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Monitoring fish habitat compensation in the Pacific region: lessons from the past 30 years

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ABSTRACT

To offset the impacts of development projects on fish and fish habitat, compensation or offsetting works can be required as a condition of an Authorization issued under the *Fisheries Act*. However, the efficacy of these works is often unknown as follow-up monitoring is infrequently conducted. Here we review past habitat compensation and restoration monitoring activities in Canada's Pacific Region. We first describe various types of monitoring schemes that differ in their objectives, the types of information collected, and required levels of expertise. We then review monitoring studies in the Region with a focus on four case histories. We found successful monitoring of biotic responses (fish or invertebrates) were few as the spatial and temporal scales of most programs were too limited to cope with natural and sampling variation. Few studies had pre-project baseline information, and subsequently sampling relied on comparisons of treatment sites against control or reference areas. A number of the most insightful studies sampled sequentially over time and identified decadal-scale changes in constructed habitats. Most monitoring programs were of insufficient scope to estimate the effect of restored or constructed habitats on fish population productivity. We conclude that when designing a monitoring program investigators carefully specify their objectives and determine whether those objectives can be met given available resources, time, and expertise.

Surveillance de la compensation de l'habitat du poisson dans la région du Pacifique : les leçons tirées des 30 dernières années

RÉSUMÉ

Afin de compenser les répercussions des projets d'aménagement sur le poisson et l'habitat du poisson, des travaux de compensation peuvent être requis à titre de condition d'une autorisation délivrée en vertu de la *Loi sur les pêches*. Cependant, l'efficacité de tels travaux est souvent inconnue, car on effectue rarement une surveillance ou un suivi. Le présent document examine les activités antérieures de compensation de l'habitat et de surveillance de la restauration dans la région du Pacifique, au Canada. Nous décrivons d'abord divers types de régimes de surveillance dont les objectifs, la nature des données recueillies et les niveaux d'expertise nécessaires diffèrent. Nous examinons ensuite les études de suivi dans la région en nous concentrant sur quatre cas types. Nous avons observé qu'une surveillance adéquate des réponses biotiques (poissons ou invertébrés) était peu fréquente, car les échelles spatiales et temporelles de la plupart des programmes étaient trop limitées pour gérer les variations naturelles et d'échantillonnage. Peu d'études contenaient des renseignements de base préalables au projet. C'est ainsi que l'échantillonnage reposait sur la comparaison de sites de traitement et de zones de contrôle ou de référence. Quelques-unes des études les plus pertinentes effectuaient des échantillonnages en ordre séquentiel au fil du temps et relevaient les changements à l'échelle décennale dans les habitats construits. La portée de la plupart des programmes de surveillance était insuffisante et ne permettait pas d'estimer l'effet des habitats restaurés ou construits sur la productivité de la population de poissons. Nous concluons donc qu'au moment de concevoir un programme de surveillance, les enquêteurs devraient définir avec soin leurs objectifs et déterminer si ceux-ci peuvent être atteints vu les ressources disponibles, le temps accordé et l'expertise à leur disposition.

1 INTRODUCTION

In the Pacific region of Canada the practise of creating habitats to offset for fish habitat lost through development activities, and the restoration of degraded habitats has a long history, particularly for the region's iconic species, Pacific salmon (*Oncorhynchus* spp.). Early examples include the development of spawning channels to compensate for habitats lost due to hydroelectric development (Hourston and Mackinnon 1956), and efforts to restore degraded estuary habitats (Pomeroy et al. 1981). Since the implementation of the 1986 Habitat Policy (DFO 1986) compensatory habitat works became much more common and have occurred in freshwater, estuary and marine habitats.

The need to evaluate the efficacy of compensation and restoration activities has also long been recognized in the region, and a number of studies, surveys and reviews have been published over the past 40 years (e.g.,Cooper 1977; Kistritz 1996; Levings and Nishimura 1997; Lister and Bengeyfield 1998; Cooperman et al. 2007; Carter et al. 2012). Assessment of compensation works was expanded to the national scale by Harper and Quigley (2005). This paper provides a brief summary of habitat compensation and restoration monitoring in the Pacific region, highlights results of four case studies, and concludes with recommendations for the design of future monitoring programs. Although these recommendations are based on the review of information collected under the framework of the 1986 Habitat Policy, the requirement for monitoring remains in its replacement, the Fisheries Protection Policy Statement (DFO 2013) and the associated regulation resulting from the 2012 revisions to the *Fisheries Act*. In the new policy the concept of compensation habitat is broadened by the use of the phrase "offsetting", however, in this report we will use "compensation" in reference to findings from the pre-2012 regulatory regime.

1.1 WHY MONITOR?

This seemingly simple question is critical to matching monitoring effort and study design to expectations and program goals. It is worthwhile to analyze potential or proposed monitoring activities to determine what information they can yield, and the types of program goals that can be addressed.

Using models developed for business applications (Clemen and Reilly 2001), we developed an objective and program hierarchy that helps to describe the value of habitat compensation monitoring (Figure 1). At the top of this hierarchy was the 1986 Habitat Policy (now replaced by the Fisheries Protection Policy Statement) and below that are some of the instruments of those policies (including Compensation/Offsetting). These describe the program at the national level. Next we consider the regional program by identifying information requirements and regulatory approaches by ecosystem type, and finally at the lowest level is the compensation or offsetting that is prescribed for a specific project. This hierarchy combines both a nested set of objectives, and the spatial scale of the program.

Monitoring provides feedback information that can be used for the evaluation of performance at each level of the hierarchy, and can be the basis for informed changes at any level. However, the nature of the monitoring program affects which level or levels of the program hierarchy will be informed by the results. These relationships are illustrated by the feedback loops in Figure 1.

The simplest and most basic monitoring is often called "compliance monitoring" as it seeks to determine if a proponent has fulfilled the requirements of a *Fisheries Act* authorization for a work or undertaking impacts fish habitat, or kills fish. Such an assessment will usually include measurement of the size of the impacted area, possibly by habitat type, and the area of the compensation works relative to that specified in the authorization. A visual assessment can be used to determine if the newly-created offsetting or compensation works meet the specifications of the authorization. In terms of the feedback loop, this type of monitoring is most strongly tied to the individual project. With this information, changes to the compensation works at the site can be implemented if the project deviates from the conditions of the authorization. There are also links to the overall program performance if this type of monitoring is conducted at a widespread scale, as the overall rate of proponent compliance across the region or nation can be estimated. Carter et al (2012) conducted a file audit of compliance monitoring in the Pacific Region that was patterned after Harper and Quigley (2005). Both reviews showed there are instances where proponents failed to comply with the requirements set out in the authorization.

We call a slightly more detailed assessment that provides a basic evaluation of effectiveness “functional monitoring” (called “Project effectiveness monitoring” by Koning et al. 1998). This type of assessment has the goal of determining whether compensation or offsetting works are functioning from a biological perspective. Monitoring might involve measurements of habitat quantity, and parameters of physical and biological condition, usually from a one-time site visit shortly after construction. A visual evaluation of the functioning of the habitat may also be included. Koning et al. (1998) provide an example of checklists and scoring of habitat function in their “routine monitoring” protocol. These data can be compared to reference data or standards, or expert opinion based on accumulated knowledge in region. In some cases control sites are sampled to permit paired comparisons. This level of monitoring can be used to inform managers at the operational level about the function of compensation prescriptions, but are less useful for overall program evaluation because the overall goal (e.g., maintain fisheries productivity) is not directly measured. Compliance of individual projects can also be addressed if the results are compared to the conditions of the Authorization.

The most detailed type of monitoring is a fully-designed scientific monitoring study (“Research evaluation”, Koning et al. 1998). Here, a science-based *a priori* monitoring plan is developed that will have sufficient scale and scope to evaluate the contribution of the compensation habitat or offsetting works to fisheries productivity or a surrogate for productivity (Minns et al. 2011). In the past this type of program has only been conducted on a limited number of sites, and thus will not greatly contribute to the evaluation of compliance at the program level. Rather, it is designed to add to the knowledge base on compensation or offsetting effectiveness and should provide information that can be used to evaluate progress to the overall program goal. Detailed process-based studies are also likely to provide insight into potential indicators or simpler approaches that can provide a scientific basis for the design of the less intensive monitoring programs.

