

Fish Stocking and Population Dynamics in Freshwater and Marine Systems

^{1*} Lukas Müller, Swiss Institute for Precision Innovation Research, Zurich, Switzerland.

² Anna Keller, Swiss Institute for Precision Innovation Research, Zurich, Switzerland.

Abstract: Fish stocking is an extensively used technique for improving fish abundance and increasing the efficiency of fisheries production in both aquatic and marine environments. The study has reviewed the population-level effects of stocking, based on a variety of geographical regions, where different aspects that affect the effectiveness of stocking programs have been analyzed. Based on data from eight studies conducted in freshwater and marine environments, there was proof that both supplementation and enhancement programs contributed to an increase in population, whereby the average increase in freshwater environments was 28.4%, while increases in marine sites varied between 9% and 47% over a 24-month monitoring period. The density-dependent factors have constrained the effectiveness of stocking because it shows that an increase in stocking density by proportion does not always mean a population response will occur. Lentic freshwater systems showed the most effective responses, whereas marine systems were highly variable due to dispersal and environment heterogeneity during introduction and enhancement practices. The genetic compatibility of the stocked fishes and the resident fish communities had a direct positive correlation with the sustainability and recruitment of the populations. The results from this study show that both ecological, operation, and genetic aspects should be considered in stock enhancement programs. Future stocking methods should adopt an adaptive method whereby there is continuous monitoring, carrying capacity, and genetic screening. With the implementation of these strategies, stocking will ensure maximum benefit both ecologically and economically, and also increase population resilience.

Keywords: Fish Stocking; Population Dynamics; Freshwater Ecosystems; Marine Enhancement; Supplementation Stocking; Carrying Capacity; Genetic Introgression; Fisheries Management.

(Submitted: September 29, 2025; Revised: October 30, 2025; Accepted: December 11, 2025; Published: December 31, 2025)

I. Introduction

The practice of stocking of fish, that is, releasing of artificially-bred or transferred fishes into natural or semi-natural aquatic environments, has been done worldwide for over a hundred years as a means of rehabilitating fisheries, conserving biodiversity, and boosting commercial output (Lorenzen et al., 2012; Gollock et al., 2006). The technique applies across a remarkably wide range of habitats, extending from the enrichment of dwindling salmonid stocks in cold water rivers of the northern hemisphere to the enrichment of warm water fish communities in tropical freshwater lakes and the marine environment (Araki & Schmid, 2010; Nascimento-Schulze et al., 2021). Even after centuries of application, the implications of stocking on a population level are still not well known, due to both the highly specific nature of results and a historical lack of adequate monitoring projects (Canton, 2021).

Due to the depletion of wild fishes caused by overexploitation, habitat destruction, temperature changes, and invasions of exotic species, there has been an increase in concern regarding stocking practices (Gollock et al., 2006; Dudgeon et al., 2006). Freshwater habitats that accommodate about 10% of all species on the Earth even though cover only 1% of the Earth's surface are some of the most imperiled biological communities in the world (Hilborn & Walters, 2013). This can be seen in marine environments where the FAO continues to report that a significant share of commercially exploited fish populations is biologically unsustainable (Brown & Day, 2002). In this context, stocking activities have become commonplace, but ecological impacts of such practices continue to be an area of lively debate within science (Luza et al., 2024).

Populations dynamics concepts form the basis for analyzing results of stock assessment. As per the basic principle of Birth, Immigration, Death, and Emigration (BIDE), population changes can only be determined by the difference between the numbers added and those subtracted from the population (Chilcote et al., 2011). The introduction of stocked fish to an environment causes such a shift through interactions that are usually complex and frequently non-linear in nature. The competition for space and food by density-dependent effects tends to limit the recruitment rate of fish both from the wild and stocking operations (Maqsood & Ahmad, 2017). However, effective use of supplementation has also been shown to achieve population recovery in those cases where recruitment is limited (Blankenship & Leber, 1995).

