A review of studies on responses of salmon and trout to habitat change, with potential for application in the Pacific Northwest

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Abstract

An inspection of abstracts from 2,350 references produced a first-cut set of 441 studies and reviews that were subsequently classified and reviewed with respect to their potential to document responses of salmonids to habitat changes, and to guide future monitoring of salmonid watersheds. Although the literature on habitat requirements is vast, it was necessary to distinguish between studies that relied on correlations based on observational designs and those which attempted experimental designs to test cause-and-effect mechanisms. Our understanding about environmental effects on fish is largely based on weak inferences from observational studies, which has a direct bearing on monitoring strategies. Such studies are useful in generating hypotheses on cause-and-effect, but such hypotheses need to be tested through appropriate experimental designs in the context of a validation monitoring approach. Findings from seven reviews (1988-2002) were assessed jointly with specific studies. Articles from 30 studies were reviewed, drawing from single or multiple streams, and purely observational or 'natural experiment' designs, in order to assess what improvements are needed in future programs. Relatively few studies were long term or from multiple watersheds; most studies were of one year or spanned a single generation. Although large-spatial scale, short-term studies have increased and provided insight into clustering of populations and dependency on environmental indicators at broader scales, there is no indication of the extent to which space can be traded for time when making inferences. The main technical deficiencies were the lack of concern about unbiased density estimates and poor statistical design, analyses and reporting. Analyses that simulate alternative sampling processes and expected biases in stream networks over time and space would help resolve some of these deficiencies. Overall, I concluded that current freshwater-based monitoring programs will either: (1) fail to indicate an improvement associated with stream habitat restoration in terms of smolt recruitment, returning adults, or population size increase at the watershed scale, or (2) indicate an improvement but fail to demonstrate which and how habitat changes were responsible so that subsequent restoration policy could be made more cost-effective. Recommendations for approaches to a large-scale monitoring design, based partly on this review are presented. The first-cut list of references, with abstracts and classification codes, is available electronically from the author.

Goal

I conducted a preliminary but broad literature review and synthesis on studies of salmonid response to habitat change in Pacific Northwest fluvial systems at the request of Washington State's Independent Science Panel (ISP). My review attempted to find studies that could demonstrate cause-and-effect through strong inference supported by viable mechanisms rather than unsupported correlative relationships. Knowledge about the dominant mechanisms responsible for restraining the recovery of salmonids in streams is essential. In the language of scientists concerned with salmonid restoration, the appropriate approach is though "validation monitoring." This preliminary synthesis built on the review results to help determine requirements for validation monitoring and how current approaches might be improved.

Objectives

(i) Conduct a thorough literature search and produce a preliminary list of potentially relevant references in electronic format,

(ii) Select and annotate subsets of references under classifications of habitat, stream type, and fish response type,

(iii) Compare and synthesize information drawn from the most relevant and better quality studies, and

(iv) Outline monitoring approaches needed to provide information that will incrementally improve the well-being of native fish populations through habitat management.

I describe the following procedure in detail under respective headings:

1. A broad online search of web-based databases of citations with abstracts was conducted, followed by a 'first cut' selection made after reading all abstracts and adding references missed by the search.
2. A classification process was devised for navigation and selection of reference sets of interest, and to provide a summary of trends and gaps in research.
3. Selected articles were reviewed to provide more insight into strengths and weakness of current approaches, with emphasis on quantitative responses of salmonid populations at different scales and life histories.
4. Results and Discussion and Conclusions and Recommendations sections were prepared.

1. Online Search

As described in Appendix 1 I searched five databases covered by Cambridge Scientific Abstracts (CSA), identifying 3,560 references. Elimination of most duplicate references was possible using EndNote software (ISI ResearchSoft), which deleted 34% of the total. Abstracts for all the remaining 2,350 references were read, and a 'first cut' of 441 references was made. This total included references from other sources that the CSA search failed to encounter, including three reports located by an ISP member. The first cut process was inevitably subjective, but the following guidelines were followed:

(i) Any reference that could have a bearing on predicting salmonid quantities as a function of instream habitat, riparian, or land-use/cover, or designing studies thereof was selected.
(ii) References that only considered specific water quality issues such as acid rain or other pollutants were not selected.
(iii) References that only considered nutrient enhancement through chemical or carcass addition were not selected.
(iv) Studies specifically oriented towards dams or reservoirs were not selected.
(v) Laboratory or microhabitat/habitat field work was included if the results were useful for defining or assessing meaningful response or explanatory variables in larger scale studies.

2. Classification

The 441 first-cut references inevitably contained a variety of interests, approaches, processes, and spatial/temporal scales. To enable use of these to locate results of interest and design monitoring surveys, classification of these references was necessary to enable navigation and focus critical evaluation on subsets of key references.

A classification process was developed (Appendix 2) that permits Boolean searches on one field to locate subsets of references of interest. For example, abstracts of all studies that predict the effect of livestock grazing on fish quantities in multiple stream studies sampled at a reach scale can be selected. Table 1 shows some examples of selections of potential interest from an initial cut of 435 references. The first cut set was also used to derive trends in the temporal and spatial scales of studies over time.

I archived all references in EndNote, so future searches under different criteria would be straightforward and options exist for exporting information to other databases or formats. Citations and abstracts from the first cut are available from the author. The original CSA search material, including abstracts, is also available upon request.

3. Review of Selected Articles

A selection of 30 articles corresponding to the first subset in Table 1 was reviewed in detail. Restriction to only 30 (6.8% of 441) articles was subjective, and was largely dictated by time constraints. The articles chosen for review were based primarily on their relevance with respect to detection of habitat change on quantitative salmonid responses, and secondarily on their potential to reveal issues, particularly statistical design and sampling biases, of importance to validation monitoring. The frequency of incomplete or inadequate reporting or analysis in articles was too high to attempt a meta-analysis without access to original data. Further sampling and more formal review of the literature is recommended, given that limited major reviews covering worldwide literature on this subject have been produced since 1991 (Meehan 1991). However, a supplement in the Canadian Journal of Fisheries and Aquatic Sciences was dedicated to Atlantic salmon (e.g., Armstrong et al. 1998). Also, an agency report (Keeley et al. 1996) and a recent publication (Roni et al. 2002), that were not revealed in the original search of May 2001, looked specifically at effects of stream restoration on Pacific Northwest salmonids. All these sources are considered here.

The emphasis of this preliminary review was on quantitative responses of salmonid populations at different scales and life histories in freshwater with respect to habitat changes. The issue of what is an appropriate measure of an anadromous salmonid population is critical. The ultimate measure of 'well-being' is the abundance of returning adults (i.e., spawning escapement), normally estimated on the basis of direct counts on spawning beds in streams, but is usually underestimated in proportion to the degree of spawning in substrate in main stems of river systems (Dauble and Geist 2000; Tschaplinski 2000). While this is an essential measure for several applications over longer time scales and is important to roughly estimate marine mortality rates, its ability to reflect improvements in freshwater habitat can be compromised by inaccuracies in those mortality estimates (Kareiva et al. 2000; Dambacher et al. 2000). Recruitment rates to smolt stage can only be estimated in a limited set of catchments whose geography permits installation /construction of special structures close to the sea for tracking of downstream migrants. Therefore, in most cases only estimates of population sizes of parr (potamodromous and anadromous stocks) at specific ages in each drainage are possible. While current technology only permits accurate estimation of local densities at habitat- or reach-scales, it is no easy task to infer basin-wide populations and changes thereof from such estimates. The ability to make these inferences, or alternatively to make arguments about habitat improvement based only on local density estimates, is the most essential factor when assessing the utility of existing studies.