1.2 MONITORING STRATEGIES

The main parameters in the design of monitoring studies are the choice of metric and decisions about space, time and replication. In cases where existing habitat is about to be altered, data can be collected at one or more intervals before and after the alteration in a Before-After (BA) design. If there is a risk of an external factor affecting the variable being sampled, one of a variety of schemes that include unaltered habitats can be used. The most well-known is the Before-After Control-Impact (BACI) design that compares the differences between the impacted and control site, before and after the treatment. These designs help to control for transient factors (i.e., drought, floods, fishing pressure) that could confound the interpretation of changes at the treatment site. The various chapters of Schmitt and Osenberg (1996) describe the merits of each study design.

In some instances pre-development data may not be available, and in the specific case of compensation works, pre-development habitat may not have existed if the compensation requirements involved the construction of new habitats such as wetlands or stream channels. In these cases, a spatial comparison is usually made between treated and control sites. Paired designs involve the selection of pairs of treatment and control sites in relative proximity to each other to enable an assessment of the impact of unrelated environmental variation that may cause sites to vary in their attributes. These data can be analysed in nested, hierarchical designs. Al-chokhachy et al. (2011) recently reviewed the components of variability in stream habitat metrics and found that most variation was due to differences among sites, compared to temporal variation or measurement error. Large inter-site variation can severely limit the utility of spatial designs (see Cooperman et al. 2007 for an example), which speaks to the need to maximize replication of both treatment and control sites if the opportunity exists.

If comparable control sites are not available, or are not sampled, data from treatment sites can be compared to relevant reference data, such as regional norms or benchmarks for similar ecosystems and habitat types. Dissolved oxygen or other water quality variables are amenable to the reference or water quality criteria approach, as guidelines have been developed from many detailed studies on these factors. It is also feasible to develop standards or benchmarks for other habitat measures or biotic indictors. For example, a long history of data collection from juvenile salmonid habitats (e.g., Mossop and Bradford 2006) gives investigators a basis for assessing the results from individual sites to general expectations for the species or habitat type (Randall et al 2017).

In the case of newly created habitats, repeated sampling over time (a trend design) can identify successional changes in habitat structure and function. Parallel sampling at control sites can be used to evaluate trends in larger-scale factors that can confound the evaluation of the treatment site. Repeated sampling creates temporal replication which facilitates a continual improvement in the comparison of treatment and controls with the option of terminating the evaluation when a conclusion can be drawn with a predetermined level of confidence (a sequential design - Cochran and Cox 1957).

Finally, a space-time substitution design can be an efficient way to understand how compensation habitats change over time. For this design a large number of treatment sites that vary in their age (since construction or modification) are sampled at one time, and comparisons of habitat conditions are made against the age of the project. Although habitat metrics will vary in space and time, this approach does yield valuable, general, information about the evolution and longevity of restored or constructed habitats (see Lennox et al. 2011 for an excellent recent example).

1.3 STATISTICS

Data collected in monitoring programs are most often analyzed with classical statistical models; often variations on ANOVA models are used that seek to evaluate the strength of evidence against the null hypothesis of no change (over time or space) in the metric of interest. However, some have argued that classical statistics (based on hypothesis tests and P-values) do not make full use of available data, and may in fact be quite misleading (Stewart-Oaten 1996; Bradford et al. 2005). Classical tests, such as ANOVA were designed for the analysis of experimental data and have been termed “kind to the null hypothesis”. That is, the decision criteria (e.g., $P < 0.05$) have been traditionally set so that the evidence must be compelling to reject the null hypothesis of no impact or no effect. Further, the dichotomous hypothesis test does not make full use of data, as it provides no information about the estimate of the effect, nor the uncertainty surrounding that estimate. Consequently, many authors encourage the use of estimation-based procedures such as the use of confidence intervals or Bayesian probability intervals rather than hypothesis tests to assist decision makers (Bradford et al. 2005).

These statistical issues are particularly important for the assessment of compensation habitats. In many cases compensation projects are considered successful when the value of a metric for the compensation habitat is similar to that of a control or reference site, or meets a target for fisheries productivity that balances losses from project-related residual effects. When data are submitted to a standard hypothesis testing procedure, a successful outcome results from the confirmation of the null hypothesis. Unfortunately, in classical statistics the null hypothesis is assumed to be true, and statistical tests evaluate the evidence against it. Thus the methodology cannot be used to confirm the null hypothesis of no effect, only to evaluate the evidence against it.

A more useful approach is similar to equivalency tests developed for comparing new and existing drug formulations (Rusticus and Lovato 2011). In this approach a predefined “range of indifference” is defined (such as ±20% difference between compensation and natural habitats). That zone is compared to confidence intervals or uncertainty bounds around the estimates of the difference between the treatment and control sites. Variability or uncertainty in the data and the adequacy of sampling is considered explicitly. For example, if the confidence interval around the effect size is large, managers may have to temper their conclusions about a compensation project, if the results of the monitoring program cannot exclude the possibility that the effect is much larger than their “range of indifference”. Figure 2 provides some hypothetical outcomes from this approach.

2 COMPENSATION AND RESTORATION MONITORING IN THE PACIFIC REGION

The construction of habitat restoration and compensation projects in the Pacific Region probably began with the removal of beaver dams from salmon spawning areas in the 1940s and development of artificial spawning channels in the 1950s, but activity accelerated in the 1980s as the Habitat Policy was developed. The need for monitoring and evaluation was recognized from the outset; for example, in the case of spawning channel assessments it was soon revealed that maintenance was required to maintain effective function (Cooper 1977).

We summarized monitoring activities for habitat restoration and compensation works in the Pacific Region by searching for published scientific papers and other reports and documents using WAVES and Web of Knowledge. No attempt was made to extract individual contract or proponent reports from area offices although some of these are summarized in the papers we did review. Most studies listed are either functional or effectiveness studies; compliance audits are not generally published (although see Quigley and Harper 2006).

Studies varied in the manner in which they were conceived. Some were conducted on behalf of the project proponent, usually within a few years after construction. These studies generally focussed on determining if the new habitat existed and was functioning as designed. As noted above, we did not make an effort to find more of type of studies; many more proponent monitoring studies are likely available.

In the second category are follow-up studies, usually commissioned or organized by Habitat Management of DFO. In these cases an independent contractor visited previously developed sites, 2-12 years after construction and conducted a functional assessment. The assessment generally consisted of a single site visit, during which measurements of area and a visual assessment of biological function were conducted. In some cases, measurements of habitat or fish presence were made. If the post-construction information was sufficiently detailed, these follow-up studies do permit an evaluation in the change in the compensation habitat over time.

Finally, there are a few instances of research-level studies. Some were detailed single site studies where the physical, chemical and biological aspects of the compensation or restoration site were studied over time, and efforts were made to evaluate effects of the project on fish production. Others were less detailed, but were more spatially extensive, permitting a meta-analysis of data across a number of sites or projects. An important difference between these studies and the previous types is the use of structured sampling designs that permitted a quantitative evaluation of results.

From a study design perspective, the absence of pre-project (“before”) data is very common and most investigations used a spatial design comparing treated sites to control sites, or made use of the reference approach for evaluating treated sites against regional benchmarks or expert opinion about what constituted functioning fish habitat. Many studies were not quantitative, and in many cases only summary statistics were provided without formal analysis.

2.1 MONITORING METRICS

A wide variety of metrics were used in the various monitoring programs (Table 1); some of that variation can be attributed to the nature of the sites being sampled, goals of the program, resources available and the research acumen of the investigators. Although it would have been ideal to have metrics to evaluate changes in productive capacity, as identified in the 1986 Policy, or fisheries productivity as per the Fisheries Act (2012), there are pragmatic limitations that often require the use of proxies for fish or habitat productivity (Minns et al. 2011). Many studies rely on measured estimates of habitat area and visual surveys to evaluate biological function. Visual assessment could be an overall rating of habitat function (poor, good etc.) or a more semi-quantitative evaluation (% successful riparian planting, % cover, large wood abundance etc.). Quantitative estimates of biological function in response to habitat restoration were made on most of the studies listed in Table 1, but only 5 of the 19 quantitatively evaluated the change in fish abundance in response to habitat restoration.

