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Conservation Biology

REVIEW

Review of ecological valuation and equivalency analysis methods for assessing temperate nearshore submerged aquatic vegetation

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Abstract

Nearshore seagrass, kelp, and other macroalgae beds (submerged aquatic vegetation [SAV]) are productive and important ecosystems. Mitigating anthropogenic impacts on these habitats requires tools to quantify their ecological value and the debits and credits of impact and mitigation. To summarize and clarify the state of SAV habitat quantification and available tools, we searched peer-reviewed literature and other agency documents for methods that either assigned ecological value to or calculated equivalencies between impact and mitigation in SAV. Out of 47 tools, there were 11 equivalency methods, 7 of which included a valuation component. The remaining valuation methods were most commonly designed for seagrasses and rocky intertidal macroalgae rather than canopy-forming kelps. Tools were often designed to address specific resource policies and associated habitat evaluation. Frequent categories of tools and methods included those associated with habitat equivalency analyses and those that scored habitats relative to reference or ideal conditions, including models designed for habitat suitability indices and the European Union's Water and Marine Framework Directives. Over 29 tool input metrics spanned 3 spatial scales of SAV: individual shoots or stipes, bed or site, and landscape or region. The most common metric used for both seagrasses and macroalgae was cover. Seagrass tools also often employed density measures, and some categories used measures of tissue content (e.g., carbon, nitrogen). Macroalgal tools for rocky intertidal habitats frequently included species richness or incorporated indicator species to assess habitat. We provide a flowchart for decision-makers to identify representative tools that may apply to their specific management needs.

KEYWORDS
compensatory mitigation, habitat quantification, kelp, metrics, seagrass

INTRODUCTION

Temperate nearshore marine ecosystems, from subtidal rocky reefs to intertidal estuaries, are some of the most productive ecosystems in the world and provide important ecological and commercial services (Hynes et al., 2021; Wilson & Liu, 2008). Within these systems, submerged aquatic vegetation (SAV), which refers here to intertidal and subtidal seagrasses and macroalgae, including kelp, play critical roles. SAV accumulates nutrients, improves water quality (Eger et al., 2023; Orth et al., 2006), traps sediment, and sequesters carbon (Fourqurean et al., 2012; Krause-Jensen & Duarte, 2016). Large areas of SAV can act as buffering systems for both chemistry changes (Hirsh et al., 2020; Nielsen et al., 2018) and wave action (Pinsky et al., 2013). Seagrasses and kelps are also foundation species and form meadows and beds that serve as critical nursery habitats for a variety of organisms, including those harvested for human use (Bruno et al., 2018; Kennedy et al., 2018; McDevitt-Irwin et al., 2016; Toft et al., 2015).

Despite their ecological and economic importance (Filbee-Dexter & Wernberg, 2018), over 65% of worldwide coastal wetland and seagrass area has been lost (Lotze et al., 2006), and almost 40% of the world's kelp forests are in decline (Krumhansl et al., 2016). Threats to these ecosystems include resource exploitation, increasing human disturbance from development and industry, subsequent trophic imbalances, invasive species, and a changing climate (Beas-Luna et al., 2020; Mooney & Zavaleta, 2016; Steneck et al., 2002). Although efforts to regulate or restore nearshore habitats and their functioning are prevalent in many regions, these efforts are often challenged by inadequate quantification of preimpact baselines and restoration outcomes.

To minimize continued degradation and loss of seagrass meadows (used here interchangeably with *beds*), kelp beds, and other coastal habitats, impacts on resources are highly managed worldwide. Agencies enforce federal and regional laws and regulations (e.g., Endangered Species Act, Magnuson–Stevens Fishery Conservation and Management Act [United States], Environment Protection and Biodiversity Conservation Act [Australia], and the Marine and Water Framework Directive [European Union]) controlling development, habitat, and species protection. These regulations can require review of development and impacts on associated habitats, often with some sort of compensatory action for lost resources. To reduce degradation and loss of habitat of managed species, a general hierarchy for mitigation (Arlidge et al. 2018; IFC, 2012; IUCN, 2016) of development impacts exists across multiple continents to, first, avoid impact (e.g., site a project away from sensitive habitat); second, minimize unavoidable impacts (e.g., use turbidity curtains to reduce sedimentation during construction); and third, restore and offset or compensate for remaining impacts (e.g., by planting seagrass).

For unavoidable impacts (see Phalan et al. [2018] for discussion of the importance of the avoidance step), the third step is known as offsetting or compensatory mitigation (used interchangeably here) and includes offsetting of lost resources through the restoration, enhancement, creation, or preservation of habitat (e.g., USACE & EPA, 2008). Offsetting or compensation is assumed to be truly compensatory, where all lost habitat value or resources are replaced following an impact, sometimes with a preference for replacing the same resources locally, when feasible (McKenney & Kiesecker, 2010). Evaluating the equivalency of this loss and gain of resources requires accurate quantification of baseline status, impact on the habitat, and subsequent benefit of the compensation action and time to recovery.

There are myriad options for quantifying impact, but regulators commonly require some sort of measurement of the area to be affected by the action, sometimes paired with a measure of habitat quality or value for one or more specific traits. Although prescribing an ecological value score undoubtedly oversimplifies the functions and services of a complex habitat, resource managers require practical tools for decision-making in the face of incomplete understanding and ecological complexity. A model that captures the complex functioning of a system will likely depend on simplified, representative metrics or proxies for ecosystem condition (Smit et al., 2021). The decision of which metrics to use may be influenced by policy mandates, the species of interest, project goals, or data availability. Metrics may be measured in the field or remotely (e.g., cover, biomass) and are often assumed to be related to functional or ecological value. Common proxies for ecosystem function include single-species traits or abundance (e.g., density of kelp stipes [stem-like part of kelp that provides structural support]) (Krumhansl et al., 2016), productivity, community structure (e.g., associated invertebrate community), and abiotic measurements (e.g., turbidity).

