A causative* network of Vital Signs:
Implications for the strategy to recover Puget Sound

[*Used in distinction to 'causal' which is generally applied to Bayesian networks.]

Report by

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Version of May 10 2017

Summary

Rationale: Uncertainties persist in how the strategy to recover Puget Sound should best be structured and managed. Given that separate recovery strategies cannot and should not be developed for all Vital Sign targets, and a finite number of recovery strategies can be managed at any time, which sub-set would yield the greatest recovery gains? If recovery can be enhanced by combining Vital Signs (or their component parts) into composite Implementation Strategies, on what basis might those mergers be made? Answers would be informed by some understanding of how Vital Signs interact with each other, and differ in their potential impact on recovery. To date, the recovery strategy for Puget Sound has focused on Vital Signs themselves, rather than their interactions. A pilot assessment of how Vital Signs functionally affect each other yielded insights that may alleviate some of the uncertainty in these questions. This report summarizes the principal results and implications of the assessment.

Terms and Methods: For these purposes, a 'Functional Effect' refers to any physical, chemical, biological, or social effect, positive or negative, induced in one Vital Sign by a substantial improvement in the condition of another Vital Sign. Expert elicitation was used to identify the mechanisms, and rate their relative strengths, of Functional Effects among all pairs of Vital Signs (a total of 25x24=600 pairwise interactions). 'Functional Influence' refers to the sum of Functional Effect scores of a given Vital Sign on all others.

Principal results and implications

1. Results are presented as scores in symmetric matrix format (Vital Signs-by-Vital Signs), and as a causative network ('directed graph'), featuring Vital Signs as 'nodes', linked by arrows representing their Functional Effects ('edges'). Network topology reproduced a cascade of Functional Effects linking upper watersheds to nearshore habitats to marine basins and into the food chain, both marine and human. Most pathways among biophysical Vital Signs converged on *Chinook Salmon*, and through *Chinook Salmon* (among others) to human wellbeing.
2. In the sense that all Vital Signs are functionally linked to at least one other, this network is 'fully connected'. This does not mean this set of Vital Signs is sufficient for recovery. But it does highlight that interactions among Vital Sign indicators have hitherto been underemphasized in the strategy to recover Puget Sound, and their inclusion may yield insights about how best to proceed.
3. Indexed by Functional Influence (sum of Functional Effect scores), the most 'influential' Vital Sign was *Sound Stewardship Index*. This is consistent with expectations, given that most pressures originate from injurious human behaviors. Improving stewardship and changing behaviors should feature prominently in Implementation Strategies for many Vital Signs.
4. Following *Sound Behavior Index* in Functional Influence were *Summer Stream Flows, Land Development and Cover*, *Freshwater Quality, Marine Water Quality* and *Chinook Salmon*. These form a strongly – and linearly – linked sub-set of Vital Signs, referred to herein as the 'principal axis' of recovery, in which greater investment may be justified (both past and future).
5. Vital Signs with the greatest Functional Influence are not well represented among Implementation Strategies that have been, or are about to be initiated. Ultimately, there should be some correspondence between Functional Influence and recovery investment.
6. Compared to positive effects between Vital Signs, negative effects are uncommon and mild. Concerns that conflicting Functional Effects will neutralize remedial actions may be overstated (but this needs confirmation).
7. Of all Vital Signs, *Economic Vitality* had the greatest total negative impact AND was negatively impacted the most. The implication is that success depends on harmonizing environmental with economic advances, preferably via 'multiple benefits'. This approach is well established in *Floodplains*, but similar creativity must be applied in other sectors, particularly *Estuaries*, and *Land Development and Cover*.

Significance: This analysis provides an initial framework with which to explore options for accounting interactions among Vital Signs in the recovery strategy for Puget Sound.

Introduction

The size and diversity of Puget Sound pose the greatest challenge to designing a recovery strategy that is sufficient (achieves recovery), representative (addresses pressures in terrestrial, freshwater, and marine systems), efficient (proceeds with minimal effort and cost), and manageable (feasibly implemented and administered).

While only time will reveal its sufficiency, the strategy as it stands may be close to representative, given that a) the *Action Agenda* originally comprised 29 Strategies and 106 Sub-strategies, b) a 2014 study assessed the severity of 47 pressures on 60 of the most-valued ecosystem components (McManus et al. 2014), and c) additions to (e.g. ocean acidification), and omissions from (e.g. sediment dynamics) these lists have been few. To enhance feasibility, the scope of the strategy was narrowed to focus actions on targets defined for indicators of so-called 'Vital Signs'. These include a set of 16 originally selected to communicate recovery progress by tracking changes in the status of key ecosystem components and attributes, most of them biophysical. Recently, 9 Vital Signs were added to track changes in aspects of human wellbeing that are affected by environmental quality (Biedenweg et al. 2016). Again, time will reveal whether Vital Signs prove an effective framework for recovery. But this narrowing of focus does provide opportunities to define strategies for specific targets (so-called Implementation Strategies), monitor effectiveness of actions, and adaptively manage recovery more deliberately than was previously the case.

Aspects of manageability remain uncertain. Given that recovery strategies cannot be developed for all Vital Sign targets, and a finite number can be managed and any time, which sub-set would yield the greatest recovery gains? If recovery can be enhanced by combining Vital Signs (or their component parts) into composite Implementation Strategies, on what basis might those mergers be made? Answers would be informed by some understanding of how Vital Signs interact with each other, and differ in their potential impact on recovery. To date, the recovery strategy for Puget Sound has focused on Vital Signs themselves, rather than their interactions. A pilot assessment of how Vital Signs functionally affect each other yielded insights that may alleviate uncertainty in all of these questions. This report summarizes the principal results and implications of the assessment.

Methods

For these purposes, a 'Functional Effect' refers to any physical, chemical, biological, or social effect, positive or negative, induced in one Vital Sign by a substantial improvement in the condition of another. Expert elicitation was used to identify the mechanisms, and estimate their relative strengths, of Functional Effects between all pairs of Vital Signs (a total of 25x24=600 pairwise interactions, assuming that Vital Signs have no effect on themselves). Recovery scientists at Puget Sound Partnership and Puget Sound Institute identified and rated effects of Vital Signs with which they were most familiar on all other Vital Signs. They also rated effects of all others on their focal Vital Signs. Thus, most pairwise interactions were rated more than once. Functional Effects were assessed assuming that 1) it was induced by a substantial and rapid improvement in the condition of the 'affecting' Vital Sign, and 2) the 'affected' Vital Sign was in a condition that could be substantially improved. Thus, raters were aiming to estimate the maximum possible effect, which was rated at four levels: no effect, negligible, minor, and major. Rather than select a single level, raters expressed their confidence by assigning a probability to each of the four levels, with the probabilities for a given rating summing to 1 (following Labiosa et al., 2014). Mean ratings were calculated, and major discrepancies between raters identified as bimodal distributions (arising, for example, because only one of two raters was aware of a given Functional Effect). All major discrepancies were resolved by a Delphi process, in which raters compared their ratings, and agreed on a unimodal distribution of probabilities. Finally, each rating was converted to a score signifying the strength of the Functional Effect by multiplying probabilities associated with each of the four levels by a set of arbitrarily chosen weightings: 0 for no effect, 0.1 for a negligible effect, 1 for a minor effect, and 10 for a major effect, and taking their sum. Thus, scores could vary on a scale of 0 to 10. Results were insensitive to widely differing weighting schemes. Raters were asked to separately rate both positive effects and negative effects, and to provide brief narrative accounts of each interaction.