Invertebrates are sometimes seen as a useful alternative to fish monitoring as many taxa are fish food, and various metrics have been developed that use invertebrate abundance and diversity as measures of habitat quality. While invertebrate samples are relatively easy to collect in the field, the cost of sample processing and the scarcity of skilled taxonomists creates challenges for generating data of sufficient quality for the evaluation of diversity. Two recent studies challenge the utility of stream benthic invertebrates as indicators of changes associated with stream restoration (Louhi et al. 2011; Miller et al. 2010); both studies note that invertebrate richness and abundance may be more affected by watershed or landscape factors than localized habitat conditions. Invertebrate density, in particular, is highly variable, and Miller et al. (2010) note that published studies had only an 11% chance of detecting a 20% change in abundance because of natural and sampling variation. This is problematic when the goals of some restoration or compensation activities are to increase the abundance of food organisms for fish.

Fish sampling metrics in the Pacific region focus almost exclusively on Pacific salmon or trout, and in most cases, on the juvenile stages. Juvenile salmon abundance and habitat use will depend on many extrinsic factors, including the abundance of parent spawners (which is in turn a function of fishing mortality and ocean survival), variation in migrations and movements, and variability in environmental conditions such as water levels, flows, tides (Vehanen et al. 2010). In addition, in many habitats, notably estuaries (Levings, 2016), capture methods vary considerable in their efficiency, making comparisons based on catch per effort statistics of questionable utility. Consequently, investigators often rely on the demonstration of fish use alone as an indicator of the functionality of the new created or altered habitats. Estimating juvenile salmon abundance is generally a research-level activity.

Wetland area has been used an indicator in several estuary monitoring programs in Pacific Region and also has been applied in numerous estuaries on the northeast Pacific (Levings 2016). The wetland area of 442 BC estuaries was given by Ryder et al (2007) and may provide useful baseline metrics. Almost 60% of the estuaries are <30 ha in area (Ryder et al., 2007) and most of these systems support salmonids with widely varying species composition and populations. A proportional relationship between salmonid productivity and wetland area is assumed, but this complex relationship is far from understood. This metric has also been used in other contexts - a key quantity indicator in the Wild Salmon Policy is estuarine wetland habitat area (riparian, sedge, eelgrass, and mudflat, Stalberg et al. 2009). In 1985 The Fraser River Estuary Management Program (FREMP) established one of the earliest estuarine classification systems for use for managing salmon habitat. Based on vegetation productivity as an indicator, habitats were classified as Red–high value, Yellow–moderate value, Green–low value habitat. The classification system enabled mapping of habitat to give managers guidance for preservation of salmonid habitat.

FREMP also established one of the earliest estuarine classification systems for managing fish and wildlife habitat on the northeast Pacific coast. It is based on ground-truthed inventories of habitats and vegetation (includes detailed GIS mapping of vegetation units and on aerial photography). Sixteen indicators, using a mixture of ecological and economic metrics and including area of red coded (wetland) habitat, were used in the monitoring program. Because the project directory of FREMP maintains good records of wetland gain and loss, it is a good source of habitat change data in this large estuary (Fraser River Estuary Management Program 2006).

Other metrics of the estuarine ecosystem such as invertebrate density, fish community structure, number of species, density of certain species and other measures have been used for research projects in the Pacific region. Sampling at regular intervals (e.g., annual or decadal) has been done in very few estuaries, one such example is surveys of salmonids at the Campbell River estuary between 1982 and 1994 (see Case 3 below). Comparisons of long term data by repetitive sampling, even with long time intervals separating surveys, can be valuable. A good example is the comparison of fish community structure between 1972–1973 and 1993–1994 in the Fraser River by Richardson et al. (2000) that showed that community structure was "remarkably similar" in the two time periods. Monitoring recovery from impacts such as sewage pollution can be achieved by comparing temporal abundance of indicator invertebrates species (e.g., polychaetes and amphipods, Arvai et al. 2002), although the aforementioned challenges with taxonomy can be limiting. Wetland plant identification is somewhat easier as they are "macroscopic" and several electronic guidebooks are available.

For analysis of the long-term function of compensation or offset sites it is vital to have reliable baseline surveys with accompanying metadata so that sampling can be replicated. An extensive review of Pacific estuary biological databases is beyond the scope of this review. However we note that significant fish surveys using seines, trawls or traps have been conducted at the Squamish, Fraser, Nanaimo, Englishman, Courtenay, Campbell, Yakoun, Skeena, Kitimat, Somass, and possibly other estuaries over the past 40 years. Many of these data are in the grey or DFO file literature and might be reasonably well documented although positional data may be difficult in the years before GPS use became common. Beach seines are the most common capture methods but nets with a variety of mesh sizes have probably been used, making data comparisons difficult if not impossible. Nonetheless these studies can form the baseline for long-term evaluations of restoration or compensation works.

Oceanographic and hydrological measurements can also be important indicators of estuarine functioning to support salmonids. Temperature, salinity, tidal exchange and freshwater flow are some of the important indicators to consider (Levings 2016). Few if any BC estuaries have long term time series on temperature and salinity. However the data bases provided by the Water Survey of Canada may provide information on flows if gauges are located in the freshwater reaches of the estuary. Tidal exchange is closely related to the morphology of the estuary as dredging and filling affects ocean water inflow in the salt wedge which may impact the effectiveness of compensation habitats. Long term assessment of the estuary's channel configuration may be possible by examination of temporal series of satellite imagery or aerial photographs.

3 CASE HISTORIES

To explore study designs in greater depth we consider 4 case histories drawn from examples in Table 1. These studies were chosen to represent a range in monitoring studies and to illustrate challenges that were experienced in each study.

3.1 CASE 1: REPLICATED SPATIAL DESIGN FOR STREAM BANK STABILIZATION PROJECTS

Cooperman et al. (2007) examined the impacts of bank stabilization projects on fish habitat in two central BC streams. This study could be characterized as research level as many quantitative measurements were made in a structured design. Sampling was independent of the construction of the physical works. No pre-construction data were available.

A total of 16 treated and 12 control sites were sampled, in a non-paired design. The authors hypothesized the treatment sites would have more diverse habitats, greater riparian cover, and more aquatic invertebrates than the control sites. A total of 9 habitat, 5 riparian and one invertebrate metric was sampled. Overall, the authors found few statistically significant differences between treatment and control sites and note the high variability in the data, and the lack of pre-project data for the treatment sites preventing the use of a Before-After design.

The author's conducted a retrospective power analysis using their data, using the observed difference between treatment and control sites to ask how many samples would have been needed to reliably detect a significant effect. This utility of this analysis has been criticized on statistical grounds (Hoenig and Heisey 2001 and many others). A more informative approach would be to specify effect sizes relevant to managers (e.g., if a 25 or 50% change represented a meaningful improvement in condition), and use the data to estimate sample sizes needed to create sufficiently precise confidence intervals for their metrics.

Irrespective of the method of analysis, the summary statistics in Cooperman et al. (2007) suggest the coefficient of variation (CV) for most metrics is in the 50 to >100% range, a range that would make the detection of an effect size of management interest very difficult. Some of this variation would have probably been reduced if a before-after comparison was possible.

This study illustrates a number of issues surrounding habitat monitoring. First, it could be argued that the monitoring program did not directly address the goal of the physical works, which was bank stabilization. A true assessment of bank stabilization would have required detailed surveys conducted at decadal intervals to capture the effects of major streamflow events on bank structure. In effect, the monitoring program evaluated some of the collateral benefits of bank stabilization, a hypothesized increase in habitat complexity. Second, the finding that the treated sites did not differ from reference sites could be interpreted as a lack of support for an increase in habitat complexity, however, the alternative view, that the treatments produced similar habitat conditions could be considered a partial success if the bank stabilization sites were initially degraded relative to the control sites. Finally, the extremely high variability in the sampled metrics does highlight the challenges of monitoring and the need to carefully consider the power of the monitoring program. The field and analytical efforts in this study far exceed that observed in typical programs executed by habitat managers or proponents (see Pehl 2009 for a relevant example). It is possible that a simpler expert or visual examination of the sites may have yielded similar insights and been a more efficient approach to these cases where pre-treatment data were not available, or intensive study of a few sites is not possible.

3.2 CASE 2: A LONGITUDINAL STUDY OF COMPENSATION WORKS

Between 1984 and 1991 a series of compensation projects were developed in south-central BC to offset habitat impacts associated with railway and highway construction. The projects consisted of the development or expansion of off-channel wetland habitats and a combination of bank stabilization and habitat complexing in the mainstem North Thompson River. The objective of these projects was mainly to provide rearing habitat for juvenile Pacific salmon. Spawning gravels for salmonids were also added to the mainstem site.

