Performance of alternative experimental strategies for developing extensive polyculture systems in small water bodies

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Table of Contents

Abstract

1. Many small water bodies are managed for fish production as extensive polyculture systems, where several species of fish are stocked and harvested concurrently to exploit the water body's natural productivity. Optimal stocking and harvesting regimes for such systems are determined by competitive relationships within species, and by inter-specific interactions that may be competitive or facilitative.
2. Such relationships are poorly understood and quantified, and many polyculture systems are likely to operate well below their optimum. Adaptive (experimental) management have been promoted as a means to improve stocking regimes, but little information is available on the true benefits of the approach, and the effectiveness of alternative implementation strategies.
3. Here, the performance of different experimental management strategies for optimising stocking regimes in polyculture systems is evaluated using a simulation model. Model specification and parameter values based on an analysis of carp polyculture systems in Bangladesh oxbow lakes, and the analysis thus provides insights that are directly relevant to the situation found in these and similar systems.
4. Experimental strategies were effective at increasing yields over and above levels achieved when stocking regimes were determined ad hoc, or based on recommendations from a pond culture manual.
5. Experimentation requires contrasting treatments and sufficient replication to provide adequate statistical power for analysis. Hence stocking regimes that are sub-optimal even by general knowledge may have to be adopted experimentally, incurring a short-term loss for the long-term benefit of optimizing stocking regimes.
6. When accounting for this trade-off by comparing the discounted net present value (NPV) of alternative strategies, experimental strategies performed less well than those simply implementing recommendations from a pond culture manual, even where experimental strategies led to significant long-term improvements.
7. When designing experimental strategies, a delicate balance has to be struck between statistical power and cost. Because of the strong effect of short-term costs, optimal strategies in terms of NPV tend to be only moderately informative and lead to moderate long-term benefit.
8. Similarly, short experiments leading to the identification of moderate improvements may be more valuable in terms of NPV than longer experiments leading to greater improvements.
9. Where experiments involve a sample of a larger set of similar systems that will benefit from application of the results, more informative and therefore costly strategies may become feasible, provided that mechanisms are found to share costs.
10. Where experimental management is being considered as an option for the optimisation of extensive polyculture systems, the temporal stream of costs and benefits and the resulting NPV of different strategies should be assessed carefully. This criterion is likely to favour designs of relatively low statistical power.

Introduction

Culture based fisheries, in which suitable fish species are regularly stocked singly, or as a mix of species, to augment the natural fish production from small water bodies are common in many parts of Asia and elsewhere. Indeed, stock enhancement in small water bodies has been found to be highly cost effective in many cases and stocked fish can come to dominate catches (Sugunan 1997, Lorenzen et al. 1998). Stocking is often ad hoc, but may also be carried out as part of co-ordinated programmes by governments or NGOs.

The yield of stocked species depends on characteristics of the water body (principally its innate biological productivity), biological characteristics of the stocked species (growth and mortality as influenced by intra- and inter-specific interactions), and the stocking and harvesting regime adopted. Fisheries productivity of lacustrine water bodies depends strongly upon the primary production, which in turn depends upon the availability of sufficient nutrients in the water. It is well documented that fish yields from small water bodies are positively correlated with primary productivity, and indeed the levels of nutrients in the water (Moreau and De Silva 1991, Lorenzen et al. 1998; Nissanka et al. 2000). Water body and species characteristics determine how total yield from the culture system responds to different stocking and harvesting regimes. Key biological processes are competitive interactions within species, and inter-specific interactions that may be competitive or facilitative. Because polyculture systems These species are often stocked as a mix, as polyculture, with the intention of increasing production by fully exploiting the natural production of the waterbody while at the same time maximising positive interactions between species and minimising any negative ones (Milstein 1992).

The species commonly stocked in Asian small water bodies are predominantly cyprinids such as the Indian carps (*Labeo rohita*, *Catla catla* and *Cirrhinus mrigala*), Chinese carps (*Aristicthys nobilis*, *Ctenopharyngodon idella*, *Hypophthalimichthys molitrix*, *Cyprinus carpio*) and other indigenous species (e.g. *Barbodes gonionotus*). Also commonly stocked are regionally exotic cichlids such as *Oreochromis niloticus* and *Oreochromis mossambicus*. Interactions between species depend upon the availability of food (related to waterbody productivity in the case of culture based fisheries) and stocking densities (Milstein 1992). If yields are to be improved then it is important to understand the interactions between species in order to calculate appropriate stocking densities. In this respect, a number of interactions have been noted between the species commonly stocked. Positive interactions have been noted for example between silver carp and mrigal (Hasan and Middendorp 1998), silver carp and common carp and tilapia and common carp (Milstein 1992).