The field of habitat valuation often refers to economic valuation, where ecosystem services are converted to some present-day monetary value (Dewsbury et al., 2016; Hynes et al., 2021; Shaw & Wlodarz, 2013). However, ecological habitat valuation refers to the process of prescribing a rank, score, indicator value, or index to a defined area of habitat based on metrics linked to ecological function. Habitat valuation models and their metrics can be used to assess the sites of impact and mitigation before and after alteration or mitigation. For example, what is the value of an existing seagrass meadow where a dock is proposed to be built? If the dock development requires mitigation in the form of planting seagrass at a nearby site, what is the value of reestablished seagrass in a bare area that once supported seagrass patches? Equivalence assessment methods (Bezombes et al., 2017) can then be used to integrate these values over time and space, ultimately providing a credit and debit system for impact and mitigation and identifying the net change of habitat resources (e.g., commonly with the ultimate objective of no net loss of habitat area, function, or productivity) (Maron et al., 2018; Moilanen et al., 2009; Salès et al., 2023; zu Ermgassen et al., 2019).

Of all marine or coastal habitats, the practice of habitat valuation and ecosystem equivalencies is most developed for vegetated wetlands (Strange et al., 2002), which commonly includes sites with emergent vegetation. Other nearshore

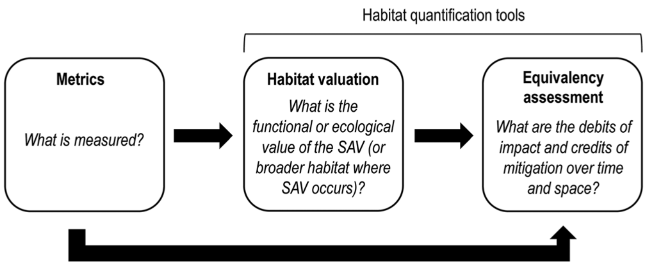

FIGURE 1 A framework for assessing impacts on an area of submerged aquatic vegetation (SAV) and assigning compensatory mitigation. Metrics may be incorporated into a habitat valuation tool to determine a score or indicator value for SAV or a broader habitat that includes SAV (e.g., an estuary). Metrics can also feed directly into equivalency tools, where the habitat value is not quantitatively defined and the metric is instead used to directly calculate equivalency between the impact and mitigation (e.g., using mitigation ratios to calculate mitigation based solely on the area of impact).

marine systems, such as eelgrass meadows and kelp forests (i.e., SAV), are underrepresented in quantification tools (Jacob et al., 2018). Less than 10% of the methods identified by Chiavacci and Pindilli's (2020) review of quantification tools were for marine species or habitats, the majority of which focused on salmonid habitat. Published literature on temperate marine system quantification has largely focused on individual organisms, such as seabirds, or bycatch rather than habitat, likely because quantifying organisms can be operationally simpler than quantifying habitat (but see Dewsbury et al., 2016; Jacob et al., 2018; Levrel et al., 2012). Tools that do exist for marine systems often focus on in-kind mitigation, where the type of habitat lost is the same type mitigated. For example, the destruction of a seagrass bed could require the creation of another seagrass bed. This leaves little guidance for when in-kind mitigation is not feasible and the mitigation involves a different habitat type (i.e., out-of-kind mitigation). For example, there is loss of sandy bottom, but restoring or converting nearby seagrass or rocky areas to sandy bottom is not desirable.

Nearshore systems pose special challenges to the choice of metrics to assess ecological value. Marine systems are biologically dynamic, with open populations, migratory species, annual species, and shifting biomass (Munsch et al., 2023) with strong temporal patterns (Hamilton et al., 2022; Stephens et al., 2015). Tides, wave action, storms, cyclic oceanographic phenomena, and land–sea connectivity also contribute to variable abiotic conditions that are constantly in flux across scales. Quantifying dynamic habitat attributes over time is often not possible due to site accessibility, project timelines, funding, and limitations of remote methods. This complexity and the underrepresentation of SAV quantification methods leave regulators with few tools to quantify impact or assign compensatory mitigation for these economically and ecologically important ecosystems.

Habitat valuation and equivalence assessment tools collectively comprise what we refer to here as *habitat quantification tools* (Figure 1) (Chiavacci & Pindilli, 2018, 2020; Chiavacci et al., 2022). We reviewed peer-reviewed literature and white-paper reports on habitat quantification tools historically used with, or applicable to, temperate nearshore habitats containing SAV. To our knowledge, there is no recent literature that compiles and describes international SAV metrics and quantification tools within this system for managers and regulators. Due to the varied terminologies used in published literature, we provided related terms and pertinent definitions in Table 1 and used the words *tools* and *models* interchangeably. We summarized valuation and equivalency tools' common input metrics or derived indicators, as well as their institutional origins, and then highlighted how some tools address common management challenges, such as uncertainty or a lack of data. We also created a checklist to assess the completeness and utility of future tools. Finally, we identified further research to benefit the offsetting and compensatory mitigation of these important ecosystems. We sought to summarize and clarify the state of SAV quantification tools, highlight existing tools, and draw attention to specific gaps where future resources should be focused.

METHODS

We searched published literature written in English with Web of Science and Google Scholar, and online white paper reports for SAV habitats ("*kelp**," "*macroalga**," "*seaweed**," "*SAV*," "*seagrass**," "*submerged aquatic vegetation*," "*nearshore*") associated with the terms "*habitat valuation*," "*habitat evaluation*," "*ecosystem equivalency*," "*mitigation ratio*," "*habitat quality*," "*intrinsic value*," "*habitat suitability index*," "*biocentric value*," "*functional assessment*," "*metric*," "*index*," "*scor**," "*ecosystem*," "*indicator*," or "*evaluation*."

To highlight the tools available to nearshore, temperate SAV managers, we chose tools that either related specifically to temperate marine or estuarine SAV or were generic across habitats and could reasonably be applied to temperate SAV. We excluded nonapplicable stream, riparian, palustrine, lacustrine, inland, and pelagic tools. We also excluded papers that described only mapping results or methods to identify a region's diversity or extant resources, compared dependent variables but did not reference a formal tool, described economic valuation, or discussed valuation based on commercial value. We did not include tools that predicted the occurrence of SAV based on environmental factors, such as species distribution models, due to the difference between measuring in situ habitat value versus predicting occurrence (Stephens et al., 2015). To keep our search relevant to methods being used today with best available science, we only included tools utilized between 2000 and 2022. If a method or paper was developed or written before 2000 but cited after 1999, it was included.