These sites received reasonably intensive post-construction monitoring by the proponent for 1-3 years after they were built. That monitoring consisted of measurements of the physical habitat area, water depth and flow, dissolved oxygen in the wetlands, and fish sampling that was designed to obtain a relative measure of fish use (catch per effort of juvenile Coho salmon). The goal of the initial monitoring was to determine if the new habitats were functioning as expected.

In 1996 DFO contracted the consultant that conducted the original post-construction monitoring to repeat the assessment using similar methods; this second round of data collection occurred 5-12 years after construction (Lister and Bengeyfield 1998). The assessment consisted of a single site visit during the low flow period in the fall.

The results revealed that most sites were still performing as expected but some of the constructed wetlands were beginning to infill as a consequence of sedimentation and possibly enhanced nutrient loading from upstream agricultural activities (Figure 3). Of 7 wetland ponds, 4 had experienced reductions in area, ranging from 9-44%, and in 2 ponds juvenile salmon were absent, possibly due to low levels of dissolved oxygen. Deterioration of a log fish ladder was noted. The mainstem river sites showed small signs of deterioration including the movement of rocks from flow deflection structures and a loss of some spawning gravel, presumably due to high freshet flows. The original post-construction monitoring indicated these sites were well-colonized by juvenile fishes relative to control sites, and limited observations of fish in the 1996 survey supported those conclusions.

Although the field studies were well conceived (albeit limited in scope) no formal statistical analysis was attempted, and the conclusions of the report relied on comparisons of means or single observations.

Despite these limitations this study highlights the value of longer term monitoring to determine the durability and potential loss rates for compensation works. The cases that were evaluated had reasonably detailed post-construction monitoring that was well documented thus permitting a long-term assessment. Metrics used in the evaluation are simple, but repeatable, and provided useful insight. A re-evaluation of these projects (now ~20 years old) would be extremely worthwhile.

3.3 CASE 3: A RESEARCH STUDY OF ESTUARY RESTORATION

The creation of intertidal habitat on artificial islands in the Campbell River estuary on Vancouver Island provided an opportunity to examine estuarine rehabilitation as a technique for modifying the capacity of coastal estuaries to produce salmon and compensate for habitat losses due to industrial intrusions into estuaries. The Campbell River estuary had been degraded by log storage activities, and a change in that activity allowed for the construction of new and restored habitats. A unique aspect of this project was that DFO Science Branch and Environment Canada partnered with DFO Habitat Management and the forest industry from the outset and monitoring began immediately after construction in 1982. Four islands totalling 18.8 ha were created and 23,000 marsh plants were relocated to populate the islands.

Data were collected from Campbell River estuary between 1982 and 2002. A spatial design that relied on a reference site to define the natural condition and variation was used as it was not possible to collect pre-treatment data. However, only one reference location was measured and, while treatment sites were replicated within the estuary, similar measurements were not made coincidentally in neighbouring estuaries limiting the extension of findings to the region. The experimental design was further sub-divided with consideration to tidal stage, sample elevation, degree of exposure to tidal and river currents, planted vs unplanted blocks and island configuration at the sample site. Many of these sub-divisions can properly be described as factors nested within the overall spatial and temporal experimental design but generalizations are hampered by the use of a number of response metrics; many of which did not share common sample locations, times or methods. Hence it was necessary to consider the metrics individually or in groups specific to an individual purpose.

Island construction in the Campbell River estuary had two objectives: creation of a network of estuarine channels as refuge and feeding stations for juvenile salmonids (particularly Chinook salmon) and to develop an extensive marsh network on the islands to create refugia and provide a food source for transient fish. Estuarine food webs tend to be detrital-based and aquatic macrophytes provide cover for fish, therefore vegetation is often used as a surrogate indicator for high-quality fish habitat (Levings 2003). Vegetation dynamics were measured periodically for 20 years (1982-2002) by staff from Environment Canada using the following metrics: plug success, total cover/transect, biomass by species and stem height. Conclusions based on 13 years of these data have been published (Dawe et al. 2000) and generally concur with independent measurements of cover by species made annually with quadrats between 1982 and 1986 by DFO (Levings and Macdonald 1991).

Results suggested that the first five years of monitoring captured the period of greatest marsh development in terms of cover and species richness, but seven to thirteen years was required for the created sites to reach vegetation levels equivalent to reference conditions (Figs. 4 & 5). This was particularly true in blocks that were allowed to re-establish passively without the initial benefit of transplants. Furthermore, cover estimates and species composition approached natural levels more rapidly than measures of vegetative quantity (biomass) and may be the preferred metrics for short-term monitoring efforts. Plug survival provides an estimate of success within the first year when planting is part of the habitat creation process. Plug survival at 90% a year after planting in the Campbell River estuary was considerably higher than restoration plots in the Fraser River estuary where Pomeroy et al. (1981) recorded survival as negligible in some plots and never more than 84% in others.

The benefits of a long-term approach were evident. In 1988 it was concluded that the marsh communities had stabilized but that proved to be erroneous in 1994 when major changes in community composition were observed to be continuing. Other influences were not anticipated or incorporated into the original design. Rates of accretion, erosion, and compaction, sometimes involving driftwood and water retention in poorly drained portions of the islands were enough of a liability to plant development to potentially jeopardize the project’s success. Recent observations suggest that grazing by growing populations of Canada Geese are having a significant impact on vegetation of the Campbell and nearby estuaries (Dawe et al. 2011) an observation that serves to highlight the potential for large-scale environmental factors to overwhelm local efforts to create or restore habitats. Consequently, Dawe et al. (2000, 2011) recommended a flexible and adaptive approach that includes intervention in order to maintain the function of restoration and compensation projects.

Metrics describing invertebrate communities in the Campbell River estuary were fundamental to the examination of the pathways of effects linking marsh creation to benefits to salmonids. However, regardless of their importance to estuarine ecosystems, they proved to be difficult to successfully incorporate into compensation monitoring programs. The cost and complexity of sampling and large amounts of inherent variability restrict their practicality to ecological process-oriented research programs. The opportunistic nature of many invertebrate species contributes to variability among replicates within years and leads to conclusions that compensation sites are colonized rapidly when contrasted with reference conditions. Larval dispersal to manufactured habitat in coastal locations is rapid (Boyd 1982) particularly at lower intertidal sites (Cammen 1976), but treatment-reference comparisons of a pooled taxa metric in the Campbell River estuary were hampered by large annual variability and a limited number of reference samples, leading to low experimental power and inconclusive results (Levings and Macdonald 1991). Temporal comparisons of individual taxa were similarly inconclusive with the exception of an abundant sabellid polychaete (*Manayunkia sp.*) and unspecified meiofauna that were persistent recruits to island habitats two or three years following their creation. The identification of reliable indicator taxa may be the most expedient means to incorporate invertebrate data into compensation monitoring programs. While *Manayunkia sp.* has some qualities that may make it a good habitat indicator (Cranston 1988), it is rarely eaten by salmon and was therefore of limited value in a study designed to link salmon production to estuarine marshes.

Sampling fish, like invertebrates, is a labour-intensive undertaking that is further complicated by their transient nature (e.g., salmonids) and external factors that influence abundance (particularly annual variation in wild and hatchery salmon production). However, proxies for fisheries productivity can provide valuable information. For example, examination of juvenile chinook salmon diets, a measure of habitat quality and fish performance, suggested a dependence on food of the sort produced on the Campbell estuary islands, especially for fish taxa that spent more time in the estuary (Macdonald et al. 1987). Furthermore, the importance of island configuration as a factor beneficial to salmonids could only be evaluated with spatial and temporal juvenile salmonid CPUE comparisons standardized with annual estimates of juvenile fish production from sources external to the estuary. Sheer zones and low-flow refugia, both created during island construction, may concentrate food and enhance feeding opportunities while marshes, once established, are widely recognized as important cover for fish (Macdonald et al. 1987). Follow-up studies in 1994 suggested that juvenile salmon growth in the estuary was density dependent (Korman et al. 1997), leading the authors to highlight the significance of the new habitats in adding to food production in the estuary.

Although none of the fish studies could directly demonstrate an improvement to fish survival, abundance or production due to the creation of new habitats, growth, diet, and distribution data point to the high likelihood that the construction of these habitats has benefitted salmon. However, even this indirect assessment required a significant multiyear research effort by a number of agencies and collaborators.

