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EVALUATING COASTAL HABITAT VALUE THROUGH METRICS OF ECOSYSTEM FUNCTION FOR USE IN HABITAT RESTORATION

by

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ABSTRACT

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Habitat restoration plays a key role in maintaining the ecological integrity of coastal ecosystems, particularly with increasing natural and anthropogenic threats to ecosystem health. The scaling of restoration efforts in response to habitat damage has traditionally focused on replacing lost habitat area. However, there is increasing recognition of the importance of restoring functionally equivalent habitat. This necessitates the use of quantitative metrics of ecosystem function to determine relative habitat values, assess restoration options, scale restoration efforts, and evaluate success or failure. This paper reviews the metrics used to describe ecosystem functions in common coastal habitats (macrophyte, bivalve reef, hard substrate, soft sediment). Habitat Equivalency Analysis (HEA) and its applicability within the Fisheries Protection Provisions (FPP) is discussed, and the implications of metric selection on each step of the restoration process are explored. Important uncertainties and knowledge gaps pertaining to metrics and their use within restoration practices were noted. The literature survey identified a recommended approach to metric selection and quantitative restoration scaling similar to the HEA framework. The selected metric should a) integrate multiple ecosystem-level functions, b) be applicable to multiple habitat types, c) be measurable from baseline or reference conditions, and d) be applicable in each step of habitat restoration from habitat valuation to restoration monitoring. Metrics representing biological production at one or more trophic levels best meet these criteria. Future restoration efforts should be scaled based on relative habitat value as determined by production, with appropriate consideration of the implications and input from expert judgment to guide metric selection. Focus on comprehensive, flexible, quantitative metrics of ecosystem function could greatly improve the effectiveness of coastal habitat restoration in Canada, and is compatible with the evolving policies within the FPP that aim to replace lost fisheries production through habitat restoration.

RÉSUMÉ

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La restauration de l'habitat joue un rôle clé dans la conservation de l'intégrité écologique des écosystèmes côtiers, particulièrement face à l'augmentation des menaces d'origine naturelle ou anthropique pour la santé des écosystèmes. La mise à l'échelle des efforts de restauration entrepris en réponse à la dégradation de l'habitat a traditionnellement mis l'accent sur le remplacement des zones d'habitat qui ont été perdues. Cependant, on reconnaît de plus en plus l'importance de restaurer des habitats aux fonctions équivalentes, ce qui nécessite l'utilisation de mesures quantitatives des fonctions des écosystèmes pour déterminer les valeurs relatives de l'habitat, d'estimer les options de restauration, de mettre à l'échelle les efforts de restauration et d'évaluer le succès ou l'échec. Le présent document examine les mesures utilisées pour décrire les fonctions des écosystèmes dans les habitats côtiers communs (macrophytes, récifs de bivalves, substrats durs, sédiments mous). Les méthodes actuelles de mise à l'échelle des efforts de restauration de Pêches et Océans Canada (MPO) ont été comparées à l'approche d'analyse des habitats équivalents basée sur les fonctions, et les répercussions du choix des mesures sur chaque étape de la restauration ont été étudiées. D'importantes incertitudes et lacunes dans les connaissances ont également été notées. L'étude documentaire a déterminé une approche recommandée de la sélection des mesures et de la mise à l'échelle de la restauration quantitative similaire au cadre de l'analyse des habitats équivalents. La mesure sélectionnée doit a) prendre en compte de nombreuses fonctions au niveau des écosystèmes, b) être applicable à plusieurs types d'habitats, c) être mesurable à partir de l'état de référence, d) être applicable à chaque étape de la restauration de l'habitat, c'est-à-dire de l'évaluation de l'habitat jusqu'à la surveillance de la restauration. Les mesures représentant la production biologique à un ou plusieurs niveaux trophiques sont celles qui satisfont le mieux à ces critères. Les efforts de restauration futurs doivent être mis à l'échelle selon les valeurs de l'habitat relatives déterminées par production, en tenant compte comme il se doit des répercussions et des commentaires provenant d'avis d'experts pour orienter le choix des mesures. Le fait de mettre l'accent sur les mesures exhaustives, souples et quantitatives des fonctions des écosystèmes pourrait grandement améliorer l'efficacité de la restauration des habitats côtiers au Canada et cette pratique serait compatible avec les récentes modifications apportées à la politique canadienne visant à remplacer la perte de production halieutique grâce à la restauration de l'habitat.

INTRODUCTION

The value of healthy marine ecosystems to human well-being is increasingly being recognized, especially given increasing pressures on coastal environments worldwide (Costanza et al. 1997, MEA 2005, Lotze et al. 2006, Worm et al. 2006, Barbier et al. 2011). Coastal marine habitats provide valuable ecosystem services such as fisheries production, shoreline protection, and nutrient cycling, which contribute greatly to the health and economies of coastal populations (Barbier et al. 2011). Increasing anthropogenic stressors associated with climate change, pollution, and coastal development have caused widespread degradation of the marine environment, and threaten to further damage the provision of critical ecosystem services if not addressed. Growing coastal populations and the increasing rapidity of changes lend a sense of urgency to the protection and restoration of lost ecosystem services and function in order to maintain ecological integrity.

Habitat restoration plays an important role in coastal management through the elevation of lost ecosystem services and functions by creating or enhancing high-value habitat. Restoration is often conducted as compensatory mitigation, where damage to ecosystem services and functions at one location is compensated for by the creation or enhancement of services and functions at a second location. Variations of this approach are widely used in many countries, including Canada (Harper and Quigley 2005) and the United States (Dunford et al. 2004, Levrel et al. 2012). However, successful restoration requires knowledge of habitat value to quantitatively determine the extent of services or functions lost and the scale of compensation required to replace the lost services. To accomplish this goal there is a strong need for quantitative and robust metrics to ascribe value to marine habitats, balance losses and gains, and evaluate restoration activities through monitoring.

