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A framework for assessing fisheries productivity for the Fisheries Protection Program

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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ABSTRACT

Regulatory decisions made by the Minister of Fisheries and Oceans about projects, works, or activities that have the potential to affect fish or fish habitat may need to consider the effects on the productivity of fish that are part of commercial, recreational or Aboriginal fisheries. Assessment of productivity changes will inform the four considerations listed in section 6 of the *Fisheries Act* (2012). A framework for assessing changes in fisheries productivity resulting from projects is described. This framework uses components of productivity, which are the vital rates and life processes needed for fish to complete their life cycle. The impacts of a project on fish habitat or the mortality of fish are identified using existing Pathways of Effects (POEs). For projects that affect the quantity or quality of habitat (or cause the death of fish) in the project vicinity, components of fisheries productivity are analyzed using a life cycle approach (reproduction, growth, survival, migration). Qualitative and quantitative metrics for each component of productivity are tabulated. For projects considered likely to result in ecosystem transformations, productivity assessments are conducted at the population or ecosystem scale. Density-dependent processes can be incorporated into productivity assessments, but detailed information on the biology of the species and a population model will be required. Examples are provided to illustrate how the approach can vary depending on the scale of the project, the fisheries resources that are affected and the information available for the assessment.

RESUME

Dans ses décisions concernant la réglementation de projets, de travaux ou d'activités qui peuvent influer sur les poissons où leur habitat, le ministre des Pêches et des Océans devrait prendre en compte les effets qu'elles exercent sur la productivité des poissons qui sont exploités par les pêches commerciales, récréatives ou autochtones. L'évaluation des changements de la productivité éclairera les quatre facteurs dont il faut tenir compte et qui sont énoncés à l'article 6 de la *Loi sur les pêches* (2012). On décrit un cadre pour l'évaluation des changements qui surviennent dans la productivité des pêches à la suite des projets. Ce cadre fait appel à des composantes de la productivité, en l'occurrence les indices vitaux et les processus vitaux dont le poisson a besoin pour compléter son cycle biologique. Les effets qu'exerce un projet sur l'habitat ou la mortalité du poisson sont déterminés au moyen de séquences des effets (SDE). Dans le cas des projets qui altèrent la quantité ou la qualité de l'habitat (ou qui provoquent la mort de poissons) dans leur voisinage, on analyse les composantes de la productivité des pêches selon l'approche du cycle biologique (reproduction, croissance, survie, migration). Des paramètres qualitatifs et quantitatifs sont compilés pour chaque composante de la productivité. Dans le cas des projets dont on considère qu'ils entraîneront des transformations de l'écosystème, on évalue la productivité à l'échelle de la population ou de l'écosystème. Il est possible d'intégrer des processus qui sont fonction de la densité aux évaluations de la productivité, mais on aura alors besoin de renseignements détaillés sur la biologie de l'espèce et d'un modèle de population. On donne des exemples pour montrer de quelle façon l'approche peut varier selon l'échelle du projet, les ressources halieutiques qui sont touchées et l'information qui est disponible aux fins de l'évaluation.

INTRODUCTION

Human activities in or around fish-bearing waters have the potential to affect the capability of those waters to produce fish for fisheries. Such activities will be managed through the Fisheries Protection Provisions (FPP) of the 2012 amendments to Canada's *Fisheries Act*. Section 6.1 of the *Act* sets out the purpose of the Fisheries Protection Provisions, which is to guide decision-making such that the sustainability and ongoing productivity of commercial, recreational and Aboriginal fisheries is maintained (Box 1; key definitions are provided in Box 2). As part of the science advice to support policy development for the FPP, the ecological concept of ongoing productivity of fisheries was described and interpreted (DFO 2013; Randall et al. 2013). In addition to conceptual definitions, various ways that productivity could be evaluated were listed, ranging from habitat-based approaches to more direct productivity-based metrics. It was proposed that the choice of metric would depend on the risk to fisheries productivity, data availability, the spatial scale and the nature of the project. The new provisions of the *Fisheries Act* imply that the focus for evaluation will be on effects of projects on fish populations and fisheries. This new fisheries-based approach differs from the habitat-based *Policy for the Management of Fish Habitat* (Habitat Policy, DFO 1986); however, Randall et al. (2013) suggest in many cases approaches and metrics from the previous Habitat Policy can be adapted for use under the FPP.

Science-based guidelines for choosing direct or surrogate indicators of productivity are important for policy development (DFO 2013). In the context of this paper, guidelines are criteria to ensure consistency of approach regardless of location or spatial scale. Projects (sometimes called works, undertakings, activities; w/u/a) that affect fish habitat can be classified into one of three types: 1) projects that reduce habitat quantity and carrying capacity; 2) projects that affect habitat quality and fish vital rates (i.e., stress, mortality); and 3) projects with impacts on scales large enough to result in ecosystem transformation (DFO 2013). Indicators or metrics of productivity should be informative, regardless of the project type. Accordingly, suggestions are made for the approach for assessing productivity and potential metrics for each project type. Our approach to assessing productivity is generic, but there is sufficient detail to allow application of an array of approaches across ecosystems and project types.

Box 1. Key sections of the *Fisheries Act* (2012).

Section 6.1 The purpose of section 6, and of the provisions set out in that section, is to provide for the sustainability and ongoing productivity of commercial, recreational and Aboriginal fisheries

Section 6: …..Minister shall consider the following factors:

(*a*) the contribution of the relevant fish to the ongoing productivity of commercial, recreational or Aboriginal fisheries;

(*b*) fisheries management objectives;

(*c*) whether there are measures and standards to avoid, mitigate or offset serious harm to fish that are part of a commercial, recreational or Aboriginal fishery, or that support such a fishery; and

(*d*) the public interest.

Guidance on metrics of productivity builds on existing tools to assess impacts on fish habitat, and in particular makes use of Pathways of Effects (PoE) diagrams. A series of PoE diagrams have been developed for common activities associated with a broad range of in-water and land-based activities. PoE diagrams describe the type of cause-effect relationships that are known to exist and the mechanisms by which anthropogenic stressors ultimately lead to effects in the aquatic environment. Each pathway represents an area where mitigation measures may be applied to reduce or eliminate a potential effect. When mitigation measures cannot be applied, or cannot fully address a stressor, the remaining effect is referred to as a residual effect which has the potential to be considered serious harm to fish (see box 2).

Box 2. Key definitions from the *Fisheries Act* (2012):

Serious harm to fish is the death of fish or any permanent alteration to, or destruction of, fish habitat

Fish habitat means spawning grounds and any other areas, including nursery, rearing, food supply and migration areas, on which fish depend directly or indirectly in order to carry out their life processes

Building on the general definition of fisheries productivity (DFO 2013), the objective of this paper is to develop a framework for the assessment of changes in productivity caused by the residual effects of development projects. We use the PoEs as the bridge between project impacts and fisheries productivity and identify indicators and metrics that can be used to directly or indirectly estimate fisheries productivity.

We note for many projects that metrics will likely serve two roles. First, during the assessment stage, metrics will be used to predict changes to productivity; these predictions will be used to assess the factors outlined in *s. 6* of the *Act* (Box 1) that the Minister must consider in making regulatory decisions. In particular, the contribution of relevant fish and the determination of how much offsetting may be required may involve productivity metrics. Secondly, some form of follow-up monitoring may be required to determine if the initial predictions were accurate, and to evaluate whether mitigation or offsetting activities are effective. For this use, field-based measurements will be used to assess change associated with the project. The information used in each of the stages need not be identical, but there will be a need to relate predictions to monitoring results.

PRODUCTIVITY ASSESSMENT

In this section we decompose the broad definition of fisheries productivity.

