Measuring Biological Sustainability via a Decision Support System: Experiences with Oregon Coast Coho Salmon

Thomas C. Wainwright, Peter W. Lawson, Gordon H. Reeves, Laurie A. Weitkamp, Heather A. Stout and Justin S. Mills

Abstract Conservation of Pacific salmon (*Oncorhynchus* spp.) has become increasingly important as major populations have declined in abundance to the point of being listed under the U.S. Endangered Species Act. The complex life-history of Pacific salmon species and the diversity of habitats they occupy require multifaceted recovery efforts, and the metrics needed to evaluate species status and progress toward recovery are necessarily complex. Formal decision support systems (DSS) are designed to assist decision-makers in integrating and evaluating many factors. We describe a knowledge-based DSS for evaluating the biological status of Oregon coast coho salmon (O. *kisutch*). We then compare our DSS to similar tools and consider its advantages and disadvantages. We show how the DSS can provide a transparent and logical framework linking multiple criteria across geographic scales for a unified assessment. Once constructed, the DSS can serve as an institutional knowledge base, codifying the pathways from data to criteria evaluation and supporting consistent future status evaluations with a path to incorporating new knowledge over time. The DSS was not trivial to implement, nor is it easy to explain to resource managers, and we offer suggestions to address these problems. The DSS was particularly helpful in providing a logical and reproducible way to quantify multiple risks and assess progress toward recovery across multiple spatial and temporal scales. Development of this DSS is an important step in the evolution of assessment tools for salmon conservation.

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1 Introduction

Decision-support systems (DSS) are widely advocated as a means of structuring diverse information to support natural resource decisions. In conservation, they are used for spatial planning and prioritization of conservation actions (e.g., Steel et al. 2008; Wilson et al. 2011; Beechie et al. 2012, other chapters, this volume) and for tracking species at risk of extinction (Wong et al. 2007). Here, we consider their use in assessing biological sustainability of Pacific salmon (*Oncorhynchus* spp.) listed under the U.S. Endangered Species Act (ESA).

Our work focuses on the Oregon Coast Coho Salmon (OCCS) Evolutionarily Significant Unit (ESU). This ESU is composed of a distinct group of coho salmon (*O. kisutch*) populations that spawn in rivers and streams along the Oregon Coast (Weitkamp et al. 1995). Abundance of OCCS formerly exceeded one million adults (Lichatowich 1989), but declined in abundance by about 90 % during the 20th century, reaching historic low abundances in the 1990s (Weitkamp et al. 1995, 2000). Concern over these declines led the National Marine Fisheries Service (NMFS) to list OCCS as a threatened species under the ESA (NMFS 1998, 2008).

Coho salmon is an anadromous species that ranges along the west coast of North America from central California to Point Hope, Alaska and along the coast of Asia from Kamchatka to the Sea of Japan/East Sea (Sandercock 1991). There is much latitudinal variation in life-history patterns, but along the Oregon Coast, coho salmon typically spawn in freshwater during winter. Offspring rear for approximately a year and a half in freshwater before entering the ocean, where they rear for another year and a half before returning to freshwater to spawn (Sandercock 1991; Weitkamp et al. 1995).

In 2002, NMFS convened an OCCS Work Group to describe the biological conditions required for recovery of the ESU. OCCS have a complex metapopulation structure, with populations spawning and rearing in a range of coastal freshwater systems including ephemeral streams, large rivers, lakes, and tidal lowlands. In describing the population structure of this ESU, the work group identified five "biogeographic strata" representing major genetic and ecological diversity within OCCS, and identified 21 major independent populations within these strata (Lawson et al. 2007; Fig. 1).

In addition to identifying population structure, the work group developed a suite of biological sustainability criteria as a formal DSS (Wainwright et al. 2008). The term "biological sustainability" implies that a population is able to survive prolonged periods of adverse environmental conditions, while maintaining its genetic legacy and long-term adaptive potential. Sustainability also implies that habitat

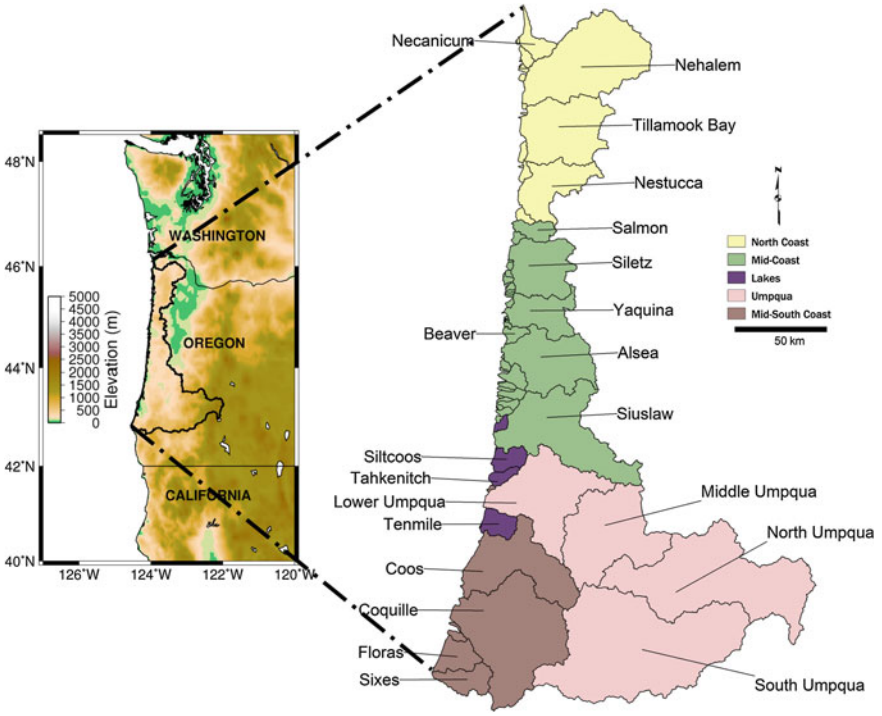


Fig. 1 Map of the range of the Oregon Coast Coho Salmon ESU, showing the locations of 21 major populations (named river basins) and numerous smaller populations (unnamed basins). The individual populations are aggregated into 5 biogeographic strata, indicated by different colors. Redrawn from Lawson et al. (2007)

conditions needed to support the full expression of the populations' life history diversity will be available into the foreseeable future (Wainwright et al. 2008).