Application of the ecosystem services paradigm to habitat restoration involves aspects of both ecology and economics (Figure 1). Ecosystem structure is defined as the composition (e.g., flora, fauna, substrate) and organization (e.g., trophic interactions) of ecosystem components, while ecosystem function represents the mechanistic processes that occur among system components (e.g., primary production) (NRC 2005). Ecosystem structure and function combine to provide goods and services that offer value to humans. Several ecosystem functions can contribute to a single ecosystem service, and several services can be provided by a single ecosystem or habitat type. For example, seagrass plants provide various services including wave attenuation and carbon storage; these services are produced through ecosystem functions such as primary production, nutrient cycling, and habitat formation.

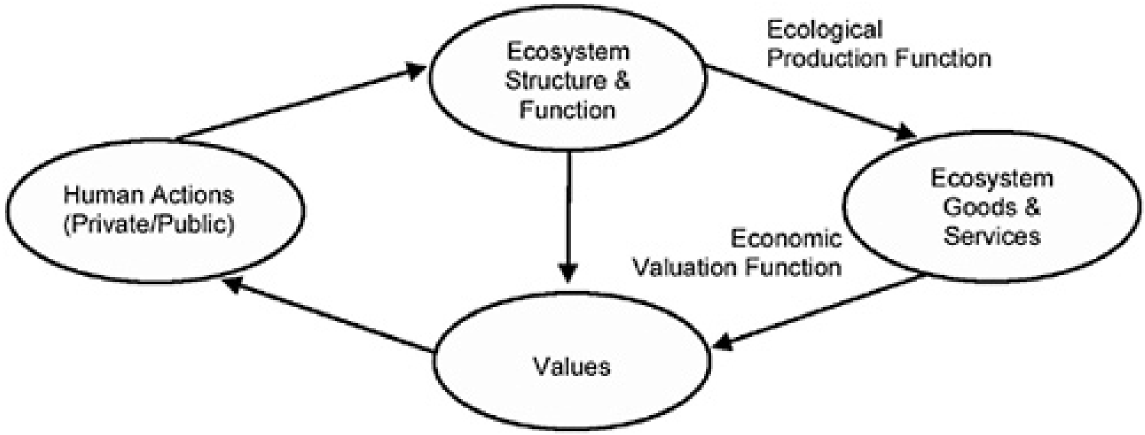

Figure 1. Conceptual schematic of the components involved in ecosystem services quantification and evaluation. From NRC (2005).

Much research and discussion has focused on the economic valuation of ecosystem services, that is, estimating the monetary value of the benefit to human well-being (Costanza et al. 1997, NRC 2005, Barbier et al. 2011). This is a very difficult task, as many different stakeholders derive benefits from marine ecosystems, and often have competing interests. These economic discussions, though important, are beyond the scope of this document.

HABITAT RESTORATION IN CANADA

Until 2012, standard practice of habitat compensation in Canada as mandated by the Federal Fisheries Act (1985) and Habitat Policy (DFO 1986) was to ensure "no net loss" of fish habitat (DFO 2002). Amendments in 2012 to the Fisheries Act had important implications for habitat compensation. The amendments include the Fisheries Protection Provisions (FPP), whose purpose (section 6.1) provides for the "sustainability and ongoing productivity of commercial, recreational, or aboriginal (CRA) fisheries". The prohibition of the FPP (section 35) is that "no person shall carry on any work, undertaking, or activity that results in serious harm to fish that are part of a CRA fishery, or to fish that support such a fisheries", where "serious harm" is defined as "the death of fish or any permanent alteration to, or destruction of, fish habitat". With these amendments, focus has shifted from compensation of lost habitat to compensation of lost CRA fisheries productivity. Despite this change, restoration of damaged or lost habitat will continue to be initiated when it is determined that damage or destruction of supporting fish habitat has caused reduced productivity of CRA fisheries. Thus, identification and discussion of metrics related to habitat value and quality remain relevant within the FPP framework. Discussion of metrics that can be used to directly measure CRA fish productivity is provided by Kerckhove et al. (2013).

When serious harm to CRA fisheries production results from damage or destruction to fish habitat, proponents may be mandated to restore or create habitat to compensate for these loses. A hierarchy of compensation options have been used in the past (Figure 2), and will continue to be useful for habitat restoration under the amended Fisheries Act. The preferred option is "like-for-like" (habitat of the same type) within the same geographic area. Use of a compensation ratio > 1:1 ensures a net gain in productive capacity, accounting for uncertainty in restoration success, variance in habitat quality, and the time lag between initial restoration and full ecological functionality (Minns 2012). As one moves down the hierarchy towards less-preferred restoration options, the compensation ratio should increase.