Results

Results are summarized as quantitative scores assembled into two Vital Sign-by-Vital Sign matrices, one for positive effects (Table 1), another for negative effects (Table 2). In both tables, biophysical Vital Signs are arranged separately from human wellbeing (HWB) Vital Signs, such that the body of the matrix is divided in to four unequal quadrants. This makes it possible to review scores for interactions between biophysical Vital Signs as a block (upper left), scores for HWB Vital Signs as a block (lower right), and similarly for their cross-wise scores. Separation of the two types of Vital Sign is warranted because currently they are not functionally equivalent. Whereas biophysical Vital Signs are now the subjects of Implementation Strategies and have thus become part of the mechanism of recovery, all HWB Vital Signs (except *Shellfish Beds*) for the moment remain passively indicative of recovery.

These matrices must be interpreted using the correct polarity: a given score in the body of the matrix estimates the magnitude of the effect of the Vital Sign in its *row* on the Vital Sign in its *column*. For example, in Table 1, the row labeled *Chinook Salmon* shows a score of 5.5 in the column labeled *Birds*. This implies that an improvement in *Chinook Salmon* is likely to have a positive effect on *Birds*. [Please review scores for pairs of Vital Signs with which you are familiar, and contact the author if you have a query about scores in Tables 1 and 2.]

A frequency histogram of scores for positive effects (Figure 1) shows a trimodal pattern, with scores of <1 predominating (70%), and low peaks corresponding with probabilities of major effects of about 0.5 and 0.7.

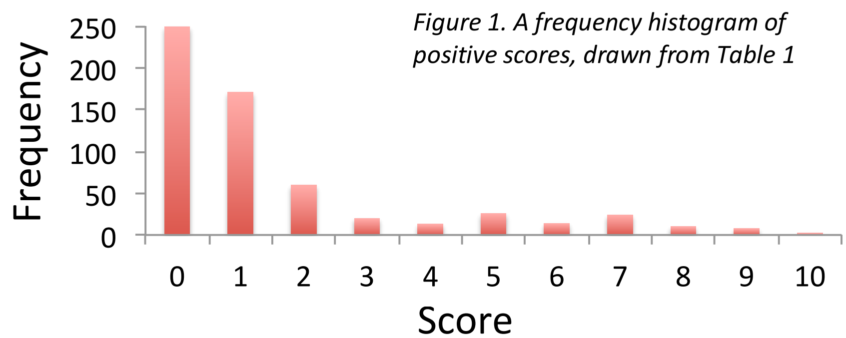


Figure 1. A frequency histogram of positive scores, drawn from Table 1

Narrative accounts of each interaction are given in Appendix 1, which has the same arrangement as Tables 1 and 2. [To date, narratives are given only for interactions with scores >= 2.5.]

Influence

In Tables 1 and 2, values in the two right hand columns (bold font) are sums of scores in each row. These totals signify the aggregate 'influence' of a Vital Sign, the sum of its direct Functional Effects on others. Two different totals are presented. Values in the penultimate column are summed over biophysical Vital Signs only. By this accounting, the most positively 'influential' of the biophysical Vital Signs, in descending order, are *Marine Water Quality*, *Land Development and Cover*, *Freshwater Quality*, *Summer Stream Flows*, and *Estuaries* (highlighted in orange).

Values in the ultimate column are summed over all Vital Signs (highlighted in red), yielding instructive changes in ranking. *Sound Behavior Index* becomes the most influential Vital Sign, largely because it has positive effects on many biophysical Vital Signs. This result is significant because it implies that *Sound Behavior Index* should not be viewed only as a passive measure of changing behaviors. Rather, recovery will depend on active strategies to change behaviors in many sectors. Additionally, *Summer Stream Flows* moves to second rank, and *Chinook Salmon* displaces *Estuaries* in the top five. These changes are largely due to both *Summer Stream Flows* and *Chinook Salmon* having positive effects on many HWB Vital Signs. In particular, when only biophysical Vital Signs are accounted, *Chinook salmon* is not among the most influential Vital Signs (partly because salmon are near the top of the food chain). But when human wellbeing is accounted, the influence of *Chinook Salmon* increases greatly due to its major positive effects on *Cultural Wellbeing*, *Economic Vitality*, *Local Foods*, *Outdoor Activity*, and *Sense of Place*.

In the same way, the two rows at the foot of each matrix (bold font) are the sums of scores in each column (again separating totals for biophysical Vital Signs from all Vital Signs). These totals signify how much each Vital Sign is influenced *by* others. *Chinook Salmon* leads this category by a large margin, being positively affected by 10 (of 16) biophysical Vital Signs, and 2 (of 9) HWB Vital Signs. This reflects the familiar reality that salmon life history relies to varying extents on many ecosystem components. Substantially, their status depends on the health of the entire ecosystem.

If a Vital Sign's 'importance' is defined as the sum of these two quantities, *Chinook Salmon* emerges well ahead of the others (list at right). This affirms that, functionally and fundamentally, anadromous salmonids are pivotal between environmental health and human wellbeing. *Sound Behavior*, *Sense of Place*, and *Marine Water Quality* also rank high. Recall, however, that these indices reflect only the number and relative strengths of *interactions* among Vital Signs, not their absolute indispensability.