We included tools that specifically assigned a score or index for SAV habitat itself (e.g., a seagrass meadow or kelp bed) based on one or more metrics. We also incorporated tools that quantified broader habitats that include SAV, such as estuaries that support seagrasses and areas that support species that rely on SAV, as seen in habitat suitability indices (HSIs) (e.g., for shrimp, fish). Tools for such broader habitats were included only if they measured one or more attributes related to SAV. We classified tools as habitat valuation tools, equivalency tools, or both (Figure 1). We noted a tool's inclusion of temporal

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TABLE 1 Definitions and related terms in ecological habitat valuation and quantification literature.

Term	Definition (as used here)	Synonyms or related terms from literature
Ecosystem function	Processes that maintain an ecosystem	Sometimes included with ecosystem services (below)
Ecosystem services	Processes through which natural ecosystems and the species that make them up benefit society (e.g., storm protection [Daily, 1997])	Sometimes included with ecosystem function (above)
Metric	Measurement or unit of an ecosystem (e.g., shoot density)	Measurement, trait, parameter
Indicator	One or more combined metrics that relate to some aspect of ecosystem functioning	Index, ecological valuation method
Habitat	Area where species or a community exists, uses resources, and interacts with other organisms	Can be described at different scales: ecosystem, system, site
Habitat quantification tool	Methods for quantifying impact or mitigation for habitats (Chiavacci & Pindilli, 2020)	Includes both valuation and equivalence methods (below)
Ecological valuation method	Procedure to assign a value to habitat, representing ecological quality or functioning (e.g., habitat suitability indices)	Ecological condition, functional assessment, suitability assessment, biological valuation, biocentric value, suitability index
Habitat equivalence assessment method	Procedure to evaluate losses and gains within ecosystems (e.g., mitigation ratios) (Bezombes et al., 2017; Quétier & Lavorel, 2011)	Ecological equivalency models, biodiversity offsets, scaling

variability (i.e., site variability over a certain time frame) in assigning habitat value, reference sites, landscape context, adjustments for uncertainty in assigning mitigation, and user complexity. Complexity was based on the effort or expertise required to obtain the input data. For example, a visual, rapid method to measure seagrass cover in the field was considered basic, whereas a tool that used multiple GIS layers or knowledge of an area's metapopulation dynamics was considered complex. We also noted tools' associated regulatory policies, the affiliation of the first author of the citation as a proxy for the institution or entity responsible for the tool, and the acknowledged funding sources.

RESULTS

Our search yielded broad results that included 47 tools that met our criteria and over 1000 publications across 6 continents that described tools excluded for one of the reasons listed above. In Figure 2, identified tools are categorized by their intended use. Ultimately, tools quantified either broader habitats that contained SAV (either generally or for a specific species) or specific areas of predominantly SAV. For each of these categories, tools either quantified quality, ecological value, or function, or translated this value into equivalency assessments. In some cases, tools could be used to value habitats or identify particularly sensitive or important areas (Figure 2).

Upon selection of the 47 tools that met our criteria (Appendix S1), we sorted valuation and equivalency tools into 3 general categories: habitat equivalency analysis (HEA) and related tools, which calculated value over time and space; valuation tools that scored areas with a ratio based on ideal conditions or a reference site; and a diverse other category that included the remaining valuation and equivalency tools from around the globe.

Habitat equivalency analysis

Six of the identified tools were based on or designed to be used with HEA (NOAA, 1995), which includes both a valuation and equivalency component. This method is based on the assumption that lost ecosystem services over space and time can be compensated for by providing an area of habitat maintained over a specific number of years. The HEA framework includes a habitat quality value or percentage loss of services, the timeline of impact and mitigation, area affected and mitigated, and a discounting rate that can value future habitat less than present habitat. Habitat equivalency analysis was widely referenced in the literature, most likely due to its frequent use in literature and natural resource damage assessments (commonly used for oil spills) in the United States and internationally (e.g., Kim et al., 2017).

Ratio-based tools

Multiple tools were associated with a ratio or scoring system. Five of these tools were associated with HSIs, a category of valuation tool that combines multiple metrics or indices that are divided by the score of an ideal habitat, resulting in a rating of 0–1 for habitat quality (1 representing ideal conditions). Ideal habitats are defined either by using reference sites or as an amalgamation of metrics' optimal ranges for a focal species (e.g., high SAV cover, temperature range). This score can then be used with the habitat equivalency procedure (HEP) equivalency tool (USFWS, 1980), incorporating the area affected or mitigated (known as habitat units) and average annual function to determine appropriate mitigation. We included the generic HSI and HEP procedures as well as 3 specific applications of HSIs in our HSI–HEP category. The HSIs have historically been most common for bird and fish species

