EXPLORING BASIC SPATIAL UNITS FOR THE OCEAN: IDENTIFYING CHALLENGES AND POTENTIAL SOLUTIONS

Ken Findlay [a], Erika Brown [a], Tainã Gonçalves Loureiro [a], and Jordan Gacutan [b]

a. Global Ocean Accounts Partnership Africa Community of Practice, Centre for Sustainable Oceans, Cape Peninsula University of Technology, Cape Town, South Africa.
b. Global Ocean Accounts Partnership, Sustainable Development Reform Hub, University of New South Wales, Sydney Australia

ABSTRACT

The System of Environmental Economic Accounting - Ecosystem Accounting (SEEA-EA) advances guidance on accounting for ecosystems, defined in the standard as a distinct set of biotic and abiotic components and their interactions. The spatially explicit framework facilitates the organisation and standardisation of biophysical data in identifying ecosystem assets and their subsequent supply of ecosystem services and benefits to society and the economy. An accounting area may contain several Ecosystem Types (ET), composed of multiple ecosystem 'patches' - defined as Ecosystem Assets (EA). Accounting for the extent and condition of multiple ecosystem types requires harmonising various datasets within the spatial domain. This is achieved by geometrically dividing the accounting area into Basic Spatial Units (BSU), either using regular grids or irregular shapes / objects (e.g., cadastral boundaries of the areas of land which are owned).

While significant progress has been made in defining BSU within terrestrial landscapes, accounting for ocean ecosystems is more complex due to the 3D nature of ocean ecosystems and their uses (e.g., sea surface, water column, seafloor and subseafloor), the highly dynamic characteristic of the ocean systems, the flows between systems and the associated porosity of their boundaries. These features result in challenges related to aligning existing biophysical data towards ecosystem accounts and aligning with other statistical standards, such as stocks and flows in accounts within the SEEA Central Framework and the System of National Accounts.

Early experiences in applying Ecosystem Accounting to coastal and marine areas have repeatedly identified two major challenges. Firstly, the selection of appropriate BSUs, in terms of scale and geometry, including volumetric aspects, dynamic flows and obscure classification units for ocean ecosystems. Secondly, to capture the 3D quality of the ocean system on accounting exercises. Both challenges are particularly relevant due to the paucity of coastal and marine ecosystem data at both spatial and temporal scales.

To address some of the challenges mentioned, it is critical to develop the ability to use and nest different data resolutions, BSU scales and configurations in line with available data and accounting areas (e.g., coastal, marine and EEZ).

This paper identifies the challenges in establishing guidance for BSU within coastal and marine areas and investigates potential solutions. We explore the selection of BSU size and geometry, based on data resolution and explore the potential to vary and nest BSU scales and configurations in line with accounting areas and the ecosystem types contained within (e.g., coastal, marine and EEZ). This paper also identifies the role of object-based units as ecosystem 'patches' and considers data harmonisation issues related to BSU within different statistical and administrative reporting areas and their boundaries. Advancing BSU enables the linking of multiple environmental economic accounts towards the holistic measurement and management of the ocean domain, where guidance on their selection is key for standardisation and coherence.

INTRODUCTION AND BACKGROUND

The health of marine and coastal ecosystems is crucial to support human well-being. The global advancement of human resource-use activities within ocean economy expansion programmes mean that ocean ecosystems are under growing pressures, which can result in ecosystem state changes and impacts on communities, livelihoods, and further economies (Elliot et al., 2017). Ocean Sustainable Development has therefore been recognised as requiring information from across three domains including economic measures (of the ocean economy), social measures of ocean inclusivity and social equity; and ecological and environmental measures of natural capital, ocean wealth and sustainability in terms of the resource uses arising from these. These pillars correspond to the Social, Economic and Environmental domains in triple bottom line theory that allow sustainable contributions of environmental health and wealth, social and inclusive well-being, and a just economy to inform ocean governance processes.

