Outline

* Many natural resource disciplines have gradually shifted towards a systems based approach that seeks to maximize the health of and services provided by ecological aggregates, rather than individual components.
  + Example – ecosystem based management of multitrophic fisheries and forests
  + One of the principle benefits of system based management is reduced temporal variability in the provisioning of ecosystem services – the dynamics of the aggregate are buffered by components varying asynchronously with one another.
    - Portfolio effect 🡪 larger number of components, greater aggregate stability
* However, many ecological aggregates have exhibited evidence of increased temporal variability in recent years, despite containing the same number of components
  + Such collapsed aggregates are generally less capable of providing key ecosystem services and their individual components may be at increased risk of extirpation.
* Although changes in aggregate variability are generally associated with anthropogenic disturbance, it is rarely possible to identify specific events that lead to instability
  + Efforts are hampered by the observational nature of the data collected, as well as relatively low statistical power since it is difficult to directly compare aggregates to one another.
* Yet we can detect important clues about causal mechanisms by examining temporal trends in the processes that contribute to aggregate variability, rather than aggregate variability itself.
  + For example, while aggregate variability is clearly associated with the number of components it is also influenced by the attributes of the components themselves, namely their synchrony (i.e. covariance) and individual variability
    - E.g. assuming the number of components is stable, changes in aggregate variability may be driven by either process.
  + Recent work (Thibaut and Connolly) has provided a framework to estimate the relative contribution of each of these processes by decomposing aggregate variability into an index of synchrony and an estimate of component-level variability, weighted by abundance
    - Importantly these metrics are robust to differences in evenness, as well as abundance, allowing for comparisons among distinct aggregates
* Decomposing changes in aggregate variability into trends in synchrony and component variability may provide clues that are critical to identifying destabilizing ecological processes.
  + For example, if the variability of a subset of dominant components has dramatically increased, but synchrony has remained relatively stable, then it would suggest that localized processes are responsible.
  + Conversely, if synchrony and aggregate variability have increased in tandem, it would suggest that regional processes are at wrok.
* Moreover, temporal patterns in synchrony and component variability may be useful in guiding conservation efforts and management interventions.
  + A targeted effort to increase the productivity of an unstable subpopulation may lead to substantial benefits at the aggregate level, but these benefits may be dampened if the aggregate has become highly synchronized.
  + Similarly, a larger number of components may be required to stabilize the ecosystem functions of a highly synchronized aggregate
* We use an empirical dataset to first present evidence that increased aggregate variability in a Pacific salmon metapopulation is associated with greater levels of synchrony, rather than changes in the variability of the components.
* We then use a stochastic closed-loop simulation model to explore how long-term changes in aggregate variable (mediated by synchrony and component variability) may influence the outcomes of large-scale recovery efforts.

**Methods**

*Sockeye salmon*

* Generic information on biology
* Information on CUs as unit of management conservation
* Description of fishery

*Synchrony metrics*

* We explored trends in aggregate variability of per capita productivity throughout the Fraser River watershed.
  + Productivity defined as log(recruits/spawner)
* We examined temporal changes in three metrics defined by Loreau and de Mazancour 2008 and Thibaut and Connolly 2013
  + Synchrony – defined as the variance of total metapopulation abundance of *n* components (i.e. sum of all elements of variance-covariance matrix), divided by the variance of a hypothetical metapopulation with same component variances, but perfect covariance (i.e. synchrony)
    - Eq. 2
    - Makes no assumptions about distributions of pairwise correlation coefficients, is normalized (i.e. always varies between 0 and 1), and explicitly accounts for unequal component variances
  + Average component CV weighted by abundance
  + Aggregate variability – sqrt(synch) \* average component CV
    - Component and aggregate variability are linearly proportional to one another, with a constant of proportionality driven by synchrony of components
      * When highly synch, agg perfect tracks components
      * When asynch, agg variability strongly dampened

*Retrospective analysis*

* We first explored recent patterns of aggregate variability in the Fraser River sockeye salmon metapopulation by decomposing aggregate variability into each CU’s (i.e. component’s) variability and synchrony among CUs.
* We examined these indices in two metrics
  + First, productivity, which is the number of recruits to the fishery produced per capita.
    - Recruits are enumerated after returning to coastal waters and being captured in fisheries, dying en route to spawning grounds, or successfully reaching spawning habitat.
    - This metric represents trends in metapopulation dynamics independent of two major mechanisms of disturbance in Pacific salmon populations - exploitation in fisheries and en route mortality.
  + To explore the potential impact of these drivers we also examined trends in absolute spawner abundance, which is simply the number of recruits that successfully reach the spawning grounds
* We calculated ten-year moving window averages of each metric and used linear models to test two hypotheses
  + 1) Has there been a significant increase in aggregate variability, consistent with a collapsed portfolio?
  + 2) Is aggregate variability more strongly correlated with component variability or synchrony, consistent with a shift in the dynamics of specific CUs or the metapopulation as a whole.

*Forward simulation*

* To explore the potential consequences of different aggregate variability scenarios, we used a stochastic closed-loop model to forward simulate the dynamics of Fraser River sockeye salmon.
  + The model includes population dynamics and harvesting, which follows current management control rules, as well as process, observation, and management implementation uncertainty.
* The salmon metapopulation dynamics were modeled using an age-structured Ricker model with demographic stochasticity.
  + Define model
  + A subset of Fraser River sockeye salmon populations exhibit cyclic dynamics and these CUs’ dynamics were simulated using a Larkin model, an extension of the Ricker that accounts for delayed density dependence among cycle lines
    - Define model
    - Whether CUs were modeled with the Ricker or Larkin was based upon their most recent assessment (WSP 2017 doc)
  + To generate future recruits we used alpha and beta parameters that were estimated from CU-specific stock recruit models.
    - To account for uncertainty in the true underlying stock recruit relationship we sampled with replacement from the posterior distribution of each CU’s estimated parameters each simulation run.
    - Note that although these models provide estimates of stock-recruit deviations, we parameterized sigma independently (see operating model variants)
* Harvest occurred each year with exploitation rates determined by a harvest control rule replicating the TAM rule that has been used to regulate catch rates on the Fraser River since X
  + A forecast of recruit abundance was made each year at the management unit level, the scale at which harvest typically occurs in mixed stock, marine fisheries.
  + A total exploitation rate was set based whether forecasted abundance was below or above two MU- and cycle line-specific reference points after accounting for losses due to en route mortality.