# Update: Tschirhart graduate research scholarship

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Salmon hatcheries provide a way to maintain higher average harvests in commercial salmon fisheries; by supplementing wild stocks, fishers can harvest more fish without depleting overall (the net total of hatchery and wild) stocks to unsustainable levels. This process, called stock enhancement, also helps to maintain more consistent harvest levels despite natural fluctuations in fish productivity. This consistency provides fishers with a more reliable and steady source of income. Recently, however, the ecological effects of stock enhancement on wild salmon populations have come under scrutiny. Research shows that hatchery releases compete with wild stocks for resources such as food and spawning grounds [1, 2, 3, 4, 5]. Ecologists argue for the importance of protecting wild salmon populations because they provide some ecosystem services that hatchery fish do not: existence values, food for inland predators, resiliency to changes in environmental conditions, and ecological services provided during the juvenile life-stage prior to when hatchery fish are normally released [6, 7]. Together, the economic benefits and ecological costs of stock enhancement programs have lead to an unresolved debate over optimal, sustainable fishery management.

To further complicate the debate over stock enhancement, climate and ocean scientists predict that anthropogenic climate-change will cause rapid ocean warming and acidification. These changes can lead to ecological regime shifts, and are predicted to negatively affect aquatic species, including salmon [8, 9, 10, 11, 12, 13]. In particular, regime shifts threaten to lower growth rates and may lead to states of critical depensation. For these reasons, they pose a significant threat to global fisheries and a difficult challenge for fishery managers. Stock enhancement can worsen the effects of regime shifts on wild populations by lowering genetic fitness and thus their resilience to environmental shocks. However, stocking may also serve as a way to ensure wild stock survival pre-regime shift through precautionary enhancement to avoid sub-optimal equilibria or critical depensation. It could also provide an emergency backstop post-regime shift if wild stock levels fall too low as a result of changing ecosystems. For these reasons, it is essential to consider the role of stock enhancement in preparing for, and responding to, these regime shifts. [14, 15, 16].

The objective of this study is to develop an economic model of a salmon fishery that incorporates both the economic benefits and ecological drawbacks of hatchery programs under the threat of future regime shifts. Specifically, the model will be used to determine the socially optimal level of salmon hatchery releases given an exogenous regime shift that occurs at a known future date.

As of May, 2022, we have developed a simple discrete-time economic model of a social planner that chooses the level of wild-origin escapement (i.e., wild-origin fish left unharvested) and hatchery releases that maximize pink salmon fishery profits over a finite horizon. Fishery profits are comprised of the wholesale value of the sum of wild-origin and hatchery-origin harvests less the cost of harvesting these fish. The system is constrained by the natural productivity of wild salmon, which is modeled as a discrete-time Ricker growth function. Wild salmon productivity is density dependent and negatively impacted by hatchery releases. At known time $t$, the fishery undergoes a regime shift that impacts both the maximum intrinsic growth rate of the stock of salmon as well as the magnitude of density dependence, but it does not impact the negative growth effect of hatchery releases.

We have worked alongside researchers at the University of Washington, the National Oceanic and Atmospheric Administration, the Alaska Department of Fish and Game (ADFG), and the University of Alaska to calibrate the model to fit the Prince William Sound (PWS) pink salmon fishery. Ohlberger et al. (2022) estimate a Ricker growth function to recover the effects of density dependence, water temperature, competitor abundance, hatchery releases, and a previous ocean regime shift on pink salmon productivity using historic PWS fishery data. We use their results to generate a pre and post-regime Ricker functions that are bivariate functions of escapement and hatchery releases. We use ADFG published PWS data to calibrate economic program parameters such as the price of an average pink salmon and the mean cost per fish-harvested. The price and cost parameters also differ by regime.

To develop our intuition and to gain familiarity with dynamic programming algorithms, we solved the model for two simplified cases. First, we excluded hatchery effects and solved (both analytically and numerically) a single-control model in which the social planner optimizes escapement in the face of a regime shift that alters key economic and ecological parameters. Our results coincide with the results of Polasky et al. (2011) in that when faced with exogenous regime shifts of known timing, reactive management is optimal. The manager observes the regime shift when it occurs and in the next period, adjusts to the new optimal level of escapement as quickly as possible. Second, we have written the code to optimize fishery profits choosing both escapement and the number of hatchery releases, omitting any regime shift effects.

Our next step is to integrate a regime shift into the two-control dynamic programming code. After we do this, we intend to adjust the model to include additional ecological realism. Our working ideas include incorporating stochasticity in natural productivity, properly calibrating hatchery-origin fish survival rates, and modeling the effects of interbreeding between wild-origin and hatchery-origin fish. Lastly, we intend to model additional benefits provided by wild-origin salmon. As of now, the economic contribution of wild-origin and hatchery-origin salmon are equal. In reality, wild-origin fish may provide additional revenue and ecosystem services that hatchery-origin fish do not, and thus these benefits must be accounted for.

## References

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