A DSS is a computer-based tool that can analyze and compare numerous pieces of data, producing results that assist managers in making decisions (Turban and Aronson 2001). These systems allow decision makers to perform complex evaluations quickly, present a consistent assessment that draws from a variety of data sources, and accurately track large sets of information, thus improving decisions by supplementing and supporting human judgment (Rauscher 1999). In addition, a DSS can incorporate substantial uncertainty about the precise conditions that are optimal for the target organisms. Uncertainties may result from gaps in information and the lack of perfect knowledge about the interrelationships among relevant factors (Reynolds and Hessburg 2005). The OCCS DSS has been used as part of recovery planning by the state of Oregon (Chilcote et al. 2005) and by NMFS as part of an updated ESA status review (Stout et al. 2012) and ongoing recovery planning activities (NMFS 2013).

To our knowledge, such systems have not previously been applied directly to the evaluation of status for species at risk. Here, we summarize the OCCS DSS

structure, illustrate its application, and discuss its utility for conservation management. In doing so, we consider whether such a DSS can improve practical decisions regarding the status of species at risk.

2 Methods

A complete assessment of the biological condition of any species is necessarily multifaceted, including a variety of interrelated criteria, with varying data quantity and quality. For OCCS, these criteria relate to biological processes at a variety of temporal and spatial scales. Time scales vary from a single salmon generation (ca. 3 yr) to evolutionary time (100–1000s of years), and spatial processes vary from individual stream reaches (ca. 1 km) to the domain of the ESU (ca. 400 km). To track this large suite of data and criteria in a transparent and logically consistent framework, the work group decided that some form of DSS was essential.

The OCCS DSS was designed to provide an integrated suite of biological sustainability criteria to be used as part of ESA recovery planning. As a "support system," the DSS was not intended to "make" a decision on ESA listing or de-listing—it was designed to inform a decision-maker's judgment, not to replace it. Our approach was inspired by that used by the U.S. Forest Service for the Aquatic and Riparian Effectiveness Monitoring Plan component of the Northwest Forest Plan (Reeves et al. 2004). In defining the component criteria, the work group sought to meet the following characteristics of good recovery criteria:

- Measurable—Criteria are quantifiable based on obtainable data
- Comprehensive—Criteria include all important aspects of sustainability
- Sound—Criteria are based on best available science
- Transparent—Criteria are clearly defined and consistent
- Reproducible—Criteria can be consistently re-applied
- Useful—Criteria provide practical advice in a form useful to decision makers

2.1 DSS Structure

Here, we present an abridged summary of the DSS's more complex structure; a full description of which can be found in the work group's report (Wainwright et al. 2008).

The OCCS biological recovery criteria encompass a variety of biological requirements that contribute to ESU sustainability. To incorporate these into a DSS, the various criteria were expressed as a network of clearly-defined logical propositions whose truth could be evaluated from data. The DSS thus consisted of a hierarchical set of individual propositions describing various aspects of sustainability (Table 1). At the lowest level, propositions were evaluated based on

Table 1 Definitions of sustainability propositions evaluated in the decision support system (DSS)

Title	Definition	Code
ESU-Scale propositions		
ESU sustainability	The ESU is self-sustaining into the foreseeable future	ES
All strata sustainable	All biogeographic strata are sustainable (see Stratum Sustainability)	ES-1
ESU-scale diversity	The ESU has sufficient broad-scale diversity to maintain its ecological and evolutionary functions into the foreseeable future	ES-2
Genetic diversity	ESU-scale genetic diversity is sufficient for long-term sustainability of the ESU	ED-1
Genetic structure	Genetic diversity within the ESU is comparable to healthy coho salmon ESUs and forms the basis for life-history diversity	ED-1a
Effects of selection	Human-driven selection is not sufficient to decrease genetic diversity	ED-1b
Effects of migration	Genetic diversity is not compromised by changes in the movements of fish	ED-1c
Phenotypic and habitat diversity	ESU-scale phenotypic and habitat diversity are sufficient for long-term sustainability of the ESU	ED-2
Phenotypic diversity	Phenotypic diversity is present within the ESU at levels comparable to healthy ESUs or the historical template.	ED-2a
Habitat diversity	Habitats are sufficiently productive, diverse, and accessible to promote phenotypic plasticity	ED-2b
Small populations	Dependent populations within the ESU are not permanently lost	ED-3
Biogeographic Stratum-Scale propositions		
Stratum sustainability	The stratum is self-sustaining (in terms of both diversity and functionality) into the foreseeable future	SS
Stratum diversity	Most of the historically independent populations in the stratum are at present sustainable (see Population Sustainability)	SD
Stratum functionality	All of the historically independent populations in the stratum are functional (see Population Functionality)	SF
Population-Scale propositions		
Population sustainability	The population is able to sustain itself into the future. Requires both Population Persistence and Population Diversity	PS
Population persistence	The population will persist for the next 100 years	PP
Population productivity	Productivity at low abundance is sufficient to sustain the population through an extended period of adverse environmental conditions	PP-1