While culture based fisheries show much promise, in many parts of Asia management remains sub-optimal (Nguyen et al 2001, Lorenzen et al 1998). Part of the reason for this is due to the approach taken to management and improving management. Often, management of culture based fisheries is based on stocking what is available and improving management through trial and error (Nguyen et al, 2001). Empirical studies (e.g. Lorenzen et al 1998) suggest that there is a great deal of potential for increased yields from culture based fisheries through improvements in management including optimising the composition of the mix of species that are stocked.

One approach to improving management that appears to have potential for culture based fisheries is adaptive learning. Adaptive learning approaches seek to either use existing contrasts between management actions, or deliberately choose management actions, such as species stocked and/or stocking density, that create contrast. The contrast provides an opportunity to compare between waterbodies that have been subject to different strategies and learn more about the underlying processes. Learning about these processes can reduce the uncertainty associated with management and potentially improve both predictions and outcomes.

Enhancements in small water body fisheries are typically characterized by two factors that have major implications for the application of experimental management regimes:

- Most are managed as polyculture, or multi-species stocking systems. Quantifying inter-specific interactions is crucial to the optimisation of such systems.
- Small water bodies are replicated systems. Experiments can be carried out on a representative sample of water bodies with an appropriate degree of replication, and the knowledge gained can justifiably be generalized to the whole population of water bodies.

In this study, a mathematical model was used to explore the use of experimental stocking strategies applied to polyculture systems in replicated small water bodies, and their ability to improve predictions and outcomes.

Material and Methods

An adaptive management simulation model was constructed to evaluate the performance of alternative management strategies. The model has three main components:

1. A system model, which represents the true state of the polyculture system and generates “actual” yield figures for the stocked water bodies.
2. An assessment model, which uses the output from (1) to estimate parameters of a yield predictive model, and calculate an optimal stocking regime
3. A decision rule, which determines the new stocking regime based on the results from the assessment model

The model was designed to simulate adaptive management involving a set of replicated systems (i.e. multiple water bodies) which could be managed separately to provide contrasting experimental treatments within a single production cycle.

The system model

The system model, describing the true underlying behaviour of the polyculture system, was defined as a multiple regression model of yield as a function of water body productivity and the stocking densities of several species. The model included quadratic terms for the stocking densities to allow for within-species density-dependent effects, and interaction terms between species to account for competitive or facultative interactions between species.

In order to create realistic system model, the model was built by regression analysis of an extensive data set from the oxbow lakes (baors) of western Bangladesh (Hasan & Middendorp 1998). Under the Oxbow Lakes project, the baors had been stocked with mixes of up to six species of Indian and Chinese carps. The major species used were silver carp (*Hypophthalimichthys molitrix)*, common carp *(Cyprinus carpio),* and mrigal (*Cirrhinus mrigala*), which were supplemented smaller numbers of *Labeo rohita*, *Catla catla Ctenopharyngodon idella*, *Barbodes gonionotus, and Oreochromis niloticus.* For the purpose of the present study, the latter species were grouped together in a category of “other” species. A multiple regression model, of the form shown below, was built to predict yields of stocked fish in a production cycle, i.e. a cycle from stocking of fish to the harvesting of those fish. The resultant model included a linear term for water body productivity, linear and quadratic terms for stocking densities, and interaction terms between the stocking densities of mrigal and silver carp, and mrigal and common carp.

Stochastic variability in yield was assumed to be due to observation error (rather than process error, i.e. stochasticity of the underlying processes), and a normally distributed observation error was applied to the deterministic predictions of the regression model to generate observations of yield in a set of waterbodies.