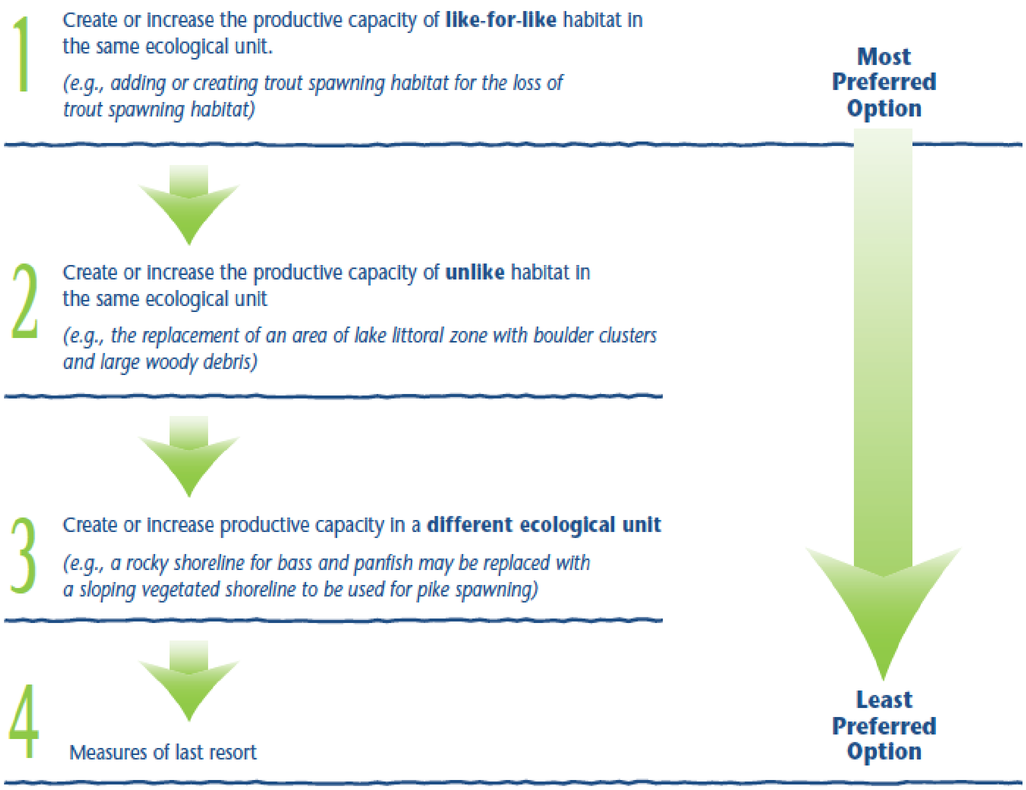

Figure 2. Hierarchy of habitat compensation activities ranked from most to least preferable (from DFO 2002). Compensation ratios are generally increased when moving down the hierarchy of preferred options.

HABITAT EQUIVALENCY ANALYSES

The primary challenge of compensation is to accurately quantify the extent of injury to the ecosystem and to estimate the scale and type of restoration required to fully compensate the damages. This is commonly addressed using Habitat Equivalency Analysis (HEA), a method widely used in the United States in response to natural resource damage (Dunford et al. 2004, NOAA 2006, EPA 2009). This framework is incorporated into the FPP, as it provides methods to account for lost CRA fisheries production that occur from both direct (e.g., destruction of fish themselves) and indirect (e.g., damage to essential supporting ecosystem components) impacts (Bradford et al. 2013, DFO 2013a).

QUANTITATIVE METRICS OF ECOSYSTEM FUNCTION

HEA (and habitat restoration in general) would greatly benefit from quantitative metrics of ecological function that allow restoration scaling on the basis of functional equivalence rather than area replacement. Despite recognition of the importance of such metrics, restoration scaling continues to be based on habitat area. This effectively reduces multiple complex ecosystem functions to a simple measure of habitat structure in terms of its composition and extent (Peterson and Lipcius 2003). Use of habitat area assumes the new habitat has the same ecological value as the old (Plummer 2009). This assumption does not always hold because of differing ecological contexts between sites. Furthermore, use of habitat area makes sense only for “like-for-like” restoration; in “like-for-unlike” restoration, lost functions may not be fully compensated if the restored habitat provides less function per unit area than the damaged habitat.

The selection of appropriate functional metrics is crucial in order to properly balance habitat compensation. Estimates of biological production in particular tend to scale with many relevant ecosystem services, providing a reasonable basis for estimating habitat equivalence (Fonseca et al. 2000, Peterson et al. 2003). For example, recent research has focused on biological production at multiple trophic levels and trophic ratios as proxies for ecosystem function (Peterson et al. 2007, Wong et al. 2011). The use of composite or multivariate metrics of ecosystem function as surrogates or proxies for ecosystem services can more accurately characterize habitat value than simple areal measures, greatly improving the effectiveness and efficiency of compensation (Viehman et al. 2009). However, there are many important considerations in selecting an appropriate metric, including the logistics of its measurement, its applicability to both damaged and restored areas, and its ability to capture all important aspects of ecosystem function (Peterson and Lipcius 2003, Dunford et al. 2004). Metric selection inevitably involves tradeoffs and assumptions that require full consideration before proceeding with restoration. Additionally, there is a demonstrable need for functional metrics that are sufficiently flexible and comprehensive for use in diverse marine habitats and applicable to each step of habitat restoration.

OBJECTIVES

The primary objective of this report is to identify, review, and investigate the application of metrics of ecosystem function for habitat restoration. While we acknowledge that implementing evolving FPP policy has it challenges, it is expected that suites of indicators will remain important and likely include secondary metrics based on habitat properties. These metrics remain valuable because they can very often be linked to fisheries production through productivity-state response curves (DFO 2013b). Our report begins by outlining a framework that balances losses and gains from damaged and restored habitats, respectively, by accounting for habitat value, spatial extent, intensity of damage and repair, and time scale. We then discuss the use of ecosystem function metrics in the restoration process, which includes assessment of relative habitat value and equivalence, the calculation of compensation ratios, and the monitoring and evaluation of restored habitats. We then present a brief outline of the ecosystem services and functions of important coastal and nearshore habitats of Atlantic Canada. Finally, we conclude with a discussion of uncertainties, knowledge gaps, and suggested new metrics. The intended outcome is to provide methods and metrics that will improve quantification of ecological function for habitat restoration within the FPP framework. These enhanced methods and tools will ensure policy compliance and evaluation of restoration success.

FRAMEWORK FOR HABITAT COMPENSATION AND RESTORATION

Restoration can be considered as a balance between negative impacts on ecological function and the positive effects of the restoration activity, while accounting for uncertainties in the success of restoration, variance in the quality of damaged and restored habitat, and time lag in service restoration. This can be represented by a conceptual equation, with negative effects of the impact ("debits") on the left, and the positive gains from restoration ("credits") on the right (Levrel et al. 2012):

Eq. 1 $$V_I A_I I(1+r)^{-tI} = V_R A_R R(1+r)^{-tR}$$

where V_I and V_R = the value of the ecosystem function impacted and restored, respectively, A_I and A_R = the habitat area impacted and restored, I and R = the intensity (relative to baseline) of the impact or restoration, r = discount rate (to account for the social rate of time preference when services are obtained), and $-t_I$ and $-t_R$ = time-scale of impact and restoration. Intensity represents the proportion of functions produced by the damaged or restored habitat relative to baseline. Discount rate reflects society's willingness to shift the obtaining of public goods (such as ecosystem services derived from ecological functions) over time and to not occur necessarily when desired. In practice, balancing the equation often requires a higher compensation ratio weighted towards restoration to account for uncertainties and ensure that lost functions are fully restored. The use of metrics of ecosystem function within Eq.1 would provide a powerful approach for restoration and compensation activities within the FPP. Metrics of ecosystem function reduce complexity by focusing on one important and easily tractable ecosystem function that is integral to multiple ecosystem services.