(continued)

Table 1 (continued)

Title	Definition	Code
Probability of persistence	The population has a high likelihood of persisting over the next 100 years, as estimated from PVA models	PP-2
Critical abundance	Population abundance is maintained above levels where small-population demographic risks are likely to become significant	PP-3
Population diversity	The population has sufficient diversity and distribution to ensure continued fitness in the face of environmental change	PD
Spawner abundance	The population has sufficient naturally produced spawners to prevent loss of genetic variation due to random processes over a 100-year time frame	PD-1
Artificial influence	The abundance of naturally spawning hatchery fish will not be so high as to be expected to have adverse effects on natural populations	PD-2
Spawner distribution	On average, the historically occupied watersheds in the population's range have spawners occupying the available spawning habitat (see Watershed Spawner Occupancy)	PD-3
Juvenile distribution	On average, the historically occupied watersheds in the population's range have juveniles occupying the available juvenile habitat (see Watershed Juvenile Occupancy)	PD-4
Population functionality	Habitat quality and quantity are adequate to support sufficient abundance to maintain long-term genetic integrity of the population	PF
Watershed-Scale propositions		
Watershed spawner occupancy	Spawners occupy a high proportion of the available spawning habitat within the watershed	W-Sp
Watershed juvenile occupancy	Juveniles occupy a high proportion of the available juvenile habitat within the watershed	W-Ju

Propositions are testable assertions; they are organized by metapopulation scale. "Code" is the abbreviation used to identify each proposition as it is evaluated in the DSS, shown graphically in Fig. 2

data collected at the *population* or *watershed* scale (Fig. 2). Various low-level propositions were combined at the *population* scale, then aggregated upward to the *stratum* scale and finally to the entire *ESU* (flow chart in Fig. 2). This approach views OCCS as a metapopulation, with substructure at a continuum of scales, from individual spawning grounds, up to the entire OCCS range. Along this continuum, the work group identified four discrete scales as important for defining attributes related to ESU status: (1) watersheds (defined as fifth-field hydrologic units, aka 5th HUCs, Seaber et al. 1987. Regional Ecosystem Office 2002), (2) populations

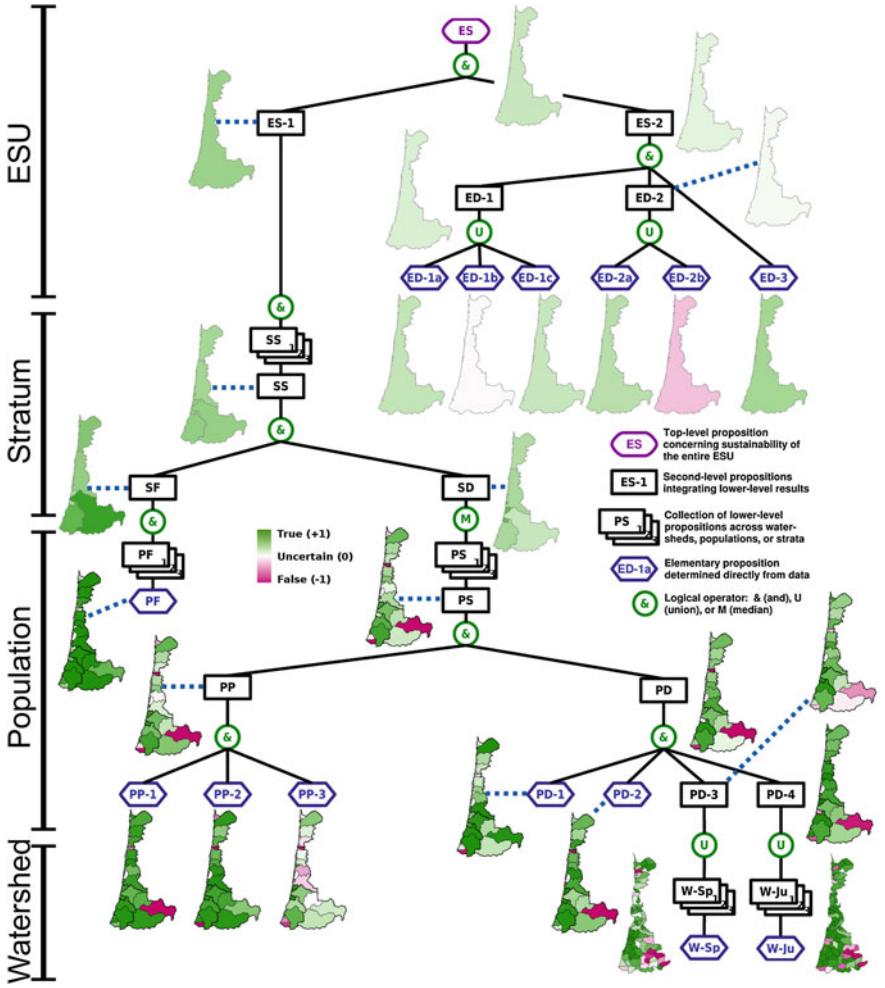


Fig. 2 The logic network for the decision support system, showing the information flow from lower-level propositions to the top-level ESU Sustainability ("ES") proposition, along with maps of resulting strength of evidence in support of each proposition. Proposition abbreviations are defined in Table 1

(fish residing in major river basins or subbasins), (3) biogeographic strata (regional population aggregates), and (4) the entire ESU (Lawson et al. 2007). Data used to assess OCCS status included juvenile salmon densities, adult spawner (a spawning fish) abundance and distribution, the proportion of spawners that were of hatchery origin, and professional judgment regarding ESU-wide genetic, phenotypic, and habitat diversity (Table 1). In our judgment, a multi-scale, multi-parameter approach would best support maintaining natural process variability, an important component of salmon restoration planning (Bisson et al. 2009).