Randall et al. (2013) define fisheries productivity as “the sustained yield of all component populations and species and their habitat which support and contribute to a fishery”. However, assessments at the scale of a fishery are only likely for the largest projects, or for those that pose significant risks (Randall et al. 2013). A defensible process is needed to consider effects on fisheries productivity at a scale that is close to that of the project itself. At these smaller scales, metrics for assessment are more likely to be surrogates for effects on productivity that can potentially be scaled up to effects on fisheries yield.

The life cycle of a typical fish species can be used as a template for considering the assessment of project-induced impacts on fisheries productivity. Fisheries productivity results from individual fish completing their life cycle, and having vital rates (reproduction, growth, survival, etc.) that are sufficient to generate a sustainable yield at the population level. Our approach is consistent with the definition of fish habitat in the *Fisheries Act* (Box 2), which includes any habitat needed to sustain life stages and processes of fish populations.

We develop a general model of fish life history patterned after a typical freshwater fish. In this model (adapted from Shuter 1990 and Hayes et al. 2009), each major life stage and the population processes and vital rates that contribute to the completion of the life cycle are identified. We assume recruitment to the adult population results from a combination of survival and growth in the larval and juvenile stages as well as the completion of necessary movements or migrations. These vital rates are also required for the adult stage, as well as the additional requirement for reproduction.

Recruitment is often affected by density-dependent processes (Box 3); these are usually due to some form of habitat limitation that causes growth or survival to decrease with increasing abundance (Shuter 1990). Density-dependent processes such as growth or space limitation can also occur in the adult stage. These processes could have some feedback on yield and reproductive potential or spawning success. Density-dependent processes are more fully explained in Appendix 2, along with options to manage those effects. For most cases the presence of compensatory processes will not affect the choice of metrics, although it may affect the scale and scope of the productivity assessment as compensation can modify the severity of a project's impact on fisheries productivity (Shuter 1990).

We define a ***component of productivity*** as an aspect of fish population productivity (e.g., growth, survival, individual performance, migration, reproduction) that may be altered by a change in conditions caused by a proposed project (these are the "key components of population production" in Minns et al. [2011]). Major vital rates may be broken out into sub-components of productivity that can be used if sufficiently detailed information is available. An adverse change in a component of productivity is expected to have some effect on fisheries productivity, although the effect will depend on which components are involved, their interaction, and the magnitude and scale of the change.

Box 3: Density-dependence. If a vital rate changes with population abundance or density, it is referred to as a density-dependent process. Often a limiting element in the environment (food, space) causes vital rates to decline with increasing abundance. In fisheries science these are referred to as compensatory, because population productivity will increase with decreasing abundance, thus serving to compensate for fishing mortality.

Major components and subcomponents of productivity from the model of Figure 1 are listed in Table 1, and some of the mechanisms that can cause a reduction in productivity are shown. Table 1 is not comprehensive, but does show the most common ways productivity may be affected. Later in this paper we identify linkages between the components of productivity and the PoE endpoints.

Projects that cause changes in *habitat quality* affect density-independent components of reproduction, growth, performance and survival by a variety of mecahnisms listed in Table 1. Also shown are non-habitat based mechanisms that contribute directly to mortality. Projects that cause a decrease in *habitat quantity* are those that cause a decrease in the supply of habitat, potentially resulting in a density-dependent limitation caused by a reduction in carrying capacity. Included under the migration heading are mechanisms that restrict access to habitats; these also serve to reduce habitat supply. Some changes to habitat quality may also affect carrying capacity if the change affects the capacity of the habitat to support fish. For example, a reduction in habitat structure (pools and cover) will likely lower the carrying capacity of the habitat without affecting quantity (defined as wetted area).

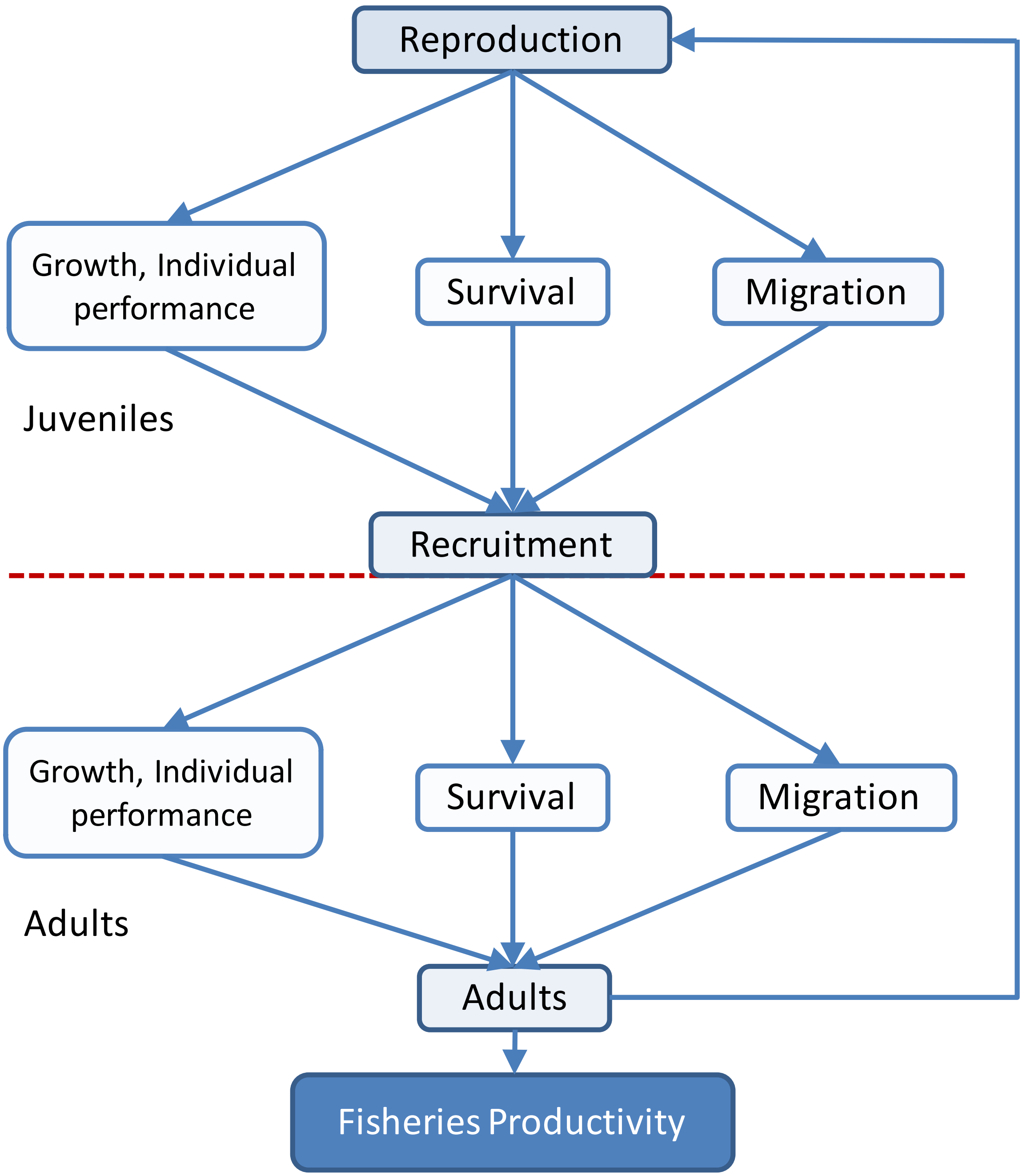

Figure 1. Generic life cycle model for a freshwater fish, showing the major components of productivity. Life cycle is divided into juvenile (before recruitment) and adult stages, and in each stage there are density-dependent and density-independent processes. Individual performance refers to density-independent growth, body condition, parasite burdens, stress or other factors that affect individual fitness. Fisheries productivity may depend on more than one species or population, potentially requiring the use of more than one model for the assessment.

Table 1. Relation between components and subcomponents of fisheries productivity and a list of mechanisms that cause changes in productivity.