The resulting model predicted the total yield (per ha) of stocked fish Y_i in water body i as:

$$Y_i = \beta_1 SD_i + \beta_2 S_{1,i} + \beta_3 S_{1,i}^2 + \beta_4 S_{2,i} + \beta_5 S_{2,i}^2 + \beta_6 S_{3,i} +$$
$$\beta_7 S_{3,i}^2 + \beta_8 S_{4,i} + \beta_9 S_{4,i}^2 + \beta_{10} S_{1i} S_{2i} + \beta_{11} S_{1i} S_{3i} + \beta_{12} S_{2i} S_{3i} + e$$

Where SD_i is the Secchi depth (a measure of waterbody productivity), S_{1i} is the stocking density of silver carp, S_{2i} is the stocking density of common carp, S_{3i} the stocking density of mrigal, and is S_{4i} the stocking density of other stocked species (a combination of grass carp, rohu and catla), all expressed in numbers per ha. The parameter values were β_1 = -0.535756, β_2 = 0.30216, β_3 = -6.33189e-5, β_4 = 0.30095, β_5 = -0.000231, β_6 = 0.205433, β_7 = -

6.12499e-5, β_8 = 0.25536, β_9 = -6.90492e-5, β_{10} = 2.0787e-5, β_{11} = 5.1325e-5 and β_{12} = -4.18175e-4. The model thus includes density dependent effects of stocking density for each of the four species, or species groups, in the form of the negative parameter values for quadratic associated with each. In addition to the stocking densities of the individual species, there were negative interactions between common carp and mrigal and positive interactions between mrigal and silver carp. The variance of normally distributed observation error term was specified as the coefficient of variation in the residual regression model, CV(Y) = 7.2 .

The assessment model

The assessment model has the same structure as the "true" system model, but its parameters are estimated from the simulated observations. The assessment model thus represents the manager's assessment of system behaviour, and is used as a basis for decision making on future management.

Once the assessment model has been estimated, it may be used to predict the combination of stocking densities that will provide the greatest yield or, using information about costs and fish price, economic benefit.

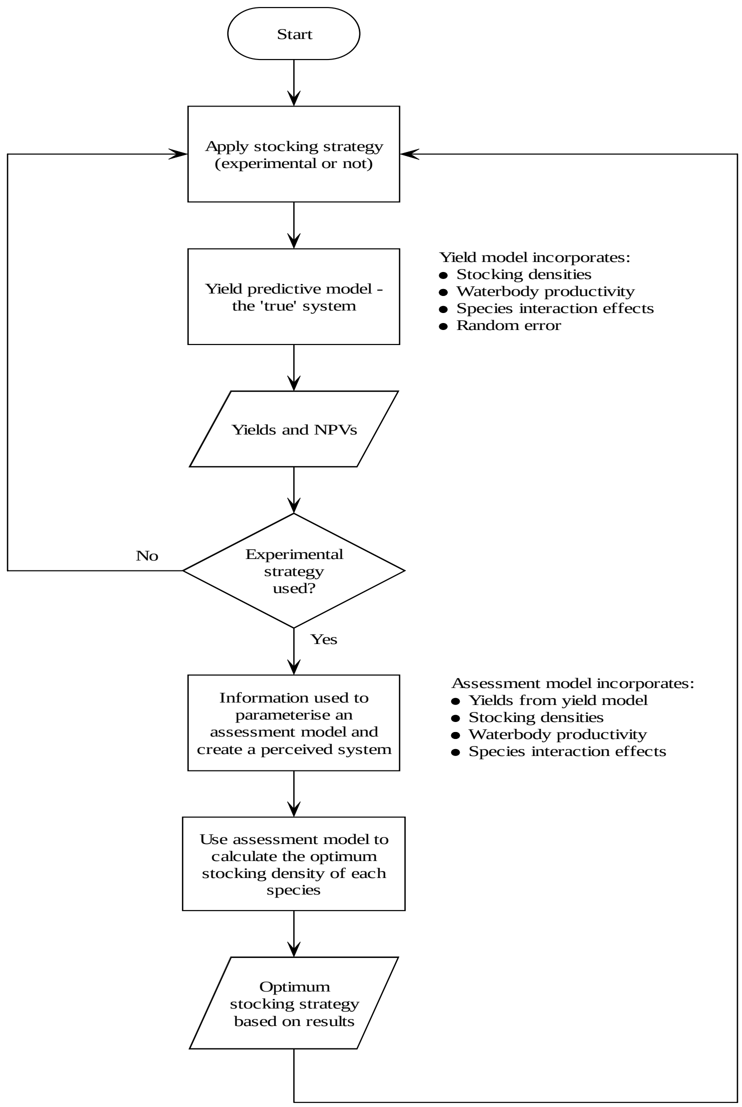
Decision rules

Different decision rules, i.e. management responses to the information obtained from the assessment model were simulated. Principally these involved changing stocking regimes to the optimum as determined from the assessment model after different periods of experimentation.