Watershed-scale Attributes. Many ecological processes occur at small geographic scales. For the most part, these considerations have been subsumed into population-scale attributes, but two watershed-scale propositions (Juvenile Occupancy and Spawner Occupancy; Table 1) were used to examine within-population diversity and distribution.

Population-scale Attributes. There are a variety of population-scale attributes that contribute to population health. For NMFS recovery plans, these attributes are typically categorized into four parameters: population size, population growth rate, spatial structure, and diversity (McElhany et al. 2000). These same four parameters appear in the Oregon Native Fish Conservation Policy (Oregon Department of Fish and Wildlife 2003). The four are not independent of one another and their relationship to sustainability depends on a variety of interdependent ecological processes. Hence, the work group included 11 parameters in our analysis at this scale (Table 1).

Biogeographic Stratum-scale Attributes. In evaluating OCCS status, biogeographic strata play two important roles. First, they represent the largest pieces of habitat, genetic, and life history diversity, thus ensuring that they preserve much of the among-population diversity. Second, by ensuring that all the strata are preserved, a hedge is provided against loss of the whole ESU from large-scale catastrophic disturbance(s). The important attributes of strata are primarily the number and status of their constituent populations and associated habitats. Thus, in this analysis, the four stratum-scale propositions were simply combinations of the propositions for their component populations.

ESU-scale Attributes. On the ESU scale, concern focuses on catastrophes (infrequent large scale disturbances), long-term demographic processes, and long-term evolutionary potential (McElhany et al. 2000). At this scale, the propositions focus on ensuring that (1) all strata are independently sustainable ("All Strata Sustainable," Table 1), and (2) the ESU as a whole maintains sufficient genetic, phenotypic, and habitat diversity ("ESU-Scale Diversity").

Network Structure. The various propositions at these four scales form the nodes in a logical dependency network (Fig. 2). The links in this network take the form of logical operators that define relations among the input values. In traditional Boolean logic (which evaluates propositions as either absolutely true or false), propositions are "knife-edged," meaning the result of an operation has only one of two values—true or false—and, when the input values are near the edge, the result is very sensitive to small changes in the input. In the knowledge-based system used here, a type of approximate logic (referred to as "fuzzy logic"; Zadeh 1965, Adriaenssens et al. 2004) allows incorporating and assessing the imprecise knowledge available for the system. The advantage of using fuzzy logic is that it allows the degree of uncertainty to be evaluated and expressed in an outcome, ranging from certainly false, to uncertain, to certainly true. Being able to work with levels of uncertainty enables decision makers to evaluate the degree of risk inherent in decision-making.

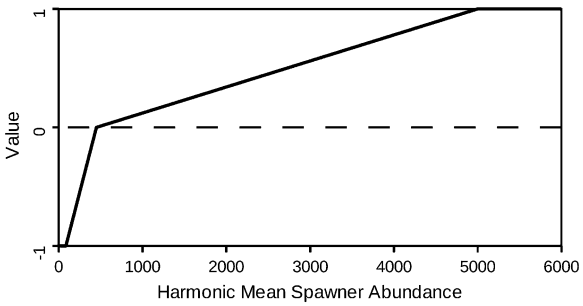


Fig. 3 Example of a fuzzy membership function for the Spawner Abundance (PD-1) proposition, showing how observations of harmonic mean spawner abundance (*horizontal axis*) correspond to the strength of evidence (*vertical axis*) in support of the proposition. Strength of evidence values range from –1 (no support) to +1 (full support) with 0 indicating unknown support. Redrawn from Wainwright et al. (2008)

The low-level metrics are evaluated on a scale from +1.0 (completely true) to –1.0 (completely false) through the application of "fuzzy membership functions" (see Chap. 2). These functions are used to evaluate the degree of evidence in support of specific propositions about current conditions. They were developed through analysis and application of the work group's best professional judgment, informed by relevant scientific literature. These functions allow intermediate values between true and false to occur when the strength of evidence supporting a proposition is intermediate, representing uncertainty in knowledge. For example, the "Spawner Abundance" proposition (Fig. 3) evaluates the degree of support for the proposition that "a population has sufficient numbers of naturally produced spawners to prevent the loss of genetic variation due to random processes over a 100-year time frame" (Wainwright et al. 2008, p. 44). Based on genetic theory (e.g., Waples 2006) and coho salmon life-history characteristics, the work group derived a range of long-term harmonic mean[1] abundance values that define the membership function for the proposition. Values ranged from 85 spawners (assigned a value of –1, = no support for the proposition) to 5000 spawners (assigned a value of +1, = full support for the proposition), with unknown support (assigned a value of 0) when spawner abundance is equal to 450.

Proposition combinations (within scales) and aggregations (across scales) are performed using three logical operators:

- "AND" (abbreviated "&" in Fig. 2)—evaluates to true only if evaluations of all of antecedent propositions are true (+1), and to false if any of the antecedents are false (–1). Between +1 and –1, the operator returns a weighted average of the antecedent values, with the weighting favoring the minimum value.

[1] Use of a harmonic mean to characterize spawner abundance reflects the nature of genetic variation in populations with fluctuating abundance (Waples 2006).

For example, in order for "Population Persistence" ("PP" in Fig. 2) to be true, all subpropositions ("PP-1", "PP-2", "PP-3") must be true.