4. Results and Discussion

4.1. General results of classification

Long term studies (Figure 1), mostly on single watersheds, undertaken between the 1950s and 1980s (Hunt 1976; House 1996; Tschaplinski 2000) have declined (Figure 2), and have been replaced by short-term, larger spatial scale studies published from the late 1980s to the present (Figure 3). However, research has been dominated by small-scale, short-term studies throughout the past quarter century (see Figure 1 for period of literature search from late 1970s). This dominant response to perceived needs reflects a combination of the prevalence of a reductionist philosophy founded on the primacy of determining mechanisms at small scales, time limitations on graduate student research, and institutional or political effects limiting the period of funding.

A good example of the short-term, small-scale approach is provided by the review and analysis reported by Keeley et al. (1996). They used two models to predict changes in adult salmonid production:

(1) For species that spawn and whose juveniles rear in streams:
*adult/area = (juveniles produced/area) * (survival rate of juveniles to adults);*

(2) For species that spawn in streams, but whose juveniles rear in either lakes or estuaries:
*adults/area =(embryos/area) *(survival rate to smoltification)*(survival rate to adult).*

Keeley et al. (1996) demonstrated significant increases (averaging 123%, analyzing species separately) in local densities of salmonids in stream habitats (corresponding to juvenile production in Model (1)), based on paired-t tests on paired reaches of unspecified dimension or stream order. They projected returning adult densities based on published ocean survival estimates (Model (1)). Only changes in area of spawnable gravel data were reported (8.5-fold mean increase for restored habitats) for species corresponding to Model (2), so projections from that model were not attempted.

Two major questions in Model (1) not discussed were: (a) how representative is the sample of the population occupying the whole freshwater environment (Bilby 2000), and (b) given that most of the samples were presumably during low-flow seasons, what seasonal effects, such as winter habitat, could change the projections? Regarding (a), it can be argued that the smaller the reach restored the greater the likelihood that it may serve as a refuge that attracts fish from surrounding habitats. Predation or other losses due to poor refuge habitat may be reduced sufficiently to affect the whole population, but its overall biological production may not be because food supply may not be increased. Regarding (b), while the study separately analyzed results from off-channel habitats, it did not recognize that the principal value of such habitats was during winter high flows (Nickelson et al. 1992a). Although inferences from Model (1) were driven by juvenile biomass densities, the strong statistical results reported by Keeley et al. (1996)

do imply that stream habitat restoration would increase smolt production and average adult returns if improvements occurred on a sufficiently large scale and that freshwater productive capacity was limiting.

The importance of question (b) is illustrated by a more recent multi-stream, experimental study (Roni 2001; Roni and Quinn 2001) in which seasonal differences in the effects of large woody debris (LWD) were reported. Juvenile coho densities were 1.8 and 3.2 times higher in LWD-treated reaches compared with reference reaches during summer and winter, respectively, while cutthroat and steelhead trout did not differ between treatment and reference reaches in summer but were 1.7 times higher in treatment reaches in winter.

Earlier reviews during 1988-1991 (Fausch et al. 1988; Bjornn and Reiser 1991; Hicks et al. 1991; Platts 1991; Reeves et al. 1991) provided good arguments for large scale or multi-scale research programs on a temporal or spatial basis. This review of literature during the past quarter century indicates that the mean time-span of studies has decreased considerably (Figure 2), while large-scale designs, as indicated by landscape and "whole basin" studies, have increased (Figure 3). This is despite analyses indicating that year-to-year variability in salmonid populations can be considerable (Platts and Nelson 1988; Holtby and Scrivener 1989; Bradford et al. 1997; Ham and Pearsons 2000) even when environmental conditions vary little (House 1996). Such variability can severely constrain the interpretation and quantification of habitat change effects on survival rates or on sizes of anadromous (Cunjak et al. 1998; Williams 1999) or resident (Crisp 1993; Clark and Rose 1997) adult populations.

Conversely, the increased attention given to spatial scale effects, including multiple watersheds and large basins, and corresponding landscape variables have provided some insight into regional fidelity of populations or patches within metapopulation domains (Rieman and McIntyre 1995; Niemelä et al. 1999). Also, an increasing realization that habitat and hydrological effects are more meaningful when measured at spatial and temporal scales larger than those at the reach sampled for fish has been demonstrated empirically (Watson and Hillman 1997). However, considering that several factors that affect temporal variability are likely to be dependent on environmental circumstances peculiar to individual populations, attempting to trade space for time produces considerable risk associated with diagnostic or prediction attempts.

Roni et al. (2002) conclude from the examination of 93 papers that little is known about the effectiveness of most restoration techniques. Most of the improvements were evaluated at juvenile life stages and little has been done to detect changes in adult populations. From Table 1, 26 of 155 (23%) multi-stream studies and 49 of 101 (49%) single stream studies were ‘experimental,’ according to my generous definition (‘experi,’ Appendix 2). However, failures in design and execution lead me to the same general conclusions as Roni et al. (2002).

More generally, the record of monitoring studies has been marred by several failures. Reid (2001) addressed 30 flawed monitoring projects (mostly hydrological, sedimentological, or wildlife), and identified twelve problems causing failures. Design problems were responsible in 70% and procedural problems in 50% of the projects. Design problems were similar among land-management agencies, research agencies, and universities, while procedural problems were relatively small in university projects. Problems causing failure in flawed projects were:
(1) under trained or unmotivated field crews (37%, procedural),
(2) a sampling plan incapable of measuring or detecting what is needed (30%, design),
(3) inadequate monitoring duration (27%, design),
(4) delays in analyzing data (27%, procedural),
(5) absence of collateral information to interpret results (20%, procedural),
(6) technological failures (17%, procedural),
(7) data irrelevant to objective (17%, design),
(8) fundamental misunderstanding of system (13%, design),
(9) inadequate statistical design (13%, design),
(10) lack of continuity due to personnel changes (13%, procedural),
(11) lack of institutional commitment (10%, procedural), and
(12) protocol changes affecting comparability (7%, procedural).

Those with fisheries experience will find many of these problems familiar, some of which are discussed in the following section.

In conclusion, although strong inferences of increase in population size of juveniles in streams have been documented, relating this to smolt recruitment and returning numbers of adults at appropriately large scales has been neglected. Therefore, studies have not so far addressed empirically the estimation of change in total population size as a result of restoration efforts.

4.2. Reviews of selected articles

Tables 2 and 3 summarize my analysis of the 30 references, of which 27 were multi-stream (multi), 13 were ‘experimental’ (experi), and 10 were both. The following generalizations are relevant to assessing the usefulness of studies in quantifying fish responses to potential causative factors describing stream habitat, but are equally relevant to considerations of improved designs of future validation monitoring studies.