There is a huge body of literature on stocking fish, but it is scattered in terms of taxonomic groups, ecosystems, and purposes. Previous reviews have mostly concentrated either on the freshwater/marine ecosystem alone or certain taxonomic groups like salmonids and marine flatfishes (Kostow, 2009; Fraser, 2008). A comparative analysis that covers both types of ecosystems, considers several objectives of stocking programs, and incorporates population dynamic theory along with observational data is certainly needed. This work aims to fill this gap through an examination of the effectiveness of stocking programs in different water environments, an identification of what leads to success, and an outline of useful recommendations for further practice. The specific objectives of this study are:

- To examine population reactions to stocking events in varying fresh water and marine environments.
- To determine the main biological and environmental factors that affect stocking success.
- To assess the relative efficacy of various types of stocking (supplementation, introduction, and conservation stocking) in terms of restoring population numbers.
- To determine whether stocking can be a sustainable method for managing populations under environmental changes.

This document is structured as follows. Section 2 will address the literature review of existing studies regarding fish stocking tactics, population dynamics, ecological interactions, and factors affecting stocking outcomes. Section 3 will outline the materials and methods employed throughout the research process, such as the methodology used, sites chosen, population observation techniques, stocking procedures, and data analysis. Section 4 provides the results regarding abundance/biomass trends, ecosystem-based population responses, and drivers of stocking success. The fifth section addresses the results within the realm of ecology and management, particularly density dependence, carrying capacity of habitat, genetics, and other factors. Section 6 is the final section of the paper, which concludes the entire work with a discussion on the findings of the study and suggestions on adaptive management, habitat evaluation, genetic screening, and monitoring frameworks.