- "UNION" ("U")—treats its antecedents as contributing compensating evidence in support of a proposition, thereby averaging the strength of evidence values of its antecedents. This operator is used where trade-offs among subpropositions fall within an acceptable range with respect to the fuzzy membership function (i.e., values falling between no support and full support, –1 and +1). For example, for "Spawner Distribution" ("PD-3" in Fig. 2) a high value from one watershed could compensate for a low value from another.
- "MEDIAN" ("M")—returns the median level of support for the proposition derived from evaluating its antecedents. Use of this operator implies that it is desirable that a majority of the subpropositions are true. For example, "Stratum Diversity" ("SD") requires that a majority of the populations within a stratum are sustainable ("Population Sustainability," "PS").

Our DSS was initially developed using the Ecosystem Management Decision Support (EMDS) system (Reynolds et al. 2002, Chap. 1). However, we were unable to fully implement our propositions within the EMDS framework, owing to unique features of our application. We developed alternative implementations of the DSS logic in both R (R Development Core Team 2013) and Microsoft Excel[2] that emulated the logic model. Further details on methods and data sets (including computer code implementing the DSS) can be found in Wainwright et al. (2008).

2.2 Application

To date, three versions of the DSS have been used by agencies in decision-making relevant to managing OCCS. The work group provided an initial example application of the DSS in its report (Wainwright et al. 2008), and that analysis was included by NMFS as part of the information considered in on-going listing decisions and recovery planning (NMFS 2008). A second version of the DSS was used by the State of Oregon in developing its Oregon Plan for Salmon and Watersheds (Chilcote et al. 2005). Most recently, NMFS and Oregon Department of Fish and Wildlife staff updated the data sets and applied the DSS to inform an updated status review for OCCS (Stout et al. 2012). Below, we briefly summarize that most recent application as a concrete example of the approach.

[2] Reference throughout this document to trade names does not imply endorsement by the National Marine Fisheries Service, NOAA.

3 Results

Running the DSS produces a systematic evaluation of the degree of support associated with each proposition, for all the population units for the geographic scale at which the proposition applies. This results in a large number of individual proposition values, which are summarized in the color-coded maps in Fig. 2. After combining propositions within scales and aggregating values across scales, the ultimate result for "ESU Sustainability" ("ES," which evaluates the proposition that "the ESU is self-sustaining into the foreseeable future"), was 0.24 (on a scale of –1–+1), corresponding to the light-green map at the top of Fig. 2.

This overall ESU value summarizes a great deal of variability in population and stratum-scale information, as can be seen in the maps for subpropositions in Fig. 2. For example, the "Population Persistence" values for individual populations ranged from –1 (Salmon River, Sixes River) to +0.98 (Tenmile Lakes), and approximately two-thirds of the populations had persistence values greater than 0.25. "Population Sustainability" values ranged from –1.0 in two populations to a high of 0.85 in the Coquille River. The values for "Stratum Sustainability" were less variable, in the narrow range of 0.39–0.48.

3.1 Communication and Interpretation

The DSS provides quantitative measures, i.e., strength of evidence in support of propositions, concerning the biological condition of OCCS at population, biogeographic-stratum, and whole-ESU scales. These values can inform decisions about ESA listing and recovery, as well as more general conservation planning; but tables of strength of evidence values are not very "user friendly," especially for decision makers unfamiliar with the technique. To ease the communication and interpretation of results, the work group took two approaches: verbal interpretations of numerical values, and visual display of results.

First, the work group addressed the verbal description of results, particularly with regard to the ESU sustainability propositions. For the extreme values, a value of –1.0 indicates a particular proposition is not met; meaning both the risk of inaction and the expected restoration cost may be high. Similarly, a value of +1.0 means that the proposition is fully met, and both risks and costs approach zero. However, between these extremes, the values do not translate directly to yes or no conclusions, and interpretation of intermediate values may prove difficult for decision makers. To aid in interpretation, the work group developed a set of verbal descriptions of the degree of certainty associated with a given strength of evidence value (Fig. 4). Values near zero are considered "uncertain," those near $\pm$ 0.1 are considered to indicate "low" certainty, those near $\pm$ 0.3 "moderate" certainty, those near $\pm$ 0.6 "high" certainty, and values near $\pm$ 1.0 are considered fully certain. Combining the sign (which indicates truth or falsity) with the magnitude of the value allows statements to be made about the propositions. Applying this

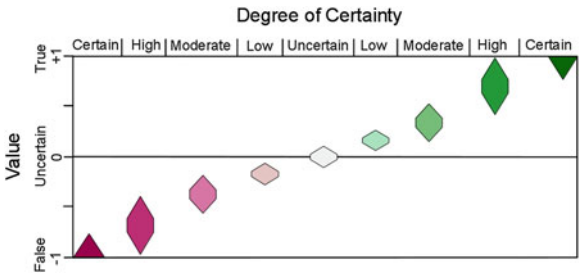


Fig. 4 Verbal interpretation of strength of evidence values produced by the decision support system. Adjectives describing degree of certainty are related to imprecise degree of support values, with color-coded levels corresponding to those used on the maps in Fig. 2. Redrawn from Wainwright et al. (2008)

semantic tool, the ESU sustainability value of 0.24 could be expressed as "low-to-moderate certainty" that the ESU is sustainable for the foreseeable future.

The second way the work group communicated results was visually, as a set of maps of the values for each proposition within the DSS network (Fig. 2). The maps provided an easy visual guide to populations and habitat areas that likely limit the sustainability of the ESU as a whole. The network of maps provided a tool for understanding how observed conditions at population and watershed scales contributed to overall population sustainability, and how populations contributed to the condition of the biogeographic strata and ESU. In addition, the maps provided a guide to areas where recovery efforts might be prioritized.