Component of Productivity	Sub-components	Mechanism
Growth	Food supply	Reduction of food quality
		Reduction of food quantity
	Efficiency	Reduction in foraging efficiency
		Reduction in bioenergetic efficiency
Individual performance	Stress	Suboptimal environmental conditions
	Disease	Increase in infection, severity of disease
Survival	Direct mortality	Direct mortality by project
		Increase in predation
		Exceedance of environmental tolerances
	Reduced habitat quality or quantity	Habitat supply limitation
Migration	Habitat isolation	Blocking of passage
	Reduced migration success	Deterioration in migration conditions
Reproduction	Adult maturation success	Sub-optimal environmental conditions
	Spawning habitat quality and quantity	Reduction in spawning habitat quality
		Reduction in spawning habitat quantity, egg or larval survival

INDICATORS, METRICS AND MEASUREMENTS

Different measures for assessing productivity are defined and described.

A prediction of the change in a component of productivity may be needed for the evaluation of a project. Different types of information may be used for the prediction and measurement of change. To avoid confusion, definitions of key terms are provided in Box 4, and are fully described below.

Qualitative or heuristic indicators are used to qualitatively predict the change in a component of fisheries productivity. In these cases the indicators will be descriptive and may be unitless. Examples might include the general terms “growth”, “stress” or “food supply”. Heuristic indicators may be used when the ability to make precise or quantitative predictions is limited by the lack of data or understanding, or when the impact is multidimensional and no single metric can capture the changes. Qualitative measures may also be appropriate when the risks associated with a particular stressor are small. Qualitative indicators are usually informed by causal linkage analysis that identifies a link between a measure of productivity and the change in habitat or fish populations caused by the project (Koops et al. 2013a). The analysis will usually be based on summaries of existing literature using a weight of evidence approach (Koops et al. 2013b). Analyses using heuristic metrics will likely only provide information on the direction of the expected response and a qualitative assessment of the severity of the change for the exposed segment of the population.

Quantitative Indicators: It may be possible to quantitatively predict or estimate the impacts of a project on a component of fisheries productivity because the scale and magnitude of the change caused by the project can be accurately described and the relation between the change and the component of productivity is sufficiently well defined. Quantitative indicators are comprised of one or metrics. For prediction of a project's residual impact, general, non site-specific models may be used, or metrics may be based on pre-project field measurements and predictions of changes caused by the project. For example, estimates of abundance, size or other characteristics made during the pre-project stage will form the information base to predict change as a consequence of the project.

Quantitative indicators can be also be based on quantities that can be measured in the field during baseline assessments and as part of post-project monitoring programs. These types of indicators are used for follow-up monitoring or adaptive management programs.

Box 4. Definitions:

Measurements are taken in the field and describe the current state of the ecosystem or its biota. Examples include fish abundance or discharge.

Metrics are used to evaluate change. A metric can be derived from before-after field measurements (e.g., change in fish abundance), or can be estimated from baseline measurements and a predicted or modelled effect.

Indicators are more general quantities used to evaluate changes in fisheries productivity. Indicators may be comprised of one or ?quantitative metrics, or may be more qualitative in nature (cf. "% change in LWD", "loss of structure").

COMPONENTS OF PRODUCTIVITY AND THE PATHWAYS OF EFFECTS

In this section we link the end points of the Pathways of Effects to the components of productivity.

Pathways of Effects are an important conceptual tool for identification and organization of possible effects of a project on fish and fish habitat (Table 2). Most of the endpoints of the PoEs are changes to habitat or environmental conditions (e.g., Fig. 2). In the assessment of a project the pathways are screened for those that are not relevant or for which the effects can be mitigated. For the remaining pathways (the "residual effects"), the predicted change in fisheries productivity may need to be analyzed for consideration under section 6 of the *Fisheries Act*.

Table 2. List of current Pathways of Effects available on the DFO website. An example PoE diagram is shown in Fig. 2.

In-water activities	Land-based activities:
Addition or removal of aquatic vegetation	Cleaning or maintenance of bridges or other structures
Change in timing, duration and frequency of flow	Excavation
Dredging	Grading
Fish passage issues	Riparian Planting
Marine seismic surveys	Streamside livestock grazing
Organic debris management	Vegetation Clearing
Placement of material or structures in water	Use of explosives
Placement of marine finfish aquaculture site	Use of industrial equipment
Structure removal	
Wastewater management	
Water extraction	
Aquaculture	
Renewable Energy	

DFO Habitat website

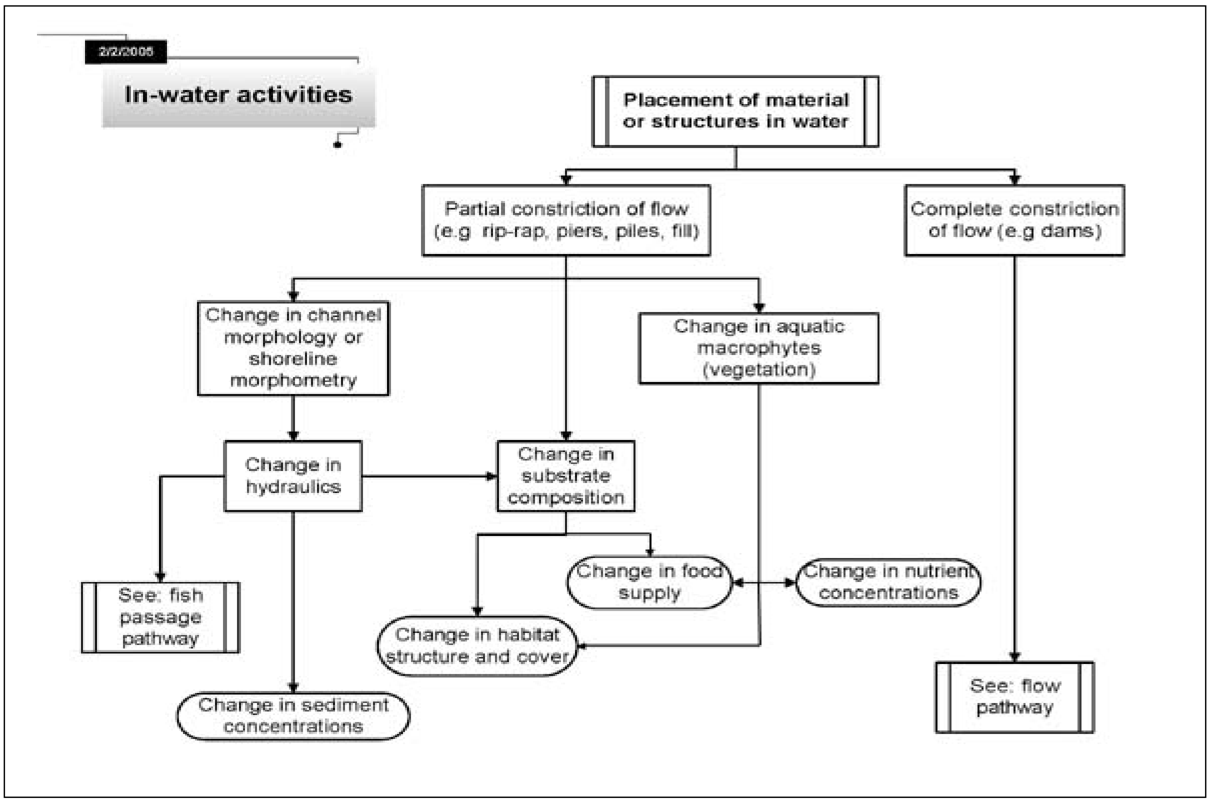

Figure 2. Example Pathways of Effects diagram for the placement of structures in water. Ovals are the endpoints that identify ways that the activity can affect fish or fish habitat.

The framework to link PoEs to fisheries productivity is outlined in Koops et al. (2013a) and DFO (2013) where productivity-state functions are used to specify causal relations between a change in a habitat or environmental condition and a change in a component of productivity. PoE endpoints can be used as inputs to the x-axis of those productivity-state relationships (Fig.3).