Vital Sign	Total Score
Chinook Salmon	145.5
Sound Behavior Index	109.3
Sense of Place	98.7
Marine Water Quality	90.2
Local Foods	85.9
Cultural Wellbeing	85.3
Outdoor Activity	80.6
Freshwater Quality	78.5
Summer Stream Flows	73.4
Economic Vitality	70.4
Land Development and Cover	67.6
Toxics in Fish	63.4
Eelgrass	60.0
Estuaries	59.1
Shellfish Beds	58.9
Good Governance	47.8
Pacific Herring	46.4
Floodplains	39.0
Birds	33.7
On-site Sewage	30.1
Orcas	26.7
Air Quality	26.3
Marine Sediment Quality	26.2
Drinking Water	20.5
Shoreline Armoring	20.1

Table 1. Scores associated with POSITIVE Functional Effects of Vital Signs on each other. Scores having a value >=2.5 are highlighted in yellow if they are featured in Figure 2, or in blue if they are NOT featured. Marginal sums in the two right hand columns (bold font) denote total influence of each Vital Sign on others, in two ways: for biophysical Vital Signs only, and for all Vital Signs. Similarly, marginal sums in the bottom two rows (bold font) are totals of how much each Vital Sign is influenced by others, for biophysical Vital Signs only, and for all Vital Signs. Cells highlighted in orange and red denote top five ranking.

Polarity: Scores signify effects of Vital Signs in rows on Vital Signs in columns		**Biophysical Vital Signs**														**Human Wellbeing Vital Signs**												
		Birds	**Chinook Salmon**	**Eelgrass**	**Estuaries**	**Floodplains**	**Freshwater Quality**	**Land Development and Cover**	**Marine Sediment Quality**	**Marine Water Quality**	**Orcas**	**Pacific Herring**	**Shoreline Armoring**	**Summer Stream Flows**	**Toxics in Fish**	**Air Quality**	**Cultural Wellbeing**	**Drinking Water**	**Economic Vitality**	**Good Governance**	**Local Foods**	**On-site Sewage**	**Outdoor Activity**	**Sense of Place**	**Shellfish Beds**	**Sound Behavior Index**	**TOTAL INFLUENCE biophysical VSs only**	**TOTAL INFLUENCE (All)**
Biophysical Vital Signs	**Birds**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.0	0.1	0.0	1.2	0.0	1.3	0.6	0.0	0.9	**0.0**	**4.9**
	Chinook Salmon	5.5	0.0	0.1	0.2	1.0	1.0	0.5	0.0	0.0	6.2	3.0	0.5	0.0	0.0	0.0	7.2	0.0	7.2	0.3	7.2	0.0	6.2	5.7	0.0	0.9	**18.0**	**52.6**
	Eelgrass	1.2	6.3	0.0	0.0	0.0	0.0	0.0	0.1	1.1	2.2	3.9	0.0	0.0	0.0	0.0	0.7	0.0	0.1	0.0	8.2	0.0	0.7	0.7	0.6	0.1	**15.4**	**25.9**
	Estuaries	1.2	9.6	7.3	0.0	0.0	0.0	0.0	0.0	2.0	1.9	1.4	0.1	0.0	0.0	0.0	1.2	0.0	1.7	0.0	8.2	0.0	1.6	2.3	1.1	0.2	**24.7**	**40.0**
	Floodplains	1.4	7.8	1.1	4.4	0.0	0.1	0.0	0.0	2.8	0.0	0.1	0.0	0.6	0.0	0.0	0.7	0.0	1.7	0.0	0.2	0.0	0.1	0.1	0.1	0.3	**18.2**	**21.3**
	Freshwater Quality	0.3	7.8	0.0	0.7	5.5	0.0	0.0	2.3	7.8	0.0	0.3	0.0	0.0	0.6	0.0	6.4	1.2	2.2	0.0	3.9	0.0	4.4	6.4	0.0	0.9	**25.2**	**50.5**
	Land Development and Cover	4.4	6.3	0.6	1.8	8.2	6.4	0.0	0.0	0.0	0.0	1.5	2.9	4.5	0.0	1.5	2.4	5.4	0.7	0.0	3.8	0.0	3.8	3.8	0.0	0.9	**36.5**	**58.8**
	Marine Sediment Quality	1.5	0.1	2.4	1.2	0.0	0.0	0.3	0.0	0.6	0.0	1.4	0.0	0.0	10.0	0.0	0.1	0.0	1.2	0.0	1.1	0.0	0.1	0.0	0.7	0.0	**18.0**	**20.6**
	Marine Water Quality	0.5	10.0	8.1	5.7	0.0	0.0	0.0	0.6	0.0	0.5	6.5	0.0	0.3	6.8	0.5	0.1	0.0	0.1	0.0	0.6	0.0	2.3	1.4	10.0	0.9	**48.8**	**54.9**
	Orcas	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.4	0.0	1.9	0.0	0.0	0.0	0.4	2.9	0.0	0.9	**0.1**	**9.7**
	Pacific Herring	5.6	8.9	0.6	0.0	0.0	0.0	0.0	0.0	0.0	1.5	0.0	0.0	0.0	0.0	0.0	1.4	0.0	1.4	0.0	1.8	0.0	0.3	0.2	0.0	0.2	**16.5**	**21.8**
	Shoreline Armoring	1.2	4.5	0.1	0.0	0.1	0.1	0.0	0.0	0.5	0.1	1.5	0.0	0.0	0.0	0.0	0.1	0.0	0.2	0.0	0.2	0.0	0.1	0.1	0.0	0.6	**8.1**	**9.4**
	Summer Stream Flows	0.3	10.0	2.8	4.0	1.0	5.5	0.0	0.0	2.8	0.0	0.0	0.0	0.0	0.1	0.4	4.5	6.3	6.3	0.0	6.3	2.8	6.3	6.3	0.7	0.0	**29.9**	**66.3**
	Toxics in Fish	1.8	6.7	0.1	0.1	0.0	0.1	0.0	0.0	0.1	4.3	2.2	0.0	0.0	0.0	0.0	4.8	0.0	4.8	0.0	4.8	0.0	4.3	7.3	0.0	0.9	**15.3**	**42.2**
Human Wellbeing Vital Signs	**Air Quality**	0.7	0.0	0.0	0.0	0.0	0.8	0.2	1.7	5.9	0.0	0.0	0.0	0.0	1.7	0.0	0.8	0.0	1.4	0.0	0.2	0.0	3.9	3.4	0.0	0.1	**-**	**21.0**
	Cultural Wellbeing	0.0	5.4	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.9	0.2	0.0	3.3	4.3	0.0	1.9	**-**	**16.6**
	Drinking Water	0.0	0.0	0.0	0.0	0.0	1.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	1.1	0.0	0.1	**-**	**3.0**
	Economic Vitality	0.0	1.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.4	0.0	0.0	1.2	0.9	0.0	1.4	4.4	1.8	2.8	**-**	**18.5**
	Good Governance	0.1	1.2	0.7	0.7	0.7	0.7	0.7	0.1	0.7	0.1	0.7	6.3	0.0	0.7	0.7	6.3	1.2	6.3	0.0	1.2	1.2	0.7	6.3	0.7	4.3	**-**	**42.0**
	Local Foods	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.1	4.8	0.0	6.3	0.0	0.0	0.0	5.3	5.3	1.2	4.2	**-**	**27.4**
	On-site Sewage	0.0	0.0	0.0	0.0	0.0	4.5	0.0	0.0	2.2	0.0	1.5	0.0	0.0	0.0	0.0	5.3	1.2	0.7	0.0	1.7	0.0	1.2	0.7	0.0	0.1	**8.3**	**19.1**
	Outdoor Activity	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.0	0.0	0.1	0.0	0.0	2.3	4.3	0.0	1.8	0.0	0.0	0.0	0.0	3.3	0.0	3.3	**-**	**15.8**
	Sense of Place	0.0	0.2	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.0	3.4	0.0	1.2	0.3	0.7	0.7	5.3	0.0	0.0	6.4	**-**	**19.0**
	Shellfish Beds	1.9	0.2	5.9	0.3	0.0	0.0	0.0	0.0	0.5	0.0	0.1	0.0	0.0	0.2	0.0	4.8	0.0	4.4	0.2	4.8	0.0	4.4	4.8	0.0	1.0	**9.0**	**33.4**
	Sound Behavior Index	1.3	6.3	4.4	0.1	1.3	7.2	6.3	1.0	8.6	0.1	0.1	0.1	1.7	1.3	0.0	0.7	2.2	0.0	2.9	1.3	6.3	7.3	8.2	8.7	0.0	**-**	**77.4**
Totals	**TOTAL INFLUENCED biophysical VSs only**	**26.7**	**78.1**	**29.1**	**18.4**	**15.8**	**17.6**	**0.8**	**2.9**	**20.2**	**16.7**	**23.6**	**3.5**	**5.3**	**17.6**	**-**	**-**	**-**	**-**	**-**	**-**	**2.8**	**-**	**-**	**13.2**	**-**	**274.8**	**-**
	TOTAL INFLUENCED (All)	**28.8**	**92.9**	**34.1**	**19.2**	**17.8**	**28.0**	**8.9**	**5.7**	**35.3**	**17.0**	**24.6**	**10.7**	**7.1**	**21.3**	**5.3**	**68.7**	**17.5**	**51.9**	**5.8**	**58.5**	**10.9**	**64.8**	**79.8**	**25.5**	**31.9**	**-**	**771.8**

