*Discussion Outline*

Major points:

1. Increases in both synchrony and component variability in the Fraser River have resulted in regular periods of low spawner abundance and reduced catches.
2. Forward simulations with equivalent levels of aggregate variability are associated with negligible declines in conservation-based PMs and moderate declines in catch-based PMs.
3. Simulations with the aggregate variability treatments, but incorporating negatively skewed recruitment deviations result in dramatic declines in both metrics.

A range of ecological processes may underpin changes in variability and synchrony in Fraser River sockeye salmon. Component variability (i.e. within CU temporal variation) may increase due to changes in local environmental conditions, such as loss of spawning habitat (REF), high levels of mortality during incubation (e.g. scouring events (REF), high water temperatures (REF)), or changes in competition and predation during juvenile freshwater stages (REF). Synchrony among components within metapopulations is often associated with connectivity (i.e. dispersal). Although Fraser River sockeye salmon likely function as a metapopulation over evolutionary time scales, dispersal is assumed to be nil from a management perspective, with each CU representing a genetically distinct population assemblage (REF). In the absence of dispersal, synchronous dynamics may be driven by a common response to shared environmental drivers (i.e. Moran effect), competitors, or predators. In the case of Fraser River sockeye salmon, such mechanisms may be more likely to occur during marine residence, when populations from throughout North America migrate to the Gulf of Alaska.