Generally speaking, this framework highlights the need for accurate representations of habitat value using metrics of ecological function. To utilize this framework, estimates of the following factors are required: (1) habitat value (represented by a metric of ecological function) in its baseline, pre-disturbance state, (2) habitat value in the restored state, (3) the amount of time habitat was damaged, (4) a cumulative estimate of ecosystem functions lost during this time, (5) the areal extent of habitat damaged and restored, (6) the amount of time required for restored habitat to reach full ecological function, and (7) the socially accepted discount rate. In practice, this information is not always available, and many other factors may need to be accounted for in carrying out compensatory restoration, requiring adjustment of this conceptual framework. Scientific literature and expert-based knowledge therefore play important roles for its application in different contexts when background information is limited.

USE OF METRICS DURING HABITAT COMPENSATION AND RESTORATION

The successful restoration of lost ecosystem functions using the framework described above is dependent on metrics representative of ecosystem function. These metrics are used during the five component stages of habitat restoration (adapted from NOAA 2006):

- **(i)** Assign relative habitat values based on metrics of ecosystem function;
- **(ii)** quantitatively determine what ecosystem functions have been damaged or destroyed, and over what duration;
- **(iii)** locate suitable habitat and location for restoration, and evaluate the potential viability of the restoration methods;
- **(iv)** determine how much habitat (i.e., area) needs to be replaced in order to compensate for lost ecosystem function (i.e., using HEA);
- **(v)** establish goals, measurable success criteria, indicators, and an appropriate monitoring strategy to ensure success and compliance

Quantitative metrics of ecosystem function play an important role in each step of the restoration process. These metrics provide information crucial to the design and success of restoration projects. In the following sections, the use of metrics in each of the above steps will be explored, with the relevant step noted in the section headings.

QUANTIFICATION OF HABITAT VALUE [Steps i, ii, & iii]

The first three steps of habitat compensation require the assessment of habitat value with respect to ecosystem function. Prior to any restoration activity, it is necessary to select an appropriate metric to serve as the basis for HEA. The selected metric must be measured against a baseline or reference condition, and this must be explicitly quantified, with particular implications for HEA and restoration monitoring (as will be discussed below; Dunford et al. 2004). Metrics can either directly or indirectly measure ecological function, contributing to or representing one or more ecosystem service. The selected metric must be flexible and responsive to site variability of the same habitat (e.g., between patchy and continuous seagrass beds). Clearly, some metrics can only be measured in the context of a specific habitat (e.g., seagrass growth rate) and would be meaningless applied elsewhere. For this reason, metrics representing ecosystem-scale functions tend to have broader applicability in multiple contexts and are most appropriate. For example, metrics of biological production, such as secondary production, integrate across environmental parameters, can be measured in any habitat type, and represent potential energy transfer at the ecosystem level. Metrics may require additional conversion factors for comparing different habitat types in HEA, as will be discussed below (step iv). Many of the metrics useful in determining habitat value can also be applied to monitoring and evaluation of success (step v); to maintain continuity through the restoration process, flexible and comprehensive metrics applicable to each step are preferable to habitat-specific metrics in most cases.

Broadly speaking, metrics tend to represent either biotic or abiotic components of ecosystem structure or function, though many representative metrics integrate both biological and physical aspects as indicators of holistic ecosystem function. There are at least as many potential metrics as there are ecological functions, though many are inapplicable in the context of HEA and habitat restoration. Metrics can represent either individual components of ecosystem function (e.g., seagrass growth rate), or encompass multiple aspects of the habitat and organism physiology (e.g., secondary productivity). The FPP focus on CRA fisheries production narrows the potential metrics to measures that either directly relate to fish production (e.g., recruitment rate, redd density) or those that can be indirectly linked through productivity-state response curves (e.g., habitat structure, prey productivity). Notably, this approach excludes the value of other potentially important ecosystem services such as shoreline protection and tourism.

Metrics of ecosystem function

Biological metrics of ecological function can be representative characteristics of individual species, organism communities, single trophic levels, or multiple trophic levels, and are summarized in the following sections:

Single-species metrics: Single-species fish metrics include measures of habitat utilization, recruitment, biomass, abundance, and density for multiple ages and life history stages (Peterson et al. 2003, de Kerckhove 2013). These metrics will be the primary focus of offsetting activities within the FPP framework. Fish metrics will be derived for fish species important for CRA fisheries, and for those species that indirectly support CRA fisheries as prey (i.e., forage fish). In addition to fish, similar single-species metrics can be calculated for other mobile species such as pelagic or benthic invertebrates. Single-species metrics may also be used to describe structural aspects of the habitats themselves, as in the case of biogenic macrophyte (e.g., growth rate, density) and bivalve (e.g., growth rate, filtration rate) habitats.

Metrics of organism communities: An alternative approach to single-species metrics is to quantify attributes of groups of species. Univariate measures of biological communities include species richness, evenness, and diversity (Minns et al. 1994, de Kerckhove 2013), as well as biotic indices such as AMBI (Borja et al. 2000). These metrics can be calculated for whole communities or for certain taxonomic groupings (e.g., pelagic or benthic fishes, epifauna, or benthic infauna). Several recent studies have investigated the links between biodiversity and ecosystem services and function, equating high biodiversity with service provision and ecological stability (Hector & Bagchi 2007, Perrings et al. 2011), although this is dependent on ecological context (Hooper et al. 2005).