Table 2. Scores associated with NEGATIVE Functional Effects of Vital Signs on each other. All scores >=2.5 are highlighted in yellow. All are featured in Figure 2. Marginal sums in the two right hand columns (bold font) denote total influence of each Vital Sign on others, in two ways: for biophysical Vital Signs only, and for all Vital Signs. Similarly, marginal sums in the bottom two rows (bold font) are totals of how much each Vital Sign is influenced by others, also for biophysical Vital Signs only, and for all Vital Signs. Cells highlighted in red denote top ranking.

Polarity: Scores signify effects of Vital Signs in rows on Vital Signs in columns		Biophysical Vital Signs														Human Wellbeing Vital Signs												
		Birds	Chinook Salmon	Eelgrass	Estuaries	Floodplains	Freshwater Quality	Land Development and Cover	Marine Sediment Quality	Marine Water Quality	Orcas	Pacific Herring	Shoreline Armoring	Summer Stream Flows	Toxics in Fish	Air Quality	Cultural Wellbeing	Drinking Water	Economic Vitality	Good Governance	Local Foods	On-site Sewage	Outdoor Activity	Sense of Place	Shellfish Beds	Sound Behavior Index	TOTAL INFLUENCE on biophysical VSs	TOTAL INFLUENCE (All)
Biophysical Vital Signs	Birds	0.0	1.2	0.3	0.0	0.0	0.4	0.0	0.1	0.3	0.0	5.5	0.0	0.0	0.0	0.0	0.1	0.0	1.1	0.0	0.1	0.0	0.0	0.0	0.6	0.9	**8.4**	**10.6**
	Chinook Salmon	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.5	0.0	0.0	0.0	0.1	0.0	0.1	1.3	0.0	0.0	0.0	0.0	0.0	0.0	0.9	**5.5**	**7.8**
	Eelgrass	0.0	1.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.7	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.0	0.0	0.0	0.1	0.0	0.0	0.1	**3.3**	**4.1**
	Estuaries	0.0	0.0	2.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.6	0.1	**2.8**	**3.6**
	Floodplains	0.0	0.0	0.6	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1	0.0	1.8	0.0	0.0	0.0	1.1	1.2	0.0	0.2	**1.1**	**6.4**
	Freshwater Quality	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.9	**0.0**	**2.0**
	Land Development and Cover	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0	2.3	0.0	0.0	0.0	0.0	0.7	0.0	0.8	**0.0**	**4.4**
	Marine Sediment Quality	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.1	**0.0**	**1.2**
	Marine Water Quality	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.2	0.0	0.0	0.0	0.0	0.0	0.1	0.8	**0.1**	**2.1**
	Orcas	0.0	1.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.5	0.0	0.0	0.0	0.0	0.0	0.0	1.2	0.0	1.2	0.0	0.1	0.0	0.0	0.9	**3.4**	**6.6**
	Pacific Herring	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.2	0.0	1.2	0.0	1.2	0.0	0.1	0.1	0.0	0.1	**0.0**	**3.7**
	Shoreline Armoring	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.0	0.1	0.1	0.0	0.1	**1.5**	**2.4**
	Summer Stream Flows	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	**1.2**
	Toxics in Fish	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.9	**0.0**	**2.0**
Human Wellbeing Vital Signs	Air Quality	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	**1.3**
	Cultural Wellbeing	0.0	1.3	0.0	0.0	0.0	0.0	0.2	0.0	0.2	0.6	1.2	0.0	0.0	0.0	0.0	0.0	0.0	1.7	0.0	1.2	0.0	0.0	0.0	1.2	0.0	-	**7.4**
	Drinking Water	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	**1.3**
	Economic Vitality	0.6	2.3	1.7	3.3	3.3	1.7	4.3	4.3	4.3	2.3	0.7	0.6	1.2	1.2	1.9	1.7	1.7	0.0	1.7	4.3	0.6	1.2	1.2	1.2	0.1	-	**47.2**
	Good Governance	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	**1.2**
	Local Foods	0.1	2.3	0.1	0.0	0.0	0.1	0.1	0.0	0.1	0.2	0.8	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.2	0.0	-	**5.1**
	On-site Sewage	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.9	**0.0**	**2.1**
	Outdoor Activity	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	1.2	0.1	0.0	0.0	0.1	0.1	0.1	0.0	0.1	0.0	1.2	0.0	0.0	0.0	0.1	0.0	-	**3.7**
	Sense of Place	0.0	0.0	0.0	0.0	0.6	0.0	0.6	0.0	0.0	0.6	0.0	0.6	0.0	0.0	0.0	0.0	0.0	0.6	0.0	0.7	0.0	0.0	0.0	0.6	0.0	-	**4.4**
	Shellfish Beds	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.2	0.0	0.0	0.0	0.0	0.1	0.0	0.1	**0.5**	**1.8**
	Sound Behavior Index	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	**0.0**
Totals	TOTAL INFLUENCED by biophysical VSs	**0.0**	**5.3**	**3.1**	**0.6**	**0.0**	**0.4**	**0.0**	**0.1**	**0.3**	**0.0**	**15.7**	**0.0**	**0.0**	**0.0**	-	-	-	-	-	-	**0.0**	-	-	**1.3**	-	**26.2**	-
	TOTAL INFLUENCED (All)	**0.8**	**11.2**	**5.0**	**4.1**	**4.0**	**2.2**	**5.3**	**4.5**	**5.0**	**5.0**	**18.4**	**1.2**	**1.2**	**1.4**	**2.0**	**5.4**	**1.8**	**24.5**	**1.7**	**9.8**	**0.6**	**2.5**	**3.2**	**5.5**	**7.6**	-	**133.7**