Koops et al. (2013a) found most projects with potential residual effects that DFO has reviewed can be reduced to eight categories of impact type. Appendix Table 1 lists these, the relevant PoE diagrams and endpoints, and the corresponding potential effects on fish or fish habitat.

Endpoints of existing PoE diagrams are listed in Appendix Table 2 in decreasing order of frequency of occurrence for PoEs listed in Table 2. Potential mechanisms for each endpoint, which help identify more precisely how residual effects of a project could affect fish or fish habitat, are also identified in Appendix Table 2.

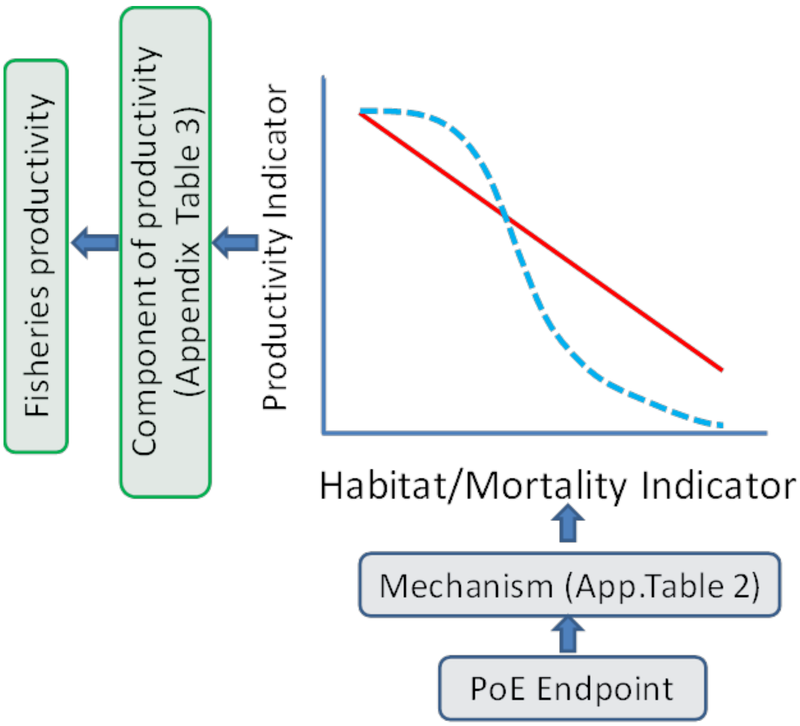

Figure 3. Hypothetical productivity-state curve illustrating the relation between PoE endpoints, indicators and productivity. This figure illustrates how the productivity-state relations of Koops et al. (2013b) fit into the framework of using PoEs and components of productivity. The curves are hypothetical but indicate linear and non-linear (with threshold) forms are possible.

The productivity-state relation links a component of productivity for a CRA fisheries species to a residual effect identified by the PoE analysis (Fig. 3). PoE endpoints or the mechanisms for each endpoint listed in Appendix Table 2 can be used as qualitative or descriptive indicators in data-poor situations. For cases where more precise predictions of change are available, we also propose quantitative indicators and measurements for the PoE endpoints in the third column of Appendix Table 2. For each entry the corresponding components and subcomponents of productivity that might be affected by the change identified by the PoE (the Y-axis of Figure 3) are shown. Pairs of PoE endpoints and components of productivity form the axes for the appropriate productivity-state relations for the project.

PRODUCTIVITY ASSESSMENTS

In this section productivity assessments for the three classes of projects are described.

Randall et al. (2013) classified development projects into three groups and briefly outlined the data requirements and indicators that might be needed for assessment and monitoring. In this section we consider in more detail how the process described above can be used for each project type.

PROJECTS THAT REDUCE HABITAT QUANTITY

Many projects that result in reduction in wetted area of habitats that support a CRA fishery fall into the category of "destruction" under the definition of Serious Harm (Box 1). Types of projects that result in loss of habitat area range in spatial scale from localized infill (a few m^2) to large scale ecosystem loss or conversion (e.g., reservoir). Destruction of habitat can affect fisheries productivity when it causes a loss of carrying capacity, which is expected to result in a direct loss of sustainable yield (DFO 2012, Fig 4). Loss of habitat capacity is one of mechanisms by which productivity can decline (components of productivity, Table 1). Loss of habitat quantity can also occur if habitat becomes isolated by blockages or passage problems.

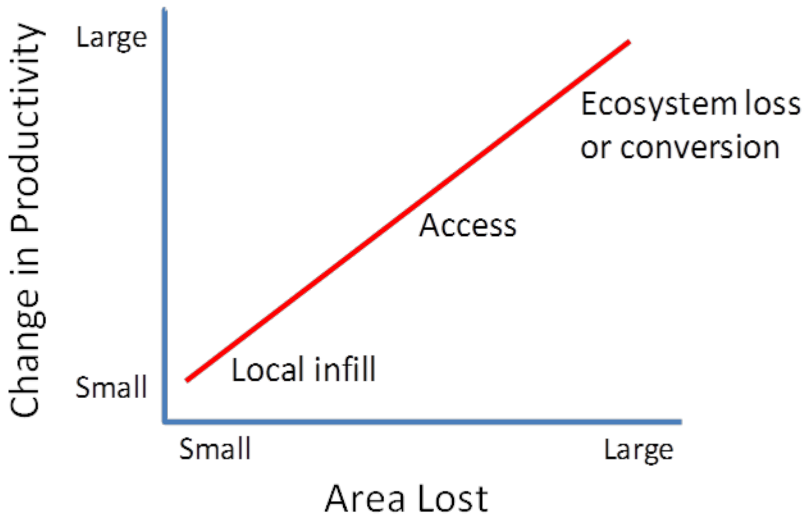

Figure 4. Generalized relationship between habitat loss and fisheries productivity. Relative area of habitat loss as indicated in examples of a localized infill, to significant area of change in access, to whole ecosystem destruction or transformation.

Impact assessment: The POEs relevant to change in habitat quantity are *placement of material or structures in water*, *fish passage issues*, and *offshore renewable energy technologies*. Reduction in habitat quantity is identified in the renewable energy POE, but is an implicit effect in many of the other POEs.

For the *placement of material or structures in water* POE, the endpoint of concern that most closely matches lost habitat (footprint) is the change in habitat structure and cover. Most of the other endpoints of concern are related to habitat quality in the vicinity of the footprint: change in sediment concentration, change in food supply, and change in nutrient concentration. For the *fish passage* POE, the relevant endpoint of concern is change in access to habitat.

***Metrics and analysis*: For localized projects involving infill or habitat loss, three levels of analysis (requiring different metrics) may be possible, depending on the nature of the project, management decision criteria, and fisheries resources at risk.

Area-based metrics. In this case, the area of habitat affected is sufficient for management needs. The primary habitat metric is square metres or hectares of lost habitat.

Habitat type or quality metrics. This level of analysis is needed to identify the type and qualities of the affected habitats. Here, the area affected is mapped and characterized by type (for example, spawning, nursery, rearing, migration corridor and food supply) and potentially by quality, usually based on inventory data or relatively simple physical measurements. From these data the relative quality of the lost habitat could be calculated by Habitat Suitability Indices or other measures of habitat quality. Such an analysis could be sufficient for describing the impacts of the project and for the design of measures to offset serious harm to fish.

Metrics for fisheries productivity. More direct estimates of the loss of fisheries productivity that are associated with an infill may be required in some cases. To estimate the loss of productivity, estimates or measures of fish production, abundance or yield on an areal basis (per m^2, or ha) are needed, along with the area of the impact. Two approaches can be used to assess change in fisheries productivity from projects involving infill: a) scaling up from localized units of habitat, and b) scaling down from ecosystem level models or analyses. Examples of the approaches are provided in Box 5:

Box 5. Scaling up and scaling down: case studies.