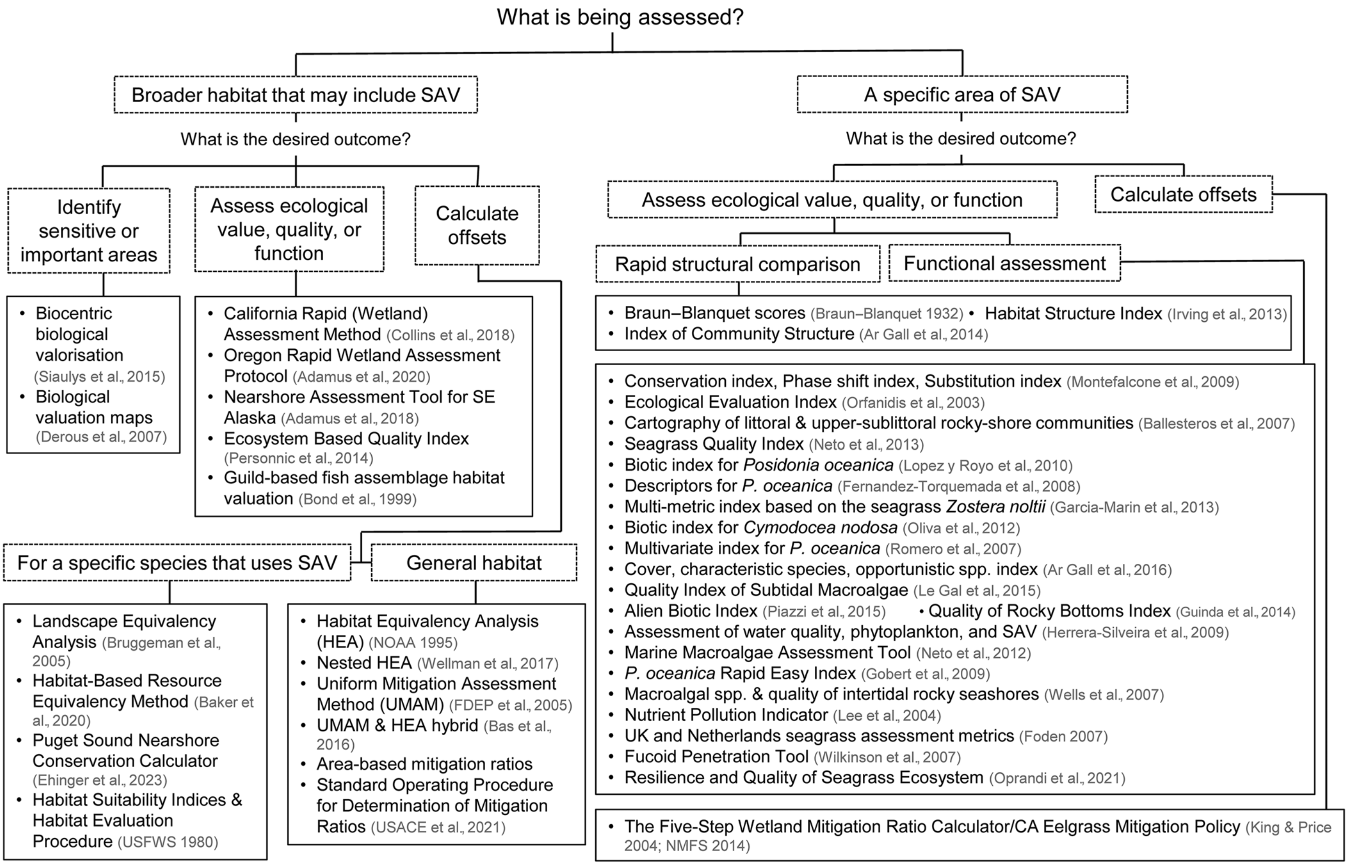

FIGURE 2 Flowchart to identify tools for specific management needs related to the assessment of specific submerged aquatic vegetation (SAV), broader habitat, such as wetlands, or specific species' habitats (e.g., salmonids). Additional details on the tools are available in the Supporting Information. In most cases, the tools to calculate offsets for broader habitats could be applied to SAV (e.g., seagrass or kelp beds).

(Terrell & Carpenter, 1997), likely because the US Fish and Wildlife Service implements the tool for managing endangered species.

The Water Framework Directive and the Marine Strategy Framework Directive, which guide the EU's goal toward coastal ecological quality objectives, have resulted in the development of ecological quality ratios (EQRs) (Gamito, 2008) for seagrass and macroalgae species. Like HSIs, the 17 EQR tools we identified assigned a score from 0 to 1, with the denominator most commonly a reference site. Additional monitoring programs in which this framework was used were referenced in the literature (D'Archino & Piazzi, 2021; Neto et al., 2015), although we did not always find specific documents describing the origin of those tools (Marbà et al., 2013).

Other tools

Nineteen tools remained and were grouped in a diverse other category. Valuation tools in this category included the Braun–Blanquet scoring method for seagrass (modified from Braun-Blanquet [1932]) and the California Rapid Assessment Method (Collins & Stein, 2018), which considers SAV presence when calculating the patch structure richness of a particular wetland assessment area. The simplest method we identified was an area-based mitigation ratio to calculate equivalency, in which an area of required mitigation was presented as a multiple of the area affected. Within this category, mitigation ratios could be an output either for tools specifically calculating equivalency based on area or for tools that incorporate valuation as well. All of the tools are listed in Figure 2 and Appendix S1.

Types of tools and origins

Ninety-one percent of our tools ($n = 43$) included a valuation component, and 23% had some sort of equivalency analysis ($n = 11$). There were tools that included both, such as the Puget Sound Nearshore Conservation Calculator (Ehinger et al., 2023), which used its own model to value nearshore salmonid habitat based on SAV density and other landscape attributes and fed the values into an HEA-based debit and credit calculator. Forty-three percent of tools ($n = 20$) were authored by a member of a regulatory agency or government research group, and 49% ($n = 23$) had first authors primarily affiliated with academic institutions. 89% of total tools ($n = 42$) acknowledged a natural resource-related government policy (Appendix S1) or source of funding. Nine percent of tools ($n = 4$) were written or developed by consultants, but, in each case, the tool was affiliated with a resource management agency.

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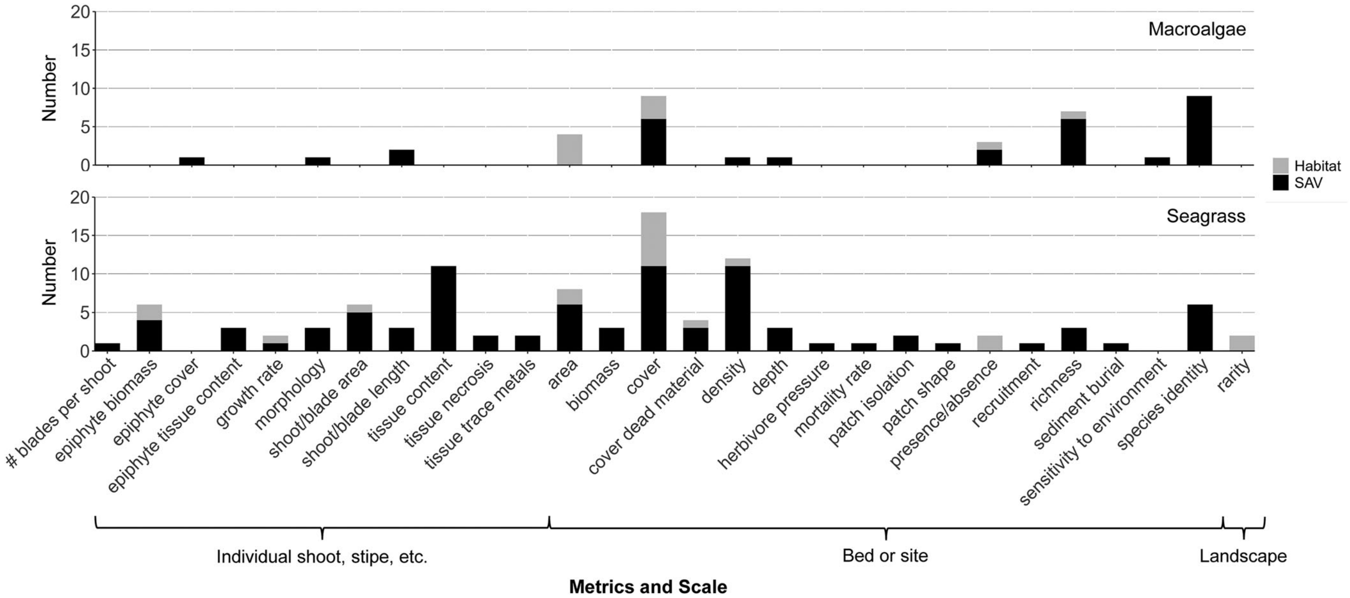