Integration of these Social, Economic and Environmental domains can be achieved through ocean accounting wherein stocks and flows are integrated into a single comparable, regular, and ongoing measurement recording system to provide an integrated, coherent, and consistent set of data. An Ocean Account can be viewed as a structured and regular compilation of consistent, standardised, and comparable information on marine and coastal environments, including associated and related human ocean social circumstances and economic activity within a defined time or space. Ocean accounts therefore organise ocean data (social, environmental, economic) into a common framework (an ocean accounts framework; OAF), using similar structure as national accounts usually maintained by National Statistical Offices or Finance Ministries. In doing so, they provide a common information infrastructure for ocean development policy, marine spatial planning, environmental management, and international reporting. An ocean accounting framework (OAF) can be viewed as a "systems of systems" approach that integrates stocks (physical and monetarized) of capitals (natural (non-produced), built (produced), financial, or human) within discrete account systems, integrated through flows between such systems in a classic systems stocks and flows approach. The discrete accounts systems incorporate recognized international statistical standard accounts systems including the System of Environmental Economic Accounts (SEEA) Ecosystems Accounts (that measures ecosystem typologies, extent and condition and their associated ecosystem services on a spatial basis), the SEEA Central Framework (that measure, a) stocks of environmental assets, b) two-way flows of natural inputs, products and residuals between the environment and the economy, and c) economic activity related to the environment) and Ocean Economy Satellite Accounts (for example the US Marine Economic Satellite Accounts) under the System of National Accounts (SNA) that may identify aspects of the ocean economy, including the industries, production output, and value-add and the employment associated with production. However, accounting for the ocean also lends itself to the further development of novel accounting systems including the advancement of Social Accounts (to identify costs and benefits of ocean resource use and the associated pressures by social and demographic components from the Ocean or Marine Economy Satellite Accounts), Ocean Risk Accounts (to identify and link pressures, state changes and their influences on ecosystems that extend beyond the residuals identified in the SEEA Central Framework) or Governance Accounts that identify ocean governance processes to manage risk

However, it is important to recognize that accounts have temporal and spatial boundaries in terms of what is being accounted for, where and when. An accounting framework requires statistical units, about which information is compiled and for which statistics are derived and presented (Bordt, 2015). It is critical to have an agreed set of classes for statistical purposes that use a common set of principles so that accounting from across different locations can align within a universal measurement framework. The historical account of the SEEA developments (through the development of the 1993 SEEA Handbook of National Accounting: Integrated Environmental and Economic Accounting, the

2003 SEEA Handbook of National Accounting: Integrated Environmental and Economic Accounting, the 2012 SEEA Central Framework (SEEA CF), the 2012 SEEA - Experimental Ecosystem Accounting (SEEA EEA) and the 2021 SEEA Ecosystem Accounts Framework (SEEA EA)) are well described in the 2021 SEEA Ecosystem Accounts (SEEA EA) document released in March 2021.

The fundamental statistical unit of ecosystem accounts is an ecosystem as a functional spatial area unit that has the capacity to provide services. A starting point for the identification of such units is data derived from remote sensing and from other data sources. The System of Environmental-Economic Accounting—Ecosystem Accounting (SEEA EA, 2021) is defined as a "spatially-based, integrated statistical framework for organizing biophysical information about ecosystems, measuring ecosystem services, tracking changes in ecosystem extent and condition, valuing ecosystem services and assets and linking this information to measures of economic and human activity". Ecosystems both provide the base on which ocean utility is often dependent and are subject to human pressures of the human-ocean resource-use nexus. Ecosystem accounting as embodied in the SEEA EA therefore provides the base layer of ocean accounting. While ecosystem accounting provides an important foundation for Ocean Accounts (through Marine Ecosystem Accounts), it is important to recognize that it is the segues between several different account systems (as described above) that provide ocean accounting with its power in boosting data through integration.

As noted above, the SEEA EA aligns with measurements of the relationship between the environment and the economy described in the System of Environmental-Economic Accounting 2012—Central Framework (SEEA CF) (United Nations et al., 2014a). This means that the System of Environmental-Economic Accounting (including both the SEEA CF and the SEEA EA) complements the System of National Accounts (SNA) by integrating physical and monetary measures about the environment in a manner comparable to those data compiled in the national accounts. Since the objective of the SEEA-EA is to compile information about ecosystems, the organization of information in relation to spatial areas as statistical units is core to ecosystem accounting. Spatial units are therefore the basic building blocks for any analyses of location-specific attributes and matters of scale become critical in such a set of spatial statistical units. Whilst the SEEA Central Framework often operates largely at the sub-national or national level, the SEEA EA requires a very fine spatial scale for the adequate compilation of ecosystem information, and a mutually exclusive hierarchical classification of spatial units is recommended, based on ground surface characteristics. Here it must be recognised that ground surface characteristics within ocean accounts are at a seafloor level, while many ecosystems and associated services arise at sea surface or seawater column levels, so that three dimensionality is a considerable challenge in compiling ocean spatial accounts.

The 2021 SEEA EA builds on the 2012 SEEA EEA and the refinement of terminologies and in description of types of spatial elements between the 2012 SEEA EEA and the 2021 SEEA EA requires noting. Bordt (2015) noted that the SEEA 2012 EEA a hierarchy for spatial representation was proposed as comprising: -

- The Basic Spatial Unit (BSU) as the smallest unit of spatial area used in an accounting process and can potentially be delineated by various shapes. BSU have been retained in the SEEA EA but are now regarded as a means to implement the accounting approach rather than being conceptually nested.
- Land Cover Ecosystem Functional Units (LCEU) as an aggregation of contiguous BSUs with homogenous characteristics (such as land cover, elevation, drainage area and soil type). While not strictly delineating an ecosystem, the LCEU could be considered an operational definition for the purposes of ecosystem accounting. In the SEEA EA, LCEU have been relabelled ecosystem assets and are regarded as the key conceptual unit.