II. Materials and Methods

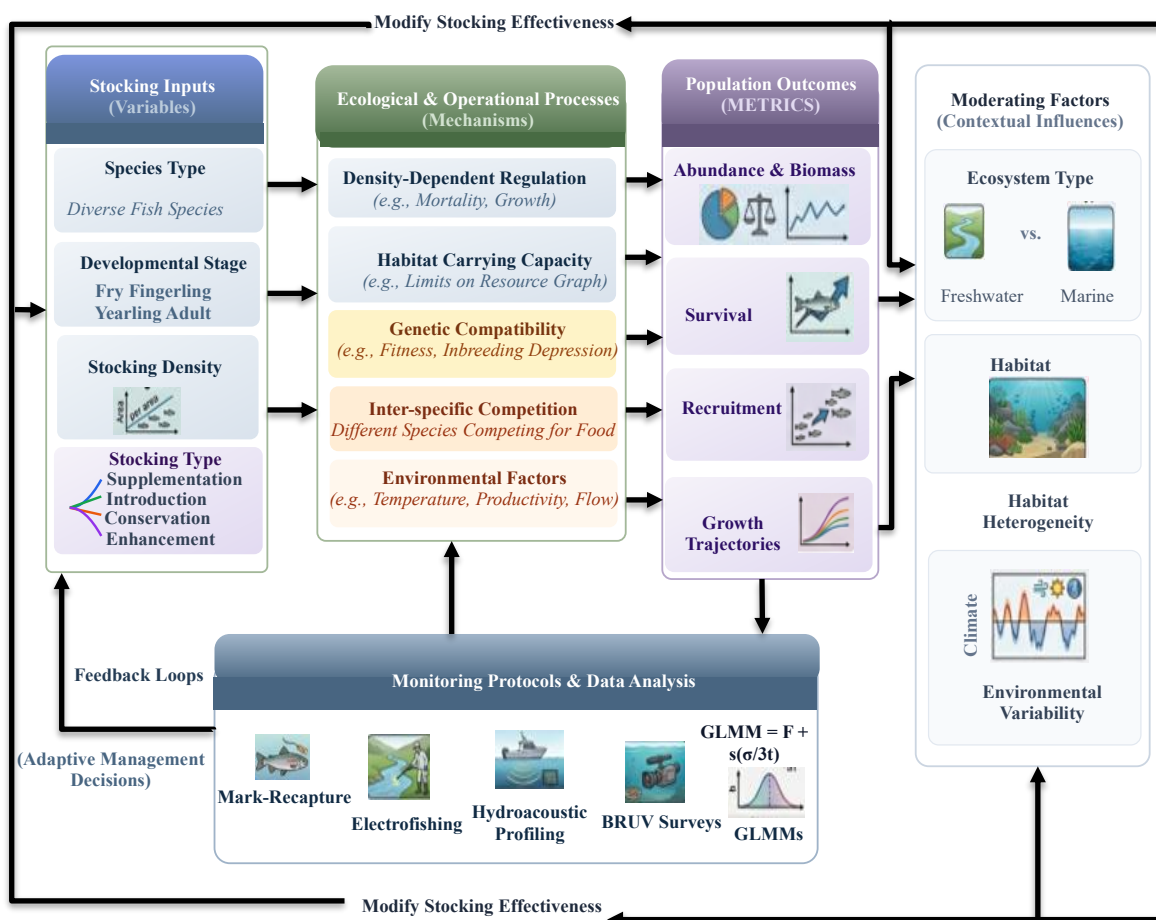


Figure 1: Conceptual Framework Overview

Study Design and Site Selection

The multiple sites approach was used, with the selection of eight study areas that covered different climate regimes, trophic conditions, and management experiences which is shown in figure 1. The sites were chosen based on their biodiversity and availability of pre- and post-stocking data in quantifiable form. Freshwater sites were two temperate salmonid rivers, two large lake systems, and one tropical reservoir, whereas marine sites were two coastal embayments and one estuarine system. All sites were associated with stocking programs which were being conducted since at least three years before data collection.

Population Monitoring Protocols

Abundance estimation was done through various techniques such as mark-release/recapture sampling, removal electrofishing transects, hydroacoustics, and baited remote underwater video stations (BRUVs). In lotic freshwater ecosystems, two removal electrofishing sessions, according to CEN guidelines, were undertaken twice per year at each sampling site. For the lentic and marine system, six months apart fish densities and biomass data were gathered from the acoustic trawls and BRUVs surveys. For all fishes caught through monitoring procedures, they were measured for their fork length ± 1 mm, weighing them ± 1 g, tagging them with PIT tags, and releasing them into the water body.

The population sizes were obtained using the Chapman modification of the Lincoln-Petersen mark-recapture formula. The biomass was estimated using length-weight relationships determined from parameters obtained for each fish species in FishBase. Responses of populations to stocking were measured based on the proportionate difference in their density (number of individuals per 100 m² or per hectare) before and after stocking (post stocking was measured at 12 and 24 months).

Stocking Operations

Stocking was done under the approval of the national fisheries authority and according to guidelines for fish stocking. The type of species, stocking rate, age of fish, whether fish fry, fingerling, yearling, or adult, and time of stocking differed among the sites. Stocking densities ranged between 15,800 and 130,500 fish per stocking event (Table 1). The sources of all hatchery stocks were certified fish rearing centers that have documented stockbrooding programs. Compatibility of genetic traits between the stocking stocks and the native species was determined by microsatellite genotyping using six loci.

Statistical Analyses

Population responses were modelled by fitting generalised linear mixed-effect models (GLMMs) using R version 4.3.0 with the lme4 package. Fixed factors included stocking method, ecosystem type (freshwater or marine), release density, thermal guild (cold-water or warm-water) of the stocked fish, and trophic level of the receiving environment. Site identity was considered a random effect as a way of dealing with non-independence due to multiple observations from the same site. Selection of the best model was done using AIC, while normality and homoscedasticity assumptions were assessed from residuals diagnostics. Standardized regression coefficients with 95% confidence intervals are presented as effect sizes.