FIGURE 3 Number of submerged aquatic vegetation metrics used in broader habitat-wide (e.g., estuary and non-SAV species tools) and SAV-specific tools (top, macroalgae; bottom, seagrass; gray, ecosystem metrics; black, SAV metrics). Spatial scale of metrics is indicated at the bottom (individual, bed or site, landscape scale).

Common SAV metrics

There were notably fewer tools adapted for kelp than seagrass and other macroalgae. Tools that could be used for kelp and other algae were most frequently based on some combination of cover, species richness, or area; many tools also included indicator species metrics. These indicator species were sometimes related to their role in community succession. Cover and density (most commonly shoot, i.e., turion, density of seagrass) were the most common metric inputs into seagrass and habitat tools; area was also common (Figure 3). Tissue content (i.e., carbon, nitrogen, etc.) and species identity (i.e., use of indicator species) were also frequent metrics for seagrass. These were primarily used in the EU EQR tools to assess system health. Seagrass metrics utilized a variety of spatial scales, ranging from sampling individual blades for tissue content, epiphytes, or morphology to site-scale metrics that sampled along transects and described larger areas. Although some tools included landscape-scale inputs, the only metric that related directly to some aspect of SAV was regional rarity.

The number of SAV-specific metrics, meaning some aspect of SAV was measured (e.g., cover), rather than a broader site metric (e.g., wave exposure), varied across tools (Figure 4). Seventy percent of tools with defined SAV inputs used 3 or fewer SAV metrics, but the EQR tools contained up to 13 inputs that varied in spatial scale (Figure 4).

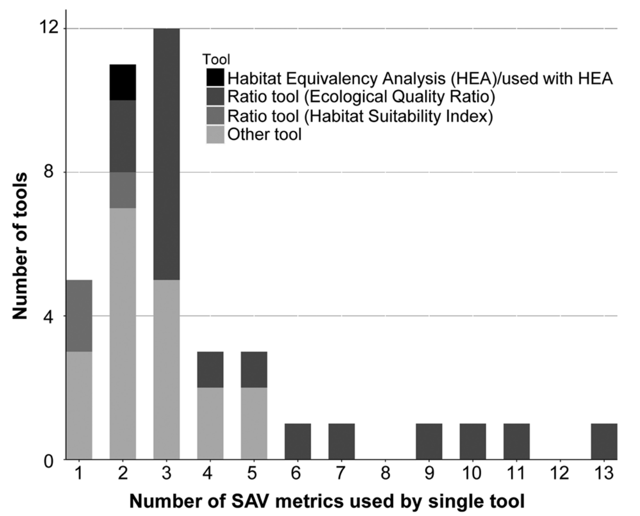

FIGURE 4 Number of submerged aquatic vegetation (SAV) metrics used in assessment tools in major tool categories.

Temporal and regional context

Perhaps due to widespread prioritization of ease of implementation and minimal sampling, tools that incorporated repeated measurements or metrics over time were rare (9%). Repeated measurements included in tools did not specifically relate to SAV metrics; rather, they pertained to other parameters in broader habitat tools that could be collected quickly or remotely. For example, the brown (*Penaeus aztecus*) and white shrimp (*Penaeus setiferus*) HSI (Smith et al., 2010; Turner & Brody, 1983) used mean water temperature over time. Although rare, there were instances of repeated, field-collected data. Bond et al. (1999) developed a method for estimating fish habitat value, including rocky reefs with kelp beds, by using fish density, fidelity, and mean fish size across multiple time points. One study factored change in seagrass cover over time (Herrera-Silveira & Morales-Ojeda, 2009).

Reference sites or conditions were used in half of the tools (51%). Reference conditions provided the highest possible score for EQRs, where another measured site would be presented as a proportion in relation to that reference site. The HSIs also presented scores from 0 to 1. In some cases, a score of 1 represented conditions at a reference site, but in other tools, a score of 1 was an amalgamation of ideal conditions based on various studies for the focal species.

Fifty-seven percent ($n = 27$) of tools were developed using metrics or weightings designed for a specific region. Although their framework can be used as a template for application in other areas, this limits their direct use to an extremely small area. Thirty-four percent ($n = 16$) of the tools included some sort of broad landscape or seascape context, either noting nearby geographic features and connectivity, or the regional rarity of a habitat. *Regional* was defined differently for different tools; for example, it was used to refer to a regulatory district or a physical boundary (e.g., a watershed).

Additional tool attributes

Any given tool's ease of implementation was generally correlated with the number of SAV and broader habitat parameters measured. Habitat metrics included salinity, temperature, and densities or attributes of other species' populations in the area. Eleven percent ($n = 5$) of the tools in our database utilized inputs from an existing database or mapping effort. For example, the nearshore assessment tool for southeast Alaska (USA; Adamus & Harris, 2018) uses the NOAA ShoreZone Program's mapping inventory (Harper & Morris, 2014) for inputs of wave exposure and beach slope.

Overall, tools meant for rapid assessment utilized in situ sampling that could be completed in less than a day and credits and debits that could be calculated using a published framework or spreadsheet. Although some methods were rapid, 81% of tools ($n = 38$) required moderate or advanced user knowledge of biological surveying or a working knowledge of a user interface, usually translating to a professional with some knowledge of regional databases, maps, spreadsheet software, and field survey methods. Other methods, such as mitigation ratios, were much more straightforward, only requiring a measure of the project area. Some complex tools (13% of total tools) had accompanying templates, spreadsheets, or interfaces to simplify the user experience. However, some tools were considered complex due to the intensive laboratory analysis required (e.g., isotope or chemistry data).

Thirty-six percent ($n = 4$ out of 11) of equivalency tools included adjustments for uncertainty in assigning required mitigation, which often included relying on best professional judgment to score the level of uncertainty.