- Ecosystem Accounting Units. The Ecosystem Accounting Unit is a reporting aggregate of the LCEUs within the area of account compilation. Given the hierarchical nature of the classification system, LCEUs should not cross Ecosystem Accounting Unit boundaries, so that the outer border of the Ecosystem Accounting Unit is defined by the outer borders of the LCEUs.

Bordt (2015) noted that the treatment of marine systems is not well defined in this process. He also suggested that there are benefits to maintaining a richer set of spatial units than the BSU, LCEU and EAU to ensure that biases introduced by scaling are minimized.

In the SEEA EA, the LCEU have been redefined as Ecosystem Assets as the key conceptual unit. The EAU has been redefined as the Ecosystem Accounting Area, with a similar role as the EAU. BSUs have been retained in the SEEA EA but are now regarded to implement the accounting approach rather than being conceptually nested within the process. The SEEA EEA Revision Working Group on spatial units noted that despite the general approach for describing different spatial areas in an accounting context (Ecosystem Accounting Areas (EAA), Ecosystem Assets and Basic Spatial Units (BSU)) having become well established, there are still important matters requiring resolution (SEEA EEA Revision Working Group, 2019).

Comparison of marine and terrestrial systems

Environmental Economic Accounts (whether in the terrestrial or ocean space) have to date been largely developed within the geopolitical or administrative boundaries. It is important to note that boundary porosities at various spatial scales (for example, ecosystem accounting areas are often defined by geopolitical or administrative limits), ecosystem assets and even basic spatial units of ecosystem accounting) or sectoral scales (of overlapping industry / resourced use sectors) are far higher in the ocean than in the terrestrial realm. Such ocean boundary porosity arises through:

a. The higher dynamic nature of the ocean in terms of flows (for example, physical or ecological flows).
b. The greater three-dimensional nature of the ocean space so that flows are both vertical and horizontal in direction.
c. A lack of clear definition of ocean – terrestrial boundaries within ocean accounting / coastal accounting so that transboundary ocean – terrestrial flows are not always clearly defined, and
d. The commons nature underpinning many oceans industry sectors that results in both horizontal and vertical overlap in resource-use sectors.
e. Furthermore, inherent within such boundary delineations is the need to recognize that ocean data are often only available at a relatively lower resolution than terrestrial data, a factor that then requires interpolation through modelling and a need for adequate spatial boundary resolution.

SPATIAL EXTENTS WITHIN SEEA ECOSYSTEM ACCOUNTS

Three mutually exclusive hierarchical spatial levels are identified within the SEEA EA, including (from broadest to finest scale):

a. The Ecosystem Accounting Area (EEA) defined as the delineated area for which the set of accounts are being compiled (including for example supra-national, national, or sub-national regions or environmentally or policy defined areas).

b. The Ecosystem Type within the defined area (the EEA above) the extent of which is the aggregated sum of the extents of Ecosystem Assets of the ecosystem type. The sum of the extents of all ecosystem types should equal the extent of the EEA.
c. Ecosystem Assets are defined within the SEEA EA as "contiguous spaces of a specific ecosystem type characterized by a distinct set of biotic and abiotic components and their interactions". As spatial entities, Ecosystem Assets are best described within Geographic Information Systems (GIS) approaches.

To operationalise the delineation of Ecosystem Assets within GIS, the SEEA EA suggests an appropriate Basic Spatial Unit (BSU) approach where a BSU is defined as a geometrical construct representing a small spatial area. The SEE EEA defined BSUs as the smallest unit of spatial area utilised in an accounting process to provide a fine-level data framework within which data can be assigned. A grid cell is an example of a BSU, but other shapes, for example hexagons or further polygons, may be used.

These three hierarchical layers are outlined in Figure 1 and Table 1 below in the context of a grid based BSU approach.