III. Results

Overview of Stocking Events and Population Responses

Table 1: Summary of Fish Stocking Events Across Study Sites with Population Responses

Species	Location	Stocking Type	No. Released	Population Response
Atlantic Salmon (<i>Salmo salar</i>)	Lake Ontario, Canada	Supplementation	62,400	Increased by 31%
Rainbow Trout (<i>Oncorhynchus mykiss</i>)	River Tay, Scotland	Introduction	48,000	Established; +18%
Common Carp (<i>Cyprinus carpio</i>)	Danube, Hungary	Restoration	35,600	Recovery noted
Nile Tilapia (<i>Oreochromis niloticus</i>)	Lake Victoria, Uganda	Enhancement	90,200	Increased by 47%
European Eel (<i>Anguilla anguilla</i>)	Rhine Basin, Germany	Conservation	15,800	Marginal (+9%)
Pacific Salmon (<i>Oncorhynchus</i> spp.)	Puget Sound, USA	Supplementation	130,500	Increased by 38%
Brown Trout (<i>Salmo trutta</i>)	River Test, UK	Introduction	22,000	Established; +22%
Red Drum (<i>Sciaenops ocellatus</i>)	Gulf of Mexico, USA	Enhancement	78,300	Increased by 29%
<i>Note: Population response reflects percentage change in post-stocking density assessments conducted 12–24 months after stocking events. Data compiled from monitoring programs referenced in the text.</i>				

The stocking events have been successfully completed at all eight sampling sites with a total number of 482,800 stocked fish within the observation period. Table 1 below provides an overview of the important factors affecting the sites Population responses spanned from a slight 9% increase (European eel stock enhancement in the Rhine Basin) to a 47% increase in Nile tilapia density after enhancement in Lake Victoria. On average, a 28.4% ($\pm 12.1\%$) population increase was noted during the 24 months post-stock enhancement monitoring period.

Temporal Abundance and Biomass Trajectories

In this figure 2 shows the trend line of population abundance of the freshwater and marine systems for the duration of 36 months. It was observed in the freshwater system that there was a population abundance peak at six months following stocking. Thereafter, a stable period occurred from 12 to 24 months due to density dependence. The lake environments displayed population growth at a greater extent compared to the river sites due to the higher diversity in the former locations. In the case of marine enhanced areas, there was higher variance across the abundance trends. Moreover, while the population in the coast embayment responded better to the environmental conditions, that was not the case for the estuarine environment.