DISCUSSION

The majority of habitat quantification tools we identified commonly included measures of cover, density, and area metrics, and, in cases of tools driven by EU habitat quality policy, indicator macroalgal species (for rocky intertidal species, rather than canopy-forming kelps), macroalgal species richness, and seagrass tissue content metrics. Our review highlights the differences driven by specific policies and intended uses, including whether a tool focused on broader habitat value or specifically evaluated areas of SAV, and the variety of metrics used.

Strengths and challenges of metrics

Measures of cover, density, and area were likely most common due to their ubiquity across SAV species, relative ease of analysis, and perceived ability to standardize these measures when collected under specific protocols (Wood & Lavery, 2000). Although a full discussion of the nexus between these common metrics and ecosystem function is outside the scope of this review, in practice our identified tools commonly assumed high cover and density of specific species of seagrasses and macroalgae positively correlated with ecosystem functioning. Alternatively, trophic imbalances may result in a seagrass bed with high cover and density but poor ecosystem-wide functioning. Thus, the details of this relationship warrant further research, and multitrophic monitoring should be included before conclusions can be drawn. It should be noted that the effectiveness or appropriateness of these metrics as proxies for ecosystem functioning is highly dependent on survey and statistical methods, as well as interpretation.

For permitting projects, logistically simple metrics are preferred by applicants but are less ideal for assessing complex ecosystem functions, such as carbon sequestration and nutrient cycling. Cover, area, and density are also not without their own nuance (Marshall et al., 2019). In the field, the buoyant medium of intertidal habitats presents challenges when attempting to quantify individual shoots or stipes, especially when shoots or stipes may be fully exposed and lie flat at lower tides. Area without a density measurement may be less informative of ecosystem function due to the variation in biomass a set area may encompass. Some protocols overcome this by multiplying area by cover or prescribing a density threshold. Although density may be correlated with biomass (Vieira et al., 2018), biomass is also influenced by shoot or stipe height and life stage. Integrating density and height can provide more accurate estimations of habitat structure, which is correlated with overall habitat function. Tools would benefit from explicit descriptions of how to survey habitat metrics. The California Eelgrass Mitigation Policy (CEMP) presents a strong example of specific survey standards (NMFS, 2014).

Although some of our identified tools relied on a single SAV indicator, usually as a way to assess broader habitat, most of the valuation tools integrated multiple metrics into a single indicator or value that could then be used with an equivalency tool. We also noted examples of multiple metrics that fed directly into an equivalency tool without first being combined. Baker et al.'s (2020) habitat-based resource equivalency method used multiple metrics to produce multiple calculations of an injury (i.e., impact). However, only the mitigation that compensated for the largest injury, or slowest to recover, was then used as the required mitigation action. This limiting factor approach allows for comparison across many metrics but uses only one that theoretically encompasses the mitigation of many functions lost, minimizing the uncertainty in undetected impacts. However, the field would benefit from further investigation of the relationship between metrics and ecosystem function.

Addressing uncertainty

A challenge with equivalency assessments, in practice, is the uncertainty surrounding restored habitat performance. There are multiple sources of uncertainty associated with habitat quantification tools and the compensatory mitigation process: uncertainty that the habitat functions quantified and accounted for, including the reference sites, are the most ecologically relevant and important to model and mitigate; uncertainty in accurately quantifying change in habitat value or equivalency when following and violating the assumptions of the tool; uncertainty in the performance or functioning of the mitigation action (e.g., restoration); and uncertainty in calculating how much area or which mitigation action is needed to compensate for the impact (due to the previous sources of uncertainty).

We discussed the first of these sources of uncertainty (connecting metrics to function) and suggest this as an area in need of further research. The second source of uncertainty relates to quantifying impact and mitigation when the assumptions of a valuation tool are violated. Many tools from our database listed tool assumptions, whereas others made implicit assumptions that were not specifically articulated. Ample documentation exists for the assumptions of HEA: the type and quality of affected and restored services need to be similar, the value of affected and restored services is assumed to be constant over the assessed time, and affected services should be limited to relatively marginal changes in ecosystem function (Desvousges et al., 2018; Dunford et al., 2004, 2019; English et al., 2009; Ray, 2009; Shaw & Wlodarz, 2013; Strange et al., 2002). These assumptions are not always met in applications of HEA. However, imperfect use of an established framework may be preferred over decisions made solely on best professional judgment.

Many of the tools we identified, although not all, relied on the assumption that restoration function will operate at the expected capacity within a certain time horizon. However, restoration is rarely successful without continued monitoring and subsequent remediation measures for underperformance (Beheshti & Ward, 2021; Eger et al., 2022). The failure of an area to support recruitment or biomass at the calculated capacity has been observed across SAV types, including seagrass (Bayraktarov et al., 2016) and restored kelp reefs (Reed et al., 2004). A common assumption is the linear recovery of an affected site or increase in performance of a mitigated site. Linear recovery is rarely the case (Fong, 2015). However, King and Price (2004) showed that the shape of the recovery curve is less important than the estimation of time to restore full functioning habitat, provided additional manipulation of the mitigation site is not implemented in response before this time horizon is reached.

To buffer against multiple sources of uncertainty, many regulators utilize mitigation ratios higher than 1:1 for mitigation:impact. Pilot studies and reviews of past projects were used to calculate a percent likelihood of mitigation failure for different regions in the CEMP. The CEMP utilized this percent likelihood of failure metric within the underlying mitigation calculator tool (King & Price, 2004) to generate a higher starting mitigation ratio (as high as 4.82:1 in northern California, United States) to provide greater assurances that the ultimate performance requirement (i.e., standard mitigation requirement is 1.2:1) is achieved. Uncertainty analyses can also be incorporated into models (Zajac et al., 2015) to increase the probability of providing sufficient mitigation.

A small percentage of the tools we identified included some sort of uncertainty factor addressing one of these above sources in their calculations. The uniform mitigation assessment method (FDEP, 2020; Levrel et al., 2012; Stantec, 2016) and its hybrids (Bas et al., 2016) included a risk factor for the failure of mitigation actions. This risk factor was chosen by the user and ranged from 1 to 3, encompassing multiple sources of uncertainty, from time to completion and restoration method. The 5-step wetland mitigation ratio calculator (King & Price, 2004), which was adapted for seagrass in CEMP (NMFS, 2014), permitted adjustments in input parameters based on differences in landscape context between the impact and mitigation areas. The USACE standard operating procedure for determining mitigation ratios allowed for a mitigation ratio adjustment to account for mitigation failure or underperformance due to permittee-responsible mitigation (rather than mitigation banks), modified or artificial hydrology, difficult to replace resources, and more (USACE, 2016, 2021). Ratio adjustment factors ranged from +0.1 to +0.3, resulting in a sum that included multiple sources of uncertainty.