3.4 CASE 4: A BEFORE-AFTER DESIGN FOR FLOW MANIPULATION

As part of the Water Use Planning process, BC Hydro has implemented a number of monitoring programs to evaluate the use of altered flow regimes as a tool for habitat restoration and the mitigation of impacts associated with hydroelectric development. The oldest of these is the Bridge River flow experiment. During the pre-treatment period (1996-2000) only residual flows occurred below the dam in the Bridge River; between 2000 and 2011 water was released from the dam in a semi-naturalized hydrograph based on an annualized water budget of 3 m^3s^{-1}. This was increased to 6 m^3s^{-1} in 2011 and remained to 2016. Results from 1996-2008 were reported in Bradford et al. (2011). This project is unique relative to the other case studies in that four years of pre-treatment data were collected, and the sampling design has remained constant throughout. No attempt was made to use a control stream as there are none comparable in this highly mountainous region. It was expected that the downstream reaches of the river would serve as a quasi-control as large tributary inflows reduce the effect of dam releases.

Water volume, chemistry, temperature, primary production, invertebrate abundance and fish sampling were all part of this annual study plan. Replicate sites have been established along the length of the river and nearly 50 sites are sampled annually using depletion electrofishing to in order to generate a river-wide estimate of juvenile salmon abundance. Fish data were analyzed with a hierarchical Bayesian model that attempts to account for uncertainty in the sampling as well as natural variation in abundance. The final outputs are probability distributions for the estimated difference in abundance before and after the flow change (Figure 6).

The intensive nature of this monitoring allows the assessment of changes in habitat, lower trophic levels and fish populations in response to the experimental flow regimes. For fish abundance, which was the primary endpoint, the sampling and analysis protocol can detect an approximately 20% change in abundance with high reliability and is appropriate for the decision-making context for the experiment.

A major challenge with a long-term trial like this is maintaining the continuity in the sampling, and keeping up with data management and analysis. BC Hydro has been very successful in terms of the field work and in the creation and maintenance of a database for the experiment. However, it has not had the resources for data analysis and consequently reporting on all aspects of the experiment has lagged. The length of the trial (>20yrs) will exceed the length of careers of many of the participants of this experiment, creating challenges for maintaining momentum. Further, the social and decision context has evolved over the course of the flow trial and rendering the original sampling program less than ideal for all of the performance indicators now under consideration (Failing et al. 2013). Thus such a lengthy and intensive evaluation is likely only warranted when the decision stakes are high and the research interest and capacity is in place to sustain the effort.

4 ANALYSIS

Ideally compensation projects would be assessed with accurate and precise metrics that would permit the estimation of each compensation site’s contribution to fish production, and would provide feedback information to all levels of the hierarchy in Figure 1. Experience in the Pacific Region suggests that studies that have had some success in estimating the effect of habitat restoration on fish abundance or production are research-level investigations, often lead by scientists that have the time, experience and resources needed to address these questions rigorously. In the past very few of these studies were mounted at any one time, even on a national scale, and the few studies that we found from the last decade suggest detailed studies are likely to be even less common in the future.

At the other end of the complexity spectrum a variety of audit or compliance surveys have been implemented, with useful findings (e.g., G3 Consulting 2000; Harper and Quigley 2005; Carter et al. 2012). The primary metric in those studies was usually area, and habitat quality was assessed visually using a variety of metrics (*sensu* Koning et al. 1998). These types of studies do not require a deep level of technical or financial commitment, and a large number of project sites visited can be considered as replicates for regional meta-analyses. However, the assessment of the impact of the project on fish production is largely an expert-driven comparison of habitat condition to a stated or internalized “desirable state”. Thus the validity of these surveys depends on the reliability with which habitat variables can predict gains or losses in fish production. The accuracy of this assessment will depend on the experience and training of the evaluator (Al-Chokhachy and Roper 2010).

We believe the challenge for habitat monitoring arises from studies that fall between these two extremes. Those studies generally involve slightly more than a single site visit, but fall far short of the effort required to fully characterize the dynamic nature of physical and biological conditions. For many studies in Table 1, the fish or invertebrate sampling was conducted with a limited consideration of spatial and temporal variability inherent in those metrics (Al-chokhachy et al., 2011). This can be the result of trying to do too much with limited resources, or can be caused by inadequate experience on the part of the investigators in establishing and following a consistent, rigorous monitoring design. Too often in these cases the resultant data are unusable (Pehl 2009), or leave the investigators lamenting the lack of power or precision in their study (Cooperman et al., 2007).

Although one can conceive a simple continuum in study designs from audits of area to large scale research programs, the benefits or insights into the value of compensation habitats and their contribution to fisheries production may in fact accrue in a non-linear fashion (Fig. 7). We suggest that some intermediate-scale studies tend to generate ambiguous results that have limited additional value compared to simple compliance surveys as the data they generate provide few new insights over those provided by a visual assessment or structured expert appraisal. Many studies that attempt to use fish sampling fall in this category. In other situations, such as vegetation surveys in estuarine habitats, there may be value in relatively modest investments. These examples illustrate the need to evaluate and challenge the value of monitoring studies to ensure the information gained meets the expectations, given the resources available.

The absence of pre-treatment or baseline data in nearly all studies listed in Table 1 is noteworthy, and has likely played a role reducing the power of the sampling programs to detect changes that can be attributed to the habitat treatment. The lack of baseline data forced most studies to use a spatial design, and investigators have to overcome the high intersite variability that makes treatment vs. control comparisons difficult. O’Neal et al. (2016) demonstrate that the inclusion of 2 or more years of baseline data greatly improves the precision of the monitoring program. Incorporating baseline data into a research-level study requires engaging scientists well before the change in habitat conditions occurs to establish an appropriate sampling regime. This was possible in the Bridge River case because of the organizational commitment to large-scale monitoring by BC Hydro and the presence of the existing infrastructure (the dam) that allowed for some flexibility in the implementation of the habitat change. A similar protocol was developed for monitoring the impacts of flow changes associated with small hydroelectric projects (DFO 2012). The information requirements set out for an application for authorization under the 2012 revisions to the *Fisheries Act* also require assessment of fish and fish habitat prior to development, although the number of years required is not specified. These enhanced information requirements have the potential to result in more rigorous monitoring program designs, which should improve the characterization of benefits of compensation or offsetting works.

The value of simple, yet repeatable metrics that are reliable predictors of environmental health and allow for assessment of habitats over time is evident in the studies evaluating trends. Either repeat sampling (Dawe et al. 2000) or space-time substitution methods (Lennox et al. 2011) provide very useful information on the establishment of new habitats, or the deterioration of created habitats. Archiving carefully documented assessments so that projects can be revisited at decadal scales will allow an assessment of change. The expected longevity of constructed habitat is an important element of the overall assessment of the program that is easily overlooked in short-term compliance monitoring (O'Neal et al. 2016). Thus the efforts of many well-meaning investigators will provide an opportunity for future follow-up studies if the will exists.