First, failings in design, analysis, or reporting were widespread, as found by Fausch et al. (1988) in fisheries studies and more generally by Reid (2001). The following problems were most common:

(1) Failure to carefully analyze and reduce the set of explanatory variables before the final analyses involving the response, so that variable confounding, non-robust predictions, and low statistical power cannot be mitigated. Stepwise regression to eliminate variables is frequently used, but is commonly recognized as a dangerous tool in the absence of prior analysis.

(2) Failure to incorporate interactions in observational studies is very common. Excuses that they complicate the analysis when prediction is needed, or that no theoretical reason exists for a 1st order interaction, are not convincing given the frequency of main effect confounding and the robustness of the model for predictions elsewhere, especially when it is difficult to approach a balanced design in observational studies. Also, there are good reasons for expecting synergistic or compensatory effects between factors, such as proxies for feeding and refuge for stream fish.

(3) Failure to summarize the effectiveness of the model as a predictive tool. Although I have summarized R^2 values in Table 3, its use in comparisons has been criticized (Bayley 1988; Fausch et al. 1988) because it is sensitive to the ranges of explanatory variables and does not directly provide a comparable estimate for the precision of the model's predictions.

(4) Failure to test for, or explain elimination of, outliers or influence points. Frequently, such points are valid, but often show up because of an inappropriate statistical model. Rarely are plots of residuals of proposed models provided.

The second concern is the continuing failure to address the issues of sampling bias in the estimation of abundance and related population properties, even though there has been increased criticism of uncorrected common methods, such as multiple removal, and practical solutions to address this have been published during the past decade.

However, there are bright spots regarding both concerns. There are some examples of prior analysis of explanatory variables (Bowlby and Roff 1986; Watson and Hillman 1997), and designs regarding spatial scales (Nickelson et al. 1992b; Rieman and McIntyre 1995; Riley and Fausch 1995; Keith et al. 1998; Dunham and Rieman 1999; Solazzi et al. 2000). There are fewer bright spots regarding bias-correction of fish samples. Sampling is dominated by multiple removal (score 4, Table 2) or removal until apparent depletion (score 3) by electrofishing, and snorkeling (score 2). There is nothing wrong with these approaches as a source of comparable, quantitative estimates, providing that the protocol is consistent and there is a bias-correction. Sophisticated computational processes based on statistical theory (e.g., Pradel 1996) will not help, unless their assumptions (mainly predictable or constant catchability and closed population) can be verified. Usually they are not, because catchability (or observability) can change considerably as a function of physical habitat and repeated passes, and size and species of the quarry. An exception is the work by a research group at the Oregon Department of Fish and Wildlife (Nickelson et al. 1992a; Nickelson et al. 1992b; Solazzi et al. 2000) who either performed local mark-recapture or corrected their multiple removal data using separate calibration results (Rodgers et al. 1992).

The foregoing includes strong criticism of peer-reviewed literature, but is based on full-text reviews of only a small number of the first-cut set of articles. Nonetheless, in order to detect changes in whole populations resulting from restoration efforts, long-term or multi-watershed surveys are needed that require comparable density estimates across habitats, crews, gear, and stream sizes. Ignoring sampling biases will magnify biases in inferences at these larger scales. I did observe that concern was frequently expressed about sampling biases in the methods sections of reviewed publications reviewed, but usually no action to determine and apply bias-corrections was taken.

4.3. Other issues

The review drew my attention to other issues that give rise to concern or optimism about current approaches to salmonid-habitat studies:

Habitat evaluation model (HEM) approaches - I have criticized the application of HEM approaches to the prediction of fish distributions (Bayley and Li 1992). The present literature search indicates that there are other studies criticizing the HEM approach, and more specifically the Instream Flow Incremental Methodology (IFIM) approach, than those supporting it (Table 1). The most common criticism was based on the frequent failure to find a proportional relationship between fish abundance and Weighted Usable Area derived from microhabitat preference curves. Making reach-level inferences from microhabitat data is subject to several errors of a non-linear nature due to a mismatch of spatio-temporal scales.

Risk analysis - Although risk-based analysis, that can take the approach of Bayesean statistics, frequentist (using combinations of Type I and II errors and given effect size), or so-called Bayesean Belief Networks, provides many advantages over use of arbitrary significance values, this search only encountered four references (Korman and Higgins 1997; Lee and Rieman 1997; Nickelson and Lawson 1998; Ham and Pearsons 2000) that attempted some risk analysis (although the search was not specifically directed towards this method). Given that results of Bayesean approaches (not to be confused with Bayesean Belief Networks) are much easier to explain to managers and to apply to economic trade-off estimates, I hope that the lag in scientific capacity to take advantage of this approach will be shortened.

Seasonal bottlenecks - As implied above, there continues to be an emphasis on surveying streams during summer months (e.g., Table 3), despite the growing evidence that quantities of certain discharge-related winter habitats may provide overriding bottlenecks affecting adult numbers (e.g., Tschaplinski and Hartman 1983; Hillman et al. 1987; Cunjak 1996; Solazzi et al. 2000). Studies that detect year-to-year effects of hydrological change (Scarnecchia 1981; Paulsen and Fisher 2001) need to attempt to distinguish between the typically positive effects of natural winter discharges and the negative effects of low summer levels, while accounting for potentially confounding variables such as temperature. Future monitoring programs risk misidentification of dominant causative factors unless summer, winter, and spring fish samples are taken regularly.

5. Conclusions and Recommendations

My overall conclusion is that current freshwater-based monitoring programs will either: (1) fail to indicate an improvement associated with stream habitat restoration in either smolt production or returning adults at the basin scale, or (2) indicate an improvement but fail to demonstrate which and how habitat changes were responsible so that subsequent restoration policy could be made more cost-effective. 'Proof' of dominant cause-and-effect relationships operational at scales appropriate for the population will always be elusive, even with the best designed field experiments. However, validation monitoring approaches that aim for strong inference based on multi-stream studies over time (see section 5.2 below) are feasible, but no good examples were found.

Solutions and limitations from existing studies (see 5.1 below) highlight issues of design and analysis given a land-use and stream habitat restoration scenario. Section 5.2 contains recommendations regarding how to proceed in designing a long-term monitoring program.

5.1. Principal findings from literature search

1. Further short-term, large spatial scale studies that attempt to trade space for time will probably not provide sufficient new information to justify costs, unless they are planned to be part of a long-term program.

2. The habitat-microhabitat evaluation modeling (HEM) approach has been criticized by a similar number of articles as those supporting it. Due to its frequent failure to substitute for direct estimates of fish densities, in the author's opinion the approach cannot justify further expenditure in the context of validation monitoring.

3. As earlier reviews found, most surveys continued to lack power through limited degrees of freedom, many lacked appropriate statistical treatment of candidate explanatory variables, and many failed to report comparable statistics. In addition, most ignored interactions, and most lacked appropriate bias corrections of abundance estimates.

4. Designs of short-term, large spatial scale studies have improved: several of these and earlier long-term studies are of sufficient quality to link their data with future designs (see 5.2 above).

5. Publications describing large-scale, multi-watershed, short-term studies have increased, and provide a glimpse of spatial scale-dependent factors, but reports on multiple year studies have decreased. Key papers highlighted the limitations of current approaches due to year-to-year unexplained population variation, and the tenuous link between juvenile and adult cohort sizes.

