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Article

Fisheries management with marine reserves: perspectives from equilibriums to transients

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Abstract

Although debates exist, marine reserves play an important role in fisheries management. Based on stable equilibrium state, theoretical frameworks of various systems suggest that fisheries management with the implementation of marine reserves has obvious advantage in achieving multiple goals such as improving the target fisheries yields as well as maintaining species persistence in comparison with strategy of traditional fishing effort control. More recently, ecologists pay attention to the transient dynamics of fisheries yields when marine reserves are established. Simulation results suggest that the relative advantages between different fisheries management strategies (the implementation of marine reserves vs. traditional fishing effort control) depend on not only life histories but also the measurement metrics of fisheries yields (measured by number vs. measured by weight). Further research on transient dynamic pattern of fisheries yields can help fishery managers adjust relevant policies at an appropriate ecological time scale to achieve both conservation and economic goals, which provide a theoretical foundation for adaptive marine reserve management.

Keywords: marine protected area, fisheries management, population persistence, transient dynamics

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Main text

Fishery resources provide an important food source for human beings. How to improve fisheries yields and ensure the sustainable development of fishery resources not only is an important issue in theoretical ecology, but also has important practical implications. To solve this problem, ecologists have proposed different fisheries management strategies [1-4]. Traditional fisheries strategies try to catch a fixed proportion of the total fishery resources to achieve the goals of both increasing fisheries yields and maintaining species persistence. With the deterioration of overfishing of fishery resources, the important role of marine reserves (marine protected areas) in the protection of fishery resources and biodiversity has gradually been noticed [2,5]. Fishermen, however, have questioned whether the implementation of marine reserves will increase fisheries yields. Intuitively, when marine reserves are established, banning fishermen from fishing leads to a significant decline in fishing output. However, theoretical predictions suggest that this intuition is not always true. Hastings and Botsford (1999), through a simple theoretical model, demonstrated that the establishment of permanent marine protected areas has absolute advantage in fisheries management in comparison with traditional fixed fisheries management: based on a series of reasonable assumptions, they found that the role of larvae dispersal leads to equivalent fisheries yields between two different fisheries strategies (i.e. harvesting fixed proportion of fish individuals each year vs. the implementation of marine reserves). However, the implementation of marine reserves has unique advantages in protecting endangered species and other species that are sensitive to environmental changes. Therefore, they believe that the establishment of marine reserves should be an essential part of the management of fisheries resources [5]. Although the debates exist, this viewpoint is widely accepted and has been demonstrated by subsequently relevant theoretical models [6,7].

Although theoretical frameworks by considering single species provide a simple and effective explanation of the importance of marine reserves, its conclusions cannot be applied to a more natural system in which the problem of by-catch is prevalent in fisheries. By-catch refers to the incidental mortality of non-target species in fisheries [8-11]. To date, how to protect the survival of by-catch species while ensuring the optimal yield of the target stock remains a very challenging problem. This mainly derives from the fact that the critical fishing effort used to maintain the survival of different fish species is different [12], and it is often difficult to distinguish different fish species and carry out selective fishing in real natural ecosystems. The cost of selective harvesting in fisheries management would be significantly reduced if a harvesting strategy could achieve two objectives (maintenance of by-catch stock survival and increasing the yield of target stock) without having to apply different critical fishing efforts to different stock species. Based on this ideology, Hastings et al. (2017) deduced the critical survival conditions of by-catch species, and compared the fisheries yields under different harvesting strategies (traditional fishing effort control strategy and the strategy with the implementation of marine reserves). According to the simulation analysis results, they found that the harvesting strategy based on the implementation of marine reserves can improve the fisheries yields of the target species under the condition that the by-catch species are not extinct [12]. These results further prove the importance of establishing marine reserves in strengthening ecological functions of conservation and increasing fisheries yields. However, one of the main limitations of these analyses is that the theoretical frameworks are based on the conditions of equilibrium stable state. Thus, these conclusions cannot be used to predict the transient dynamics of population density and fisheries yields in relatively short time scales. More recently, ecologists pay attention to not only the equilibrium state of fisheries yields but also the transient dynamics as well as the adaptive management of marine protected areas.