Indirect Influence

'Functional Influence' was defined above as the sum of a Vital Sign's direct effects on others. Indirect influence refers to the sum of a Vital Sign's effects on others that are *more than* one causative link removed. The second order influence of a Vital Sign is calculated by summing the influence values of all the Vital Signs it affects after weighting them by how strongly they are affected. When these values were calculated for biophysical Vital Signs only, the Vital Sign with the greatest second-order influence was *Freshwater Quality*. The Vital Sign with the greatest *third* order influence was *Land Development and Cover*. It is easy to see why these topped the rankings in each case: *Freshwater Quality* is the Vital Sign with the greatest effect on the (biophysical) Vital Sign with the greatest *direct* influence, *Marine Water Quality*. In turn, *Land Development and Cover* has the greatest effect on *Freshwater Quality*.

Applying the same principles with HWB Vital Signs included, those with the greatest **indirect** influence were, in descending order, *Sound Behavior Index*, *Land Development and Cover, Freshwater Quality*, and *Marine Water Quality*. It is not surprising that *Sound Behavior Index* emerged as the Vital Sign with by far the greatest direct *and* indirect influence: it has strong positive effects on the three biophysical Vital Signs identified above as having the greatest direct and indirect effects.

Negative effects

Compared to positive effects, non-zero scores for negative effects were few (Table 2). Scores for negative effects valued at <1 comprised 90% of the total number (compared with 70% for positive effects). Only two scores had values >5 (compared with 61 for positive effects). Both involved food web (predator-prey) interactions between *Pacific Herring* (as prey), and *Chinook Salmon* and *Birds* (as predators). An important result of this assessment, therefore, is that negative interactions between Vital Signs are relatively few, and relatively mild.

Economic Vitality had the greatest negative influence, with mild to moderate negative effects on many other Vital Signs, both biophysical and HWB. Consequently, it had far greater total negative influence than any other Vital Sign (Table 2, highlighted in red). Moreover, *Economic Vitality* was negatively affected by more Vital Signs, and cumulatively was more negatively impacted, than any other Vital Sign. These patterns are familiar, reflecting conflicts between economic growth and environmental health that are among the most challenging to address. The implication is that successful recovery will depend on innovative solutions that yield economic *and* environmental benefits (often referred to as 'multiple benefits') in many sectors.

A causative network of Vital Signs

Results in Tables 1 and 2 can be portrayed graphically as a 'causative' network (or directed graph), featuring Vital Signs as 'nodes', linked by arrows representing their Functional Effects ('edges'; Figure 2). While this causative network includes predator-prey effects (e.g. herring-salmon, herring-bird, salmon-orca), this is *not* the same as a food web or ecological network, which *exclusively* depicts trophic relationships among species. The links in this causative network represent a much broader suite of functional relationships, including, as examples, improvements in water quality and quantity, restoration of specific habitat types, and cultural benefits for humans.

All 25 Vital Signs are featured in this graphic, but not all of their Functional Effects could be represented and still retain clarity. To exclude minimal and low probability effects, only scores of value 2.5 or greater were depicted (see Figure 1). This cut-off value was chosen arbitrarily, and resulted in omission of 243 effects, including major effects with a probability of less than 0.16. Even then, not all scores that made the cut could be featured in the network. The following order of precedence was applied in selecting what would and would not be featured: all interactions between biophysical Vital Signs, all effects of HWB Vital Signs on biophysical Vital Signs, and all but two effects of HWB Vital Signs on other HWB Vital Signs were represented in Figure 2. However, most (27 of 33) effects of biophysical Vital Signs on HWB Vital Signs were omitted. The rationale for their omission was that a major objective of this assessment was to explore options for managing Implementation Strategies, for which HWB Vital Signs do not yet qualify (excepting *Shellfish Beds*). In Tables 1 and 2, scores with value >=2.5 that are featured in Figure 2 are highlighted in yellow, while those *not* featured are highlighted in blue.

Additional features of the network are:

1. *Bubble height and color.* In the network, the total 'influence' of each Vital Sign is represented by the vertical dimension of the bubble associated with each node. Each bubble is colored according to biome (terrestrial, fresh water, marine, or combinations of these).

2. *Arrow thickness.* Three classes of arrow thickness represent effects of progressively greater strength: probable minor effects (scores of 2.5-5), possible major effects (scores of 5-7.5), and probable major effects (scores of 7.5-10). The network shows, for example, that an improvement in *Land Development and Cover* would likely have a major positive effect on *Floodplains,* possible major positive effects on *Freshwater Quality* and *Chinook Salmon,* and probable minor positive effects on *Summer Stream Flows* and *Birds.* In turn, improved *Floodplains* would likely have a major positive effect on *Chinook Salmon,* and so on.

3. *Arrow color.* Black arrows denote positive effects, and red arrows denonte negative effects. There were only two negative scores >2.5, both representing food web interactions between predators (*Chinook Salmon*, *Birds*) and prey (*Pacific herring*).