6. Although more fisheries biologists are becoming concerned about the importance of obtaining unbiased density estimates for joint analyses among surveys, watersheds, and stream sizes that necessitate the deployment of different sampling protocols, there is little evidence from the literature in general that the practical steps to achieve this are being undertaken. Although consistent protocols are an essential prerequisite, they are insufficient to account for biases that can be caused by the very habitats that are of potential ecological interest.

7. Preparation of an efficient design for validation monitoring that involves fish sampling depends on the experience of the practitioners. This is insufficient given the complex process of finding a 'natural experiment' in watersheds replete with non-random distributions of 'nuisance variables' that influence salmonids in addition to the habitat factors of interest.

Even with relatively simple systems, it is difficult to make credible predictions of statistical power based on experience alone. However, no publications were found that model fish sampling designs in realistic settings, such as by simulating the data collection process under alternative designs using sample variances from previous studies. Therefore, no guidance exists for optimizing survey designs, particularly at multiple watershed scales, that purport to detect changes at given probabilities.

5.2. Recommendations - Where do we go from here?

Based on my review of the literature and personal experience I offer the following recommendations to improve understanding of the responses of salmonids to habitat changes. Future monitoring surveys should take advantage of existing, comparable fish sample information, providing that the information contributes to a design that incorporates current or planned contrasts between basins with extensive habitat restoration (treatments) and those with unchanged habitat (controls). Essential components of future validation monitoring surveys are as follows:

1. Reassess existing long-term and basin-wide, short-term data sets with repeatable protocols, and identify drainage basins that have contrasts in degree of habitat restoration (with or without existing fish samples). Utilize these sources in conducting components 2 and 3.

2. Develop simulation models of cost-limited, alternative fish sampling designs that incorporate empirical variances and biases, to provide a quantitative template for recommendation 3.

3. Develop long-term (decades) monitoring programs that treat a series of basins and wild fish populations as natural experiments along a gradient of habitat restoration. The sampling design should track metapopulations or extensive populations and physical changes within and among watersheds down to reach or segment scales. Because seeding and early survival variation can change the habitat variables that are limiting, a measure of year-to-year reproduction success of key salmonids (at least down to watershed scales) should be concurrent with juvenile and adult monitoring of all fish species. Reach-scale, stratified random fish sampling effort using protocols that are bias-correctable should be divided between mid-summer and winter periods. Spatial strata should be watersheds expecting/not expecting significant human alteration, litho-geomorphological zones within watersheds, and stream sizes.

4. Monitor flows to predict changes in seasonal habitat availability, including floodplains, among watersheds, and monitor sediment transport at least sufficiently for models to distinguish substrate size fractions among candidate watersheds and orders of streams.

5. Record key physical habitat variables, such as maximum pool depth, area, and frequency, large wood, and substrate on a broad spatial scale, but on 5-year or more cycles. Devise a parallel system of monitoring of an index of stream fertility.

6. Record physical habitat variables in fish-sampled reaches to: (1) reduce unexplained variance with ecologically plausible variables when abundances are estimated on broader scales, and (2) provide data necessary to correct fish abundance estimates when catchability is known or suspected to be affected by such habitat variables (see 7 below). Current and prior sampling protocols should be 'quantifiable' so that they can be calibrated with accurately known abundances (through mark recapture on temporarily closed populations, not removal) to correct for biases due to physical attributes of reach (6), fish size, and species. The aim is to provide local abundance estimates from past and future samples that are independent of the capture process.

8. Support studies at microhabitat or habitat scales when the processes identified and quantified can be scaled to watershed and decadal scales. In particular, studies are needed that investigate groupings of fish responses by taxa and size or age that are ecologically meaningful at those larger scales.

Long-term validation monitoring surveys should not be expected to produce results before ten years (barely two generations of many salmonid populations), but matching designs with existing surveys, particularly broad-scale ones, may detect large effects in a shorter time. Such surveys are not, and cannot be, designed to determine mechanistically how the many processes indicated at habitat/microhabitat scales are linked to those indicated at population or metapopulation scales. Rather, they aim at 'strong inference' that indicates the effects of a subset of small-scale mechanisms that have been independently shown to be valid candidates. In conclusion, based on the review of 441 abstracts and the subsets of 30 articles and other reviews, I believe that in the absence of a well-designed, broad spatial and temporal scale monitoring program, no clear reasons for stock recoveries or collapses will be found, and expenditure on scientific approaches to improve future management will remain unjustified.

Appendix. 1. Web Search Process.

Five databases were searched using Cambridge Scientific Abstracts (CSA) (http://osulibrary.orst.edu/research/databases/csaccess.htm) applying the following Boolean string:

Keyword (KW)=(salmon* OR trout*) AND KW=(stream* OR creek* OR channel* OR river* OR tributar*) AND KW=(abundance OR population* OR densit* OR biomass OR catch*) AND KW=(habitat* OR restor* OR graz* OR enhance* OR rehabilitate* OR e?closure*),
where KW directs selection to title, keywords and abstract combined,

* = additional wildcard string of characters of length ≥0,

? = single wildcard character (to include exclosure(s) and enclosure(s)).

The search was applied to all references available, which included 'grey' literature and references going back to 1973 with respect to Aquatic Sciences and Fisheries Abstracts (ASFA), and all languages providing abstracts were in English. Results were:

Database	# references
ASFA: Aquatic Sciences and Fisheries Abstracts	1,337
Conference Papers Index	9
Environmental Sciences and Pollution Mgmt	1,251
Oceanic Abstracts	259
Zoological Record Plus (2001)	37
Zoological Record Plus (2000)	137
Zoological Record Plus (1997-1999)	225
Zoological Record Plus (1993-1996)	298
Recent References Related to Your Search	1
Web Resources Related to Your Search	6
Total	3,560

Dealing efficiently with this quantity of abstracts and duplicate references required some trial and error. Selecting references on the CSA web site proved laborious, and I deferred weeding out duplicates. Conversely, downloading all complete references, and uploading into EndNote (cross-platform software by ISI ResearchSoft), using filters appropriate for each database (www.isiresearchsoft.com/en/help/enfilters.asp), permitted elimination of a majority of duplicates and efficient selection of references.

The main problem with CSA (and probably any other computerized literature search system, that should all be regarded as state of the art) was that it missed several key references, because not all years of ‘core’ journals were present in any of the five databases. For example, no North American Journal of Fisheries Management references existed for 1986 and only 8 for 1985. Also, volumes 19 through 21 of American Fisheries Society Special issues were missing, which included the key review papers in volume 19 (Meehan 1991).

Appendix 2. Classification Code Words

I used the following codes for classification of 'first cut' set of references (see Table 1). They are entered under the 'label' field in an Endnote database available upon request.