5 ACKNOWLEDGEMENTS

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7 FIGURES

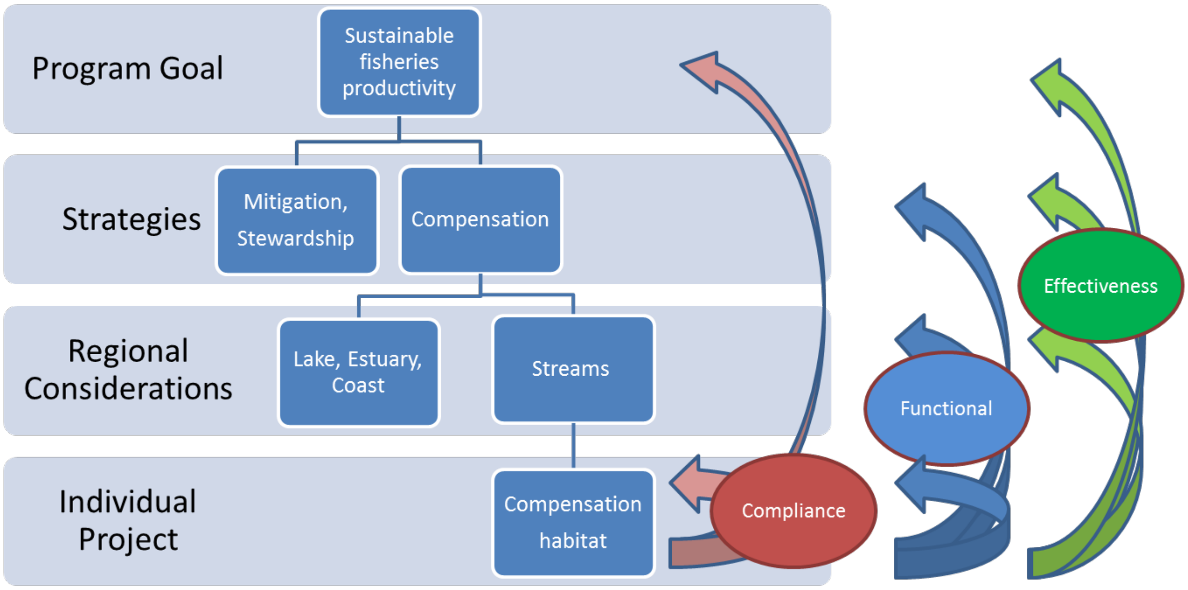

Figure 1. A program hierarchy for fish habitat compensation and some feedback loops or learning opportunities provided by different types of monitoring programs. Compliance monitoring is expected to be used for the oversight of individual projects, and provide insight at the program level into regulatory success. Functional monitoring usually provides a quick appraisal of habitat function and can provide feedback on the design of compensation works (regional level). Effectiveness monitoring is a long-term endeavour that addresses the whether the compensation policy option is achieving the ultimate goal of maintaining fisheries productivity. It is unlikely to provide timely feedback on individual projects, but informs regional prescriptions and national program direction.

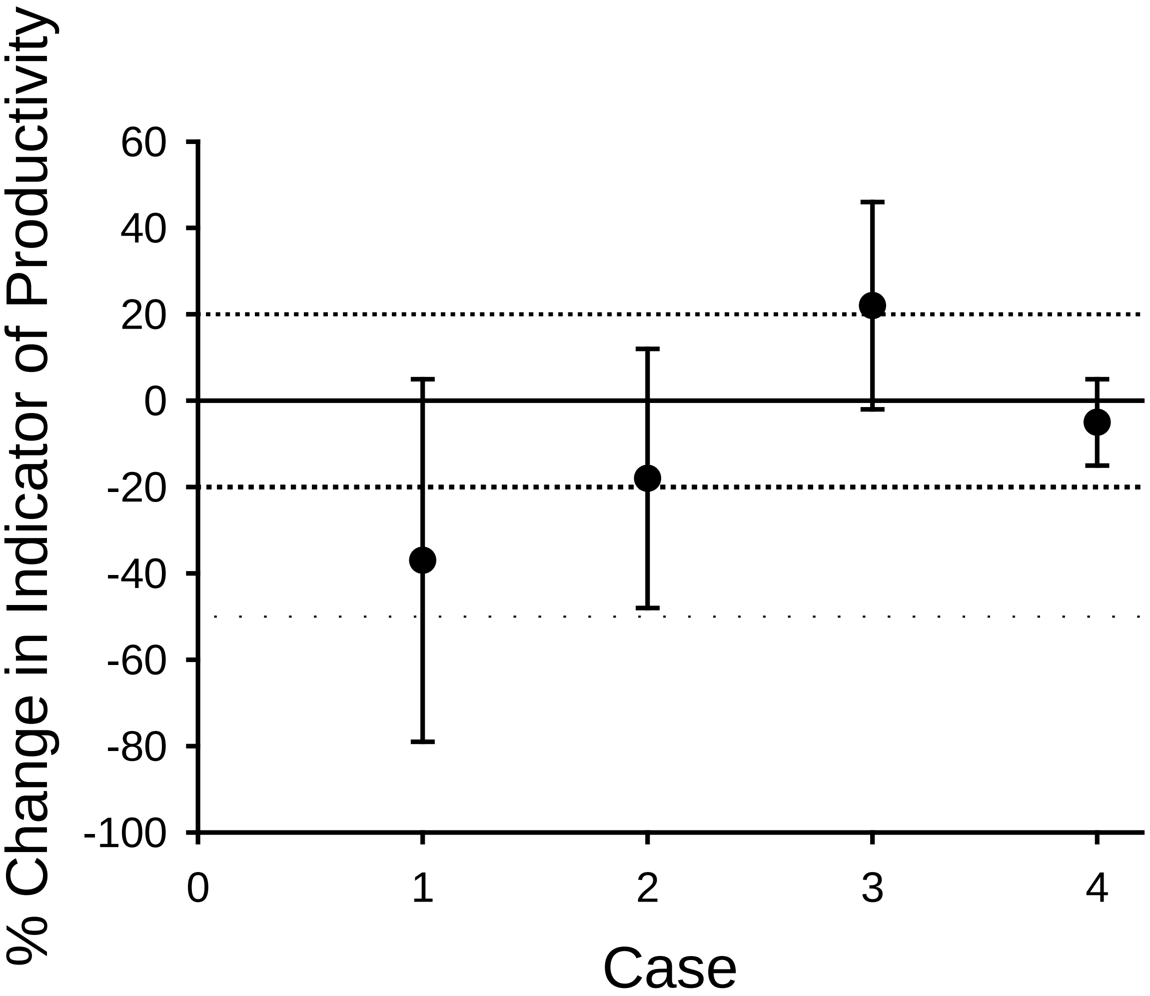

Figure 2. Hypothetical results from 4 compensation monitoring studies that estimate the change in productivity (or surrogate metric) from a habitat modification.Circles indicate the "best" estimate, and the error bars indicate the 95% confidence intervals. Reference lines at ±20% bracket a management range of indifference (i.e. a tolerance range that would satisfy the requirement that the new habitat was functioning similarly to reference sites). The lower reference line at -50% indicates a hypothetical negative change of great concern. In all cases a classical statistical test would indicate P > 0.05 for the rejection of the null hypothesis because the confidence limits cross 0, but the confidence intervals reveal more information than can be inferred from a hypothesis test. In case 1 the uncertainty is so great many hypotheses about change are tenable given the data. In subsequent cases the uncertainty is reduced; for case 4 there is relative certainty there is little difference between the treatment and control sites. For cases 2 and 3 alternative hypotheses about relatively large differences cannot be ruled out by the data.

Figure 3. Aerial photograph taken in 2004 of 6 ponds constructed in 1987 as compensation for highway widening near Malakwa BC. Infilling by vegetation and sediment noted by Lister and Bengeyfield (1998) is evident in the 2nd to 5th ponds (arrows).

Figure 4. Time series of artificial island created in the Campbell River, B.C. estuary showing growth from plugs planted in 1982, to a maximum density in the late 1980s. Vegetation density decreased in the 1990s, as a result of compaction and settling of the islands. From Dawe et al. (2000). Subsequent to this series, vegetation has all but been eliminated from this area by Canada Goose grazing (Dawe et al. 2011).