Scaling up from regional standards: In the Great Lakes, infilling of habitats were assessed, pre and post project, by calculating habitat suitability and then quantifying weighted suitable area (WSA) as the product of suitability and area for each habitat type (MacNeill et al. 2008). Impacts to productivity could then be determined by converting WSA to biomass units using a regional benchmark approach (Randall et al. 2013). WSA and predicted biomass are the metrics resulting from the analysis.

Scaling down from ecosystem-level predictions: For a project involving infill of a shoreline area of a lake in Newfoundland, unit area of trout biomass could be determined using an empirical model for lake-level abundance (Cote et al. 2011), scaled down to determine the value (biomass) of the infill area. Adjustment for the higher value of near shore relative to offshore habitat could be estimated from literature and regional expertise.

Some examples of empirically based models of productivity for data-rich fishery species that can be scaled down to medium or small spatial scales are listed in Appendix Table 4. Here the productivity value of small quantities of habitat can be calculated using the ecosystem models, potentially modified by additional knowledge about the qualities of the affected habitats.

PROJECTS THAT AFFECT HABITAT QUALITY

Some projects do not reduce the amount of habitat (defined as wetted area), but alter the characteristics of the habitat, or aspects of the populations in proximity to the project, such that one or more of the components of productivity are adversely affected. Other project types may cause direct or indirect mortality of fish. In both cases a change in fisheries productivity may occur because the project will affect one or more of the key vital rates (e.g., growth, survival, migration, reproduction) of fish populations in the project area.

Metrics and Analysis: Similar to the case for the habitat loss, different levels of analysis and metrics may be used depending on the nature and scale of the project, the fisheries resources at risk, and the decisions required.

Qualitative directional analysis. For smaller projects the assessment may be limited to defining the components of productivity likely to be affected, using a POE analysis, and the direction of change. For example, a long-term sediment release might be expected to cause a reduction in the component of productivity "*growth*". However there are a number of mechanisms that can lead to a reduction in growth (food production, foraging efficiency, sub-lethal stress) and in many cases it will be very difficult to combine or integrate these mechanisms to generate a quantitative prediction of a change in mass for an individual species and life stage. In such cases using a qualitative indicator "growth" is appropriate and is scientifically defensible based on causal analysis (a literature-based analysis) that confirms that a cause-effect relation likely exists for each mechanism (Koops et al. 2013b). Proposed qualitative indicators are listed in Appendix Table 3.

Semi-quantitative analysis. In cases where the impact (expressed through the PoE endpoint) can be reasonably quantified (e.g., a predicted change in temperature), a semi-quantitative prediction of impact may be adequate for decision-making purposes. This could involve a relative ranking of risk or impact on an ordinal scale (e.g, low-medium-high), based on the magnitude of impact to habitat (or direct effects on fish) caused by the project. The ranking would be informed by the productivity-state relations developed for the impact type (Koops et al. 2013b).

Included in this category are cases where a threshold exists for the x-axis variable (e.g., a change in the flow change, or a temperature limit); exceeding a threshold is assumed to result in an impact to a component of productivity. A precise assessment of the change in productivity is not required as decision-making is based on the threshold for the change in habitat conditions (or mortality).

Quantitative analysis. In other situations a quantitative estimate of the impact of the project on an aspect of productivity may be appropriate. Such cases require a quantitative productivity-state relation, reasonably accurate predictions of the change imposed by the project and baseline environmental conditions. For example, if a project causes a change in nutrient levels in a lake, there are a variety of models that can be used to evaluate the impacts on fisheries productivity. Quantitative indicators for productivity can usually be employed in these cases.

PROJECTS THAT RESULT IN ECOSYSTEM TRANSFORMATION

Projects that result in an ecosystem transformation or remove a significant part of the ecosystem are most often the subject of case-specific studies that are part of a directed Environmental Assessment (EA). These projects by definition change ecosystem structure and function and have a tendency to affect habitat quantity and quality which can alter both productivity and local biodiversity (Randall et al. 2013).

Impact assessment: Projects in this category will be subject to a detailed impact assessment. The EA would be expected to include a detailed site description, which would outline the existing biophysical environment, the proposed project design and a prediction of environmental changes expected as a result of the project. Fisheries are generally considered a valued ecosystem component (VEC) within most EAs. Thus, a description of the species present within the project area, their habitat use based on the main life history components (Fig. 1) and their relative importance to existing fisheries will be included. Baseline sampling should yield information that can serve as inputs for the assessment of the change in fisheries productivity as a result of the project.

The PoE framework can still inform the *Fisheries Act* assessment but complex projects can have many impact types. For example, a hydroelectric dam may affect the environment through five of the eight impact types listed in Appendix Table 1 and thus have many PoEs and endpoints potentially affecting many species. This complexity can also include interactions between the impacts and thus there usually is a need for a ecosystem level assessment which is beyond the scope of process outlined in this paper. These are usually specified in the guidelines for the EA.

Metrics: Projects that lead to an ecosystem transformation are likely best evaluated by directly assessing changes in fisheries productivity at the fishery, ecosystem or population scale. Both habitat quantity and quality may change and the quantitative approaches outlined in the previous sections will be employed. In some cases whole ecosystems will be lost and the impact on fisheries productivity can be expressed in terms of fish production or fishery-based statistics such as yield or use. In other cases the ecosystems can undergo large-scale transformations and the change to fisheries can be estimated using productivity or production measures. Bérubé et al. (2005) and McCarthy et al. (2008) provide examples of habitat-based production models for evaluating large hydroelectric projects. Similar approaches include habitat-related biomass, population structure and production/biomass ratios to estimate production (and by inference, potential yield) (Randall and Minns 2000).

Changes in biodiversity will also need to be considered with ecosystem change as there is potential for impacts on fisheries productivity that are not easily captured in typical fish production assessment and modelling. This is especially important when changes to habitat features can be expected to reduce the quality of the habitat for one set of species but improve it for another set (e.g. reservoir creation). However, this is an area where there is little directed research, and there is a need for a focused effort at understanding the nature of the trade-offs. Biodiversity trade-offs in this context are usually considered with respect to the fisheries management objectives of the area where the project is located.

DISCUSSION

This paper describes a defensible process for linking residual effects of projects to fisheries productivity, and provides a path for evaluating the “contribution of the relevant fish” as required in Section 6 of the *Fisheries Act*. By breaking the PoE endpoints down to specific mechanisms, where appropriate, and by considering the components of fisheries productivity, it then becomes possible to populate the axes of the productivity-state relations of Koops et al (2013a,b).

A summary of the proposed process is found in Box 6.

This report only describes the framework, and there are many issues that need to be resolved (including step 5 in Box 6) before the approach can be fully implemented. Some of these are itemized in the following sections.

Box 6: A summary of the proposed framework for the assessment of project-related effects on fisheries productivity

1. Determine project type (quantity/quality/transformation) and scale
2. Use PoEs to determine residual effects (unmitigated effects on fish or habitat), and identify indicators for endpoints
3. Identify potential metrics of productivity (qualitative, semi-quantitative, quantitative) based on the appropriate components/ecosystem in question and the residual effects
4. Assess impacts to productivity based on project type (see examples in text)
5. Combine assessment of effects on productivity from multiple stressors for an overall assessment to be used in the decision framework (new guidance is needed on this step).

Linking indicators to decisions. The best indicators are those that provide sufficient information for effective decision making, but no more (Failing et al. 2003). Detailed, precise and complex indicators are not needed if the fundamental decision being made is at a much coarser scale. At the time of writing (July 2013) the exact decision system that the factors of Section 6 of the *Act* will inform has not be identified. As the policy for the FPP is developed, the nature of the productivity assessments and the information requirements should be further refined to match the decisions to be made.