Another source of uncertainty in compensatory mitigation arises through out-of-kind mitigation, that is, when an impact is mitigated for using a different habitat type. For example, this may include the restoration of a rocky reef for impacts to soft bottom habitat. The CEMP calculator (King & Price, 2004; NMFS, 2014), HEP (USFWS, 1980), and USACE mitigation ratio checklist (USACE, 2021) all provide options to adjust mitigation amounts due to out-of-kind mitigation. Of course, ensuring equivalency relies on sound habitat valuation tools in conjunction with rigorous monitoring and compliance efforts (Hough & Harrington, 2019; Race & Fonseca, 1996). Adequate remediation and performance criteria attention relies on proper funding and resource allocation to compliance and enforcement divisions of regulatory agencies. Out-of-kind mitigation conversions and changes in related functioning warrant further research.

Addressing variability in impacts and mitigation over time

The spatially and temporally dynamic nature of some SAV species poses a challenge to quantifying impact and appropriate mitigation. The edges of seagrass meadows may migrate up to tens of meters annually (Munsch et al., 2023), suggesting that currently unoccupied habitat near an existing bed should also be acknowledged in mitigation plans. Rhizomatic growth in seagrasses and shifting substrates with SAV can complicate mapping efforts, as well as lead to patchiness and landscape heterogeneity that should be acknowledged in tools. The ecological value of small-perimeter benthic patches of seagrass versus larger patches is not fully understood. Although resistance to invasion and patch stability has been shown to increase with kelp and seagrass patch size (Cunha & Santos, 2009; Layton et al., 2019; Reeves et al., 2022), small patches facilitate connectivity and can help recover areas of dieback (Greve et al., 2005).

Temporal variability also exists due to some SAV's annual growth cycles and vulnerability to extreme events, such as storms and marine heatwaves (Hamilton et al., 2022). Consequently, most regulators assign specific time periods for surveying to minimize seasonal variability across years (Calloway et al., 2020; NMFS, 2014). Both broader habitat and SAV-specific tools commonly defined preferred SAV survey times during the summer growing season to capture the maximum extent of distribution and allow for interannual comparison of surveys. For instance, the CEMP (NMFS, 2014) recommended surveys be done during the spring and summer growing season. Similarly, a methodology based on the cartography of littoral and upper-sublittoral rocky-shore communities (CARLIT; Ballesteros et al., 2007) specified an April–June timeframe. Biological value map scores (Derous et al., 2007) were calculated based on population maximums throughout the year. Annual surveying across multiple spatial scales can help detect changes in both perennial and annual populations. Tools with documentation of specific survey protocols provide a better context for the assumptions of their outputs.

Metric choice is relevant for accurate determination of the response time to impact and restoration. Beheshti and Ward (2021) and Roca et al. (2016) found varying timelines of seagrass response to stressors and recovery, and varying degrees of response across types of indicators. For instance, physiological measures responded less to stressors than structural and demographic indicators. However, physiological measures were much faster to show indications of recovery than demographics. Of course, the rate of change across metrics can vary across species and stressors (Han et al., 2016); thus, metric selection could influence calculations of impact and mitigation if not planned for in advance.

Time may be incorporated into equivalency assessments differently depending on the method and nature of impact. Time can be included by considering the duration of the impact (e.g., the lifespan of a structure); time until full recovery from an impact or the time for initial mitigation action to reach full functioning; duration of mitigation (usually incorporated via monitoring requirements); delay between impact and mitigation; or a discounting factor to adjust debits and credits for present and future value. The HEA-related tools most commonly addressed these factors. Although HEA poses some challenges in its application (Desvousges et al., 2018), there is precedent for its use in courts and across agencies. Other equivalency methods, such as the USACE checklist (USACE, 2021), increased mitigation ratios based on the number of months full functioning of the mitigation was delayed. The CEMP also included factors for discounting, the time between impact and start of mitigation, and time until full functioning was achieved. This consideration of time itself, rather than just the temporal fluctuations of a system, can be important to achieve fully compensatory mitigation.

Regional and landscape or seascape considerations

In addition to temporal changes, nearshore SAV habitat functions can be affected by site- and landscape-scale factors. Protected areas, such as pocket estuaries, can increase growth and survival in juvenile salmonids (Beamer et al., 2003; Hodgson et al., 2020). Function of SAV is also affected by landscape (or for subtidal SAV, seascape) context, supporting higher diversity when included in a connected mosaic of various habitats (McAfee et al., 2022; Olds et al., 2016). Terrestrial influences and connectivity between areas may also influence ecological value (Yeager et al., 2020). For example, a culvert limiting fish access to a stream or proximity to a sewer outfall would reduce value. Landscape context can also highlight SAV rarity. For example, the sole eelgrass habitat in a bay may serve as the only herring spawning habitat, thus increasing its importance.

A portion of the identified tools addressed regional considerations by including an input for landscape or seascape context, which can refer to the spatial arrangement of habitats (Henderson et al., 2017) and connectivity with other non-SAV areas (Swadling et al., 2019). Some tools included population connectivity or special weighting or scoring for areas near key features, such as pocket or natal estuaries for salmonids (Puget Sound Nearshore Conservation Calculator; Ehinger et al., 2023). In other cases, and related directly to SAV rather than the broader habitat, the tool incorporated a metric for rarity of a habitat by looking at regional occurrences of the same habitat (e.g., biological valuation map tool; Derous et al., 2007). The USACE mitigation ratio checklist (USACE, 2021) equivalency tool allowed for lower mitigation ratios to be used when a mitigation action converted a more common habitat type to a rarer and ecologically more valuable habitat.