Response variables:

quant empirical, field or lab data, as density or biomass or production estimate of salmonids at fry=>juvenile stages
qual inc. non-density data such as individual growth rates
spawn redd densities, egg=>alevin studies, spawner survey
popdyn thinning, max. density production
migrat movement, dispersal, migration
nofish a few references with fish habitat or inverts as endpoints

Design features:

experi 'natural experiment' design, or habitat restoration, enhancement, (before-after control-impact) BACI, other paired comparisons (e.g., day vs. night); includes experimental stocking of fish with control.
multi >1 'replicate' streams involved, unless a contrasting pair is used in an experiment
temporal multiple year-by-year comparison, except for simple before/after comparison
enclos artificial enclosures, includes artificial streams, excludes temporary blocking for fish capture
lab laboratory study

Spatial scales of fish measurements and inferences (see Frissell et al. (1986)):

basin basinwide production estimates such as smolt production, and other aggregated estimates, such as of abundance or biomass, at this scale
segment
reach including home range; papers with quantitative fish sampling that was not specifically bounded by habitat types were normally included in this category.
habitat pools, riffles, glides or runs, etc.
microhab including territory (and used for habitat-based models such as IFIM, habitat quality index (HQI), etc.)
offchann off-channel habitats studied, including small, floodplain tribs., alcoves, sloughs.

Explanatory variables:
<u>graz</u> any riparian grazing effect
<u>ag</u> agricultural not specific to grazing, e.g., row crop, general
<u>ripar</u> including canopy, bank vegetation, logging or clearcutting in riparian zone
<u>instream</u> any 'physical quantity' in the stream: width, depth pool dims., cover (including plants), undercut banks velocity gradient, weirs or other instream structures (includes <u>substrate</u> and <u>lwd</u>)
<u>substrate</u> including sediment
<u>lwd</u> large wood, including brush bundles
<u>lulc</u> land-use/cover, but also includes geomorph/litho contrasts/basinwide info (including basin area)
<u>hydro</u> inc upwelling, hyporheic, ice effects
<u>lakehydro</u> effects of lakes upstream, including reservoir operation effects
<u>wtemp</u> water temperature
<u>watqual</u> water quality (chemical, DO, turbidity)
<u>fishing</u> effect of stream fishing effort estimated
<u>trophic</u> invertebrate data, stable isotope
<u>sppinter</u> species interactions (predation, competition) including allo- vs. sympatric comparisons, and joint salmonid-non-salmonid studies or when salmonids don't dominate the fish fauna
<u>noenv</u> no 'physical' environmental effects tested (macrophytes included, watqual excluded) from microhab=>landscape scales.

Miscellaneous:
<u>hem</u> habitat evaluation (HEM) or numerical habitat models (NHM) methods, including IFIM and HSI (below), HQI, HABSCORE (but this also includes catchment variables), HPI, NHM
IFIM includes PHABSIM, IFIM, HSI, WUA using Bovee et al.'s approach
<u>review</u> literature review (excluding data mining studies)
<u>modeling</u> alternatives to normal statistical analysis (regression or discriminant) , e.g., Bayesian, neural network, non-linear models, simulation
<u>risk</u> any risk probability or power analysis
<u>design</u> statistical sampling
<u>method</u> sampling methods or comparison of different measurement methods
<u>warnings</u> criticism or failure to get expected results
<u>economic</u> any estimates of costs or benefits
<u>philosophy</u> including approach to assessment, management
<u>datasource</u> primarily source of data
<u>foreign</u> foreign language article with English abstract: French Norwegian German encountered.

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Table 1. Frequencies of references from 435-references from the first cut set (see glossary of codes (underlined) in Appendix 2):

Subset of ‘quantitative’ references (total 216) with habitat or reach -based quantitative fish sampling (excluding refs with stream enclosure, laboratory, or nofish studies and reviews).

	Number of references with multi (>1 stream)	NOT multi (1 stream only)
All in subset	115	101
AND experi	26	49
AND graz	10	9
AND graz AND experi	3	7
AND ripar	28	19
AND ripar AND experi	9	11
AND temporal	11	26
AND temporal AND experi	2	9

Reference frequencies with habitat evaluation or numerical habitat models (hem and instream flow incremental methodology-related (ifim) subset):

with hem NOT warning	20	with ifim NOT warning	12
with hem AND warning	24	with ifim AND warning	19

Reference frequencies from all 435 references, that include:

reviews	25 (10 with quantitative analysis)
lab or enclosure	28
temporal	62
modeling	41
risk	4
economic	4
stream fishing variable	3
warning	50
nofish	11
foreign language	11

Table 2. Papers reviewed in detail (30 articles): with location, response variables (normally density or biomass per surface area), fish sampling method, and classification. (See Table 3 for outputs)

Author(Year)	Location[1]	Fish species[2]	Gear[3]	Score[4]	Classification codes (see Appendix 2) all with quant
Barnard et al (1995)	UK	TRT-0 TRT-j TRT-a ATS-0 ATS-j	PE +B	4.0	multi reach instream lulc temporal hem
Bjornn et al (1991)	SE AK	CHO-0 CHO-1 DVD SAL	PE	3.0	experi multi habitat migrat ripar
Bowlby & Roff (1986)	S ONT	TRT (BKT, RBT, BRT)	PE +B	3.0	multi reach instream wtemp trophic
Bremset & Berg (1997)	Norway	ATS-j BRT-j	POO: SS + diver with net mk-rec. RIF: PE(3)	4.5	multi habitat migrat instream
Bryant et al (1998)	SE AK	"CHO-j CHO-0 (DVD, STT, CUT ignored)"	SN	2.0	multi habitat offchann lulc watqual
Clarke & Scruton (1999)	NFD	BKT (only salmonid)	PE	4.0	multi reach instream trophic
Connolly & Hall (1999)	W OR	CUT	PE +B	4.0	multi habitat ripar lwd lulc
Dolloff (1986)	SE AK	CHO-j DVD	T mk-rec	5.0	experi multi reach lwd
Dunham & Vinyard (1997)	NV	CUT TRT	PE +B	4.0	multi reach popdyn noenv temporal
Eaglin & Hubert (1993)	WY	TRT (BKT BRT) >10cm	PE(3)	4.0	multi reach lulc substrate
Ebersole et al (2001)	E OR	RBT	SN	2.0	multi reach wtemp
Giannico (2000)	W BC	CHO-j	"PE, SS +B"	3.0	experi habitat lwd trophic
Grant et al (1986)	NS NB	SAL ATS TRT(BKT BRT)	PE(5) +B	3.5	experi multi reach substrate ripar
Herger et al (1996)	WY	CUT	PE(2) +B	4.0	multi habitat instream hydro
Horan et al (2000)	NE UT	CUT	PE(3)	3.0	multi reach segment instream lwd substrate
Hubert et al (1996)	WY	TRT (RBT BRT BKT)	PE +B (rem/mk-rec)	4.5	multi reach instream
Jenkins et al (1999)	CA	BRT TRT	PE(3-5) +B	4.0	experi reach habitat popdyn temporal noenv
Jowett (1992)	NZ	BRT, RBT: 10-20,20-40,>40cm	SN	2.0	multi reach instream wtemp watqual lulc trophic hydro ifim hem
Keith et al (1998)	SE AK	CHO-0 CHO-j DVD-0 DVD-j	PE(2,3)	4.0	experi multi reach migrat ripar lwd
Knapp et al (1998)	CA	RBT-0, -1, -2 (only salmonid)	PE(3) rem and SN(surf)	3.0	experi reach graz spawn popdyn