Quantifying and linking the change in a component of productivity to fisheries productivity. For certain projects a population-level evaluation will be needed. There are at least three considerations that come into play: (1) the magnitude of change in the component of productivity, (2) the sensitivity of overall (fisheries) productivity to a change in the component, and (3) the scale at which the assessment will be conducted. The process for the first consideration is outlined in this paper and Koops et al. (2013a,b), however guidance needs to be developed on estimating or ranking the relative importance of a change in a component of productivity. The importance of scale has been discussed in Randall et al. (2013), and policy guidance regarding the scale of assessment is needed in order to properly evaluate project-related effects and their risk to CRA fisheries.

Projects that have more than one residual impact. We have not addressed the common situation of projects with many residual effects, affecting a number of components of productivity. These may include impacts to both habitat quantity and quality, but are not yet on the scale of ecosystem transformation. In some cases there may be merit in accumulating the effects; in other cases the largest effect may effectively overwhelm smaller ones allowing the smaller ones to be ignored. An additional facet to this problem is situations where many, potentially diverse, species are affected. Working backward from the decision that needs be made may be useful in determining how precise and detailed the “roll-up” of multiple effects needs to be.

Incorporating the current state of the fishery, the CRA fish populations, and habitats into the assessments. From a population dynamics perspective impacts of projects may depend on the current status of the population and the habitats they use. For example, if a population is depleted by external factors, compensation will play a lesser role in mitigating impacts. Knowledge of the state of stressors or habitat supply within the ecosystem may also affect decisions. Cumulative effects issues have been identified by Randall et al. (2013) and Koops et al. (2013a).

Assessments involving changes to biodiversity. There is growing evidence (reviewed in Randall et al. 2013) that aquatic biodiversity can contribute to fisheries productivity. This paper does not address how risks to biodiversity should be addressed in this framework, or the types of indicators or metrics that should be used.

Despite these outstanding issues that need to be resolved in future, this document significantly advances a science-based framework that can be implemented in the near term to assess habitat-related impacts to fisheries productivity, and inform Section 6 of the amended *Fisheries Act*.

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APPENDIX 1: TABLES

Appendix Table 1. List of works, undertakings and activities classified by impact type and linked to the Pathways of Effects and ecosystem component of concern (endpoints) from those Pathways diagrams. Reproduced from Koops et al. 2013a (Table 5).

Impact Type	Works/Undertakings/Activities	Pathway of Effect Titles	Effect on Ecosystem Component (endpoints from Pathways of Effects)
Infilling/footprint	Any structure constructed within a water body (e.g., piers, abutments, dams, bridges, culverts, wind turbines), urban, cottage and harbour development (e.g., docks, boathouses, moorings, wharves, breakwaters, berms, groynes, boat launches and ramps), shoreline stabilization works (e.g., retaining walls, rock protection, erosion control, armouring)	Placement of Material or Structures in Water; Fish Passage Issues; Structure Removal; Offshore Renewable Energy Technologies: Construction and operation; Aquaculture: Placement/removal of site infrastructure.	Change in structure and cover of habitat, change in food supply, change in nutrient concentrations, change in sediment concentrations, change in access to habitat, change in contaminant concentrations, change in temperature, change in sediment transport, erosion and deposition patterns, change in hydrodynamic characteristics and patterns.
Deposition of non-deleterious substances in water	Organic material from aquaculture facilities operations, logging operations, or open water dredging spoils.	Dredging; Excavation; Aquaculture Site and Stock Management.	Change in structure and cover of habitat, change in sediment concentrations, change in food supply, change in contaminant concentrations, change in nutrient concentrations, mortality of organisms, change in dissolved oxygen, change in water temperature, change in baseflow, change in primary productivity.
Changes in Flows/Water levels	Water taking including groundwater/upwelling extraction (e.g., bottling, municipal, industrial, agricultural, thermal/nuclear generating station uses) and operation of water control structures (e.g., hydro). Water deposition.	Change in Timing, Duration, and Frequency of Flow; Water Extraction; Fish Passage Issues; Wastewater Management.	Displacement or stranding of fish, change in migration/access to habitats, change in sediment concentrations, change in habitat structure and cover, change in food supply, change in water temperature, change in contaminant concentrations, change in nutrient concentrations, change in total gas pressure, change in salinity, change in dissolved oxygen, pathogens, disease vectors, exotics.
Dredging and excavating	Any dredging or excavation below the high water mark (e.g., for recreational purposes, navigation, mining and oil sands projects, aggregate removal, drainage maintenance,	Dredging; Excavation; Vegetation Clearing; Addition or Removal of Aquatic Vegetation; Organic Debris Management.	Change in food supply, change in water temperature, change in sediment concentrations, change in baseflow, change in structure and cover of habitat, change in

Impact Type	Works/Undertakings/Activities	Pathway of Effect Titles	Effect on Ecosystem Component (endpoints from Pathways of Effects)
	under water cables and pipelines).		contaminant concentrations, change in nutrient concentrations, change in dissolved oxygen.
Permanent watercourse alteration	Realignment/relocation, obstruction to fish passage, channel modification, channelization, reservoir creation (e.g., from culverts and dams), water control structures.	Fish Passage Issues.	Change in access to habitat, change in thermal cues or temperature barriers, changes in total gas pressure, changes in salinity, interbasin transfer of species.
Fish mortality	Killing of fish via use of explosives (in or near water), turbine operations (tidal power, hydrokinetic, hydro dams and spillways), dewatering and temporary flow diversions, impingement of fish onto screens and fences, or entrainment.	Water Extraction; Fish Passage Issues; Use of Explosives; Use of Industrial Equipment; Marine Seismic Surveys; Streamside Livestock Grazing; Offshore Renewable Energy Technologies: site investigation, construction, maintenance, decommissioning, operation.	Lethal or sublethal effects on fishes/eggs/ova; direct or indirect mortality of fish.
Fish disturbance	Any W/U/A in water generating noise, vibration, electromagnetic radiation, or light.	Use of Industrial Equipment; Use of Explosives; Marine Seismic Surveys; Offshore Renewable Energy Technologies: site investigation, construction, maintenance, decommissioning, operation.	Physiological effects on fishes (including hormonal, egg/larvae development), change in sediment concentrations, change in contaminant concentrations, change in nutrient concentrations, change in habitat structure and cover, change in access to habitat, change in migration/movement patterns, change in behaviour, communication, navigation, orientation or predator/prey detection.
Riparian alteration	Affecting riparian vegetation, riparian slope, or direct inputs into water from land-based activities.	Vegetation Clearing; Riparian Planting; Cleaning or Maintenance of Bridges or Other Structures; Grading; Use of Industrial Equipment; Streamside Livestock Grazing.	Change in habitat structure and cover, change in sediment concentrations, change in water temperature, change in food supply, change in nutrient concentrations, change in contaminant concentrations, change in pathogens/bacterial levels, chemical barrier to fish passage.

Appendix Table 2. Hierarchical listing of Pathways of Effects (PoE) endpoints, mechanisms that cause a change to fish or fish habitat, and quantitative indicators or measurements to measure the change in the endpoints (x-axis from the assessment framework, Koops et al. 2013a). Also indicated are likely components of productivity that could be affected by the change. Numbers in brackets represent the frequency of occurrence of each endpoint among the PoE diagrams listed in Table 2.

