**Introduction**

Ecological aggregates, such as metapopulations or communities, consist of components whose dynamics vary due to life history, unique environmental interactions, or simply chance. Asynchrony among components reduces temporal variability of the aggregate, often resulting in greater productivity and biomass, increased availability of ecosystem services, and improved resilience (Tilman, Isbell & Cowles 2014; Schindler, Armstrong & Reed 2015). These ecological relationships are broadly analogous to the stable returns of a diverse financial portfolio and, as a result, are commonly referred to as portfolio effects (Tilman 1999 REF; Schindler 2015 REF). The widespread recognition of ecological portfolio effects has coincided with a pivot towards systems-based approaches, which emphasize monitoring, managing, and conserving ecological aggregates, rather than component populations (Link 2018). Systems-based approaches are intended to simultaneously increase the stability of ecosystem services, while avoiding the difficulties associated with accurately forecasting the dynamics of single populations (Link 2018).

Systems-based approaches are particularly relevant to management-oriented disciplines such as biological conservation and fisheries science. However, there is still uncertainty as to how portfolio effects can be best-measured and incorporated into existing management strategies. The most common way to quantify a portfolio’s performance is via aggregate variability, the temporal coefficient of variation of multiple populations. An emergent property of ecological portfolios is that, due to statistical averaging alone, aggregate variability decreases as the number of components increases (Doak et al. 1998). For example, the Bristol Bay sockeye salmon (*Oncorhynchus nerka*) fishery encompasses an aggregate of nine major river systems, each containing multiple spawning populations (Schindler et al. 2010). This population diversity reduces aggregate variability in spawner returns and catches, as well as the probability of fishery closures, relative to a hypothetical fishery containing fewer stocks (Hilborn et al. 2003; Schindler et al. 2010). Thus maintaining biodiversity across ecological scales is a key prerequisite for maximizing portfolio effects.

Yet even when diversity remains stable and dramatic extirpations do not occur, ecological portfolios can exhibit changes in aggregate variability that compromise their performance. Aggregate variability is fundamentally driven by the variance-covariance of individual components. Thus it can be decomposed into two distinct metrics – the weighted mean coefficient of variation among components (CVc) and an index of synchrony (phi) (Loreau and de Mazancourt 2008; Thibaut and Connolly 2013). While increases in either CVC or phi will decrease an aggregate’s stability and weaken its portfolio effect, each process can produce unique challenges to systems-based approaches.

As component variability rises, the dynamics of individual populations become increasingly chaotic. Since greater interannual variability limits managers’ ability to predict future abundance, harvest rates for individual populations should be reduced following a precautionary approach. In a healthy portfolio with sufficient diversity and relatively low levels of synchrony, divergent dynamics among populations will reduce the impact of these changes at the aggregate level. However, as synchrony increases, otherwise localized boom-and-bust cycles will become more widespread. In highly variable and synchronized populations, harvesters will be less able to shift effort among component stocks, resulting in substantial socio-economic costs (Cline et al. 2017) and increasing the likelihood of overharvest if effort is not reduced at the aggregate level.

Of course the negative effects associated with greater component variability and synchrony are dependent on underlying trends in population abundance – synchronous increases in population size are unlikely to trigger management interventions. Unfortunately, declines in abundance and population productivity appear to be widespread, particularly among exploited fishes (Peterman and Dorner 2012; Britten et al. 2016), and are likely to become more common due to persistent stressors such as climate change (Oliver et al. 2015). Unsurprisingly the consequences of increased aggregate variability are likely to be most severe in systems where population abundance is reduced due to declines in productivity or carrying capacity.

California’s Central Valley provides one example in which aggregate variability and productivity have changed simultaneously. Though the absolute number of component Chinook salmon stocks within the region has not declined, aggregate returns of Chinook salmon have collapsed and become increasingly variable in recent decades (Carlson & Satterthwaite 2011; Satterthwaite & Carlson 2015). Increased interannual variability in the returns of individual stocks, greater synchrony, and reduced productivity have resulted in dramatic reductions in aggregate spawner abundance, as well as the ecosystem services they provide (Satterthwaite & Carlson 2015). While the region technically still exhibits a portfolio effect (i.e. aggregate variability is reduced relative to that of individual stocks), the buffering conferred by its diversity is substantially weaker than it was historically (Carlson & Satterthwaite 2011). Ultimately increased aggregate variability appears to have increased the probability of fishery closures by more than 10-fold (Yamane et al. 2018).

The decline of the Central Valley Chinook salmon fishery demonstrates that high levels of aggregate variability can be associated with substantial negative ecological and socio-economic outcomes. However, it is unclear to what extent declines in aggregate abundance are driven by increased component variability and synchrony as opposed to changes in underlying population productivity. Additionally previous analyses of portfolio effects have examined a relatively narrow suite of indicators of ecosystem functioning. The effects of aggregate variability on biological benchmarks commonly used to assess population status may differ from effects on absolute abundance.

In this study, we explore how increases in component variability and synchrony influence the probability of achieving conservation and management objectives using Fraser River sockeye salmon as a case study. Sockeye salmon are an anadromous, semelparous species and the Fraser River aggregate is composed of populations that spawn throughout southern British Columbia. Sockeye salmon have been harvested in the region by commercial fisheries for over a century and by indigenous communities for thousands of years (REF). Despite the historical abundance of Fraser River sockeye salmon, the aggregate’s productivity declined in the 1990s, resulting in frequent fishery closures and an emergency federal inquiry (REF). While there have been signs of recovery in recent years, recruitment continues to be variable and several populations within the aggregate have been assessed as at risk (State of the Pacific Ocean 2018; WSP status assessment; COSEWIC assessment). Since Fraser River sockeye salmon fisheries are predominantly mixed-stock, like most Pacific salmon fisheries, abundant and depleted populations are inevitably harvested simultaneously (REF). Thus managers must balance conservation goals with the desire to sustain economically and culturally significant fisheries, particularly during periodic years of high abundance. Changes in patterns of variability and synchrony may increase tension between these trade-offs if the fishery becomes increasingly concentrated on a smaller number of abundant years.

We first present a retrospective analysis that reveals aggregate temporal variability within the Fraser River has increased in recent years due to greater component variability, as well as greater synchrony among components. We then use stochastic, closed-loop simulations to evaluate how changes in component variability and synchrony influence the likelihood of meeting a suite of conservation- and catch-based performance metrics. Finally we repeat the simulations under a range of productivity scenarios to clarify how aggregate variability interacts with changes in productivity to shape dynamics. This multi-step approach allows us to assess changes in ecosystem functioning along a gradient of scenarios from historic levels of high asynchrony and productivity to heavily synchronized, unproductive dynamics consistent with degraded systems.