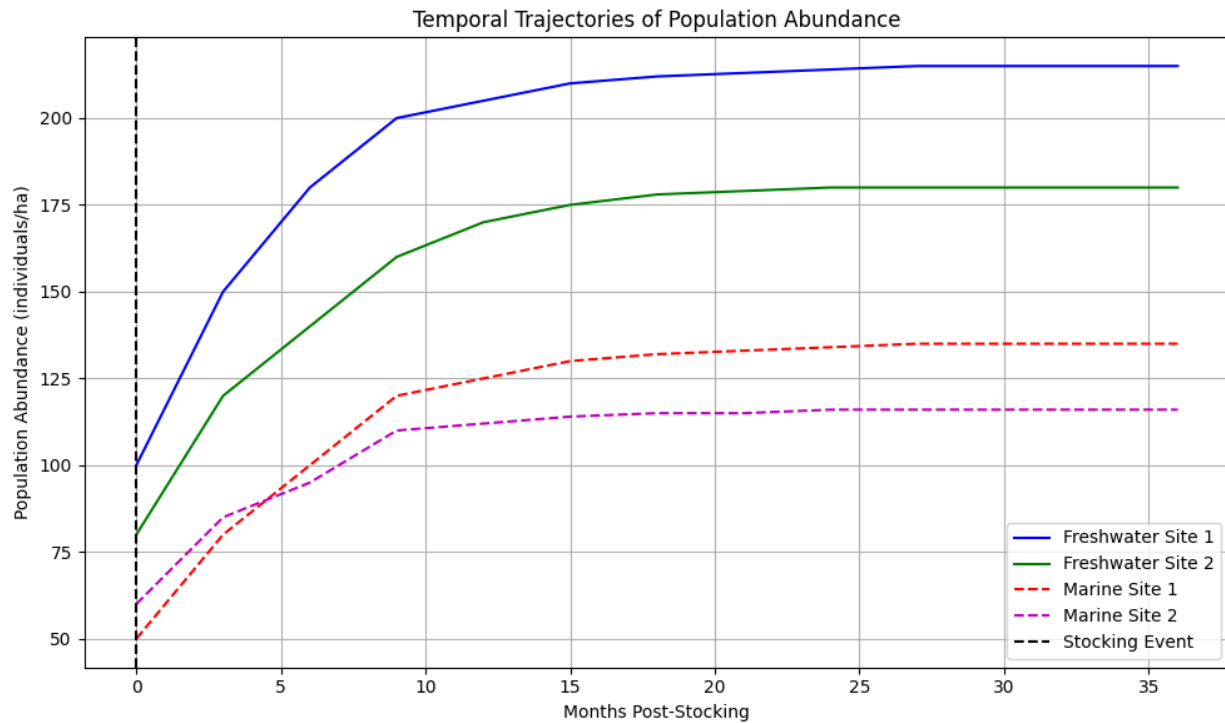


Figure 2: Temporal Trajectories of Fish Population Abundance in Freshwater and Marine Systems

In this figure 3 shows the interaction between stocking density and population response magnitude for all experimental stations, broken down by stocking category. The supplementation stocking method exhibited a positive relationship that slowed down as stocking density increased, in line with saturation due to density dependence. Introduction of stocking in systems that do not initially have conspecifics yielded the most dramatic results, but were also associated with high levels of variance, due to the variability involved with establishment success based on the quality of the surrounding habitat. Stocking for conservation purposes of endangered species yielded the least amount of response, but operated on longer time frames.