Management simulation procedure

The model simulation procedure is shown in Figure 1. At first, the system model is used to predict yields in each of the experimental water bodies. Then, the assessment model uses the results from the experiment to calculate an optimal stocking regime. The manager then decides to either, stop the experiment and apply the estimated optimal stocking regime to all water bodies, or to continue the experiment for another cycle. In the simulations reported here, the experimentation period was predefined by the user, but experimentation was continued beyond the predefined period if optimisation yielded "obviously" nonsensical results, i.e. optimal stocking at densities greater than 15000/ha or less than 1/ha.

Figure 1. Flowchart of the simulation procedure



Measures of management strategy performance

Three criteria were used to assess the performance of alternative management strategies and approaches:

1. The mean yield from the water bodies in the final year, i.e. the end result of the experiment
2. The time average of mean yields from the water bodies achieved over the period of experimentation.
3. The Net Present Value (NPV) of the catch from the waterbodies over the period of the experiment. NPV is discounted to reflect the higher value placed on immediate benefits and costs compared to those occurring further in the future.

The discounted NPV was calculated using the equation:

$$NPV_j = \sum_{j=1}^{t} \frac{(P_j \times Y_j) - C_j}{(1+d)^j}$$

Where Pj is the output price, Yj is the yield, Cj are the costs of fingerlings for stocking, all in the jth year, and d is the discount rate. NPV was calculated for a period of t = 10 years. The prices and costs used are given in Table 1.

Table 1. Costs and prices used in the calculation of NPV.

	Silver carp	Common carp	Mrigal	Other
Fingerling cost (US$/piece)	0.012	0.03	0.014	0.017
Price of produce (US$/kg)	0.42	0.42	0.42	0.42

Management strategies evaluated

The simulation model was used to evaluate management strategies for a hypothetical set of 40 with different innate productivity levels. All strategies were evaluate over a period of 10 production cycles.

A total of 9 alternative management strategies were evaluated, including both experimental and non-experimental strategies (Table 2). Strategy A involved stocking all water bodies with randomly selected numbers of the different species, subject to a constant total density of 4000, and without learning over the 10 year period. This scenario reflects a situation where species combinations are not actively controlled because for example, no information is available on suitable species combinations, or stocking combinations are driven by variable seed supply. Strategies B and C involve using information from an extension manual, or following traditional practice as embodied in the observed stocking patterns in Bangladesh oxbow lakes.

Table 2. Overview of management strategies simulated

Code	Management strategy
A	Random allocation of species densities subject to a constant total
B	Constant stocking regime based on a pond culture manual (Kumar 1992)
C	Constant stocking regime based on average observed densities in Bangladesh oxbow lakes
D	Experiment without constant total constraint, no optimisation
E	Experiment without constant total constraint, optimisation after one cycle
F	Experiment without constant total constraint, optimisation after three cycles
G	Experiment with constant total constraint, no optimisation
H	Experiment with constant total constraint, optimisation after one cycle
I	Experiment with constant total constraint, optimisation after three cycles

Strategies D to I use stocking of a set of species combinations designed by the manager to provide contrast in treatments, while also incorporating some information from the extension manual (Kumar 1992). Details of the stocking combinations are given in table 3. In treatments D, E, and F, total stocking densities were allowed to vary in order to provide the greatest possible contrast, while in treatments G, H, and I, total densities were kept constant. The latter strategy is of practical interest because constant total density strategies are more readily acceptable to communities than strategies that involve very different levels of input in different communities. The experimental strategies involved randomly stocking water bodies with different treatments consisting of different species combinations.