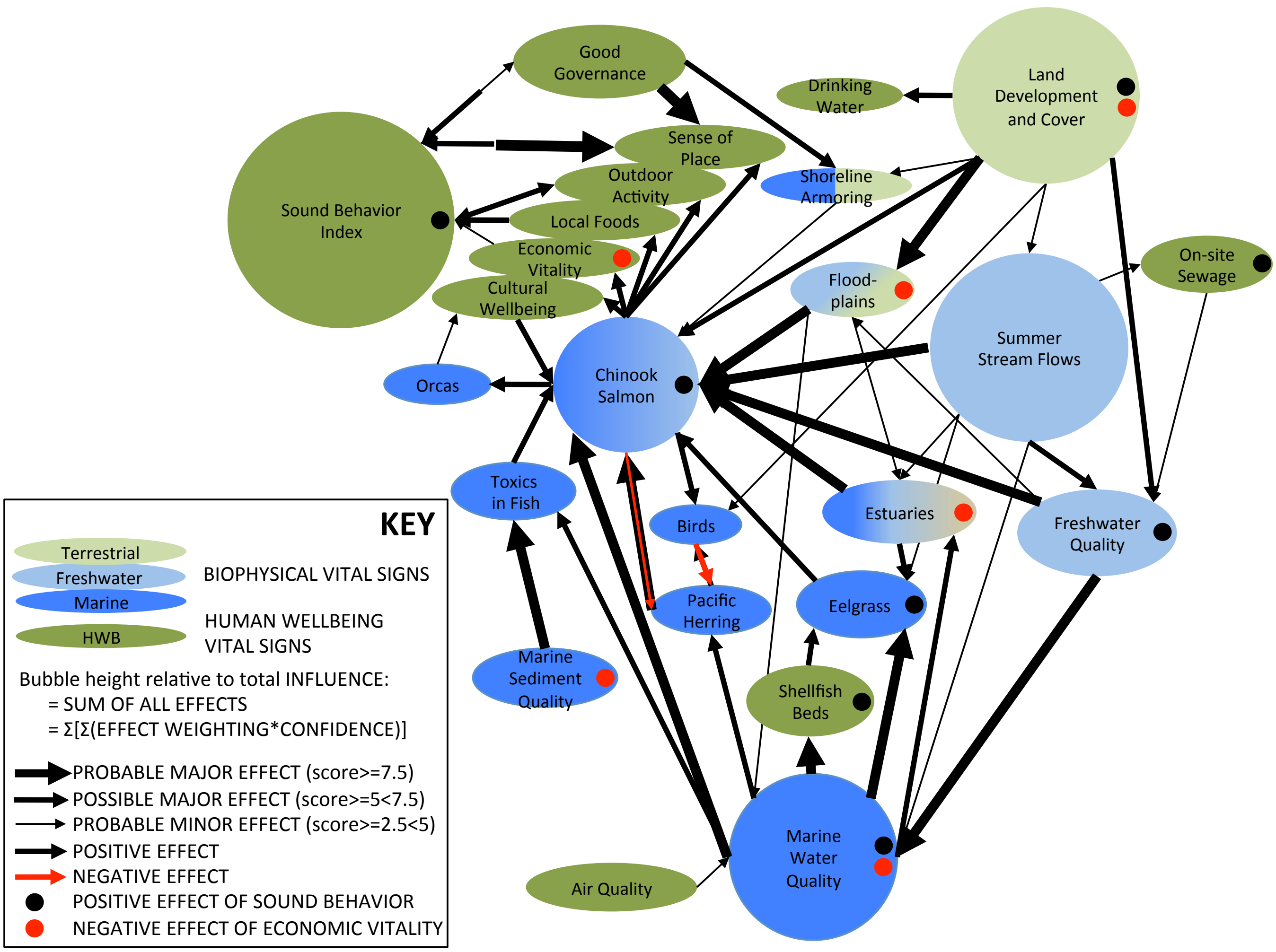
4. *Double-ended arrows* denote effects in both directions. For example, *Sound Behavior Index* was scored as having a probable major positive effect on *Sense of Place*, which in return has a possible major effect on *Sound Behavior Index*. These effects are not necessarily of the same magnitude.

5. *Black dots.* Positive effects of *Sound Behavior Index* were too important to leave out, but could not be drawn as arrows without loss of clarity. Instead they are featured as black dots, on the *Sound Behavior Index* node, and on the seven biophysical Vital Signs it affects: *Land Development and Cover*, *On-site Sewage*, *Freshwater Quality*, *Marine Water Quality*, *Shellfish Beds*, *Eelgrass*, and *Chinook Salmon*.

6. *Red dots.* Negative effects of *Economic Vitality* were also too important to be omitted. A similar system of red dots was used to depict these negative effects on *Land Development and Cover*, *Floodplains*, *Estuaries*, *Marine Water Quality,* and *Marine Sediment Quality.*

7. *Stacked nodes.* Five of the HWB Vital Signs (*Cultural Wellbeing*, *Economic Vitality*, *Local Foods*, *Outdoor Activity*, and *Sense of Place*) were linked to each other in ways too complex to represent explicitly in the graphic, including several two-way effects, and one negative effect (*Economic Vitality* on *Local Foods*). These effects are reported explicitly in the lower right sector of Tables 1 and 2. In the graphic they are represented implicitly by stacking the nodes for these Vital Signs.

Figure 2. A causative network of Vital Signs (see text for explanation of symbols).



Implications

By design, scores relating the strength of interactions between pairs of Vital Signs reflect what is known or assumed by relatively few raters, intentionally dimmed somewhat by uncertainty. Linked together by these scores, the Vital Signs yielded a causative network with many familiar features. For example, network topology reproduced a cascade of Functional Effects linking upper watersheds to nearshore habitats to marine basins and into the food chain, both marine and human.

The presence of familiar features should increase our confidence in the validity of 'emergent' properties that are not so familiar. Ratings will need validation (for example, by adding expert opinions) before these results should influence decision-making. But insights emerging from this simple accounting of Functional Effects are potentially instructive for recovery, and their implications warrant scrutiny. Some of the more important are listed below.

1. Most pathways of Functional Effects among Vital Signs lead to *Chinook Salmon*. Indeed all biophysical Vital Signs have direct, major effects on *Chinook Salmon*, except one: *Marine Sediment Quality,* which has a major effect on *Toxics in Fish* (but salmon are not really exceptional, since they *are* fish). One might reasonably conclude that this is essentially a salmon-centric recovery strategy. It is not. It is essentially a strategy that emphasizes human dependence on a healthy environment, with pathways leading through *Chinook Salmon*, among others (see scores highlighted in blue in Table 1), to human wellbeing.

2. The most influential Vital Sign is *Sound Stewardship Index*. The implication is that recovery depends heavily on changing behaviors, especially those that are injurious to the 7 directly affected Vital Signs (*Land Development and Cover*, *On-Site Sewage*, *Freshwater Quality*, *Marine Water Quality*, *Shellfish Beds*, *Eelgrass*, and *Chinook Salmon*). Improving stewardship should feature prominently in Implementation Strategies for these Vital Signs.