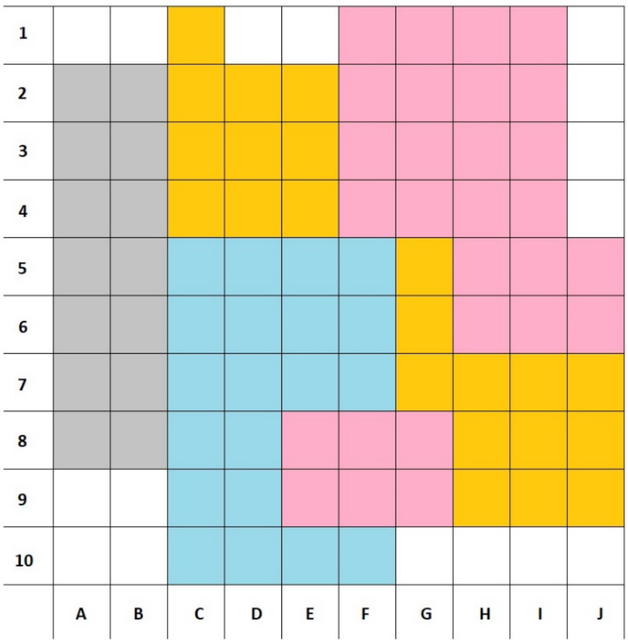

Figure 1. Hypothetical spatial representation of an 84 BSU Ecosystem Accounting Area (within a 100 BSU grid) that comprises four Ecosystem Types (gray, orange, blue and pink) made up of six Ecosystem Assets (one gray, two orange, one blue and two pink) of contiguous (by typology (colour)) BSUs.

Table 1. Accounting of the Ecosystem Accounting Area; Ecosystem Types and Ecosystem Assets outlined within the Basic Spatial Unit approach within Figure 1.

Ecosystem Accounting Area	Ecosystem Type	Ecosystem Asset	Basic Spatial Unit
Sum of Ecosystem Types	Sum of Ecosystem assets (by colour)	Contiguous BSUs of same typology (colour)	
1 (84 units)	1 (gray) (14 units)	EA1 (gray) (14 units)	A2, A3, A4, A5, A6, A7, A8, B2, B3, B4, B5, B6, B7, B8
	2 (orange) (22 units)	EA2 (orange) (10 units)	C1, C2, C3, C4, D2, D3, D4, E2, E3, E4
		EA6 (orange) (12 units)	G5, G6, G7, H7, H8, H9, I7, I8, I9, J7, J8, J9
	3 (blue) (20 units)	EA3 (blue) (20 units)	C5, C6, C7, C8, C9, C10, D5, D6, D7, D8, D9, D10, E5, E6, E7, E10, F5, F6, F7, F10
	4 (pink) (28 units)	EA4 (pink) (22 units)	F1, F2, F3, F4, G1, G2, G3, G4, H1, H2, H3, H4, H5, H6, I1, I2, I3, I4, I5, I6, J5, J6
		EA5 (pink) (6 units)	E8, E9, F8, F9, G8, G9

SPATIAL CHALLENGES WITH RESPECT TO OCEAN ECOSYSTEM EXTENTS

There are several spatial challenges in the above hierarchical approach to spatial ecosystem accounts. While these may be common to both ocean and terrestrial systems, the more dynamic and three-dimensional ocean environment exacerbates these challenges in the marine realm, particularly in terms of boundary porosity. Furthermore, there are aspects of lower data resolution and confidence within ocean data compared to those from terrestrial systems. It is therefore considered critical that spatial boundaries of Ocean Accounts be investigated across the different spatial scales, including at the Ecosystem Accounting Area scales, the scales of Ecosystem Type and Ecosystem Asset or at BSU scales when datasets may have considerably different resolutions. Furthermore, the boundaries of activities or sectors to include within ocean / marine economy satellite accounts or within the SEEA Central Framework (which may transcend the ocean terrestrial boundaries, for example) require important consideration.

This paper introduces some of the challenges and potential solutions of spatial boundaries that arise within ocean accounting processes. It does not however prioritise any solutions or approaches that have been investigated to date.

Obscure classification units for ocean ecosystems, data resolution and confidence

Ecosystems are usually defined in terms of a suite of complex interacting biological (e.g., plants and animals) and physical (rocks, minerals, water, etc.) components. The delineation of Ecosystem Assets therefore requires the use of a broad range of physical and biological criteria. Several options are presented as candidates for the SEEA-EA reference ecosystem type classifications by the SEEA EEA Revision Working Group (2019) including: -

1. The IUCN Red List of Ecosystems or the aligned IUCN Global Ecosystem Typology
2. USGS/Esri Globally Distinct Biophysical and Biogeographic Settings (GDBBS)
3. A two-tier approach that builds upon the two above classification approaches
4. Existing habitat classifications (e.g., IUCN, EUNIS)
5. Existing land cover classifications (e.g., FAO; Corine)

The SEEA EA provides an agreed classification of ecosystem types based on the IUCN Global Ecosystem Typology, the structure of which comprises a nested hierarchy of units at six levels. Units in the upper three levels (realms, biomes, and Ecosystem Functional Groups) are distinguished based on ecosystem function, while those in the lower three levels (biogeographic ecotypes, global ecosystem types and sub-global ecosystem types) identify units with progressively finer compositional (assemblages of species) distinctions. This is a significant advance on the broad classes of LCEU provided in the SEEA 2012 EEA.