Many of the valuation tools we identified were procedures specific to certain regions and policy frameworks. Figure 2 shows tools sorted by management scenario, but some valuation tools were highly specialized for certain regions or used specific indicator species metrics and are more useful as examples rather than immediately applicable to all areas. Meanwhile, equivalency methods were geographically broad, with a few notable exceptions (e.g., the region-specific planting ratios of CEMP) but could be used with more region-specific valuation. This diversity in site geographies and policies presents a barrier for the widespread use of specialized methods, but general nearshore frameworks, many of which originated from North America and Europe (also see Droste et al. [2022]), have been and can continue to be incorporated or adapted (Alavian et al., 2018; Kim et al., 2017) into region-specific tools.

Regulatory mandates and tool framing and inputs

Just over half of the tools we identified were written or commissioned by government agencies to serve specific regulatory needs associated with the protection and conservation of managed species and their habitats. Many of the remaining tools developed by academic institutions, especially from the European Union, were written to directly meet the requirements of the Water Framework Directive or Marine Strategy Framework Directive, which sets aquatic and nearshore marine resource standards. This significant policy influence over tool design specifications can shape tool outputs and may limit utility across agencies. For example, HSIs are commonly used to manage listed species that utilize SAV. Although they may comprehensively guide decisions concerning a single species, they may not be the right tool for an agency more holistically concerned with a larger ecosystem. The fact that tools and metrics may be selected to address regulatory missions also highlights the importance of strong policy design that identifies tangible, measurable goals reflective of ecosystem functioning.

There is increasing manager and regulator interest in tools that assess habitat at the seascape or ecosystem scale (e.g., ecosystem-based modeling approaches [Pittman et al., 2021]). This broader assessment approach is usually achieved by incorporating multiple abiotic and biotic attributes, such as oceanographic conditions and multitrophic interactions. More research is needed to identify the trade-offs that come with assessing specific areas, communities, or species with broader ecosystem tools that are more holistic versus tools with a more specific or narrow focus. The utility of broader models may be driven by regulatory mandates. Those tasked with monitoring smaller areas (e.g., a local seagrass mitigation area and reference site) or a single species might find tools with focused metrics, such as many of the tools identified in our study, more useful. Alternatively, those tasked with managing species that utilize a variety of habitats (e.g., salmonids) or place-based managers (e.g., marine protected areas or multispecies fisheries [Thorson, 2019]) may benefit from the broader habitat tools or ecosystem-based models with a suite of input criteria. These more complex models necessarily require more diverse source data to adequately parameterize, potentially making the cost of developing, or adapting, a tool prohibitive or inadvisable despite the desire to employ it.

Some tools relied on best professional judgment not only to choose or weight specific metrics in the tool design, but also to adjust ratios or other model outputs depending on a variety of factors (e.g., habitat rarity, out-of-kind mitigation). Those adjustments, while bounded, were often left to project managers or analysts. Best professional judgment, while sometimes the only resource available for final management decisions, can lead to varying interpretations across professionals (Murray et al., 2016). This allows for mitigation decisions to incorporate unique details of the project but can also lead to inconsistent decisions and project applicants being unable to estimate mitigation requirements at the start of projects, effectively slowing the compensatory mitigation process (Kihslinger et al., 2020). However, well-documented best professional judgment decisions informing overall tool design, including metric selection and weightings, can enhance consistency as compared to reliance on best professional judgment for every habitat evaluation or mitigation decision. In either case, carefully documenting the justifications for how metrics are selected, weighted, and used in tool calculations can ameliorate the lack of transparency as well as inconsistencies between different tools (Mancini et al., 2020), but this can also add considerable time to the decision timeline.

Looking forward

No tool is perfect, but if targeted to address the question at hand, such methods can help resource managers make decisions when faced with incomplete information. We identified the following strengths in tools from our database that could be incorporated into new or existing methods: clear description of the tool's goal, objective, and scale; clear description of the ideal or highest scoring habitat attributes, or guidance on reference site selection; detailed monitoring protocols that include best practices for survey conditions (time of year, tidal considerations, etc.); description of tool assumptions and consequences of assumption violations; transparency in weighting of metrics in valuation (i.e., if best professional judgment was used, description of logic behind weightings); options for metric inputs over time to capture temporal variation; landscape or seascape context, region-specific, or both features; and incorporation or adjustments for sources of uncertainty.

For practical application, the ideal tool will depend greatly on the goal of the project, the scale of interest, the best science available to inform that goal, and all relevant regulations motivating the tool use. Tool refinement will also depend on continued research connecting metrics and tools to ecosystem functioning within these unique systems.

When not based on reference systems, HSIs relied on identifying optimal conditions. If tools do not rely on reference conditions and, rather, choose predetermined optimal values, there is a continued need to identify those ranges and provide the context under which they may occur. There is also a need for identifying thresholds that will play key roles in determining habitat changes resulting from anthropogenic climate change. Assigning mitigation should also include possible climate impacts that may influence the success of restoration or habitat quality in the future (Abelson et al., 2020).

Our review of the habitat quantification literature revealed a large gap in canopy-forming kelp valuation (see also, e.g., Lefcheck et al., 2019) versus available tools for rocky intertidal macroalgae and seagrass. With an increasing shift toward large-scale monitoring with aerial and satellite imagery (Finger et al., 2021; McPherson & Kudela, 2022) and sonar technologies (Phinn et al., 2018), additional research connecting bed and canopy cover, other metrics, or valuation scores to SAV functioning is also needed. However, basing value on just a few surface metrics may overlook important subcanopy and other community measurements.

We excluded tools that economically valued SAV, but there is a wealth of tools based on nonmarket valuation and examining the value of ecosystem services, or functions, that directly benefit human society. In the 1980s and early 1990s, impacts to the environment were commonly assessed with methods to elucidate revealed preferences, which attempted to quantify how much money one was willing to pay to use or travel to a resource (Boyer & Polasky, 2004). Some of these methods were replaced by HEA (NOAA, 2000), but this should not discount the importance of including socioeconomic impacts in injury and mitigation determinations (Unsworth et al., 2019; van Teeffelen et al., 2014). Future research should be aimed at methods that include socioeconomic factors as well as ecosystem-level functioning.

Although we identified over 29 SAV metrics, further research is needed to connect metrics and habitat functioning to guide metric selection. Identifying metrics that can be measured rapidly and easily by consultants or agency staff and predictably relate to habitat functioning will be integral in identifying feasible and ecologically meaningful tools moving forward. A region-specific understanding of the relationship between metrics and an area's ecological value will continue to refine how SAV, including systems that support managed species, can be valued.

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