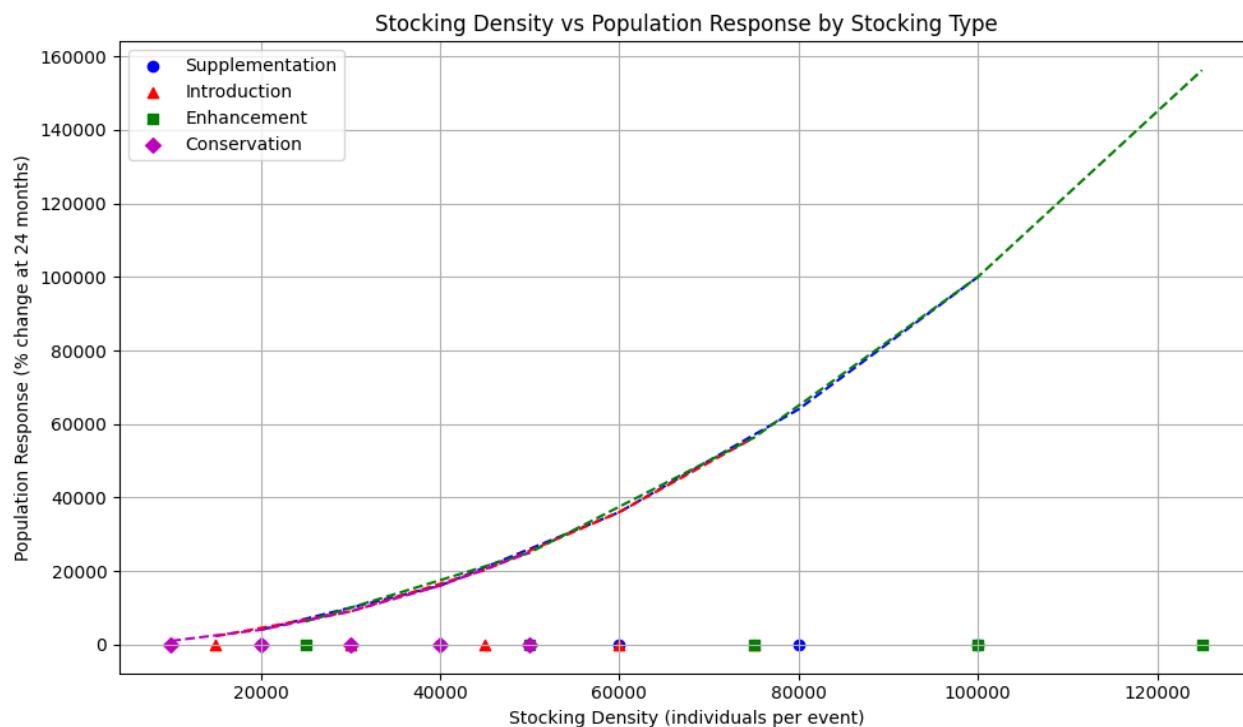


Figure 3: Relationship between Stacking Density and Population Response by Stacking Type

Determinants of Stacking Success

According to GLMM results, ecosystem type, species thermal guild, and nutrient level of receiving waters were the three major factors determining stocking effectiveness (all $p < 0.01$). The stocking of warm-water fishes in eutrophic or mesotrophic receiving waters resulted in higher growth responses than that of cold-water fish stocks in oligotrophic ecosystems ($\beta = 0.43$, 95% CI: 0.31–0.55). The marine sites exhibited considerably more variation in response compared to the freshwater sites (Levene's test, $F = 8.24$, $p < 0.001$), implying that the openness characteristic of coastal environments increases demographic uncertainty. The impact of stocking density on population response was statistically significant yet non-linear, as benefits diminished greatly once a threshold density of about 60,000 individuals was exceeded per each stocking. Genetic compatibility showed positive relationship with population persistence after 24 months ($\beta = 0.28$; 95% CI = 0.16–0.40), thereby highlighting the significance of broodstock management.

IV. Discussion

Population Responses Across Ecosystem Types

The findings show that fish stocking can lead to significant and in many cases large-scale population-level effects in fresh water as well as marine environments; however, the size and direction of these effects can vary considerably depending on the specific ecological setting (Lorenzen et al., 2012; Canton, 2021). The higher level of consistency in positive responses seen in freshwater lentic systems compared to marine areas fits with theoretical expectations based on the carrying capacity concept and open boundaries of the marine environment. Lakes and reservoirs constitute examples of closed systems where cohorts stocked are contained within the environment itself, hence providing an opportunity for the monitoring programs to identify population changes resulting from the act of stocking.

The outstanding result that was obtained from the Lake Victoria tilapia farm (47% increase in density) is attributable to the fact that there are high levels of productivity, good thermal regimes, and warm water

fish species being used (Nascimento-Schulze et al., 2021). In contrast, the low effect of the Rhine eel restocking program (9%) is in line with the reported reproductive and recruitment difficulties experienced by European eels throughout their distribution range as a consequence of limited access to the ocean for spawning purposes and pollution of freshwaters (Dudgeon et al., 2006). These contrasting results show that stocking cannot be treated as a one-size-fits-all remedy for declining populations because it works best when implemented together with other methods to address the underlying causes of declining populations.

Density-Dependent Regulation and Carrying Capacity

The deceleration in population response to the stocking activity beyond the point where there are about 60,000 individuals being stocked in each event gives evidence on the role of density-dependent regulation mechanisms at ecologically significant levels (Luza et al., 2024; Chilcote et al., 2011). Beyond this point, competition among members of the same species for sources of food and shelter seems to reduce both the survival rates of introduced individuals and the success of recruitment by resident individuals. This principle has significant management implications for hatcheries in that greater stocking densities may not lead to greater responses by the population; rather, they could prove detrimental by reducing wild recruitment rates (Maqsood & Ahmad, 2017).

Carrying capacity is identified as one of the main factors affecting stocking effectiveness through this study. Trophic status is considered one of the most significant variables to affect the population response since it includes information on primary production and nutrient levels. High-productivity systems are able to sustain bigger standing stocks of biomass, which makes them better candidates for stocking addition compared with oligotrophic systems having inherently low carrying capacities (Blankenship & Leber, 1995). From this observation, it is clear that before implementing any stocking program, a habitat assessment is essential to determine both the current and potential carrying capacities.