While coastal ocean measurement and data availability may be comparable to those in terrestrial environments, open ocean measurement and therefore data availability generally occurs at a far coarser scale than in terrestrial environments. Ocean ecosystem classification units are likely to therefore be less well defined than for coastal or terrestrial systems. There may also be a far higher degree of modelling utilised in describing physical or biological measurements within an ocean environment and it is considered critical that modelling results (as modelled estimates) and associated degrees of confidence in estimates be considered. The interrelationship between *in situ* measured data and ocean model data (which are ideally driven by *in situ* measurements) remains a challenge in ocean ecosystem classification systems.

Dynamic Flows and Boundary Porosity

Ocean currents and oceanographic flow processes (for example upwelling of nutrient rich waters) means that ocean characteristics in a particular area are often highly dynamic, much more so than in terrestrial systems. Flows or dynamic characteristics may be entirely stochastic or be seasonally modulated (for example seasonal ice retreat or seasonal wind induced upwelling processes) that temporally do not align with time-based accounting processes. Therefore, a strong need exists for such temporal dynamics to be incorporated into spatial accounting processes and several potential solutions include:

Temporal data scales (in terms of data availability) may vary considerably with coarser availability of certain metrics (for example annual stock assessments versus seasonal ocean environmental conditions). Temporally segregating an account may be useful to account for seasonal characteristics (for example mean summer, winter, autumn, and spring temperatures) within a longer-term accounting process. The introduction of ranges of temporal characteristics may allow these to be captured to some extent in the spatial process.

Spatial flows between systems need to be adequately captured across time. For example, final ocean ecosystem services may be dependent on a broader series of ecosystems than those in which the final service is rendered (for example the harvest of species that move between systems at different life cycle stages), or residual sources may occur at ranges from where residuals are measured. Furthermore, both the vertical (for example vertical migration or nutrient sinking) and the horizontal nature of such flows require recognition.

The definition of ocean space and ocean activities is important in the context of across boundary flows between ocean, coastal and terrestrial systems. Ocean boundaries are most often delineated by administrative boundaries (such as national EEZ limits) where flows across such boundaries (for example, to and from areas beyond national jurisdiction (ABNJ)) are generally considered as import-export components within models. While the issue of on land activities, sectors, or residual sources to include in an accounting process is beyond the scope of this paper, it is important that the ocean space be adequately defined. Administrative boundaries of a nation's ocean space are in most cases set by a high-water mark and distances derived from these (for example territorial waters at 12 nautical miles or the EEZ at two hundred nautical miles). Ocean systems however straddle such administrative boundaries (for example, a sandy beach system that extends from above to below a high-water mark) so that there is some need for the selection of coastal Ecosystem Assets to be included or excluded from ocean ecosystem accounting processes. For example, a hard ocean boundary could be drawn on the landward side of any Ecosystem Assets that straddle a high-water mark. The delineation of such Ecosystem Assets that straddle the outer EEZ boundary are possibly more complex in that assets are likely to be extensive in the pelagic realm and such assets may need to be sliced by administrative boundaries to allow for the EAA to be area representative of an administrative EEZ.

The 3D Ocean Environment and Overlayed (or Stacked) Ecosystem Types or Assets

While there are some requirements for three dimensionality (for example atmospheric considerations) and boundary porosity (for example in relation to say migratory species as resource assets, or aerial pollutants) in all spatial accounting processes, both vertical and horizontal movements within the ocean space result in considerably higher complexity in ocean spatial delineation compared to similar processes in the terrestrial space. In fact, even fixed ecosystems (and therefore Ecosystem Assets and Ecosystem Types will occur at different overlayed vertical levels within a horizontal 2D ocean space. Although SEEA EEA Revision Working Group (2019) noted that there are two options to define ecosystem assets for the marine environment (aggregation to a single Ecosystem Asset layer or a stacked series of Ecosystem Assets), the challenge of overlayed ecosystem types within a three-dimensional space may be handled in several manners including

a. As a two-dimensional approach that integrates / aggregates the characteristics of the third vertical dimension
b. As a series of discrete two-dimensional layers that are stacked in the third dimension (such layers for example could include sea surface, water column (or a series of water column layers by depth, for example, epipelagic, mesopelagic, bathypelagic), seafloor or sub-seafloor layers),
c. As a mix of two dimensional (sea surface or seafloor) and three dimensional (water column) layers, or
d. As a series of different thickness three dimensional volumetric layers, dependent on layer type (seafloor and seabed thin layer; water column thick layer).