Metrics of a single trophic level: Biological production can also be used as a representative metric of ecosystem function, as many ecosystem services are believed to be associated with high biological productivity (Fonseca et al. 2000, French McCay and Rowe 2003, Peterson et al. 2003, Peterson et al. 2007). Its effectiveness, however, is dependent on the trophic level chosen for assessment. For example, compensating for lost ecosystem services by enhancing primary production through water column nutrient enrichment could lead to unintended negative consequences, because enhanced production of phytoplankton and benthic algal mats can lead to hypoxia and degradation of ecosystem functioning (Cloern 2001). This example illustrates the importance of metric selection and ecological context in restoration activities.

Metrics of trophic levels above primary production offer many advantages as integrative measures of ecosystem function. Secondary production has recently been used as a metric of habitat value, and is an appropriate representative metric of ecosystem function because it synthesizes the effects of local food production, food subsidies from other habitats, and protective benefits of habitat structure (French McCay and Rowe 2003, Peterson and Lipcius 2003, Wong et al. 2011). Secondary production also functions as a direct link between primary producers and the higher trophic levels that contain important CRA fish species. Secondary production can be quantified with relatively little logistical effort; the sedentary or sessile nature of most secondary producers means that they are easily sampled and scales of variability can be taken into account.

Metrics of multiple trophic levels: A further application is to use metrics representing ratios between trophic levels, providing composite information representing multi-trophic ecosystem function (Peterson et al. 2007). Multi-trophic level metrics account for ecological efficiencies that depart from expected, and contribution from external subsidies.

Recommended metrics

Identification of appropriate metrics to use during the restoration process requires careful consideration of site- and project-specific factors. In general, metrics used in habitat restoration should:

- relate to ecosystem or population-level aspects of ecological function;
- integrate across multiple ecosystem functions;
- be capable of measurement from a baseline or reference condition;
- apply to both damaged and restored habitat;
- be relevant to multiple habitat types, and
- be useful in steps i-iv of habitat restoration.

Of the metrics described, measures representing biological production at intermediate trophic levels (i.e., secondary production) are the most useful for restoration. These metrics are widely adopted in the literature and in practice, particularly due to their frequent use in HEA (Dunford et al. 2004, NOAA 2006, Peterson et al. 2007, Wong et al. 2011). In cases of like-for like restorations, it may be useful to focus on a metric specific to the habitat of interest that is linked to enhanced fish productivity (e.g., shoot density in seagrass habitat). However, the substitution of like-for-unlike habitat is increasingly common, and may in many cases be more effective at replacing ecosystem function. Generalized and flexible metrics such as secondary production will enhance the success of like-for-unlike habitat restoration. Metrics of secondary production can also play a central role when attempting to restore lost production from CRA fisheries. These metrics can more easily be measured and quantified relative to metrics of fish production, particularly in coastal and nearshore ecosystems. Secondary production metrics can then be directly and indirectly linked to fish production using knowledge of trophic energy transfers, energy requirements, and diet compositions. As such, metrics of secondary production should play a dominate role when assessing and restoring lost services from fish production.

HABITAT EQUIVALENCY ANALYSIS [Step iv]

Once relative habitat values are defined according to the chosen metrics, it is necessary to determine using HEA the extent of impacts and the amount and type of restoration necessary to balance losses of ecosystem function. As noted above, the intensity of the impact must be measured against quantitative baseline data, and the shape of the recovery curve through time must also be considered (Dunford et al. 2004). To determine the amount and quality of habitat required as compensation, it is necessary to first assess the available restoration options and select the type and location of habitat to be restored. The most common restoration methods are the transplanting or seeding of macrophytes such as marsh plants (e.g., Broome et al. 1988, Strange et al. 2002) or seagrasses (e.g., Fonseca et al. 2000, van Katwijk et al. 2009), seeding or enhancement of bivalve reefs (e.g., Coen et al. 2007, Grabowski and Peterson 2007, Powers et al. 2009), and the construction of artificial reef structures (e.g., Pickering et al. 1998, Thanner et al. 2006). In cases involving a direct replacement of like-for-like habitat of the same quality, balancing the debits and credits is relatively straightforward. However, most restoration situations involve habitats that are dissimilar in type or quality, necessitating the use of conversion ratios to assess equivalence (Peterson et al. 2007). In these cases, comprehensive metrics are likely best suited to estimate relative habitat values from a functional perspective. Conversion ratios are difficult to quantify, and can vary significantly between applications, often requiring extensive “professional judgment” in practice (Dunford et al. 2004). However, recent research has focused on quantifying relative habitat values based on biological production (e.g., Peterson et al. 2007, Wong et al. 2011), further supporting the use of these comprehensive metrics in habitat restoration and HEA.

MONITORING AND EVALUATION OF RESTORATION SUCCESS [Step v]

The final step of habitat compensation involves the establishment of goals, success criteria, and a monitoring strategy to ensure compliance and to ultimately evaluate the effectiveness of the compensation process. Metrics of ecosystem function play an important role in this step by providing the means to measure the functional value of restored habitats to quantitatively assess whether goals have been met. Metrics should be evaluated with respect to reliable baseline data in order to accurately assess change, and/or against data obtained from reference sites that are representative of the habitat to be restored (Dunford et al. 2004, NOAA 2006). Metrics of ecosystem function are particularly powerful for use during monitoring because of the time-lag often associated with restored habitat area and ecological functioning. For example, while seagrass beds can be easily planted, it can take 7-15 years for the restored beds to support the full complement of fish and benthic invertebrate communities observed in reference sites. Thus, metrics based on function rather than habitat area or presence are most relevant when monitoring restoration success.

RELEVANT HABITATS FOR RESTORATION IN ATLANTIC CANADA

In Atlantic Canada, three broad categories of coastal marine habitats likely enhance CRA fisheries production and as such are appropriate as restoration candidates. For the purposes of this review, the coastal marine habitats were defined as those extending from the upper limit of the intertidal zone to depths of 10 meters. The three categories include: 1) macrophyte-dominated, 2) bivalve-dominated, and 3) hard substrate. A fourth category, soft sediment habitats, is also included because of its dominant representation within the region. Other habitats that are relevant to restoration and discussion of marine ecosystem services on a wider geographic scale, but are not addressed in this report, include coral reefs (Mumby et al. 2008, Viehman et al. 2009), salt marshes (Broome et al. 1988, Konisky et al. 2006), and mangroves (Lewis 2005).