4 Discussion

The OCCS DSS represents an important step in the evolution of approaches to Pacific salmon status evaluations. Beginning around 1990, early status reviews (e.g., Waples et al. 1991) relied on biological information evaluated by a Biological Review Team, with a decision reached using professional best judgment without any defined set of criteria. In the mid-1990s, NMFS initiated a series of coordinated coast-wide reviews of Pacific salmon from California, Oregon, Washington, and Idaho; this led to a standardized set of metrics for population abundance, trends, and hatchery influence (Weitkamp et al. 1995), while the decision still relied on group professional judgment. This system was replaced by a more formal risk-matrix approach (Wainwright and Kope 1999). The specific risks were categorized as abundance, trends/productivity, genetic integrity, and other risks, and review team members voted on five levels (ranging from very low to high) within each risk category. While decisions still relied on team member professional judgment, this new approach clarified which risk categories were of greatest concern, and documented the degree of uncertainty and disagreement within review teams.

Following the development of NMFS' "Viable Salmonid Populations" (VSP) approach (McElhany et al. 2000), the risk matrix was further refined to provide consistent evaluations of the four VSP risk categories (e.g., Good et al. 2005). However, even with this added structure, status assessments strictly relied on professional judgment, and were neither transparent nor easily repeatable. The approach summarized here provides a suite of criteria that are based on well-defined data, have explicit statements of their scientific basis, and are connected via logical operations that provide a repeatable and explicit methodology to evaluate overall ESU status. The DSS still involved professional judgment in defining propositions, designing the logic network, and in drawing management conclusions from the results. However, that judgment was constrained and organized into documented steps such that persons outside the review process could follow (and potentially repeat) the logic of any management decisions based on the DSS.

The manner in which the work group implemented the DSS involved a number of subjective choices that could influence decision outcomes; several of these merit further discussion (immediately below).

4.1 Alternative Approaches

The work group considered a number of alternatives before choosing the DSS approach. First, we considered an approach with no formal DSS, where each criterion would be evaluated separately, with ESU status decided by subjective integration of the various criteria. This approach was rejected for two primary reasons: (1) by leaving the integration of criteria and the aggregation from populations to ESU open to subjective interpretation, it would not provide an objective means to evaluate ESU status, and (2) it lacks an explicit description of the logical connections among the criteria, thus reducing the reproducibility and transparency of analysis.

Second, we considered a logic framework with strict pass/fail propositions. This approach would ignore uncertainties in the science and available data, and would require a priori determination of acceptable risk prior to assessment. No such determination was available, and the work group believed the choice of acceptable risk should be a sociopolitical decision, and thus outside the scope of work. Another problem with pass/fail propositions would arise where results approach threshold values, in which case decisions could flip-flop with minor changes in data, potentially reducing the credibility of the process. Based on these considerations, the work group sought a method that expresses the degree of biological risk facing an ESU, rather than a pass/fail result.

Finally, other approaches to evaluating risk within the DSS framework were considered, notably Bayesian probabilistic risk assessment (Marcot et al. 2006). A Bayesian approach could provide an integrated measure of risk, resulting in a final status evaluation that may be easier to interpret. However, it would have

required a number of complex assumptions regarding conditional probabilities, which can hide important details of analysis. The work group concluded that a logic-based DSS provided greater transparency than probabilistic approaches, while retaining a full description of the logical connections leading from low-level data to the integrated ESU evaluation.

4.2 Advantages and Disadvantages

As part of the initial DSS design, the work group focused on a knowledge-based system that codified the best available scientific knowledge. Our approach to assessing biological sustainability has several advantages over other approaches:

1) The method organizes quantitative and qualitative knowledge about numerous and diverse factors into a single, coherent logical framework that reflects the current state of knowledge about processes affecting biological sustainability, how they are logically connected, and how they operate at different spatial scales.
2) The DSS allows us to explicitly disclose how the aggregate of various indicators was evaluated; not only the grouping of indicators, but the nature of the interdependence among them as they represent biological sustainability.
3) The DSS clearly represents the data used, assumed relations among the data, information used as the basis for assumed relations, and how conclusions were drawn.

The DSS design incorporates a hierarchy of geographic population structure representing different scales of genetic and life-history diversity. Our ability to display this geographic structure as maps of values for the various propositions (Fig. 2) provides two distinct advantages. First, it provides a quick basin-by-basin overview of areas with good and poor conditions, which provide a starting point for prioritizing recovery actions. Second, when the proposition maps are viewed alongside the logic network, they provide a means of directly visualizing how the parts contribute to the whole.

Knowledgebases provide consistent data interpretation in a specified framework that is clear and unambiguous. Many current sustainability assessment efforts do not have an accompanying logic framework providing consistent, integrated interpretation of data. This lack may lead to differences of opinion about what the data mean and inconsistent conclusions over time. Knowledgebases can clearly articulate relations between indicators and biological condition as well as relations among indicators. As a result, calculations of aggregate indices are consistent and less likely influenced by successive assessments of individual evaluators.

Another advantage of the knowledge-based framework is that its transparency and logical rigor can provide a clear road map for revision and adaptation. The DSS can serve as a "snapshot" of institutional knowledge, codifying the scientific knowledge and data at the time of its creation. This means there is no need to re-create this process at each subsequent decision point, so updates are easier.

However, the DSS also provides a structure for incorporating new information; as new knowledge becomes available, changes in relationships can be redefined without losing prior knowledge. Similarly, new propositions can be added if new data types become available.