Such discussion excludes ocean atmosphere interaction, which may require further layering in similar manners in which the atmosphere is accounted in terrestrial accounts.

An important aspect in the consideration of stacked gridded BSU layers is the interdependence and alignment of layer BSU scales as square factors of others so that layers align to be divisible (e.g., 1 to 1; 1 to 4; 1 to 9, 1 to 16, etc.) to allow some border commonality. An alternative independent stacked layer approach results in different indivisible layer scales with no border commonality between layers.

Three Dimensional Challenges

ESRI has tackled the challenge of approach b above and devised a scientifically accepted standard for capturing and characterising 3D ocean space in a manner that is described here. This is a collaborative body of work compiled by individuals from several institutions cited and described in Sayre et al. 2017 (Esri, USGS, NOAA, NASA, USFWS, NIWA, MCI, NatureServe, GEO, Duke Marine Geospatial Ecology Lab, GRID Arendal, Woods Hole Oceanographic Institution, University of Auckland). The Ecological Marine Unit (EMU) is an objectively derived and globally comprehensive (macroscale) set of 37 distinct volumetric regional units. EMUs are constructed on a regularly spaced ocean point-mesh grid, from sea surface to seafloor, and attributed with data from the 2013 World Ocean Atlas version 2. Point attribute data are identified as the means of the decadal averages from a 57-year climatology of six physical and chemical environment parameters (temperature, salinity, and dissolved oxygen, nitrate, phosphate, and silicate concentrations). The database includes over 52 million points that depict the global ocean in three dimensions. Point data are statistically clustered to define 37 EMUs, which represent physically, and chemically distinct water volumes based on spatial variation across the six marine environmental characteristics used. The aspatial clustering to produce the 37 EMUs did not include point location or depth as a determinant, yet strong geographic and vertical separation was observed. Twenty-two of the 37 EMUs are globally or regionally extensive, and account for 99% of the ocean volume, while the remaining 15 are smaller and shallower, and occur around coastal features. The vertical distribution of EMUs in the water column were assessed and placed into classical depth zones representing epipelagic (0 m to 200 m), mesopelagic (200 m to 1,000 m), bathypelagic (1,000 m to 4,000 m) and abyssopelagic (>4,000 m) layers. The mapping and characterization of the EMUs represent a new spatial framework for organizing and understanding the physical, chemical, and ultimately biological properties and processes of three-dimensional oceanic water bodies by an initial objective partitioning of the ocean using long-term historical average data. As an open-access resource, using both a standardized geographic framework and a baseline physicochemical characterization of the oceanic environment, they are intended for disturbance assessments, ecosystem accounting exercises, conservation prioritisation, and marine protected area network design, along with other research and management applications.

Additionally, visualization and analysis of 3D oceanographic data in alignment with EMUs may be realized using multidimensional data storage and Voxel layer creation in ESRI ArcGISPro. A voxel layer represents multidimensional spatial and temporal information in a 3D volumetric visualization (ESRI, 2018). For example, visualization of atmospheric or oceanic data, geological subsurface models, or space-time cubes may be achieved through voxel layers. Voxel layers may be used to explore spatial relationships between variables.

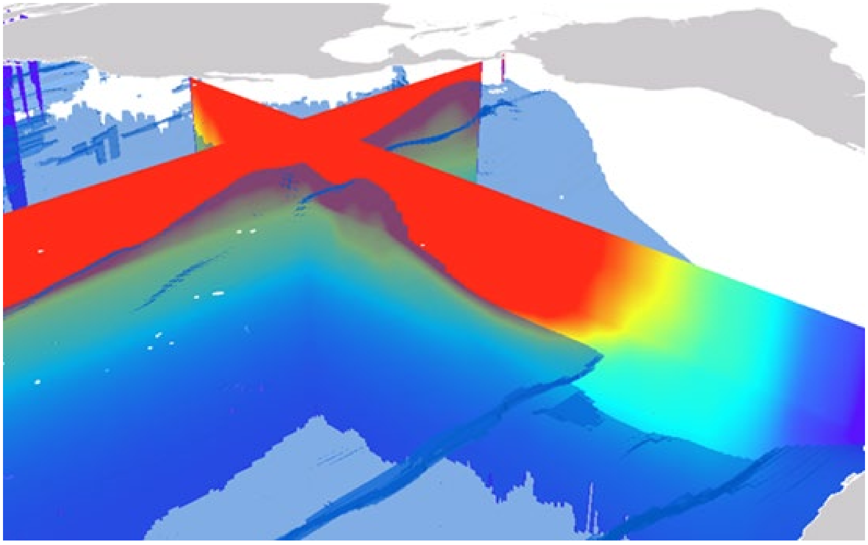

Figure 2. The ecological marine unit voxel layer shows a cross section of temperature with an isosurface of oxygen saturation.