POE endpoint	Mechanism	Metrics for the Endpoint (x-axis of framework).	Components or subcomponents of Productivity
Change in sediment concentrations (19)	Increased suspended sediment in water column.	% fines in substrate, turbidity, suspended sediment concentration.	Reduction in: survival (salmonid eggs/larvae), foraging efficiency, food supply, habitat quality
	Increases in fine material in bed		Increase in sub-lethal stress
Change in habitat structure and cover (17)	Habitat lost (removed), area of habitat altered, loss of heterogeneity	Area of habitat lost, reduction in habitat complexity, change in cover/shade, LWD pieces	Reduced habitat quality or quantity
Change in nutrient concentrations (14)	Increase or decrease in nutrients required for primary production	Change in concentration of nutrients (N, P), chlorophyll *a*, stream respiration, invertebrate indices, algal indices, DO	Eutrophication: reduced food availability, habitat capacity, growth, reproduction, mortality. Increase in sub-lethal stress (DO). Reduced nutrients: reductions in food supply and growth.
Change in contaminant concentrations (14)	Increases in the concentration of harmful chemicals in water	Change in concentration of contaminants in water, sediment chemistry.	Increase in sub-lethal stress. Reductions in growth, survival, reproduction
Change in food supply (13)	Reduction in habitat suitability for production of food organisms (usually invertebrates). Many mechanisms	Nutrients (N,P), chlorophyll *a*, vegetation density, invertebrate indices.	Reduced growth, survival, reproduction, recruitment.
Direct mortality of fish (11)	Fish stranded, displaced, entrained, impinged, concussed, or otherwise killed	Rapid changes in flow, volumes of water that pass turbines, pumps. Direct estimates of fish killed.	Reduced survival, recruitment
Change in temperature (9)	Increase or decrease over ambient temperatures	Change in temperature compared to ambient conditions	Reductions in growth, survival, reproduction can occur if temperatures are suboptimal
			Increase in stress, disease
Change in noise, vibration, light, electromagnetic field (EMF) (8)	Project causes changes in physical or sensory environment that alters behaviours, migration, communication, navigation or orientation. Light can	Change in noise, vibration, EMF, and timing of artificial light use compared to ambient conditions.	Reduced survival, reduced rate of successful migration, Increased sub-lethal stress

POE endpoint	Mechanism	Metrics for the Endpoint (x-axis of framework).	Components or subcomponents of Productivity
	change photosynthetic rate, risk of predation.		
Change in access to habitat (7)	Works cause physical barrier	Rate of successful passage	Reduced habitat quantity, recruitment, survival due to migratory delays, loss of access to spawning habitat, reduced habitat quality, increased population fragmentation.
	Reduction in accessibility to habitats due to changes in hydraulic conditions or other factors.	Amount of habitat lost due to access limitation.	
Sublethal physiological effects (6)	Increased stress, energy expenditure due to suboptimal conditions	Blood chemistry (lactate, pH, glucose, cortisol). Lipids and other body constituents, condition	Sub-lethal stress resulting in reduction in other vital rates
Change in dissolved oxygen (3)	Oxygen levels fall below optimal values	[O_2], indirect measures (indicator species).	Sub-lethal stress resulting in reduction in other vital rates
			Mortality
Pathogens, disease vectors, exotics (2)	Increase exposure to pathogens or to exotic or invasive species.	Pathogen prevalence in the environment.	Infection, disease, sub-lethal stress resulting in reduction in other vital rates
		Prevalence in hosts.	Mortality
Change in salinity (1)	Change from ambient conditions	Salinity measurements	Sub-lethal stress resulting in reduction in other vital rates
Change in hydrodynamic patterns (1)	Deviation from natural flow regimes affect many ecological and physical processes	Annual hydrographs (river), flow dynamics around and beyond structures, substrate and depth characteristics.	Reduction in food supply, growth, survival, reproduction. Increases in stress.
Change in gas pressure (1)	Increase in TGP above tolerable levels	Total gas pressure (TGP)	Sub-lethal stress leading to increase rates of mortality (predation), reduction in growth
Interbasin transfer of species (1)	Negative interactions with non-native fauna	Presence of new/non-native species in a system. Volume of water transferred	Reduction in growth (competition). Reduction in survival (predation). Increase in disease incidence.
Change in baseflow (1)	Lower or higher baseflow can cause many physical and ecological changes	Deviation from optimal or natural flow	Reduction in food supply, habitat quality and quantity, spawning habitat quality and quantity.

Appendix Table 3: Qualitative and quantitative indicators and examples of measurements of components of fisheries productivity for projects that affect the quality of fish habitat or have impacts on individual fish (e.g., stress, mortality). Qualitative indicators are descriptive but are based on the evidence in support of linkages between a project and a component of fisheries productivity. Quantitative predictions are from models, analyses or field studies that make explicit predictions of how a component of productivity will be affected by the residual effects of the project. Measurements result from field studies and can be used to make predictions, or for follow-up (before-after) monitoring.

Component of Productivity	Sub-components	Mechanism	Qualitative Indicator	Quantitative Indicator	Measurements
Growth			Directional change in the rate of increase in body size over time	Modelled change in growth based on environmental and biotic factors	Changes in size (length, weight) over time by age by hard-part analysis, tagging.
	Food supply	Quantity	Direction of change in invertebrate or forage fish abundance, biomass	Prediction of biomass; composition	Abundance, biomass or productivity of prey species (drift/net samples).
		Quality	Description of change in community structure	Predicted species composition relative to preferred prey	Species/size composition of prey species. Energy content.
	Efficiency	Foraging	Directional change in foraging efficiency based on changes in environment	Predictions of energy intake from foraging models	Stomach content analysis, stable isotopes.
		Bioenergetics	Description of change in energy conversion efficiency due to changes in environmental conditions	Predictions of surplus energy from bioenergetics models	Change in mass/condition. Lipid or body constituent analysis
Survival			Presence of mortality and assessment of scale.	Predictions of the number of fish killed	Survival rates estimated from tagging/telemetry or sequential abundance estimates. Mortality inferred from age composition
	Density independent mortality	Direct mortality	Conditions that result in the death of fish	Implications of mortality best assessed using a population-based modelling approach that accounts for compensatory and density independent mortality throughout the life cycle	Sampling for direct evidence of death
		Exceedance of environmental tolerances	Area of habitat or proportion of population exposed to potentially lethal conditions		

Component of Productivity	Sub-components	Mechanism	Qualitative Indicator	Quantitative Indicator	Measurements
	Density-dependent mortality	Habitat supply limitation	Assessment of change of habitat capacity	Quantitative prediction of habitat capacity based on habitat-fish production model.	Changes in density estimates for “fully seeded” habitats. Changes in production (egg-fry, egg-smolt) rates.
Individual performance	Stress	Suboptimal environmental conditions	Inferred from the change in Temperature; O2, TGP, contaminants, noise, flow changes, other water quality variables relative to optimal values	Quantitative prediction based on stress-response models or evidence	Blood chemistry parameters. May cause changes in growth, condition, reproduction.
	Disease	Infection	Inferred from change in temperature; exposure	Prevalence based on empirical predictors Predictions of consequences for individuals or populations	Histopathology, seriological or molecular analysis for presence of pathogens and disease
Migration		Disruption of normal behaviour	Inferred migration success	Probability of success based on models, empirical data.	Hydroacoustic surveys, tagging studies to estimate migratory success rate, weirs or direct observation
Reproduction	Adult maturation and reproduction	Suboptimal environmental conditions	Inferred decrease in reproductive success	Predictions based on empirical evidence	Sampling for reproductive development (GSI index etc.), hormones.
	Density-independent reproductive success	Spawning habitat quality	Assessed changes in habitat conditions relative to historical or optimal values	Predictions based on empirical models relating survival or reproductive rate in relation to environmental conditions (flow, temperature, substrate etc.) relative to optima.	Field estimates of fertilization success, egg, larval and juvenile survival and condition.
	Density-dependent reproductive success	Spawning habitat quantity	Directional change in habitat supply	Population-level prediction based on predictions of habitat capacity.	Estimates of spawner density relative to habitat quality and availability. Measurements of incubation environment and survival rates.

Appendix Table 4. Example models to predict productivity of fishery species in lakes and rivers using surface habitat area as a predictor.