While a DSS such as ours works well in data-rich environments, the approach may also be robust to missing data. Although full results require that consistent data series be available for all primary propositions, where data are lacking, the DSS defaults to a result of zero, indicating complete uncertainty regarding that proposition. This provides an indication of the consequences of missing data to decisions.

The approach is of course not without disadvantages. One disadvantage is the time required to design and implement a DSS, which involves extensive literature review and discussions to elucidate interacting ecological processes that define the logic network. Once the basic propositions have been linked in the network, the next task is developing specific metrics (statistical summaries of data) and fuzzy membership functions for them. In our application, this process took over a year of subcommittee work. A second disadvantage is the difficulty of communicating DSS results, and how biological conditions affect results, to policy-makers and interested public, particularly explaining the meaning of numerical results. While the DSS provides transparency in the sense that all parts of the process are documented and the software to run the analysis is available, the knowledge network is not simple to explain. As an analogy, describing the DSS is like describing a clock with a transparent case: all the parts can be seen, but understanding how it works requires a bit more effort, and perhaps a copy of *The Way Things Work* (MacCaulay 1988). This difficulty is to some degree inherent in any decision model—some effort and expertise is required to understand the workings of a complex system.

4.3 Lessons Learned

A number of issues were important during development of the DSS, and led to modifications in either the overall approach, or how results were communicated. These included (1) consistency with other Pacific salmon recovery plans, (2) the role played by professional judgment, (3) the use of fuzzy logic, and (4) the level of resources needed to implement the approach.

Consistency. To ensure that the biological recovery criteria were comprehensive and consistent with approaches used by other Pacific salmon recovery plans, the work group incorporated the aforementioned VSP approach (McElhany et al. 2000). VSP identifies four key population parameters that influence the sustainability of populations.

- Population size—the abundance of all life stages of the species
- Population growth rate (productivity)—production over the entire life cycle

- Spatial structure—fish distribution among habitats and habitat connectivity
- Diversity—variation in phenotypic and genetic traits among individuals in a population and among OCCS populations.

While recognizing the importance of VSP parameters to population sustainability, problems were identified while using them as organizing principles for a consistent set of recovery criteria. Two primary concerns were (1) the lack of direct connection with habitat characteristics, and (2) strong interdependency among the four parameters. The goal of recovery and restoration is not merely to meet a set of artificial criteria, but to restore or repair ecological processes that contribute to long-term sustainability of the resource. As the propositions used in these analyses were developed, the work group focused on connections between the criteria and fundamental processes, specifically those that contribute to sustainability at various scales.

Professional Judgment. All ESA evaluations rely to some degree on professional judgment, and this judgment is often implicit and intractable. In a DSS approach however, judgments can be well-defined and constrained by a logical structure, and the pathways by which judgment influences evaluations are traceable. In addition, because the judgment is contained within the logic structure of the DSS, it is codified in the model and cannot be influenced by analytical results.

In our DSS, judgment entered three ways, when the work group defined the structure of the logic network, established fuzzy membership functions, and developed metrics to evaluate ESU-scale diversity propositions. The first two of these are common to (and unavoidable in) all decision-support applications; it is how scientists apply expert knowledge and judgment formed through experience to the art of decision making. The third case—basing some propositions on professional judgment rather than objective data—was a design choice made reluctantly by the work group. Evaluating diversity at the ESU scale proved to be somewhat intractable. While there was some theory as to the processes important to maintaining broad-scale diversity, there were no quantitative models of those processes, no clear relationships between diversity measures and sustainability, and little available data. Because the use of professional judgment introduced great uncertainty in these propositions, their values were given a reduced weight relative to the population and stratum-scale propositions (Wainwright et al. 2008).

Fuzzy Logic. Of all the parts of the DSS, the concept of fuzzy logic was probably the most difficult to communicate to non-technical audiences. While fuzzy logic is widely recognized (though perhaps not well understood) in the scientific community (Adriaenssens et al. 2004), with policy-maker and public audiences we found the term to be an unfortunate name for a useful approach. In fact, during a stakeholder review meeting, one of the review panel members quipped: “Fuzzy logic? That sounds like the federal government!” Because of widespread misunderstanding of the term, for public venues the work group adopted the informal term “approximate logic” to reduce initial negative reactions.

Beyond the problem of terminology, another problem with using fuzzy logic is that it results in numerical strength of evidence values that are difficult to directly

interpret. The structure of fuzzy membership functions with numeric values between "false" and "true" is unfamiliar and uncommonly used. Interested parties want to ask "is the ESU sustainable?" and get a simple yes or no answer. Instead, we evaluate the statement "the ESU is sustainable" and get a numeric value between true (+1) and false (–1). A value of "0" (complete uncertainty) can result from two different cases: either the input value is 0 on the fuzzy membership function (e.g., 450 spawners in Fig. 3), or there is a complete lack of information. This frequently requires further explanation to avoid confusion.

Similarly, it is not always clear how to interpret numerical DSS results for an ESA listing or de-listing (yes/no) decision. Verbal interpretation of the final value 0.24 for the ES proposition ("The ESU is self-sustaining into the foreseeable future") suggests a qualified answer: "Yes, but with a low to moderate degree of certainty" (Fig. 4). Whether that value leads to de-listing would of course depend on other factors, including consideration of the desired level of precaution in the decision, legal interpretations of the phrase "likely to become endangered" in the ESA, and evaluations of other ESA listing factors such as habitat conditions, exploitation, or the adequacy of regulatory mechanisms.