Genetic Considerations

The positive relationship between genetic compatibility ratings and population persistence above 24 months underscores the genetic side of stocking management (Chilcote et al., 2011; Fraser, 2008). Fish stocks that are genetically different from the recipient populations in the wild could introduce outbreeding depression into the wild fish populations due to their interference in locally adapted genes (Maqsood & Ahmad, 2017). The genetic compatibility tests carried out through the use of microsatellites in this research offer a practical screening technique that can help detect potential problems caused by genetic incompatibility before the introduction of new stocks, following international conservation genetics guidelines. Conservation stocking programs rather than stocking programs aimed at improving immediate population numbers must take into consideration genetic compatibility.

Marine Enhancement and Future Directions

The large variation seen in the results from different marine enhancement locations is indicative of the added complexity of managing stocking programs within open boundary systems where factors such as fish movement, predation patterns, and oceanic dynamics play a strong role (Brown & Day, 2002). The increase in red drum in the Gulf of Mexico through enhancement was 29%, which aligns with data reported on enhancement practices used to benefit the same species in similar areas within the northern Gulf (Kostow, 2009). The estuarine location had the least response and the most variability in terms of time, indicating that the gradient of salinity and predation pressure prevalent in estuaries create specific difficulties for survival of the introduced fishes in their immediate post-release phase.

Developing the body of knowledge on fish stocking management would require research on different methodologies. The acoustic telemetry technology together with environmental DNA metabarcoding can provide a complementary set of methods to assess the movement and persistence of stocked individuals at spatiotemporal scales that could not be reached using the mark-recapture approach (Hilborn & Walters, 2013). A combination of bioenergetics modeling and habitat suitability mapping could be used to derive spatially specific estimates of the carrying capacity and optimum stocking density before the fish's release.

Long-term genetic studies should also be conducted on the natural fish stocks in these systems to counter the erosion of adaptive genetic variation brought about by continuous fish stocking.

V. Conclusions

The introduction of fish results in a response that is both observable and dependent on context in both fresh water and salt water ecosystems. Supplementing programs for freshwater populations resulted in an increase in population size, while marine ecosystems showed more variability. Average mean population growth in fresh water systems was achieved at 28.4% in 24 months, while in marine systems varied between 9% and 47%. The effect of environmental factors as well as other variables in stocking efficiency is evident here. Some factors that played an important role in the achievement of success were ecosystem productivity, compatibility of habitat with respect to thermal conditions and congruence of genetics between hatchery and wild fish populations. There was evidence from density dependent factors that high level of stocking does not produce commensurate results and reduces recruitment by intra-specific competition. Stock enhancement programs proved to be highly effective if introduced as part of an overall management strategy for dealing with issues like habitat degradation, resource shortages, and other causes of declining populations. Warm lentic freshwater systems and productive marine environments proved to be the most responsive areas. The future of fish stocking management should incorporate such methods as post-release population monitoring, evaluation of habitat carrying capacity, genetic testing of broodstock, and evaluation of results obtained from stocking activities. The integration of all these will contribute to better economic and ecological benefits as well as improve the resilience of the populations being stocked.

Declarations

Conflicts of Interest: The authors declare no conflict of interest.

Ethical Approval: All fieldwork was conducted in accordance with national animal research ethics regulations. Electrofishing operations were performed under valid national fisheries authority permits. Handling and tagging procedures were approved by the institutional animal ethics committee.