Species	Productivity metric	Equation	Reference
Brook trout (NL)	Log Biomass(kg/ha)	2.71 -0.54(log area)	Cote et al. 2010
Lake trout (ON)	Log_{10} (yield, kg/ha)	0.50 + 0.83 (log_{10}area)	Payne et al. 1990
	Biomass (kg/ha)	84.33 area -0.76 + 0.038 (log area)	Shuter et al. 1998
Walleye (ON)	Log_e (kg/yr)	0.914(log_earea) + 0.407	Lester et al. 2004
Atlantic salmon (NB, NS, NL)	Eggs	2.4 (area)	Chaput et al. 1998
Coho salmon (BC)	Log_e (smolt abundance)	6.9 + 0.97(log_estream length)	Bradford et al. 1997

APPENDIX 2. DENSITY-DEPENDENT AND DENSITY-INDEPENDENT MORTALITY

Population processes are often categorized as those that are density-independent (where vital rates are unrelated to population density), and those that are density-dependent (i.e., that co-vary with density). The presence of density-dependent processes (often colloquially referred to as "limiting factors" or "bottlenecks") can complicate the evaluation of project effects on fisheries productivity.

Density-independent processes are often those associated with physical or environmental factors that cause growth, or mortality to vary in response to adverse water quality, extreme flows, or changes in growth associated with variation in water temperature.

Density-dependent processes are those that vary with population density, most commonly because there is an aspect of the environment that is limiting. For example, density-dependent survival in the juvenile stage is common among fishes, because juvenile habitat or the availability of food resources are limited. For many stream-dwelling fishes the amount of suitable rearing habitat caps the production of juveniles in that habitat (Figure A1). At high abundances increased competition for food can reduce survival as individuals have to spend more time foraging (a risky activity) to meet their needs. Density-dependent survival in the juvenile stages generates stock-recruitment relations that are often the basis of models used for harvest management.

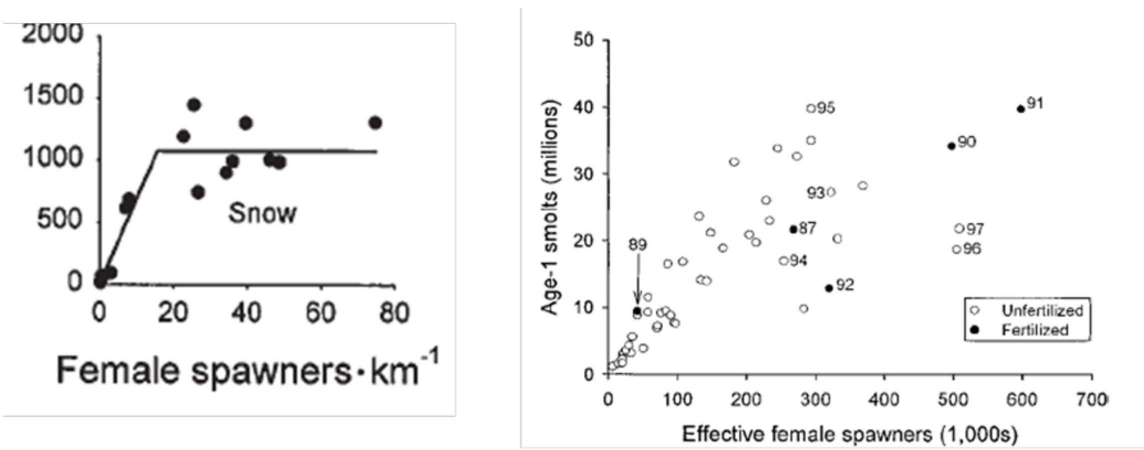

Figure A1. Two examples of compensatory relations between the abundance of parent spawners, and the resultant production of juveniles (smolts) 2 years later for (left) coho salmon in a small stream, (right) sockeye salmon from Chilko Lake, BC. The coho stream is an example of strong density-dependence as once the stream is fully seeded, additional spawners have no impact on smolt production. For sockeye salmon the relation is more linear as density-dependent survival is probably related to food supply limitation (Bradford et al. 2000a,b).

Density-dependent processes can occur in the adult stages. For example, density-dependent growth is commonly observed in small lakes, with growth decreasing at higher abundances due to competition for limited food resources. Reductions in growth can affect survival and reproductive potential, and lower the average size of fish available to fisheries. Density-dependent limitations can also occur during reproduction if the habitat used for spawning is in short supply.

Vital rates that decrease with density are considered *compensatory* in nature because they will tend to stabilize population abundances. When populations increase in numbers, survival or growth will decrease and that causes a reduction in productivity and abundance. Conversely, when populations are reduced in numbers due to fishing or another agent of mortality, vital rates will increase. Population productivity will then increase which will offset the effect of the increased mortality. Compensatory processes are the basis for sustainable yield as they result in an increase in population productivity when populations are reduced in abundance by harvest.

There are some situations in which *depensatory* process are important. In these cases vital rates increase with abundance, usually when populations are very small. Depensation can be caused by predation that causes the per-capita mortality rate to increase as populations get smaller, environmental conditioning, where a minimum abundance is needed to affect the quality of spawning or rearing environments, or if there are benefits to fitness from group or social mechanisms. Depensatory processes cannot mitigate the impacts of residual impacts of projects. Rather, they are a risk factor for projects or cumulative impacts that cause populations to become very small.

Although density-dependent mechanisms are explicitly modelled (e.g., stock-recruit analysis) or implicitly considered in decision making for fisheries management, only rarely are they considered in environmental impact assessment (Shuter 1989). Shuter (1990) highlighted that compensatory processes can mitigate environmental impacts, but the extent depends on the temporal sequence of events and the strength of the compensatory response. In general, if an impact to a population occurs in a life stage before the density-dependent stage, the effect of the impact may be reduced by compensation on one or more vital rates.

For most populations the nature and extent of compensatory processes is generally not well understood and a range of approaches have been used to deal with this issue in the context of environmental impact assessment (adapted from Shuter 1989). These are arranged by the degree of belief in the strength of density-dependent effects in the life cycle.

1. Ignore compensation and assume that effects on any life stage will translate proportionately to adult abundance. For example, a project that causes a 10% mortality rate among eggs is assumed to result in a 10% reduction in adult abundance. This is a risk-averse approach that could be used when information on compensatory processes for the affected populations is not available. Impacts to other vital rates are more difficult to translate into population-level effects, but it is assumed that there will be negative effects.
2. If fish populations are depleted by overfishing or other factors compensatory processes can be safely ignored. In these cases abundances may be too low for density dependent processes to mitigate project effects. For example, in Figure A1, if the spawning population is reduced to less than 20 fish$\cdot$km^{-1}, a stressor that reduced adult abundance would be expected to cause a corresponding reduction in juvenile production.
3. Assume that some compensation occurs and analyse the effects of a project using a population model that takes into account density-dependent processes (Power 1997). For most populations that are part of CRA fisheries (and are therefore at abundances less than the unfished equilibrium) compensation will partially mitigate an environmental impact, but is unlikely to be able to completely offset it. For example, a stressor that causes a reduction in the number of adult spawners in the sockeye salmon example will cause the number of smolts to decline although the non-linear nature of the relation means that there may not be a direct proportional reduction in smolts (i.e., a 10% reduction in spawners will only cause a 5% reduction in smolt yield). As noted by Shuter (1990) the sequence of events is important in evaluating effects: if the stressor occurs after the density-dependent stage, then no compensation is expected. For example, a stressor that causes smolt mortality in salmon (after the early freshwater processes shown in Figure A1) is expected to be density independent and cause a proportional reduction in adult abundance and productivity. Depensatory processes can also be included in the analysis where appropriate.
4. Assume that compensation is strong and impacts to growth and survival at life stages prior to the compensatory stage will be completely absorbed and mitigated. This approach may be justified

when the evidence for strong compensation is compelling. An example are stream dwelling salmonids such as coho salmon (Figure 1A) for which abundance is limited by physical space and many more juveniles are produced than there is space for them in the stream.

For many project reviews option 1 will be used as the default in the absence of detailed information. Options 2 and 3 will require detailed modelling or analysis to both calculate the implications of compensation on population impacts, and to determine if those conclusions are robust to the uncertainties that are inherent in such analyses.