Resources Needed. For most members of the work group, this was their first exposure to constructing a knowledge-based DSS, and this DSS was the most complicated that any of us had designed. The experience provided a few lessons that should be useful to other teams that try this approach. Development of both the recovery criteria (propositions to be evaluated) and the fuzzy membership functions took far longer than anyone expected. Because propositions and membership functions form the foundation of analysis, it is essential that all are carefully worded and structured to faithfully capture the attributes of interest, and ensure that propositions, functions, and metrics are based on the best available science. Thus, although the process was time consuming, it was critical for success.

The process was also iterative. Once the DSS was complete, the work group revisited several propositions and membership functions that were not representing the attribute under evaluation as intended. In addition to the appropriate scientific expertise, successful implementation of the DSS required support staff with expertise in scientist herding, database management, GIS, and programming.

Even though the OCCS is one of the most data-rich Pacific salmon ESUs, there were still major data gaps. For example, the work group used professional judgment to assess genetic and phenotypic diversity, hardly satisfying when compared to extremely good data sets on juvenile or spawner abundance. Application of this method to other ESUs that are less data-rich would be more difficult, and would require more professional judgment. Clearly, the utility of developing a formal DSS system should be established early, especially where data are limited.

To reduce the possibility of implementation errors, the work group relied on two independent software implementations of the DSS: one spreadsheet-based (in MS Excel), and the other programmed in the R language (R Development Core Team 2009). This extra effort turned out to be essential to a reliable analysis. During initial development, test runs of the two implementations identified several

ambiguities in verbal definitions of propositions and metrics. Even during the analysis phase, a few errors were caught in data alignments that resulted from the complexity of the spatially structured time series data sets. Had there been only one version of the DSS and one person implementing it, reliability of the analysis would have been sacrificed and, worse, we probably wouldn't have known there were problems.

4.4 Future Directions

The DSS fell somewhat short of initial expectations. We suggest a number of improvements that could be made within the existing framework, then a few new directions.

Improvements. The work group was unsatisfied with several of the propositions. Most problematic was the set of ESU-scale diversity propositions evaluated solely based upon expert opinion. We would like to revisit these in the future and suggest specific monitoring that could directly inform them, or, failing that, define a rigorous future method of eliciting expert opinion (e.g., Aspinall 2010). Other propositions that should be revisited include "Population Functionality" and "Stratum Functionality", which are based on habitat models rather than direct measures of available habitat, and "Population Persistence", which is based on a suite of four models that are time-consuming to update and run.

Another area where there is room for improvement is in software implementation. As noted above, we started DSS development in the EMDS system, but found that our needs were better met by implementing the DSS logic in both R and MS Excel. This decision was made because of software limitations and portability issues. First, we could not implement our full logic network (in particular, the median operator used in the Stratum Sustainability proposition) in EMDS, nor could we easily conduct desired sensitivity analyses (Appendix A in Wainwright et al. 2008). Second, EMDS is not portable, in the sense that it is designed for a single operating system and requires additional proprietary commercial software. The work group felt that it was important that our decision system be accessible to government decision-makers and stakeholders so that they could recreate and potentially modify our results without specialized commercial software.

One effect of this decision was that we no longer had a fully integrated system that could be used from network design through presentation of results. Although the work group used two versions of the model, neither could be considered user-friendly, particularly in the level of effort needed to update and cross-check the many data series that drive the analysis. This could be improved by developing direct database linkages from agency-maintained data sets to the DSS software. Additional improvements could be made in the user interface, which currently requires script programming or intimate familiarity with multi-page spreadsheet management, as well as GIS expertise to translate the results into maps. A more integrated system would better support frequent and rapid data updates integrated

with direct GIS results display. Such improvements would make it much more likely that the DSS would play an active role in ESA recovery scenario planning.

New Directions. The work group was unable to address two important issues in the current version of the DSS: freshwater habitat issues, and climate variation and trends. Habitat availability and quality are important statutory considerations in ESA recovery planning, but this DSS does not directly capture habitat quality in any meaningful way. The Oregon Department of Fish and Wildlife conducts extensive annual salmon habitat surveys, so it should be possible to incorporate habitat data into the population diversity criteria, or possibly to form a separate branch of the DSS to evaluate habitat and other statutory listing factors (ESA Sect. 4a). Recently developed habitat trend models (Ward et al. 2012) suggest a possible approach.

Much of the concern that led to the ESA listing of OCCS arose in the 1990s during a prolonged period of marine conditions that led to poor juvenile survival for northwest coastal coho and other salmon stocks (Stout et al. 2012). One concern of the work group was to define criteria that would ensure that OCCS would survive another period of similar conditions without substantial loss of diversity. Presently, the DSS considers only the most recent 12 years of data (except for long-term means in the "Spawner Abundance" proposition). This is problematic when one considers that climatic fluctuations often persist longer than 12 years, and it also does not account for long-term trends in climate conditions. Climate change is an emerging issue for conservation planning for this and other ESUs (Stout et al. 2012; Wainwright and Weitkamp 2013).

5 Conclusions

The Oregon Coast coho salmon DSS is a unique approach to informing ESA listing and recovery decisions by contributing an integrated and comprehensive analysis of important biological sources of risk. This DSS meets goals for measurable, transparent, and reproducible criteria. Although initially time-consuming to build, the DSS has served a variety of useful functions. The formal process of developing the DSS network provided a basis for finding common ground and consensus building among scientists with diverse backgrounds and priorities. It summarized a variety of objective, measurable information, creating statistics that were comparable among multiple populations. Based on these statistics, reported in table and map form, patterns in the status of a listed species and the underlying causes of these patterns became evident. Through periodic updates the DSS has quantified incremental changes in biological status. Likewise, the DSS has provided a unifying platform for discussion of OCCS status and has supported the decision-making process.

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