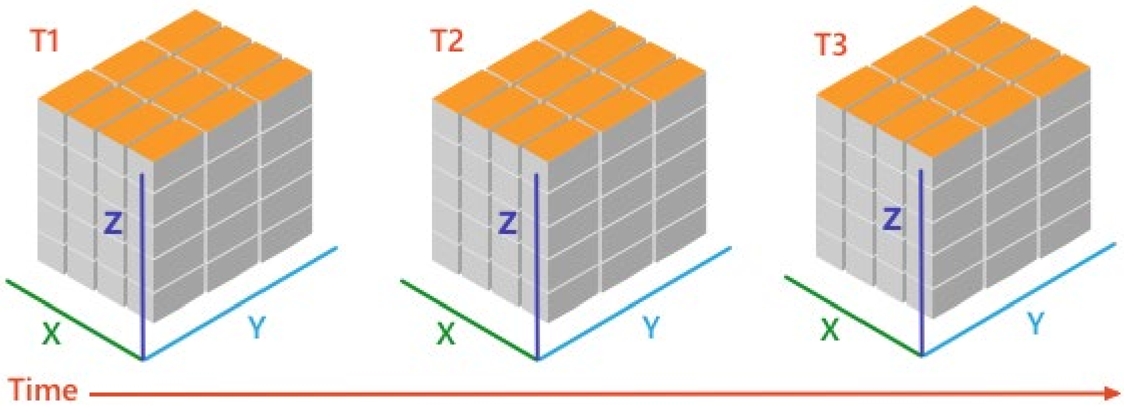

Figure 3. Multi-dimensional representation (across the x, y, z, and t axes) in which each dimension represents geographic coordinates and includes a fourth dimension representing time.

As described by ESRI (2018), the spacing between the cubes in any voxel axis layer must be identical but can vary between the different axes. For example, x may be 100 meters, y may be 50 meters, and z may be 50 centimetres. The dimensions across axes can therefore be different but must follow the same axis spacing. Each cube in the voxel layer has one or more variables that represent a data value of the voxel cube. For example, a voxel layer may contain salinity and temperature data, defined for each voxel cube. Furthermore, variables can represent quantitative continuous data or discrete or qualitative data. In addition to the spatial aspects, a voxel layer can also contain time information.

Two dimensional Challenges of BSUs

Regardless of the integrated 2D or stacked 2D approaches there are a variety of factors that challenge 2D approaches in the aggregation of BSUs to determine ecosystem extents.

<u>Data resolution and BSU shape and scale</u>

Vardon et al. (2011) noted that the size of the BSU (they define a grid approach) varies with the source of data, and in general the source of the data determines the BSU size. They note that grid-based approaches are used commonly for remote-sensed data and that different spatial resolution data products result in the need for different BSU scales and resolution. It is well understood that the availability, benefit, resolution, and confidence of ocean data are likely to be considerably lower than for the terrestrial space. Furthermore, these characteristics are likely to be highly variable across the ocean space with coastal shallow regions likely having far higher availability and resolution that offshore or deep ocean space. Furthermore, as noted above, many or most ocean data are in fact likely to arise from modelled rather than an in-situ measurement process (although such modelling processes are driven by in situ measurements). Application of BSU resolution at different scales aligned to data resolution may result in challenges in terms of spatial unit selections (as the basic building blocks for the analysis of location-specific attributes), scaling (as the process of attributing information from one spatial, thematic, or temporal scale to another); and aggregation (as the process of reducing several measures to a simpler one). (See Bordt, 2015).

Spatial Unit Scale and Shape Selection

Basic Spatial Units can be thought of as the smallest unit at which spatial analyses are carried out, and examples include vector-based polygons (such as cadastral units, grid squares or rectangles or hexagons) or raster-based pixel delineations of area. Many 2D shapes are initially interpreted as objects (for example as vector-based polygons within in situ mapping or aggregated raster-based polygons through segmentation and object-based image analyses of remote sensing). It is imperative within object disaggregation (to BSUs) and reaggregation (to Ecosystem Assets) approaches, that BSU resolution is selected at the finest resolution scale possible without any data downscaling (for example at the raster pixel resolution of the object-based image analysis) to minimise edge, shape, and therefore asset extent estimation effects. Bordt (2015) noted that since the intent of an ecosystem account is to integrate information at various spatial scales, using too coarse a resolution may impose unnecessary simplifications in this integration and that spatial scale needs to be dependent on the analytical objective of the account.