Knudsen & Dilley (1987)	WA	SAL CHO-j TRT-0 STT-j CUT-j	BS+SS/PE	4.5	experi multi reach substrate instream
Milner et al (1995)	W UK	BRT-0 BRT>0 ATS-0 ATS-j	PE +B	4.0	multi reach instream lulc temporal hem
Nickelson et al (1992a)	W OR	CHO-j	PE & SS mk-rec or corrected removal +B	5.0	experi multi habitat instream offchann
Nickelson et al (1992b)	W OR	CHO-j	PE & SS mk-rec or corrected removal +B	5.0	experi multi habitat instream offchann
Platts & Nelson (1989)	ID NV UT	SAL	PE(4)	4.0	experi multi reach graz ripar
Rieman & McIntyre (1995)	ID	BUT	PE(1) or SN(2) + assumed detectability	2.0	multi reach segment basin instream
Riley & Fausch (1995)	N CO	BKT-1, -2+ BRT-1, -2	PE(2-4) +B rem	4.0	experi multi reach migrat popdyn instream
Solazzi et al (2000)	W OR	CHO-1,j STT-1,j CUT-1,j TRT-0	"PE mk-rec, corrected removal or SN, +B, T"	5.0	experi multi habitat lwd offchann
Watson & Hillman (1997)	WA ID MT	BUT (5 l-grps)	"SN, if present PE & night SN"	3.0	multi habitat reach segment ripar instream substrate
Paulsen & Fisher (2001)	ID WA OR	CHI-j	NA (Pit tag-based survival)	NA	multi basin popdyn lulc hydro

[1] non-US locations: BC British Columbia, NB New Brunswick, NS Nova Scotia, NFD Newfoundland, UK United Kingdom, often preceeded by bearings N, S, E, W, etc.

[2] Taxa in Response variables:

CODE	COMMON	SCIENTIFIC
CUT	Cutthroat trout	Oncorhynchus clarki
CHO	Coho salmon	Oncorhynchus kisutch
RBT	Rainbow/golden/redband trout	Oncorhynchus mykiss
STT	Steelhead trout	Oncorhynchus mykiss gairdneri
KOK	Kokanee	Oncorhynchus nerka kennerlyi
SOC	Sockeye salmon	Oncorhynchus nerka nerka
CHI	Chinook salmon	Oncorhynchus tschawytscha
CHU	Chum salmon	Oncorhynchus keta
SAL	All salmonids	
MOW	Mountain whitefish	Prosopium williamsoni
ATS	Atlantic salmon	Salmo salar
BRT	Brown trout	Salmo trutta
DVD	Dolly varden trout	Salvelinus malma
BUT	Bull trout	Salvelinus confluentus
BKT	Brook trout	Salvelinus fontinalis
TRT	All trout	

suffixes: -0 YOY, -1 age 1, -1+ age 1 and up, -j juveniles, -a adults,
() species included in preceding group code, e.g. TRT.

[3] Gear: PE(2) BackPack Electrofisher(2 passes), SS net Seine, SN(2) Snorkeling (2 divers), T Trap, BS Boat electrofisher, +B blocknets set, mk-rec mark-recapture estimate, rem = removal estimate (qualifications often implied in Score - below)

[4] Score = relative accuracy of fish abundance estimation (averaged when >1 method used):

1	unqualified presence/absence in catch
2	snorkeling count
3	1+ electrofishing or net seine passes
4	multiple removal estimate
5	mark-recap or applied calibration based on mark-recap
6	rotenone or antimycin with mark-recap
7	draining or partial draining and rotenone

Table 3. Papers reviewed in detail to date (30): Explanatory variable groups, sampling summary.

Author(Year)	reach length (m)	wetted width (m)	#explan. vars[1]	explan.vars groups[2]	corr?[3]	inter-ac-tions?[4]	seasons	#yrs	#streams	#sites	N	R^2%	CV?[5]	analy-sis score[6]
Barnard et al (1995)	25-50		130 > 6-19	INS RIP BAS	N	N	Su	2		602	602	29-46	N	3
Bjornn et al (1991)		2-12	4 > 0	INSns RIPns	NA	N	Su	1	6	30	60		N	4
Bowlby & Roff (1986)		1.7-18	> 5	INS BIO	Y	N	Su Fa	1	20	30	30	62	N	7
Bremset & Berg (1997)			1 > 1	INS	NA	N	Su	2	3	24	24	NA	NA	5
Bryant et al (1998)		?	4 > 0	INS	N	N	Su	1	6	?	?	N	N	3
Clarke & Scruton (1999)		3 1stO, 1 2ndO	3? > 1	BIO	NA	NA	Su	3	4	4	11	N	N	2
Connolly & Hall (1999)		1stO & 2ndO	12 > 1-3	INS BAS-ns	Y	N	Su	3	16	16	16	36-71	N	5
Dolloff (1986)	85-170	1.6-2	1 > 1	INS (LWD)	NA	NA	Su	3	2	4	12/48	N	NA	3
Dunham & Vinyard (1997)		1-4	1 > 1	BIO (fish dens)	NA	Y	Su		14			NA	NA	8
Eaglin & Hubert (1993)	200	0.7-6.3 (BF)	6 > 2	INS BAS	N	N	Su Fa	2		28	28	34	N	4
Ebersole et al (2001)	100-500	?	9 > 1	INS	N	N	Su	1	4	12	12	50	N	4
Giannico (2000)	4	2	2 > 2	BIO	NA	Y	Su	1	1		?	NA	NA	5
Grant et al (1986)	≈60-70	2ndO 3rdO	1>1	INS RIP	NA	N	Su	1	13	13	26	NA	N	5
Herger et al (1996)	1.7-16	1.1-3-8		INS			Su					NA	NA	4
Horan et al (2000)	100	1.8-5	11 > 1-4/1	INS	Y	Y/N	Su	3	6	88/4	88/4	12-46/?	N	4
Hubert et al (1996)	30-330	0.9-80	20 > 4	INS BAS	Y	Y	Su	>10	95	158	166	38	Y	7
Jenkins et al (1999)	4.4-31/ 340-500	?	1 > 1	BIO (fish dens)	NA	N	Su-Fa	3	1	294/4	294/4	87/97	NA	6

Jowett (1992)	1000+	?	101> 1-8 (22 sep)	INS BAS BIO	Y*	N	Su	3	82	89	89	44-88	Y	5
Keith et al (1998)	20-76	2ndO 3rdO	3 > 1	INS RIPns	NA	Y/N	Su	1	3	72	120	N	N	6
Knapp et al (1998)	45-130	2-3.6	1 > 1	INS	N	N	Su	4	1	3	9	50-83	N	2
Knudsen & Dilley (1987)			1 > 1	INS	NA	N	Su Fa	1	4	5	10	NA	NA	5
Milner et al (1995)	50		130?	BAS TMP	N	Y	Su	4-10	13	26	?	26-72	N	5
Nickelson et al (1992a)	?	?	1 > 1	INS (pool types & brush)	NA	N	Su Wi	4	21	199	380	N	N	7
Nickelson et al (1992b)	?	?	1 > 1	INS (pool types & depth)	NA	N	Sp Su Wi	5	52	199	958	N	N	7
Platts & Nelson (1989)	122-183	3-11	4 > 1	INS (temp) RIP (canopy ns)	Y	N	Su	2-11	17	53	53	7-96	N	3
Rieman & McIntyre (1995)	100	1-14	3 > 2	INS BAS	Y	Y	Su	1	67	85	85	NA	NA	8
Riley & Fausch (1995)	250	2.9-5.8	6 > 1	INS	Y	N	Su	4	4	8	14	N	Y	9
Solazzi et al (2000)	?	3.2-4	1 > 1	INS (const. pools)	NA	N	Su Sp	8	4	120	120+	N	N	7
Watson & Hillman (1997)	100	0.3-46	23 > 5-8	INS RIP	Y	Y	Su		31	358	358/ 31	53-90	N	9
Paulsen & Fisher (2001)	NA	NA	NA	BAS BIO (fish size)	Y	N	Su-Wi	7	20	20		54-64	N	5