A summary of the ecosystem services and functions provided by each of the habitats can be found in recent literature reviews (see MEA 2005, Barbier et al. 2011). Spatially, these habitats can occur on exposed coasts, bays, and in estuarine environments, as single isolated patches or as part of a larger habitat mosaic. Habitats can be described by the nature of their dominant structural components as being either biotic (i.e., macrophytes, bivalves) or abiotic (i.e., sedimentary, rocky). Biogenic habitats tend to be preferentially selected for restoration due to their establishment of physical structure assumed to support ecosystem function and by extension ecosystem services (Peterson and Lipcius 2003). In Canadian waters, eelgrass (Pacific coast) and artificial reef balls (Atlantic coast) have often been the focus of restoration within coastal marine ecosystems (DFO 2006).

In Atlantic Canada, aquatic macrophyte habitats occur in intertidal or subtidal areas as beds of seagrass (eelgrass, *Zostera marina*, and widgeon grass, *Ruppia maritima*) or macroalgae (common genera include *Ascophyllum, Fucus, Laminaria*). These habitats are recognized for their high ecosystem service provision, derived through ecosystem functions such as primary production, physical substrate for many associated species, and regulating the physical and chemical environment (Duarte et al. 2006, Barbier et al. 2011). Additionally, macrophytes can be useful indicators of ecosystem health (Orth et al. 2006). Seagrasses in particular are often used as restoration habitat due to the suite of ecosystem services they support (Fonseca et al. 2000, van Katwijk et al. 2009).

Bivalve reef habitats are formed by aggregate communities of the blue mussel (*Mytilus edulis*) or the Eastern oyster (*Crassostrea virginica*). Bivalves, similar to macrophytes, affect several aspects of the ecosystem and support numerous ecosystem services, providing physical substrate and habitat and altering the physical and chemical conditions of the surrounding ecosystem (Gutiérrez et al. 2003, Commito et al. 2005). These habitats are associated with ecosystem services such as water filtration and clarification, shoreline protection, and wave attenuation, in addition to their value as a resource for commercial and recreational fisheries. Bivalves are also often used as targets for habitat restoration or enhancement (Coen and Luckenbach 2000, Coen et al. 2007). Oyster restoration activities are common and generally successful in the United States (Powers et al. 2009, Allen et al. 2011), particularly where large oyster beds once occurred naturally (e.g., Chesapeake Bay), though this situation is not common in Atlantic Canada.

Aside from biogenic habitats, coastal ecosystems can also be classified according to the geological composition of their substrate. Sedimentary habitats tend to occur in low-energy environments such as estuaries, while rocky shore habitats most often occur in high-energy areas along the exposed coast. These habitat components are generally assumed to be of lower ecological value than biogenic habitat, though both sedimentary and rocky habitats provide several important ecosystem services. The physical complexity of rocky and cobble habitats can be very important for certain species, providing substrate for a number of species as well as buffering and shoreline protection. As such, these habitats are often targets for habitat construction through the construction of artificial reef structures (Pickering et al. 1998, Thanner et al. 2006). Mud flats and other soft-bottom habitats similarly support productive benthic communities, are home to commercial and recreational clam fisheries, are an important location for nutrient cycling, and act as a major source of suspended particulate matter (Snelgrove 1999, Short et al. 2000, Peterson et al. 2007).

KNOWLEDGE GAPS AND UNCERTAINTIES

There remain several knowledge gaps and uncertainties concerning restoration metrics that if addressed would benefit habitat restoration practices within the FPP framework. One important area that requires additional study is the link between commonly used metrics (i.e., those that describe attributes of habitats or biological production) and fisheries production. This is especially important for coastal marine ecosystems, where detailed stock assessment data are not readily available for CRA fisheries species. Knowledge of contributions of coastal habitats to CRA fisheries production through nursery function or provision of food resources, aspects that could easily be represented using well defined metrics, would be highly beneficial for policy implementation of the FPP.

Additionally, further aspects of metrics representative of ecosystem function require study. Data compilations and data collection of selected representative ecosystem functions across habitat types and regions would be useful within restoration practices. This would address the current uncertainties in habitat conversion ratios. Spatially explicit information of habitat value should be examined to determine how it changes across differing landscape scales and configuration. Finally, metrics of ecosystem function should be evaluated in terms of temporal variability, allowing integration across entire restoration projects to fully account for losses and gains in ecosystem services through time.

CONCLUSIONS

As evidenced above, there is a broad consensus in the scientific literature supporting the need for quantitative metrics of ecosystem function to improve habitat restoration. Previous approaches based on the simple metric of habitat area require several assumptions and approximations that limit the effectiveness of restoration, and do not provide a direct link to the function of marine ecosystems. Focusing on metrics of ecosystem function allows a quantitative assessment of the success of replacing functional equivalence through habitat restoration, providing benefits through each step of the process.

The selection of a functional metric has many implications for restoration, and is perhaps the most important parameter associated with HEA. A diverse suite of metrics can be used to approximate ecosystem function in each step of the restoration process. The selected metric should measure ecosystem-level functions, encompass multiple aspects of ecosystem function, and should be ecologically relevant and measurable against baseline or reference conditions. The metric also should be flexibly applicable to multiple habitat types for use in HEA through conversion ratios. The metrics that best meet these criteria are those representing biological production, in particular for secondary and upper trophic levels as well as trophic ratios. Within the FPP framework, it is important to establish a direct or indirect link between the metric and fisheries production. This will be especially important when data of fisheries production is not readily available, as is often the case for coastal marine ecosystems. Following the approach outlined in this report could greatly advance the efficiency and effectiveness of habitat restoration in Canada, in turn providing support and enhancing policy implementation related to the FPP framework.