Transient dynamics and adaptive marine protected areas management

Monitoring and studying transient dynamic patterns of population density and fisheries yields plays an important role in the adaptive management of marine protected areas [13-15]. The adaptive reserve management strategy is a widely adopted iterative method in fisheries management, which continuously adjusts the promulgation and implementation of fishery policies according to the differences between actual monitoring data and theoretical predictions [16-18], so as to achieve the optimal state of fishery regulation results. This management strategy is a typical case of applying ecological transients [19-22] to the management of fisheries with the implementation of marine reserves. In a marine ecosystem that is overfished and a marine reserve is established, studies on adaptive fishery strategies suggest that it is very important to establish an appropriate expected timeline for the scientific and accurate prediction of how fish stocks will recover after the reserve is established [17]. This derives from the fact that a series of influencing factors such as life history make the population density of the fish population fluctuate irregularly after the establishment of marine reserves, which eventually leads to the unpredictability of population dynamics in fisheries [16-18]. These findings provide important implications for comparing the relative advantages of different harvesting strategies (traditional fishing effort control vs. the implementation of marine reserves) in short time scales in terms of increasing fisheries yields as well as maintaining species survival. Recent research suggests that if the transient dynamics of the population fluctuate sharply with large amplitudes, fisheries yields based on traditional harvesting strategies may be higher at one time point and lower at the other time point than that based on marine reserves, making it difficult for decision makers to determine which harvesting strategy is better [23]. According to this hypothesis, it is particularly urgent to study the transient dynamics of fisheries yields and the internal mechanism that determines the fluctuations, which can lay a theoretical foundation for formulating scientific fishery management strategies to achieve multiple objectives such as ecological and economic benefits.

Effects of measurement method on fisheries yields

Theoretical studies based on equilibrium and stable states suggest that the establishment of marine reserves is an important way to solve the bycatch problem and should be regarded as the primary harvesting strategy [12]. However, the estimation of the optimal harvesting strategy in the transient dynamic pattern tends to be complicated. By extending the classical theoretical model from low dimension to high dimension, Chen et al. (2020) found that, compared with the traditional harvesting strategy, fisheries strategies based on the implementation of marine reserves in the transient dynamic pattern does not always show absolute advantages in terms of improving fisheries yields and maintaining species survival. The relative advantage of the two fisheries management strategies depends on how the fisheries yields are measured. If the fisheries yields are calculated by the number of fish individuals, the harvesting strategy based on the implementation of marine reserves shows obvious advantages. If fisheries yields are measured in terms of individual biomass or weight, traditional harvesting strategies are not always disadvantage in terms of increasing fisheries yields and maintaining species survival [23]. The mechanism under which the measurement of fisheries yields can affect the optimal harvesting strategy has been explored. In the reserve-based strategy, the adult fish that appear in the harvesting area each year all come from the dispersal and growth of juvenile fish in the marine reserves. Thus, the adult fish caught are young (only one year) and the individual size is small; However, in the traditional harvesting strategy, due to the age structure, the older individuals (more than one year) occupy a certain proportion of the adult fish caught each year, and the individual biomass or weight is relatively large. The harvesting characteristics of the two strategies ultimately lead to individual measurements that underestimate the advantages of traditional harvesting strategies [23].

Effects of life history strategies on fisheries yields

Further study found that the optimal harvesting strategy in the transient dynamic pattern was not only affected by the fishery yield measurement method, but also affected by the life history strategies of both the target stock and bycatch stock [23]. If the target population matured at an earlier age and adult fish had a higher survival rate, fisheries yields obtained by the traditional harvesting strategy were higher than that obtained by the reserve-based strategy. The life history strategies of by-catch mainly influence the optimal harvesting strategy by regulating the critical reserve size (reserve-based strategy) and critical escapement rate (traditional harvesting strategy) to ensure the survival of species. For example, if the life history strategy of by-catch makes the critical reserve size always equal to the critical escapement rate, then the traditional harvesting strategy can still increase the fisheries yields and maintain the species survival even if the bycatch species have long life span and low fecundity [23]. This conclusion is quite different from the conclusion that the system is in stable equilibrium state. According to the conclusion from stable equilibrium state, the reserve-based strategy is more suitable for the species with long life span and low fecundity [12]. In addition, the life history strategies of target and by-catch species can also regulate the optimal harvesting strategy by adjusting the fluctuation amplitude of the transient dynamic pattern [23]. When the fluctuation amplitude leads to the variations of fisheries yields with time, it is necessary to clarify the mechanism that produces the fluctuation to compare the advantages and disadvantages of different harvesting strategies. Although fisheries yields are often predicted based on population density, the internal mechanism under which life history strategy regulate the transient fluctuation of fisheries yield is different from that of population density. Studies have found that the transient dynamics of fisheries yields regulated by life history strategy is periodic, while the population density is monotonously regulated [16, 23]. In fact, the variation of fisheries yields and population density in the transient dynamic pattern is not completely coupled [24].

Future research should pay more attention to the transient dynamics of fisheries yields with the implementation of marine reserves. Both empirical analyses and theoretical predictions can promote the balance of ecological benefits (such as maintaining species survival) and economic benefits (such as increasing fisheries yields) in fisheries management, and make fishery policy formulation more scientific, accurate and reasonable. Among which, particular attention should be paid to a two species system consist of target strong species and by-catch weak species, which has important implications. The study of the transient dynamic pattern of fisheries yields of the target species under the persistence of the by-catch species can help fishery managers adjust relevant policies at an appropriate ecological time scale to achieve multiple goals (such as maintaining the biodiversity of the ecosystem as well as reducing the conflict between fishermen and fishery managers), which will narrow the difference between theoretical predictions and practical observations, and provide a theoretical foundation for adaptive marine reserve management.

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