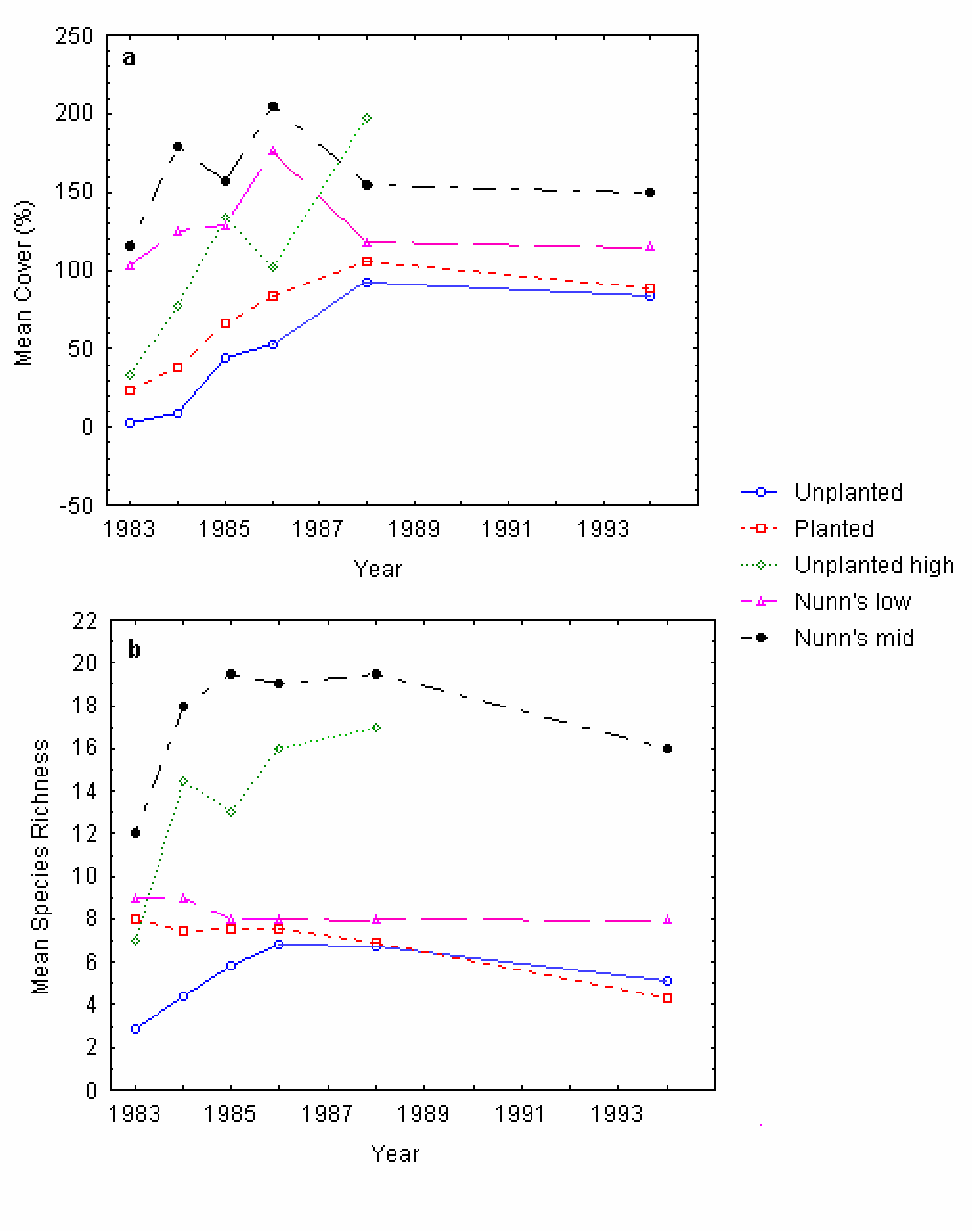

Figure 5. Time trends in vegetation statistics for the Campbell River estuary. Shown are data combined over 3 artificial islands created in 1982, and a reference site (Nunn's Island). From Dawe et al. 2000.

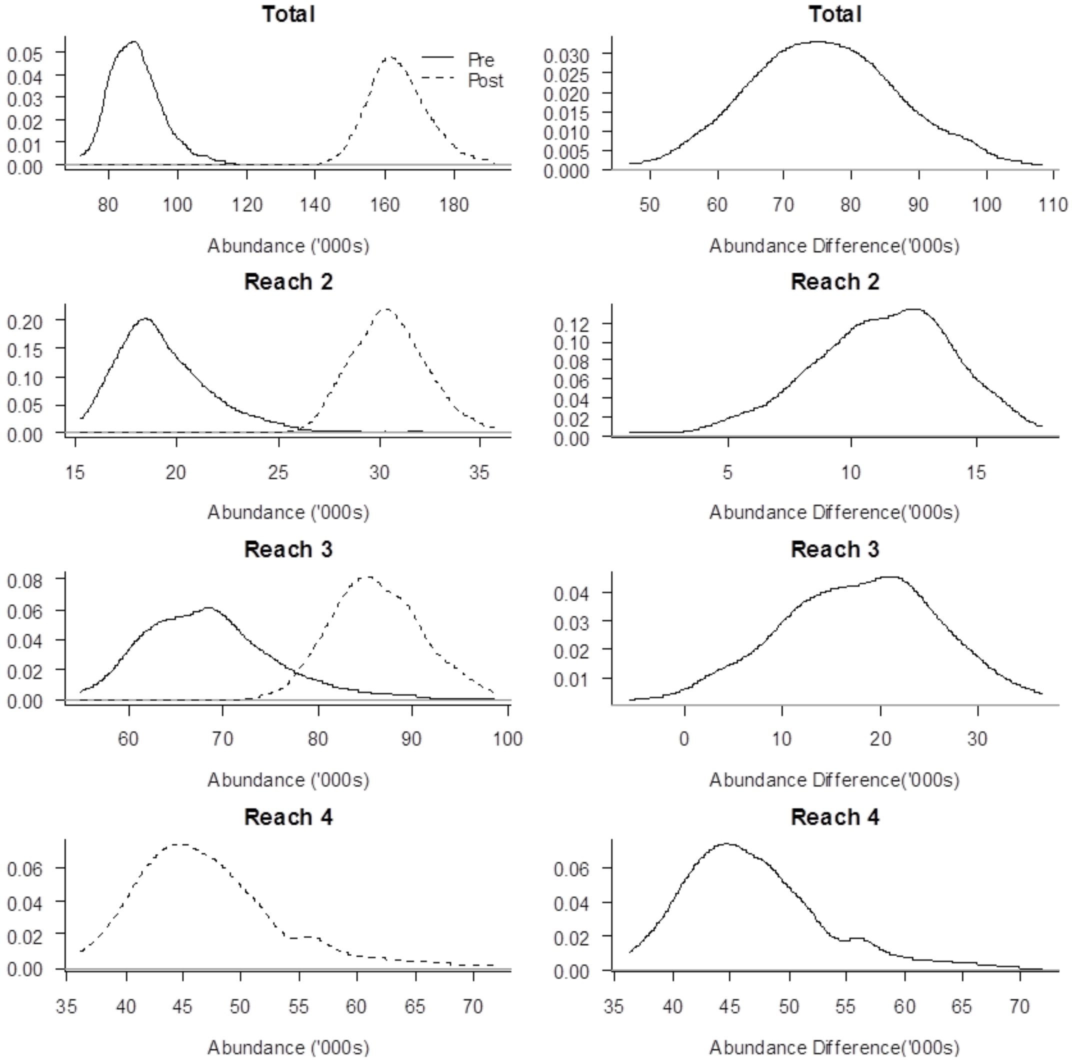

Figure 6. Bayesian posterior probability plots for the change in age-0 rainbow trout abundance before and after a regulated flow release in the Bridge River, BC. The column on the left shows the estimates of abundance for the whole study area, and 3 reaches within it. Reach 4 was dewatered before the flow release and there are no "pre" data. The right column depicts the change in abundance after the flow release and the associated uncertainty. Results from Reach 3 indicate the sampling and analysis was adequate to detect a 20% increase in abundance with reasonable confidence. Unpublished analysis from Bradford et al. (2011).

