheries and Conservation Authorities in the UK, ideally complementing the traditional fisher community (van chai) level management (Ruddle, 1998) or existing fisher cooperatives, such as those that exist for some small-scale fisheries, such as clams.

Conclusions

We present the first integrated ecological assessment of patterns within the EEZ of Vietnam and find evidence for clearly defining spatially refined management units across relevant environmental and biological data. The present assessment essentially follows an approach developed in data rich-ocean regions but owing to the paucity of data in the present study, the method is certainly not without its shortcomings. Nevertheless, it serves to highlight that it is possible to generate ecologically explicable gradients in the environment with relatively little data, which can be adapted through the integration of information from other sectors, to better inform the development of future monitoring and assessment programmes and the implementation of management measures.

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Data availability

The data used here form part of the Vietnamese national marine database and are not published alongside the present manuscript. Any person wishing to use these data is recommended to make enquiries at RIMF with Nguyễn Khắc Bát.

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