3. The assertion that, in terms of Functional Influence, *Sound Behavior Index, Summer Stream Flows, Land Development and Cover*, *Freshwater Quality, Marine Water Quality*, and *Chinook Salmon* form the 'principal axis' of recovery resonates with our intuition, but has hitherto not been affirmed. In this analysis, all but one are affected by the *Sound Behavior Index* (the exception is *Summer Stream Flows,* which does not feature in the *Index*, but perhaps should because it is strongly affected by human behavior). In the network, they form a linear chain linked directly by major effects. Based on combined influence, they comprise a sub-set of Vital Signs in which greater investment may be justified (both past and future).

4. If negative interactions between Vital Signs are as mild as scores imply, concerns that conflicting Functional Effects will neutralize remedial actions may be unwarranted. However, ratings of negative effects should be validated before this conclusion can be drawn.

5. Of all Vital Signs, *Economic Vitality* had the greatest total negative impact AND was negatively impacted the most. The total negative influence of *Economic Vitality* was more than twice its total positive influence. Does this mean that recovery will not 'turn the corner' until this deficit is eliminated? Since no effects were actually measured in this assessment,

quantitative comparisons of this kind are not valid. But they may provide a qualitative indication. For example, we might be encouraged that the overall total for positive effects (775.3) was six times greater than the overall total for negative effects (129.3). The implication is that success depends on harmonizing environmental with economic advances, via 'multiple benefits'. This approach is well established in *Floodplains*, but similar creativity must be applied in other sectors, particularly *Estuaries*, and *Land Development and Cover*.

Perhaps the most important inference to draw from this simple accounting of interactions is that the existing set of Vital Signs is more functionally *connected* than has been generally recognized, in the sense that no network node is *un*-connected by a major effect with at least moderate probability. While full connectivity was not an inevitable outcome of this rating exercise, it turns out that functional connectivity *was* a criterion used in selecting at least the original set of Vital Signs (personal communication between Tessa Francis and Phil Levin). However, the significance and potential role of Functional Influence has since been forgotten or discarded. A functionally connected set of Vital Signs may provide a more effective framework for recovery than would an unconnected set, provided functionality is integrated into the recovery strategy. In a final section, examples are given of how accounting functional links among Vital Signs can streamline the structure of the recovery strategy, and improve its manageability.

How many Vital Signs are 'enough'?

Compared to other large coastal ecosystems in the US, the scope of Puget Sound's recovery strategy is broad (box at right). In effect, it aspires to discover how a modern social-ecological system can thrive sustainably. These comparisons prompt questions about the relative merits of a focused vs. diversified approach to recovery. Should allocation of recovery effort reflect the true diversity and intensity of stressors? Do fewer recovery goals yield a more cost-effective recovery?

In addressing these issues, practitioners have learned that narrowing the focus of recovery in complex systems may be the greatest challenge of all. Selecting a combination of recovery goals that would yield greatest gains is hard when goals are incommensurable. Moreover, experience in the Bay Delta, where water supply is almost entirely human-controlled and multiple system stressors interact intricately, cautions against oversimplification of recovery strategies in complex systems.

Comparing the scope of coastal ecosystem recovery strategies

A comparison of recovery strategies among large coastal ecosystems in the US revealed marked differences in scope (defined by the number of targeted stressors; Georgiadis 2013, unpublished report). Some focused on only a few key stressors from the beginning. In Long Island Sound, for example, the principal focus was on managing effluent from New York City and the Connecticut River. The Lower Columbia River strategy focuses on improving survivorship of migrating salmon in the estuary. In the Florida Everglades, after decades of drainage and levee building, the original goal was to restore water quantity, in the form of sheet flow over former wetlands. Water quality targets were added later. In Chesapeake Bay the main focus has always been on reducing nutrients in runoff from agricultural lands, first targeting nitrogen, and then phosphorus, with sediment added later.

Others started with a broader agenda. On the Louisiana Coast, multiple species and habitats were targeted initially. However, these were found to present too many conflicting outcomes. Eventually, reclaiming eroded land became the principal goal. In the Sacramento–San Joaquin River Delta (Bay Delta), after decades of drainage and development intended to supply land and water for agriculture, the principal objective is to recover wetlands.

The strategy to 'restore Puget Sound' initially targeted multiple stressors on salmon, then expanded to include pollution in stormwater runoff, coliform contaminated nearshore habitats, terrestrial habitat fragmentation, and many more (currently 25 Vital Sign indicators with >30 recovery targets).

To date, the recovery strategy for Puget Sound has targeted Vital Signs, rather than their interactions. This analysis provides a framework with which to begin to explore options for accounting interactions among Vital Signs. For example, the network from Figure 2 is reproduced in Figure 3 with one feature changed, and one added. The change is that Vital Signs are colored by their assignment to three Strategic Initiatives, based on an analysis that clustered Vital Signs by their shared approaches to recovery (Georgiadis and Redman 2016). In this scheme, Vital Signs representing species and habitats were assigned to the Habitat Strategic Initiative (light green), those addressing water quantity and quality issues to Stormwater SI (yellow), and those aiming to reduce coliforms to the Shellfish SI (blue).

Added to the figure are black squares representing existing recovery indicators for each Vital Sign (Appendix 2). These are filled if an Implementation Strategy has been or is about to be initiated for that indicator. For example, *Land Development and Cover* has four indicators, only one of which (so far) is the focus of an Implementation Strategy (conversion of ecologically important lands due to development).

The figure captures salient features of the theory, structure, function, organization, and approach of the strategy to recover Puget Sound. Several observations are worth considering:

1. ***Balancing influence and investment:*** Vital Signs with the greatest influence are not necessarily well represented among Implementation Strategies that have been, or are about to be initiated. There are good reasons for this, including the need to learn how to develop ISs with the most well-developed cases (e.g. *Shellfish Beds*). Ultimately, there should be some correspondence between influence and investment.

2. ***Merging Vital Signs / indicators within Implementation Strategies:*** The clustering analysis referred to above (Georgiadis and Redman 2016) revealed two tight clusters of Vital Signs, comprising: *Land Development and Cover*, *Shoreline Armoring*, and *Floodplains* in one group, and *Marine Sediment Quality* with *Toxics in Fish* in another. These are candidates for ultimate consolidation into two Implementation Strategies. Mergers based on other criteria are also candidates. For example, Vital Signs addressing fecal coliform reduction (*Shellfish Beds*, *On-site Sewage*, *Swimming Beaches*) could be merged in a single Implementation Strategy. In this way, processes served by multiple indicators could be addressed by a single Implementation Strategy. To achieve this, it is important that Vital Signs are assigned to Strategic Initiatives such that mergers yield groups that are nested within Strategic Initiatives.