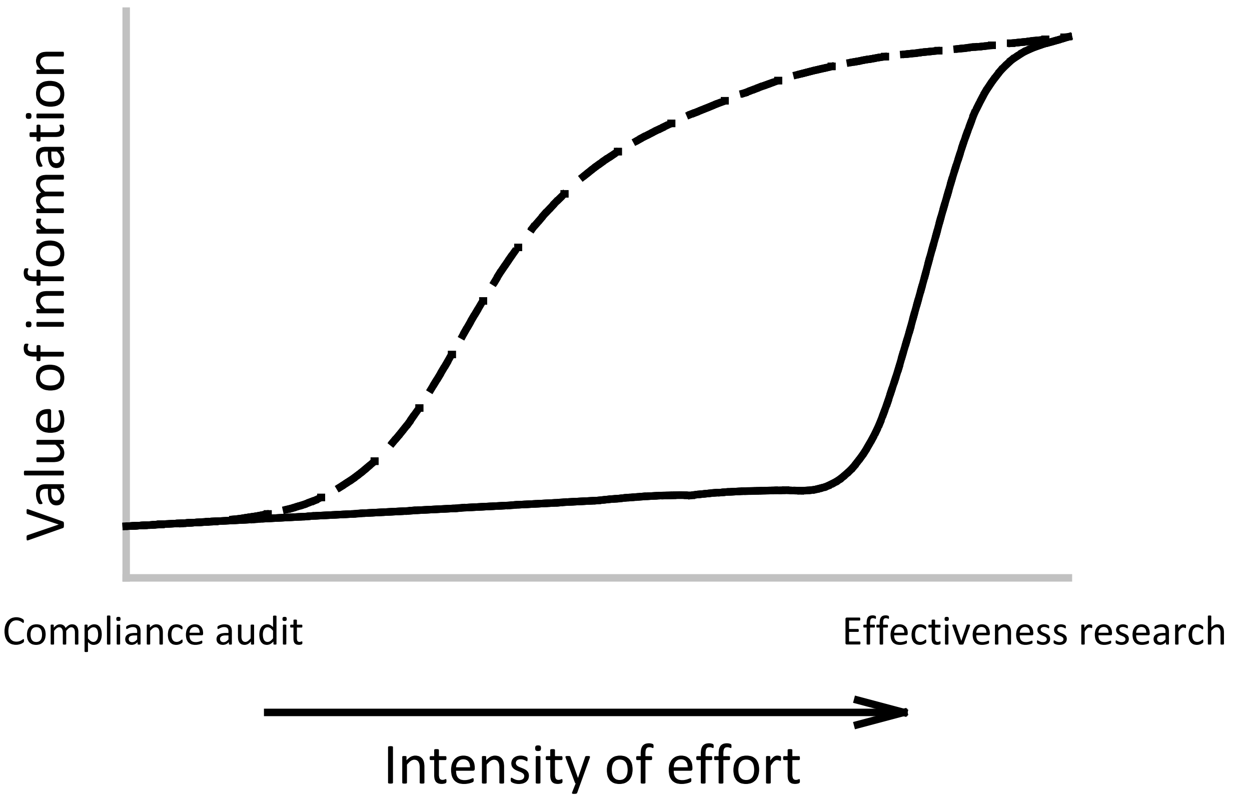

Figure 7. Hypothetical relation between the value of information gained from a monitoring program, and the intensity of sampling and analysis. Dashed line is the case where large gains in information accrue from modest studies; studies of vegetative cover for estuary restoration are likely in this category. The solid line represents the situation where a large investment must be made to achieve gains; programs that use fish abundance as a metric may fall in this category.

8 TABLES

Table 1. Summary of selected monitoring studies for compensation and restoration works in British Columbia. Studies listed were those available in the published literature and the WAVES database for the Pacific Region.

Compliance and Functional Monitoring

Habitat Type	**Compensation works**	**Key Metrics**	**Design**[1]	**Duration**[2] **PCI**	**Spatial Replication**	**Intensity**	**Comments**	**Reference**
All	Diverse	Physical habitat	Spatial	Dur: 1 PCI: 4+	52 sites	Visual assessment, area measures	National audit of compliance with authorization. Estimation of compensation ratio	Quigley & Harper 2006
River	Bank stabilization to prevent riparian erosion	Riparian vegetation; Invertebrate abundance	Spatial	Dur: 1 PCI: 3-7	16 treatment, 11 control sites	3 vegetation transects, 2 invert samples/site	No pre-construction data to allow BA design Noted that power was too low, many more samples needed to detect small changes	Cooperman et al. 2007
River	Bank stabilization, riparian planting	Physical habitat, fish abundance	Spatial	Dur: 1 PCI:2-10	42 sites, varying treatments, few control sites	Visual assessment, minnow trapping	Low catches and inconsistent use of control sites prevented formal analysis of fish data.	Pehl 2009
Estuary	Riparian, marsh	Area, visual assessment of function	Spatial	Dur: 1 PCI: 1-11	23 sites	Visual assessment, area measures	Surveyed every Fraser River estuary compensation site. Sites were assessed as NNL partially or fully achieved, or as a loss of habitat.	Kistritz 1996
Estuary	Artificial Islands	Vegetation	Spatial	Dur: 13 PCI:1	4 treatment, 1 reference site	23 transects, >200 quadrats	Documents long-term changes in vegetation.	Dawe et al. 2000.
Coastal	Eelgrass beds	Eelgrass density	Paired spatial	Dur: 1 PCI: 2-11	15 sites, some with controls	20 0.25m^2 quadrats/site	Some post construction monitoring allowed for evaluation of temporal trends in density.	Precision Identification Ltd 2002.
Coastal	Marshes, Reefs	Area, marsh vegetation	Spatial	Dur: 1 PCI: 1-5	14 sites. Some control sites	Visual assessment, area measures Nine 1 m^2 vegetation samples	Assessment of compensation for coastal log dumps. Largely a narrative approach. Diverse array of compensation types.	G3 Consulting Ltd. 2000

Effectiveness Monitoring

Habitat Type	Compensation works	Key Metrics	Design[1]	Duration [2] PCI	Spatial Replication	Intensity	Comments	Reference
River	Bank stabilization	Physical habitat, fish catch	Spatial	Dur: 1	34 treated, 28 control	10 minnow traps/site	Statistical differences between habitat types in coho catches in summer, not winter. Species-specific catchability noted.	Lister 2004
River	Bank stabilization	Physical habitat, fish catch	Paired Spatial	Dur: 1	11 pairs	2 snorkel passes/site	Statistical differences between habitat types in coho catches in summer, not winter. Species-specific catchability noted.	Lister 2004
River	Bank stabilization	Physical habitat, fish catch	Paired Spatial	Dur: 1	18 pairs	2-3 sites depletion electrofishing	Greater use of riprap in the winter.	Lister 2004
River	Artificial cover	Function, fish use	Spatial	Dur: 3	20 km shoreline 3x/yr	Snorkel observations	Loss rate of artificial structures noted. More fish at structures but effects on production no known.	Slaney et al. 1994.
River	Bank stabilization, diversity enhancement	Habitat conditions, fish use	Trend	Dur: 1 PCI: 5-12	3 sites	Snorkel observations	More difficult habitats to assess for fish use; relied on a visual comparison of changes over time.	Lister and Bengeyfield 1998
River	Diverse	Riparian vegetation Periphyton, invertebrates, fish	Paired spatial	Dur: 1 PCI: 4-7	16 sites 2-4 subplots in treatment and control sites	5 replicates of periphyton, invertebrates, riparian. 2-pass electrofishing	Encouraged multivariate approach to assessment. Needs estimates of precision to evaluate NNL rather than failure to reject null hypothesis.	Quigley & Harper 2006
River	Increased flow	Invert, fish abundance	BA	Dur: 4 pre, 9 post	None	Fish: 40-60 sites, once /year Inverts 6 sites/6 reps/ 4x year	Bayesian analysis used evaluate change in total fish abundance. Invert program dropped due to expense and lack of power	Bradford et al 2011; Perrin, unpubl[3].
River	Off-channel habitat creation	Area, fish abundance	Spatial	Dur: 1 PCI: 2-6	7 channels	Salmon smolt migrants counted each spring	Maintem (natural) production also estimated that allowed the contribution of restoration works to total production to be determined.	Ogston et al. 2015
Wetlands	Wetland creation	Water quality, fish presence	Trend	Dur: 1 PCI: 5-12	5 wetlands	DO and flow measurements; 10 minnow traps/site	This study followed a detailed analysis 1-2 yr after construction and documented the long-term changes in physical habitat.	Lister and Bengeyfield 1998

Habitat Type	Compensation works	Key Metrics	Design[1]	Duration [2] PCI	Spatial Replication	Intensity	Comments	Reference
Estuary	Marsh reclamation	Physical habitat, detritus, invertebrates, fish	Spatial	Dur: PCI: 1	Treatment and control site	Monthly sampling. Fish sampling every 2 weeks during salmon season	Science Branch assessment of marsh habitat created by dyke breaching. Invertebrate and fish use confirmed. No formal statistical analysis of data.	Macdonald et al. 1990
Estuary	Marshes	Area Vegetation Invertebrates Fish	Paired Spatial	Dur: 1 PCI: 2-6	7 sites, with disrupted, natural and treated subsites	6 monthly sampling trips in one year. 5 benthic sleds, 5 beach seines/subsite	This was a study conducted by Science Branch under the Green Plan to complement Kistritz (1996).	Levings and Nishimura 1996, 1997
Estuary	Artificial Islands	Vegetation, Invertebrates, fish	Spatial	Dur: 5 PCI:1	3 treatment, 1 refrerence site, 3+ times/year	6 replicates per site for vegetation and invertebrates.	This is a summary report of a series of publications. Intensive study with multiple partners, agencies and many staff.	Levings and Macdonald 1991

[1] Design refers to the study design. **BA**: Before After. **Spatial**: comparison of treated and control sites. **Paired**: comparison of nearby treatment and control pairs. **Trend**: Repeated sampling of the same site over time.

[2] **Dur** (duration) refers to the number of years of sampling. **PCI** is the post-construction interval (years), and is the age of the works at the time of first sampling.

[3] C. Perrin, Unpublished manuscript. Limnotek Research and Development, Vancouver BC. www.limnotek.com