REFERENCES

Allen, S., Carpenter, A.C., Luckenbach, M., Paynter, K., Sowers, A., Weissberger, E., Wesson, J., and Westby, S. 2011. Restoration goals, quantitative metrics and assessment protocols for evaluating success on restored oyster reef sanctuaries: report of the Oyster Metrics Working Group. Chesapeake Bay Program, Annapolis, MD. 32 p.

Barbier, E.B., Hacker, S.D., Kennedy, C., Koch, E.W., Stier, A.C., and Silliman, B.R. 2011. The value of estuarine and coastal ecosystem services. Ecol. Monog. 81: 169-193.

Borja, A., Franco, J., and Pérez, V. 2000. A marine biotic index to establish the ecological quality of soft-bottom benthos within European estuarine and coastal environments. Mar. Poll. Bull. 40: 1100-1114.

Bradford, M.J., R.G. Randall, K.S. Smokorowski, B. Keatley and K.D. Clarke. 2013. A framework for assessing fisheries productivity for the Fisheries Protection Program. DFO Can. Sci. Advis. Sec. Res. Doc. 2013/nnn. v+44 p.

Broome, S.W., Seneca, E.D., and Woodhouse Jr., W.W. 1988. Tidal salt marsh restoration. Aquat. Bot. 32: 1-22.

Cloern, J.E. 2001. Our evolving conceptual model of the coastal eutrophication problem. Mar. Ecol. Prog. Ser. 210: 223-253.

Coen, L.D., and Luckenbach, M.W. 2000. Developing success criteria and goals for evaluating oyster reef restoration: ecological function or resource exploitation? Ecol. Eng. 15: 323–343.

Coen, L.D., Brumbaugh, R.D., Bushek, D., Grizzle, R., Luckenbach, M.W., Posey, M.H., Powers, S.P., and Tolley, S.G. 2007. Ecosystem services related to oyster restoration. Mar. Ecol. Prog. Ser. 341: 303-307.

Commito, J.A., Celano, E.A., Celico, H.J., Como, S., and Johnson, C.P. 2005. Mussels matter: postlarval dispersal dynamics altered by a spatially complex ecosystem engineer. J. Exp. Mar. Biol. Ecol. 316: 133-147.

Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R., Paruelo, J., Raskin, R., Sutton, P., and van den Belt, M. 1997. The value of the world's ecosystem services and natural capital. Nature 387: 253–260.

de Kerckhove, D. 2013. A review of promising indicators of fisheries productivity for the Fisheries Protection Program assessment framework. Fisheries and Oceans Canada, 79p.

DFO (Fisheries & Oceans Canada). 1986. Policy for the management of fish habitat. Ottawa, Ontario. 23p.

DFO (Fisheries & Oceans Canada). 2002. Practitioners guide to habitat compensation for DFO Habitat Management staff. DFO, Ottawa, ON.

DFO (Fisheries & Oceans Canada). 2006. Proceedings of the Workshop on Marine Habitat Assessment and Compensation; 21 March – 22 March 2006. DFO Can. Sci. Advis. Sec. Proceed. Ser. 2006/040.

DFO. 2013a. A science-based framework for assessing changes in productivity, within the context of the amended Fisheries Act. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2013/071.

DFO. 2013b. A science-based framework for assessing the response of fisheries productivity to state of species or habitats. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2013/nnn.

Dunford, R.W., Ginn, T.C., and Desvousges, W.H. 2004. The use of habitat equivalency analysis in natural resource damage assessments. Ecol. Econ. 48: 49-70.

Duarte, C., Fourqurean, J., Krause-Jensen, D., and Olesen, B. 2006. Dynamics of seagrass stability and change. *In* Seagrasses: biology, ecology and conservation. Edited by A.W.D. Larkum, R.J. Orth, and C. Duarte. Springer, Dordrecht. pp. 271–294.

EPA (U.S. Environmental Protection Agency Science Advisory Board). 2009. Valuing the protection of ecological systems and services: a report of the EPA Science Advisory Board. EPA, Washington, D.C.

Fisheries Act [House of Commons, Canada]. 1985. Fisheries Act. R.S.C., c. F-14, s. 1. http://laws-lois.justice.gc.ca/eng/acts/F-14/index.html [Online] Accessed 21/4/2013

Fonseca, M.S., Julius, B.E., and Kenworthy, W.J. 2000. Integrating biology and economics in seagrass restoration: how much is enough and why? Ecol. Eng. 15: 227-237.

French McCay, D.F., and Rowe, J.J. 2003. Habitat restoration as mitigation for lost production at multiple trophic levels. Mar. Ecol. Prog. Ser. 264: 233-247.

Grabowski, J.H., and Peterson, C.H. 2007. Restoring oyster reefs to recover ecosystem services. *In* Ecosystem engineers: concepts, theory and applications. Edited by K. Cuddington, J.E. Byers, W.G. Wilson, and A. Hastings. Elsevier-Academic Press, Amsterdam. pp. 281-298.

Gutiérrez, J.L., Jones, C.G., Strayer, D., and Iribarne, O.O. 2003. Mollusks as ecosystem engineers: the role of shell production in aquatic habitats. Oikos 101: 79–90.

Harper, D.J., and Quigley, J.T. 2005. No net loss of fish habitat: a review and analysis of habitat compensation in Canada. Env. Man. 36: 343-355.

Hector, A., and Bagchi, R. 2007. Biodiversity and ecosystem multifunctionality. Nature 448: 188-190.

Hooper, D.U., Chapin, F.S. III, Ewel, J.J., Hector, A., Inchausti, P., Lavorel, S., Lawton, J.H., Lodge, D.M., Loreau, M., Naeem, S., Schmid, B., Setala, H., Symstad, A.J., Vandermeer, J., and Wardle, D.A. 2005. Effects of biodiversity on ecosystem functioning: a consensus of current knowledge. Ecol. Monog. 75: 3-35.

Konisky, R.A., Burdick, D.M., Dionne, M., and Neckles, H.A. 2006. A regional assessment of salt marsh restoration and monitoring in the Gulf of Maine. Rest. Ecol. 14: 516-525.