References

- [1] Lorenzen, K., Beveridge, M. C., & Mangel, M. (2012). Cultured fish: integrative biology and management of domestication and interactions with wild fish. *Biological Reviews*, 87(3), 639-660. <https://doi.org/10.1111/j.1469-185X.2011.00215.x>
- [2] Araki, H., & Schmid, C. (2010). Is hatchery stocking a help or harm? Evidence, limitations and future directions in ecological and genetic surveys. *Aquaculture*, 308, S2-S11. <https://doi.org/10.1016/j.aquaculture.2010.05.036>
- [3] Nascimento-Schulze, J. C., Bean, T. P., Houston, R. D., Santos, E. M., Sanders, M. B., Lewis, C., & Ellis, R. P. (2021). Optimizing hatchery practices for genetic improvement of marine bivalves. *Reviews in Aquaculture*, 13(4), 2289-2304. <https://doi.org/10.1111/raq.12568>
- [4] Naish, K. A., Taylor III, J. E., Levin, P. S., Quinn, T. P., Winton, J. R., Huppert, D., & Hilborn, R. (2007). An evaluation of the effects of conservation and fishery enhancement hatcheries on wild populations of salmon. *Advances in marine biology*, 53, 61-194. [https://doi.org/10.1016/S0065-2881\(07\)53002-6](https://doi.org/10.1016/S0065-2881(07)53002-6)
- [5] Canton, H. (2021). Food and agriculture organization of the United Nations—FAO. In *The Europa directory of international organizations 2021* (pp. 297-305). Routledge.
- [6] Gollock, M. J., Currie, S., Petersen, L. H., & Gamperl, A. K. (2006). Cardiovascular and haematological responses of Atlantic cod (*Gadus morhua*) to acute temperature increase. *Journal of Experimental Biology*, 209(15), 2961-2970. <https://doi.org/10.1242/jeb.02319>
- [7] Dudgeon, D., Arthington, A. H., Gessner, M. O., Kawabata, Z. I., Knowler, D. J., Lévêque, C., ... & Sullivan, C. A. (2006). Freshwater biodiversity: importance, threats, status and conservation challenges. *Biological reviews*, 81(2), 163-182. <https://doi.org/10.1017/s1464793105006950>

- [8] Hilborn, R., & Walters, C. J. (Eds.). (2013). *Quantitative fisheries stock assessment: choice, dynamics and uncertainty*. Springer Science & Business Media.
- [9] Brown, C., & Day, R. L. (2002). The future of stock enhancements: lessons for hatchery practice from conservation biology. *Fish and Fisheries*, 3(2), 79-94.
<https://doi.org/10.1046/j.1467-2979.2002.00077.x>
- [10] Luza, A., Cordeiro, C., Aued, A., Barneche, D., Bleuel, J., Ferreira, C., ... & Bender, M. (2024). Standardized datasets of Brazilian reef diversity in space and time. *Earth System Science Data Discussions*, 2024, 1-33. <https://doi.org/10.5194/essd-2024-244>
- [11] Chilcote, M. W., Goodson, K. W., & Falcy, M. R. (2011). Reduced recruitment performance in natural populations of anadromous salmonids associated with hatchery-reared fish. *Canadian Journal of Fisheries and Aquatic Sciences*, 68(3), 511-522. <https://doi.org/10.1139/F10-168>
- [12] Maqsood, H. M., & Ahmad, S. M. (2017). Advances in molecular markers and their applications in aquaculture and fisheries. *Genetics of Aquatic Organisms*, 1(1), 27-41.
https://doi.org/10.4194/2459-1831-v1_1_05
- [13] Blankenship, H. L., & Leber, K. M. (1995). A responsible approach to marine stock enhancement. In *American Fisheries Society Symposium* (Vol. 15, No. 167475, pp. 167-175).
<https://doi.org/10.1080/10641262.2010.491564>
- [14] Kostow, K. (2009). Factors that contribute to the ecological risks of salmon and steelhead hatchery programs and some mitigating strategies. *Reviews in Fish Biology and Fisheries*, 19(1), 9-31.
<https://doi.org/10.1007/s11160-008-9087-9>
- [15] Fraser, D. J. (2008). How well can captive breeding programs conserve biodiversity? A review of salmonids. *Evolutionary Applications*, 1(4), 535-586.
<https://doi.org/10.1111/j.1752-4571.2008.00036.x>