3. ***Merging thematically related sections of different implementation strategies:*** An alternative consolidation approach is to form ISs around themes that recur in multiple ISs. For example, the need to promote stewardship and change behaviors is a consistent theme emerging from ISs developed for *Shellfish Beds*, *Estuaries*, *Floodplains*, and *Land Cover*. The same theme is likely to feature in *On-site Sewage* and *Shoreline Armoring*. It is worth exploring whether a single strategy can be developed to address this theme, addressing regulations as well as incentives, across multiple Vital Signs.

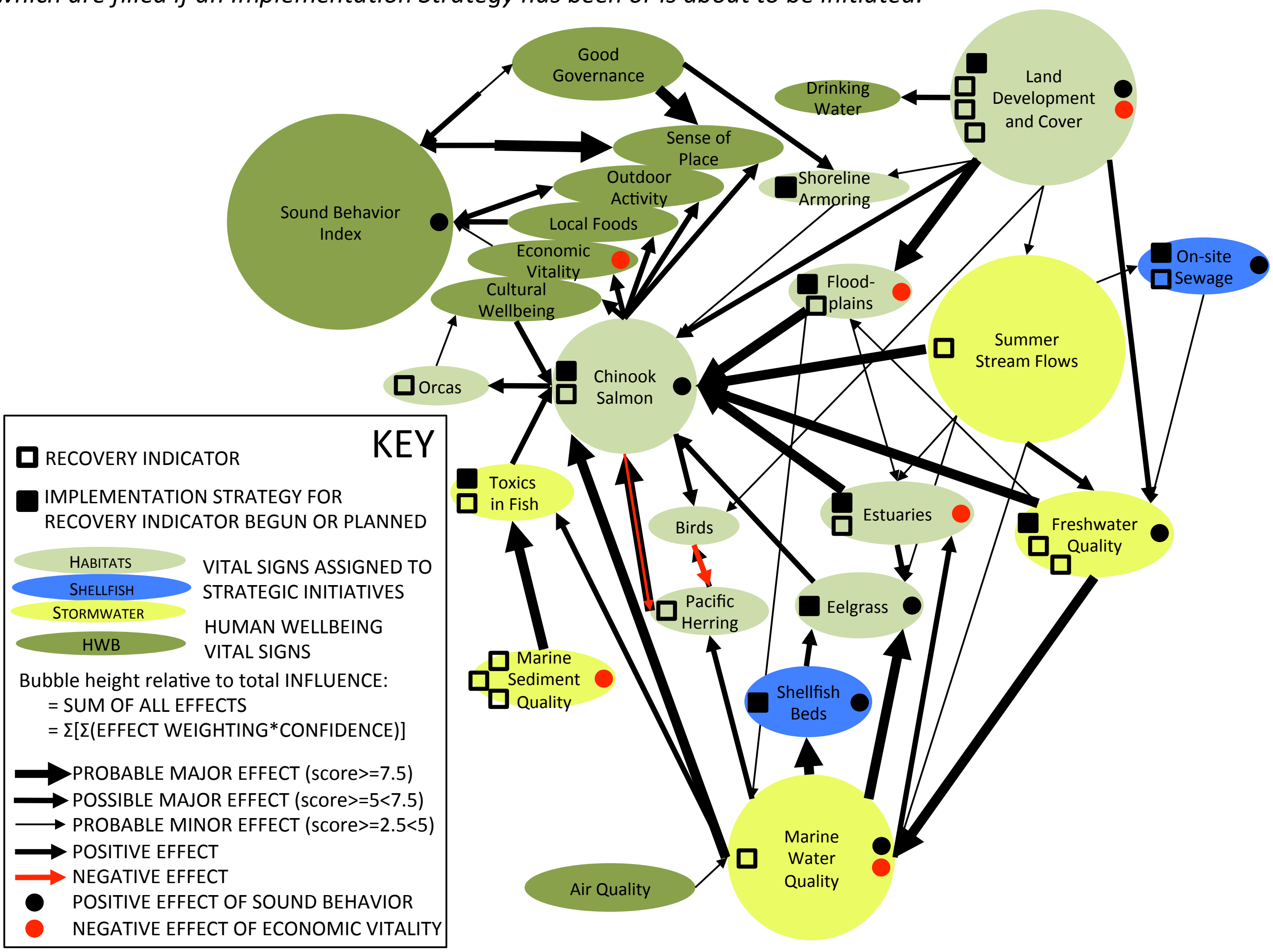
4. ***A glaring omission*** from the figure (and from much of the strategy) is geographic specificity. It is assumed that for Functional Effects to be propagated among Vital Signs as depicted in Figures 2 & 3, recovery actions must either have regional effects, or

coincide locally. That this is rarely the case underscores the need to examine how actions associated with one Vital Sign might influence others on the ground. The information presented here permits a preliminary assessment of how processes represented by indicators (Appendix 2) might functionally affect each other (Appendix 1) in a given geographical context.

Conclusions

Given that additional ratings are needed for results to be definitive, the results of this analysis are more suggestive than conclusive. However, results are intuitively plausible. As expected, for example, Vital Signs that are 'upstream' in pathways of cause and functional effect tend to be more 'influential' than Vital Signs that are 'downstream', with injurious human behaviors the ultimate source of most pressures. Whether and how Functional Effects and Functional Influence should feature in recovery, if at all, needs further scrutiny. For example, should recovery actions directed at different targets be combined, say at sub-watershed level – or even at the Implementation Strategy level – such as to maximize Functional Effects? A corollary would be enhanced probability of detecting the intended impacts of recovery actions. This assessment of Vital Sign interactions should help to inform discussion.

Fig. 3. A graphic summary of the strategy to recover Puget Sound, featuring: 1) Vital Signs as nodes, colored by their assignment to Strategic Initiatives (as suggested by Georgiadis and Redman 2016), with Habitat *in light green,* Stormwater *in yellow, and* Shellfish *in blue; 2) their Functional Effects (described in Appendix 1) signified by arrows; and 3) their associated indicators (described in Appendix 2) signified by black squares, which are filled if an Implementation Strategy has been or is about to be initiated.*



Appendix 1 is attached to this document as an Excel worksheet tab-labeled '*Appendix 1 Functional Effects*'. It is a matrix with identical structure as Tables 1 and 2 above, but with scores supplemented by text describing the mechanism of Functional Effects (not yet complete).

Appendix 2 is attached to this document as an Excel worksheet tab-labeled '*Appendix 1 Vital Signs*', with summary descriptions of the Vital Signs and their respective indicators.

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Acknowledgements

For their rating contributions, thanks to Scott Redman, Kari Stiles, Ken Dzimbal, Nathalie Hamel, Todd Hass, Leska Fore, Dave Ward (all PSP), Kelly Biedenweg and Tessa Francis (both PSI). N. Georgiadis was supported by funds awarded by EPA to the Puget Sound Institute.