Table 3. Details of the stocking combinations simulated

	Silver	Common	Mrigal	Other	Total density
B (Kumar 1992)	1600	800	600	1000	4000
C (traditional)	1390	490	1306	409	3595
Experimental strategies D , E, F					
Treatment					
1	2000	800	500	1000	4300
2	2500	300	2500	0	5300
3	0	1000	0	2500	3500
4	3000	0	300	0	3300
5	1000	300	2200	2000	5500
6	500	1400	200	1000	3100
7	3000	0	0	500	3500
8	2200	0	800	1000	4000
9	0	0	3000	500	3500
10	1300	500	1200	1000	4000
Experimental strategies G, H, I					
Treatment					
1	2000	1000	500	500	4000
2	1500	700	700	1100	4000
3	1000	1000	0	2000	4000
4	2500	0	1000	500	4000
5	600	1200	500	1700	4000
6	1000	750	750	1500	4000
7	1500	1700	0	800	4000
8	2750	0	1200	50	4000
9	2500	0	1000	500	4000
10	1250	1000	1000	750	4000

Experimental treatments were applied for two or six cycles before assessment and optimisation were carried out. Each strategy was simulated 500 times to obtain means and 5% and 95% percentiles of the performance measures.

Results

Figure 2 shows the average yield per hectare for all the waterbodies in the final year of the simulation. The experimental strategies (E, F, G and H) were able to produce substantially higher final yields than either of the baseline strategies using stocking regimes based on extension advice or tradition. Strategies using variable stocking densities but not using the information for optimisation (A, D, and G) performed least well. The more powerful experimental strategies inducing variation in total density as well as species combinations (E, F) provided allowed greater yield gains than those using constant total densities.

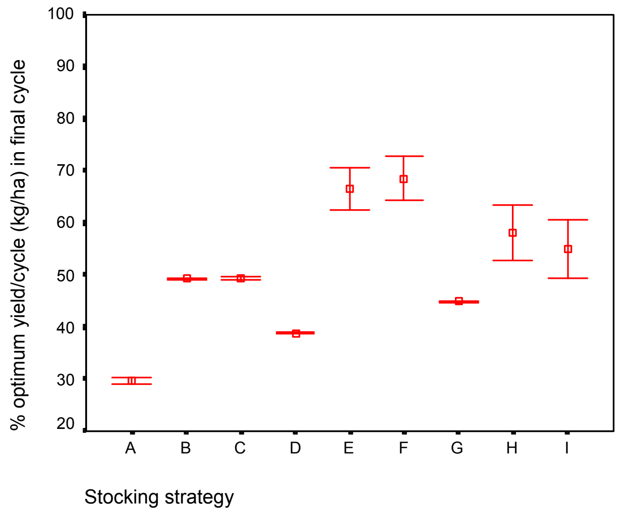


Figure 2. Average yield from the final (10^{th}) production cycle for each management strategy, expressed as a proportion of the true optimum yield.

The averages of yields achieved throughout the experimental period show a pattern similar to that of the final yields (Figure 3). As with the final yields, experimental strategies E and F produced higher total yields over the ten production cycles than H and I. In both cases, however, shorter experiments with optimisation after only two cycles produced higher overall yields than the longer experiments with optimisation after six periods. This provides a first indication of the costs involved in experimentation.

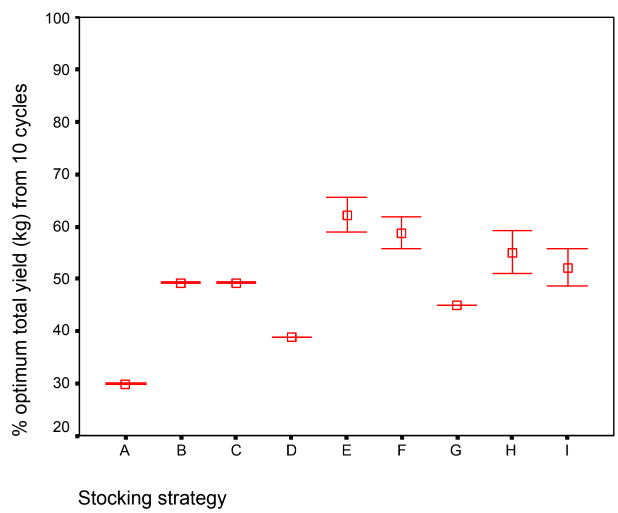


Figure 3. Average total yield per hectare from the waterbodies over ten production cycles.

The costs associated with experimentation are more clearly seen in Figure 4 where the NPVs of the different strategies are shown. The NPVs are highest for the baseline stocking strategies (using existing knowledge). The experimental strategies resulting in the highest final yields (E, F) perform worse in NPV terms than the less informative strategies (H, I). The reason for this is that experimentation can impose costs in terms of lower yields during the experimental period. Only the "no knowledge" random strategy A performs worse than the experimental strategies. While experimental strategies can provide increased annual yields in the longer term and increased overall yields the short term benefits may be affected. The importance of this and the magnitude of the effect will depend upon the discount rate used.