[1] x > y, where x = number of explanatory variables considered, y = number of explanatory variables retained in model

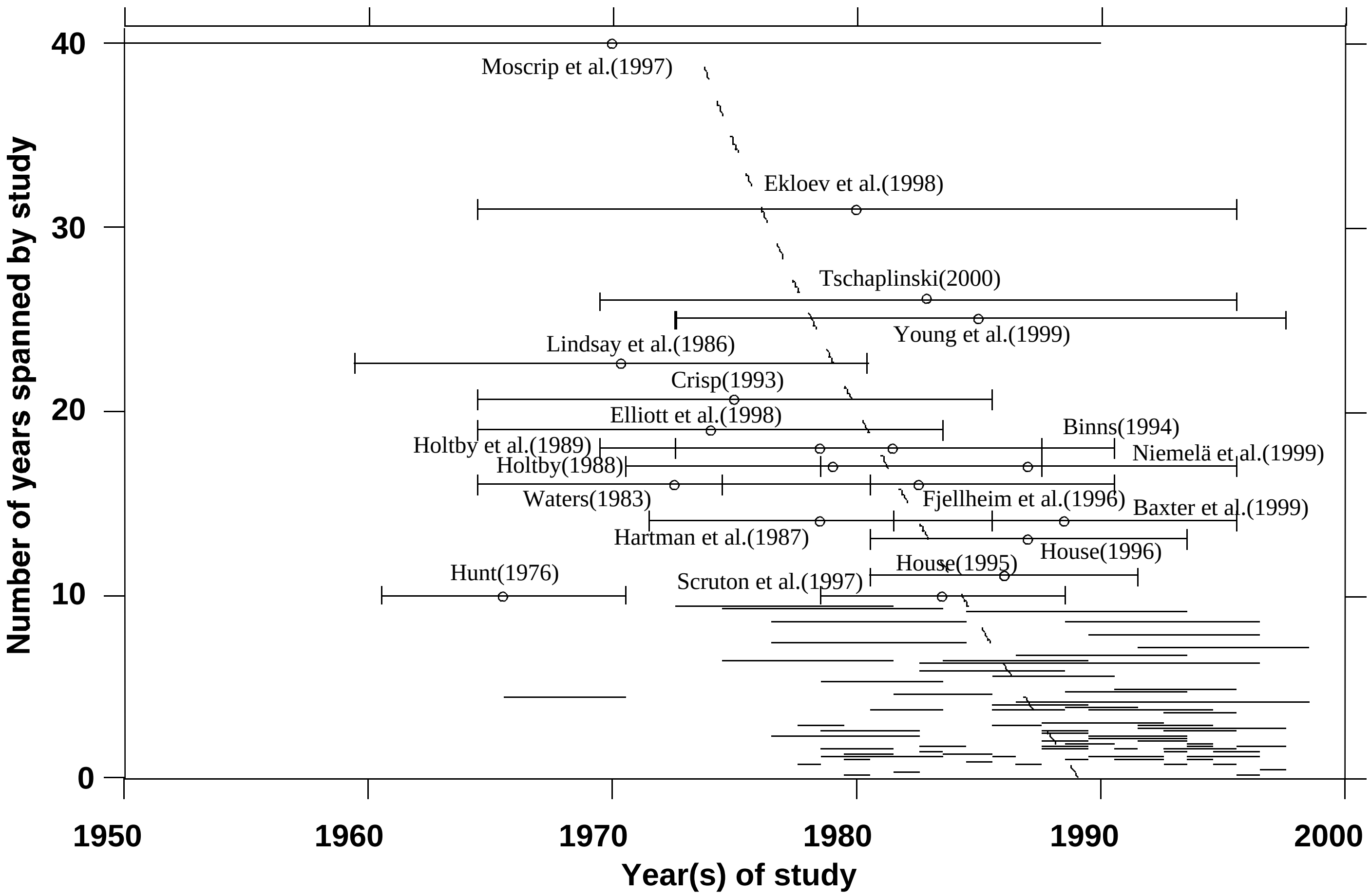
[2] broad classification of explanatory variables: INS = any physical instream habitat variable, including bank overhang, macrophyte cover and water quality, temperature;
(ns - not significant)
RIP = any riparian vegetation variable, including canopy cover, grazing in buffer zone.
BIO = any biological variable, including fish properties, invertebrates, except macrophyte cover.
BAS = any landscape, land-use/cover (lulc), geomorphic or geologic reiobal variable
TMP = temporal variable as year-ro-year effect

[3] Were explanatory variables investigated separately for correlations beforehand ?

[4] Were interactions investigated?

[5] Was some measure of precision of the predicted fish response, such as standard error of regression or coefficient of variation, calculated?

[6] Author's score (0 irredeemable, 10 perfect, 5 average) of design and analysis.



Citation (1st author)	Yrs	Classification codes (see Appendix 2)	Notes
Moscrip et al.(1997)	40	multi experi reach spawn lulc hydro temporal	Urbanization WA, early/late comparison
Ekloev et al.(1998)	31	multi habitat quant watqual noenv	S Sweden strms, early/late comparison
Tschaplinski(2000)	26	experi reach basin quant ripar lulc temporal	Carnation Cr., B.C.
Holtby et al.(1989)	18	modeling reach quant hydro ripar lulc temporal	Carnation Cr., B.C.
Holtby(1988)	17	quant popdyn basin wtemp lulc offchann temporal	Carnation Cr., B.C.
Hartman et al.(1987)	14	quant reach offchann migrat substrate	Carnation Cr., B.C.
Young et al.(1999)	25	experi reach quant ripar wtemp lwd temporal	East Cr. B.C. logging; disjunctive
Lindsay et al.(1986)	22	late entry; codes to be entered	John Day River basin
Crisp(1993)	20	multi reach quant popdyn migrat temporal	5 N Pennine strms, UK. dispersion/survival
Elliott et al.(1998)	19	quant popdyn spawn noenv	Wilfin Beck, UK. Age structured, stock/rec..
Binns(1994)	18	experi reach habitat quant hydro temporal	Beaver Cr. WY inst. structures
Niemelä et al.(1999)	17	multi reach quant temporal noenv	Teno basin, N Finland. density cluster analysis
Fjellheim et al.(1996)	16	experi quant trophic temporal	R Ekso, Norway. weir effects
Waters(1983)	16	reach quant popdyn sppinter substrate hydro temporal	MN, production; communuty change
Baxter et al.(1999)	14	reach spawn instream wtemp substrate lulc	Swan R. MT bull trout redd counts
House(1996)	13	experi reach instream substrate temporal	E. Fork Lobster Cr. OR inst. structures
House(1995)	11	reach quant ripar instream temporal warning	Dead Horse Canyon Cr. OR const. env
Kondolf(1994)	11	substrate graz qual economic	N Fork Cottonwood Cr.
Hunt(1976)	10	experi reach quant instream temporal	Lawrence Cr. WI inst. structures
Scruton et al.(1997)	10	reach quant spawn lakehydro instream substrate ifim temporal	W. Salmon R. NFD. flow regul.