* We present evidence that aggregate variability in productivity within Fraser River sockeye salmon has increased in recent years due to increases in mean component variability, as well as greater synchrony among CUs
  + Coincides with a period in which spawner abundance has remained variable and fishery openings are less frequent despite several decades of reduced exploitation relative to historic levels.
* Differences in the strength of portfolio effects (i.e. aggregate variability), through time and among regions, have been widely examined in Pacific salmon salmon
  + Generally stocks rearing in relatively pristine habitats and without a history of overexploitation appear to exhibit the greatest stability.
    - Bristol Bay (Hilborn et al. 2003; Schindler et al. 2010); Bristol Bay vs. Snake River (Moore et al. 2010); northern vs. southern populations (Griffiths et al. 2014)
  + Furthermore, increases in synchrony are thought to be associated with increased anthropogenic disturbance, particularly processes that increase genetic homogenization such as hatchery influences and hydropower development
    - Moore et al. 2010; Carlson and Satterthwaite (2015), Yamane et al. (2018)
* Like other Pacific salmon in the southern portion of their range, Fraser River sockeye salmon inhabit a heavily impacted watershed; however the specific mechanisms that resulted in increased synchrony remain unclear
  + Hatchery influences and mainstem dams are not widely spread
  + Changes in synchrony do coincide with a period where marine survival is considered broadly unfavorable
  + Assuming freshwater survival has remained stable or increased, periodic and synchronous declines in productivitu may suggest that variability in marine survival has increased relative to freshwater
  + These issues may be exacerbated by a relatively simple age structure
    - Refs on age structure for southern vs northern populations more generally?
* Regardless of the mechanisms that shape trends in variability and synchrony, it is widely predicted that weakened ecological portfolios will be less able to provide critical services.
  + Generally this has been demonstrated via increases in aggregate variability as individual components are sequentially removed
    - Non-salmon examples, followed by salmon examples
    - Yamane et al. exception
  + We expand these previous analyses by testing for negative effects of greater aggregate variability, assuming aggregate diversity (in this case component richness) is stable.
  + Specifically, we used stochastic, closed-loop simulations to determine how the relative status of the Fraser River aggregate would change if component variability and synchrony decline to previously observed values, remain elevated, or continue to increase.
* Increases in aggregate variability were generally associated with declines in status; however these effects were strongly dependent on the underlying productivity regime, as well as performance metric
  + When productivity was moderate, increases in component variability or synchrony led to increased inter-trial variability in median recruit abundance and the proportion of CUs above their benchmark, but did not result in changes in median status.
    - Probability of extirpation was static.
  + Declines in median catch and the likelihood of meeting catch targets also declined modestly with greater aggregate variability – only catch stability decreased strongly
* Conversely, simulating process variance with a skewed normal distribution resulted in severe declines in both conservation- and catch-based metrics
  + To some extent these trends were driven by reduced productivity independent of aggregate variability.
    - Median recruit abundance declined by approximately X% between the skewed and reference productivity scenarios,
    - All three conservation-based PMs declined relative to reference values even under low levels of component variability and synchrony
  + Yet increased synchrony in particular exacerbated these effects.
    - Moving from a low to moderate synchrony operating model resulted in Y% decline in median spawner abundance. When high synchrony was paired with greater component variability recruit abundance declined even further.
    - Similar patterns observed with ppn of CUs above BM and even the probability of extirpation, which was low at low levels of aggregate variability, increased considerably.
* Despite growing recognition that variability can serve as a valuable indicator of ecosystem health, many assessments remain focused on changes in mean status over time. Our results clarify that changes in aggregate variability can magnify the effects of declines in average abundance.
  + Pro - As long as productivity remains relatively high, increases in aggregate variability will not necessarily be associated with a reduction in median status
    - They will however result in severe declines in stability which may have negative consequences depending on management objectives
  + Con – the impacts of relatively moderate declines in productivity will be exacerbated by paired increases in aggregate variability
    - Given projected declines in the productivity of many exploited fishes, including P salmon at the southern portion of their range, it is critical that these interactions are accounted for
    - Declines in catch metrics particularly concerning given the stress that is already occurring in the fishery and the fact that even a resource-intensive harvest control rule is incapable of sufficiently buffering the system
    - Studies that fail to account for covariance among populations may underestimate the risk associated
* Likely a conservative estimate
  + Large number of populations, relatively moderate decline in prod via skewness
  + Focus on catch-based implications
    - E.g. forecasts, inefficacy of complicated HCR, potential for overfishing to occur, overcapacity
* Suggested management actions
  + 1) Conserve ecological diversity by default, but do not assume that portfolio effects are stable through time
  + 2) Track aggregate variability and identify across which ecological dimensions the greatest stabilizing impacts occur; spatial, species, age-class, life history (Yamane, Thorson papers)
  + 3) Do not be fooled by stable intermittent returns
* Caveats
  + Focus is on median status (except catch stability)
  + Declines in average alpha give weaker effect, although skewed distribution seems more accurate
  + Dynamics modeled at relatively coarse life history scale
* The results presented here, as well as those of others, suggest that salmon aggregates at the southern extent of their range may be under increasing pressure if environmental and anthropogenic drivers continue to destabilize stock portfolios.
  + Our results indicate that greater aggregate variability will decrease median abundance, reduce fishery yields, and constrain the likelihood of recovery
  + Even more concerning, these patterns were present in simulations that replicated the Fraser River’s data-intensive harvest control rule.
    - The probability of overharvest is likely higher for fisheries that do not have sufficient resources to sustain the high-resolution test fisheries necessary for estimates of in-season abundance
    - Insert note on fixed ER sens analysis
* Periodic, synchronized recruitment failures may be particularly common in migratory species, such as Pacific salmon.
  + Ansychronous dynamics are necessarily dampened, even among stocks that spawn thousands of miles apart, due to common rearing conditions during marine residence.
  + Indeed evidence suggests that a range of processes (SST, pathogen infection, predation, low prey availability) can result in periodic years of poor marine survival across Pacific salmon species, resulting in low returns and reduced opportunities for harvest
  + Certain dimensions of biocomplexity may moderate this influence (e.g. ocean entry timing)
  + Blurb on prevalence of migratory fishes among exploited stocks
  + Given extreme variability in the strength of spawner-recruit relationships, high levels of component variability may also be common.
* More broadly our findings demonstrate some likely hurdles for managers seeking to rebuild stocks or maintain adequate catch levels in mixed stock fisheries as aggregate variability increases.
  + Assuming productivity remains stable, increases in component variability will reduce the likelihood of meeting recovery targets, but result in only moderate changes in median recruit abundance
  + Simultaneously, managers will likely observe declines in catch-based performance metrics (e.g. variability, number of years above minimum TAC thresholds), which are relatively more severe than declines in conservation status.
  + Intuitively this could result in greater pressure to alter HCRs to increase catch rates, but managers should be vigilant to the risks associated with increased exploitation of weakened portfolios.
* Shortcomings and future directions
  + Assume that underlying stock recruit relationship is accurate and static – beyond the scope of this study to incorporate temporal changes in multiple SR parameters
  + Minimal life cycle resolution – ideally would be able to assess how changes in patterns of survival at different stages may produce patterns in synchrony
  + Lack of mechanistic linkages prevents us from explicitly testing hypotheses about the relative impact of development
  + Investigate impact on forecasting accuracy and harvest control rules that are not generated via test fishing
* Systems based approaches are increasingly advocated in fisheries biology and other systems to ensure ecosystem functioning is maximized.
  + By no means are we arguing for a return to single species approaches – instead we seek to clarify that the benefits of focusing on aggregates rather than components are not guaranteed.
  + Temporal changes in aggregate variability should be monitored and addressed accordingly depending on whether driven by CV or synch