Levrel, H., Pioch, S., and Spieler, R. 2012. Compensatory mitigation in marine ecosystems: Which indicators for assessing the “no net loss” goal of ecosystem services and ecological functions? Mar. Pol. 36: 1202-1210.

Lewis, R.R. III 2005. Ecological engineering for successful management and restoration of mangrove forests. Ecol. Eng. 24: 403-418.

Lotze, H.K., Lenihan, H.S., Bourque, B.J., Bradbury, R.H., Cooke, R.G., Kay, M.C., Kidwell, S.M., Kirby, M.X., Peterson, C.H., and Jackson, J.B.C. 2006. Depletion, degradation, and recovery potential of estuaries and coastal seas. Science 312: 1806–1809.

MEA [Millennium Ecosystem Assessment]. 2005. Ecosystems and human well-being: wetlands and water synthesis. World Resources Institute, Washington, D.C. 80 p.
Minns, C.K., Cairns, V.W., Randall, R.G., and Moore, J.E. 1994. An index of biotic integrity (IBI) for fish assemblages in the littoral zone of Great Lakes' area of concern. Can. J. Fish. Aquat. Sci. 51: 1804-1822.
Minns, C.K. 2012. Canadian fish habitat management: symptoms and remedies. American Fisheries Society Symposium 78: 1-36.
Mumby, P.J., Broad, K., Brumbaugh, D.R., Dahlgren, C.P., Harborne, A.R., Hastings, A., Holmes, K.E., Kappel, C.V., Micheli, F., and Sanchirico, J.N. 2008. Coral reef habitats as surrogates of species, ecological functions, and ecosystem services. Cons. Biol. 22: 941-951.
NOAA [National Oceanic and Atmospheric Administration]. 2006. Habitat equivalency analysis: an overview. National Oceanic and Atmospheric Administration, Washington, D.C.
NRC [National Research Council]. 2005. Valuing ecosystem services: toward better environmental decision making. National Academies Press, Washington, D.C. 290 pp.
Orth, R., Carruthers, T., Dennison, W., Duarte, C., Fourqurean, J., Heck, K.L. Jr., Hughes, A., Kendrick, G., Kenworthy, W., Olyarnik, S., Short, F., Waycott, M., and Williams, S. 2006. A global crisis for seagrass ecosystems. BioScience 56: 987–996.
Perrings, C., Naeem, S., Ahrestani, F.S., Bunker, D.E., Burkill, P., Canziani, G., Elmqvist, T., Fuhrman, J.A., Jaksic, F.M., Kawabata, Z., Kinzig, A., Mace, G.M., Mooney, H., Prieur-Richard, A., Tschirhart, J., and Weisser, W. 2011. Ecosystem services, targets and indicators for the conservation and sustainable use of biodiversity. Front. Ecol. Env. 9: 512-520.
Peterson, C.H., and Lipcius, R.N. 2003 Conceptual progress towards predicting quantitative ecosystem benefits of ecological restorations. Mar. Ecol. Prog. Ser. 264: 297-307.
Peterson, C.H., Kneib, R.T., and Manen, C. 2003. Scaling restoration actions in the marine environment to meet quantitative targets of enhanced ecosystem services. Mar. Ecol. Prog. Ser. 264: 173-175.
Peterson, C.H., Wong, M., Piehler, M.F., Grabowski, J.H., Twilley, R.R., and Fonseca, M.S. 2007. Estuarine habitat productivity ratios at multiple trophic levels. Final Report to NOAA Office of Response and Restoration, Assessment and Restoration Division, Silver Spring, MD. 62 p.
Pickering, H., Whitmarsh, D., and Jensen, A. 1998 Artificial reefs as a tool to aid rehabilitation of coastal ecosystems: investigating the potential. Mar. Poll. Bull. 37: 505-514.
Plummer, M.L. 2009. Assessing benefit transfer for the valuation of ecosystem services. Front. Ecol. Env. 7: 38-45.
Powers, S.P., Peterson, C.H., Grabowski, J.H., and Lenihan, H.S. 2009 Success of constructed oyster reefs in no-harvest sanctuaries: implications for restoration. Mar. Ecol. Prog. Ser. 389: 159-170.
Short, F.T., Burdick, D.M., Short, C.A., Davis, R.C., and Morgan, P.A. 2000. Developing

success criteria for restored eelgrass, salt marsh and mud flat habitats. Ecol. Eng. 15: 239–252.

Snelgrove, P. 1999. Getting to the bottom of marine biodiversity: sedimentary habitats. BioScience 49: 129-138.

Strange, E., Galbraith, H., Bickel, S., Mills, D., Beltman, D., and Lipton, J. 2002. Determining ecological equivalence in service-to-service scaling of salt marsh restoration. Env. Man. 29: 290-300.

Thanner, S.E., McIntosh, T.L., and Blair, S.M. 2006. Development of benthic and fish assemblages on artificial reef materials compared to adjacent natural reef assemblages in Miami-Dade County, Florida. Bull. Mar. Sci. 78: 57-70.

van Katwijk, M.M., Bos, A.R., de Jonge, V.N., Hanssen, L.S.A.M., Hermus, D.C.R., and de Jong, D.J. 2009. Guidelines for seagrass restoration: importance of habitat selection and donor population, spreading of risks, and ecosystem engineering effects. Mar. Poll. Bull. 58: 179-188.

Viehman, S., Thur, S.M., and Piniak, G.A. 2009. Coral reef metrics and habitat equivalency analysis. Ocean Coast. Manage. 52: 181-188.

Wong, M.C., Peterson, C.H., and Piehler, M.F. 2011. Evaluating estuarine habitats using secondary production as a proxy for food web support. Mar. Ecol. Prog. Ser. 440: 11-25.

Worm, B., Barbier, E.B., Beaumont, N., Duffy, J.E., Folke, C., Halpern, B.S., Jackson, J.B.C., Lotze, H.K., Micheli, F., Palumbi, S.R., Sala, E., Selkoe, K.A., Stachowicz, J.J., and Watson, R. 2006. Impacts of biodiversity loss on ocean ecosystem services. Science 314: 787-790.