The selection of appropriate spatial units for analyses are critical in terms of potential edge effects that might arise through inappropriate spatial shape or scale in the selection of BSUs. Differences in data resolution (and therefore data confidence at the same BSU spatial scale) require that a two-dimensional BSU model is best applied at different spatial resolutions for different resolution datasets with a coarser divisible BSU resolution in the offshore or deep ocean regions where datasets may be coarser. Furthermore, stacked two-dimensional ecosystem layers may have to be resolved at different nested and aligned spatial scales of BSUs, although alignment of such layers become imperative in BSU approaches that require alignment in border commonality across vertical stacked layers.

The challenge of assigning a particular BSU to an ecosystem typology and therefore contiguous Ecosystem Asset is further compounded when a BSU is equally shared by two or more ecosystem typologies. Any such assignment based on proportional extent results in area trade-offs and potential over or under estimations in extents of the defined Ecosystem Asset. Vardon et al (2011) noting that BSU shapes will almost certainly not align with the shape of the object area, suggest that in such cases the cells be split into two smaller “analytical” units, the attributes of which may then be divided between object areas.

Scaling

Bordt (2015) noted that information on ecosystems arise on many different scales, so that the compilation of ecosystem accounts requires guidance on attribution or transfer of information from one scale to another. There are three main areas of scaling that require recognition in the assignment of data to spatial units, including

a. *Upscaling* as the aggregation of data to larger spatial scales. Critical in upscaling is that data need to be representative across the entire area of the larger spatial scale to which the data are being scaled. Furthermore, the confidence in the data (as a range or variance) being scaled requires recognition.
b. *Downscaling* as the disaggregation of data to smaller spatial scales. Downscaling increases the spatial resolution in the scale conversion process increases and may therefore decrease the spatial confidence in the data (for example the application of a 1 km square data resolution to a 1 ha spatial resolution).
c. *Transfer* as the assignment of information measured in one area to another area such as in benefit transfer. Such information transfer needs to be carried out with considerable care with respect to the similarity of the areas.

Aggregation

Aggregation in ecosystem accounting involves the combining of measures into simpler metrics. While the process of aggregation across common metrics is straightforward, aggregation across different metrics and scales may require conversion to common units and the development of indices.

Alternatively, the use of object-based approaches to ecosystem extent requires consideration. In many cases system characteristics or even Ecosystem Assets extents (as surface cover proxy or ecosystems) may be derived through pixel or object-based image analyses (OBIA) of remote sensed products (including various satellite derived products, aerial (including drone) products or even sonar derived imagery of benthic seafloor environments). While pixel-based systems classify and aggregate characteristics based on the finest available spatial resolution available (the pixel), object-based approaches segment image pixels to objects prior to classification. The use of BSU approaches to object resultant from OBIA requires object disaggregation and re-aggregation to the BSU format, allowing for the incorporation of error if object and BSU scales are not aligned. The use of object-based approaches may carry some merit in terms of disaggregation and re-aggregation, the selection of appropriate spatial shapes and scales, ecological representation, or spatial harmonisation.

Bordt (2015) provided a review of implementation approaches used in accounting processes and makes recommendations for further testing of spatial units, including the testing of approaches to delineation of LCEUs/ Ecosystem Assets, developing spatial criteria and testing of intermediate spatial units.

The identification of adequate spatial units is fundamental in the analyses of data required for the compilation of ecosystem extent accounts to ensure standardised statistical methods for the collection, compilation, processing, and presentation of available data (which may arise from disparate sources and under different collection methods). Adoption of standardised and consistent units and classification of units is critical for data from different sources to be integrated and analysed in spatial accounts, particularly where often disparate datasets are utilised. Aspects that require careful consideration in the selection of spatial units for the interpretation of Ecosystem Assets include the sizes of the BSU in relation to data resolution (and the issue of fractional dimensions with lengths that diverge to infinity), the shape of the BSU in relation to three dimensionality, and potential two dimension stacking processes, the representativeness of boundaries arising from BSU or object base approaches and the harmonisation of existing boundaries (be they administrative, physical, ecological, social or economic by definition).

SPATIAL ASPECTS OF ECOSYSTEM CONDITION

The use of ecosystem accounts to inform management policy cycles requires information beyond ecosystem asset extent to include condition, to identify change over time in relation to a reference state. Keith et al. (2017) indicated that indicators of ecosystem condition used in accounts will be most effective when they are designed to answer specific management questions. While, condition accounts are complex and beyond the scope of this spatially focussed paper, it is important to note that different areas within a spatial extent (for example, an Ecosystem Type or Ecosystem Asset) may show markedly different condition values as a departure from a reference condition. Assigning one set of average conditions to an entire spatial extent obscures any spatial heterogeneity in condition. System condition therefore has important underlying spatial components, both in terms of identifying locations of different conditions and the proportions of conditions of an Ecosystem Asset or Type (for example as a proportional area of the total Ecosystem Asset extent metric).

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