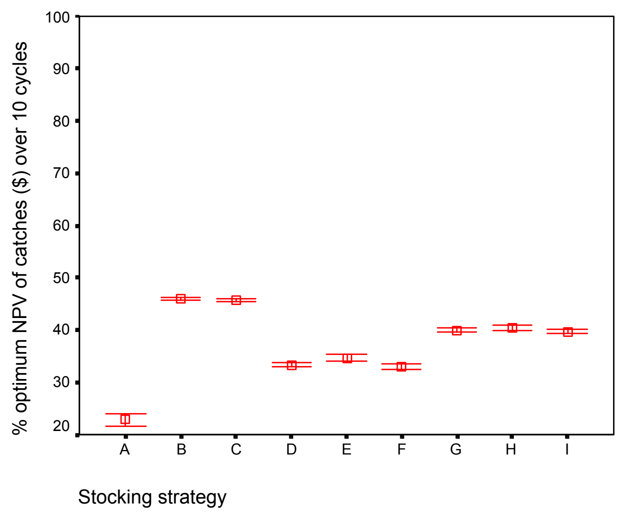


Figure 4. NPV of management strategies over ten production cycles.

Discussion

Yield predictive models can be effective tools for the optimisation of multi-species culture based fisheries. These models allow stocking density and species combination to be optimised for the particular management objectives. The development of such models relies on the availability of data with sufficient contrast in order to be able to identify important relationships. Experimental management can provide data with sufficient contrast for model development and lead to substantial improvements in management.

Experimental strategies were effective at generating information on system dynamics, and ultimately increasing yields over and above levels achieved when stocking regimes were determined ad hoc, or based on general recommendations from a pond culture manual or traditional knowledge. Similarly, in other cases where an experimental approach has been taken, the estimation of model parameters have been improved (Sainsbury 1988, Collie and Walters 1991, McAllister et al 1992). This is in contrast to programmed approaches where several waterbodies may be stocked at similar densities and with similar combinations of species. In such cases there is very little opportunity for learning because there is no variation in, and hence contrast between, what has been stocked. Deliberately manipulating conditions though can potentially allow for even greater improvements in learning as it can allow for greater contrasts between treatments. Peterman and McAllister (1993) also point out that deliberate manipulation can provide a wider range of conditions under controlled conditions. The experimental approaches taken here suggest that the greater the contrast in the experimental options, the more effective the learning.

Experimentation requires contrasting treatments and sufficient replication to provide adequate statistical power for analysis. Hence stocking regimes that are sub-optimal even by general knowledge may have to be adopted experimentally, incurring a short-term loss for the long-term benefit of optimizing stocking regimes. The use modelling techniques to assess the benefits and costs from experimental strategies makes it useful in cases where experimentation is being considered. If experimentation is to occur in a number of waterbodies, this may require the collaboration and co-operation of resource users and other stakeholders. If this is to happen, it is important that they are fully informed of what is entailed. Modelling can be used in such a situation to assess various potential experimental strategies and the benefits that such approaches might provide as well as the potential costs and risks. The potential strategies can be discussed with stakeholders in terms of the likely costs and benefits of different experimental options and consensus reached.

When accounting for this trade-off by comparing the discounted net present value (NPV) of alternative strategies, experimental strategies performed less well than those simply implementing recommendations from a pond culture manual, even where experimental strategies led to significant long-term improvements.

When designing experimental strategies, a delicate balance has to be struck between statistical power and cost. Because of the strong effect of short-term costs, optimal strategies in terms of NPV tend to be only moderately informative and lead to moderate long-term benefit. Similarly, short experiments leading to the identification of moderate improvements may be more valuable in terms of NPV than longer experiments leading to greater improvements.

Where experiments involve a sample of a larger set of similar systems that will benefit from application of the results, more informative and therefore costly strategies may become feasible, provided that mechanisms are found to share costs.

Further analysis of the management system model developed here is being conducted in order to evaluate the implications of using different numbers of species, strength of inter-specific interactions, and interactions with water body productivity for the feasibility of experimental strategies.

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