Fig. 1. Periods of investigation spanned by 128 studies from the ‘first cut’ database in which time period that fish were sampled could be ascertained from the abstract (studies >9 yrs long shown in table).
Plot jittered for studies 1-9 yrs; dotted curve shows trend of study period versus mid- point year.
Some studies were disjunctive.

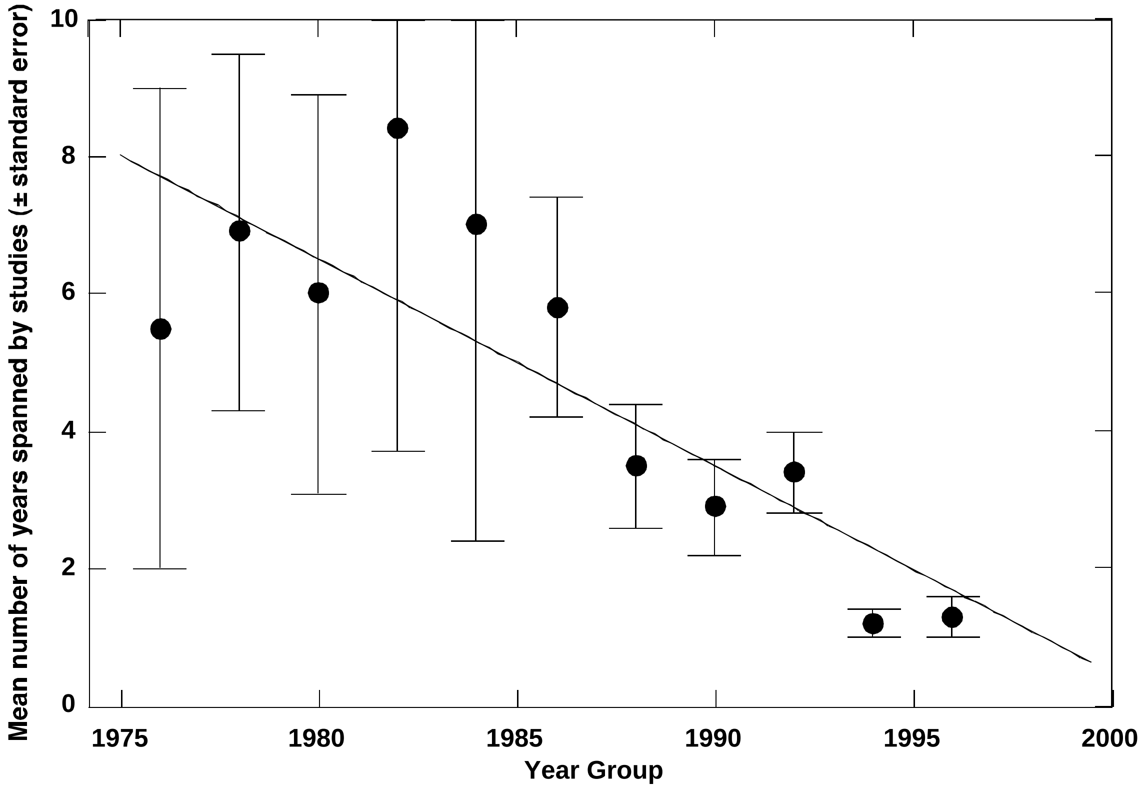


Fig. 2. Mean number of years spanned by studies (± standard error) as a function of biennial year group in which median of study period occurred (based on 128 studies from quantitative subset in Table 1). Regression line through means sig. at P=0.002.

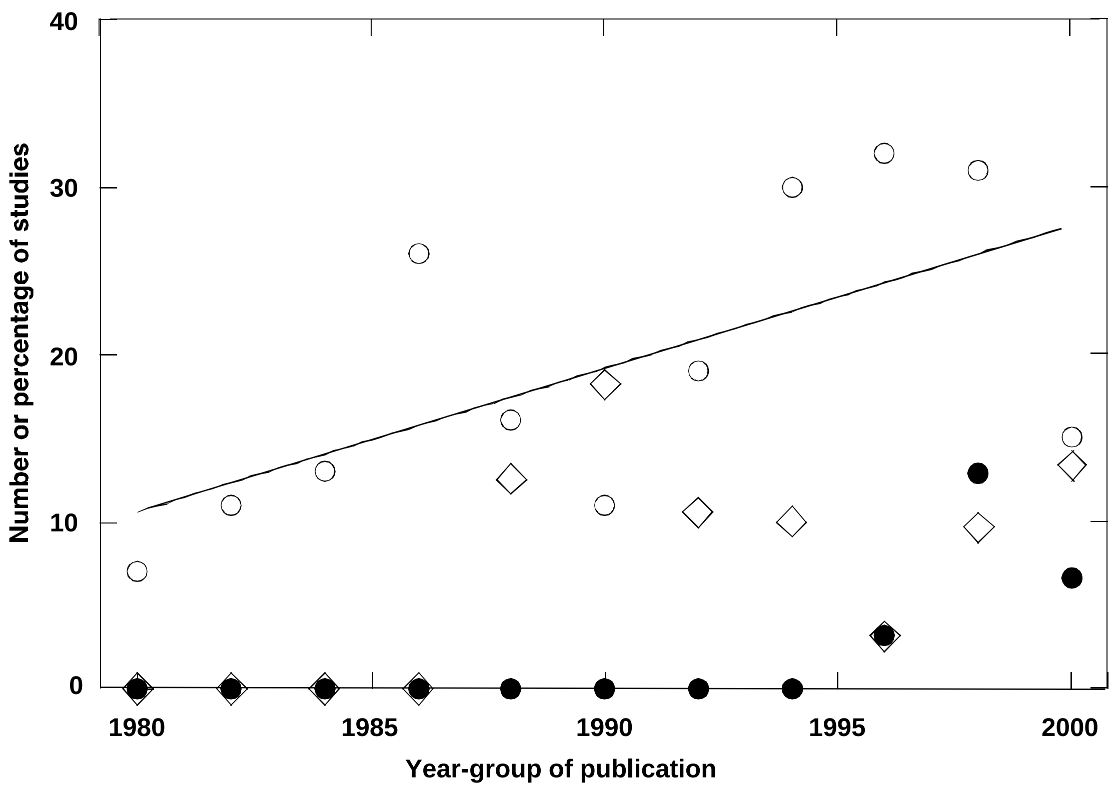


Fig. 3. Numbers of studies as a function of biennial year group of publication (based on 216 studies from 'quantitative' subset in Table 1), and percentages of studies with landscape-scale variables and those with inferences to basin scale.
open circles = no. of quantitative studies (regression line shown, P=0.039)
diamonds = percent of studies incorporating lulc or other landscape scale variables (P=0.048)
solid circles = percent of studies with basinwide inferences (P=0.021)
(studies assigned the ripar classification, bot shown, indicated a small negative trend with time.)