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From Phytoplankton to Fish: Exploring the Trophic Levels of Aquatic Ecosystems

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Abstract This study reviews the interactions between different trophic levels in aquatic ecosystems and their impact on ecosystem functioning. Aquatic ecosystems are complex networks of energy and nutrient flows, where interactions between various trophic levels—from primary producers like phytoplankton to apex predators like fish-determine ecosystem stability and productivity. The paper details the critical role of phytoplankton as primary producers in energy transfer, emphasizing the importance of predator-driven trophic cascades in shaping community structures in both freshwater and marine environments. It also explores the influence of factors such as eutrophication, climate change, and predator abundance on these cascades. Case studies further illustrate the trophic relationships between krill and whales in marine ecosystems, the impact of carp populations on zooplankton in freshwater lakes, and the multi-trophic interactions in coral reef ecosystems. This review provides essential theoretical support for the management and conservation of aquatic ecosystems, contributing to a deeper understanding of ecosystem dynamics under global change.

Keywords Trophic levels; Aquatic ecosystems; Energy transfer; Predator-prey interaction; Ecosystem stability

1 Introduction

Aquatic ecosystems are like a large net, where energy and nutrients are transmitted from lower levels to higher levels of organisms. For example, phytoplankton is the bottom producer, and fish are the top predators. The relationship between them is very complex. To better protect these waters, we must understand how they affect each other, especially when the environment is changing so quickly.

In this system, predators can influence the creatures below, and this "top to bottom" effect is called the Predator Cascade. This has a great influence on the species and quantity of flora and fauna in freshwater and oceans (Su et al., 2021; Rakowski and Leibold, 2022). However, sometimes things like water body fat (eutrophication), climate warming, and changing predators' numbers can also change the strength and direction of this impact (Li et al., 2019). If the upper and lower levels of the food chain are out of balance, the entire ecosystem may become unstable and even affect its output capacity (Bhele et al., 2022).

There are about three main types of organisms in the aquatic system: the first layer is phytoplankton, which relies on photosynthesis to produce energy (Stock et al., 2017); the second layer is zooplankton, which eats phytoplankton, and the third layer is fish, which eats zooplankton. A food web is formed between these three layers, which is not fixed, but is constantly changing. Many factors will affect them, such as whether there is enough nutrients in the water, whether there are natural enemies, and the temperature and light of the water, etc. So we need some models to help us see the changes in these relationships and facilitate the formulation of management methods (Mukherjee et al., 2023).

Nutritional grade refers to the "position" of organisms in this food web, that is, who eats whom. Each level plays an important role in the transmission of energy and nutrients. This transmission is sometimes fast and sometimes slow, which is called "nutrition transmission efficiency". This efficiency is related to the size of the organism, predation status, environmental changes, etc. This study is to take a closer look at the role of each layer in the system and how they influence each other. This can help us better understand this ecosystem and provide advice on protecting waters and achieving sustainable development.

2 Classification and Characteristics of Aquatic Ecosystems

2.1 Differences between marine and freshwater ecosystems

The water in marine ecosystems contains a lot of salt. They cover most of the surface of the earth, and places like the sea and bay belong to the marine system. There are a lot of species in the ocean, and the food web is also very complex. At the bottom are phytoplankton, which provide energy to large animals such as fish and whales (Stock et al., 2017). The freshwater ecosystem is different. It includes lakes, rivers and wetlands, and there is very little salt in the water. These places are often relatively independent and not connected, so the ecological situation is also very special. Freshwater systems are sensitive to external changes, such as temperature rise, water pollution, etc., which may affect the relationship between animals and plants and the circulation of nutrients (Rakowski and Leibold, 2022).

2.2 Characteristics of lakes, rivers, and wetland ecosystems

Lakes, rivers, and wetlands each have distinct ecological characteristics. Lakes are typically closed systems with stratified layers that influence nutrient distribution and biological activity. Rivers are dynamic, flowing systems that connect different habitats and facilitate nutrient and organism transport. Wetlands, with their water-saturated soils, support high biodiversity and act as natural filters for pollutants (Li et al., 2019; Bhele et al., 2022). These ecosystems are crucial for maintaining ecological balance and providing habitat for various species.

2.3 Nutrient cycling in different aquatic systems

Nutritional circulation is a natural process that is very important in aquatic systems, which mainly includes the movement and changes of nitrogen and phosphorus. In the marine system, the nutrient circulation is mainly driven by ocean currents and seawater upstream. These water flows bring the nutrients of the deep sea to the sea, which is conducive to the growth of phytoplankton. In freshwater systems, nutrient circulation is not only affected by external land inputs, such as nutrients brought in by river water, but also by internal processes, such as the decomposition and deposition of organic matter. However, if the water is too nutritious, it is prone to eutrophication. This can cause a large reproduction of algae (also known as algae blooms), which in severe cases can destroy the ecological balance in the water (Ersoy et al., 2017; Mukherjee et al., 2023).

3 Major Trophic Levels in Aquatic Ecosystems

3.1 Primary producers – the role and function of phytoplankton

Phytoplankton is the basis of aquatic systems. They are the lowest “producers”, relying on photosynthesis to create energy and provide food to other organisms. They can also help absorb carbon dioxide and release oxygen, which is also important for the Earth's carbon cycle. Phytoplankton, such as diatoms and dinoflagellates, are rich in omega-3 fatty acids and are a high-quality food source (Winder et al., 2017; Yan et al., 2023). The nutritional value of phytoplankton is related to their chemical composition, which can change due to excessive water (eutrophication) or increased water temperature. In coastal areas, when the nutrients brought by rivers become more, the phytoplankton will grow more and the quality will improve. This can further support the growth of other animals in the water (Su et al., 2021).

3.2 Secondary consumers – small fish and carnivorous invertebrates

In the water, small fish and meat-eating invertebrates are secondary consumers. They mainly eat zooplankton or creatures smaller than themselves. These animals play a “transfer” role, transmitting energy from the plant layer to higher predators. The number of small fish will affect the species and amount of zooplankton. For example, if there are too many fish, it may eat a lot of zooplankton, which in turn affects the number of phytoplankton and eventually changes the state of the entire ecosystem (Thomas et al., 2022). Omnivorous fish like crucian carp will eat large zooplankton and may also inhibit the growth of aquatic plants. In this way, water quality will change and the original nutritional structure in the lake will be disrupted (Razlutskij et al., 2021).

3.3 Tertiary and higher-level consumers - large fish and apex predators

In the water, the largest fish and animals like whales are the top predators. They belong to the third trophic grade or higher. These animals will control populations by eating the animals below and keep the food web balanced. Generally, the larger the animal, the higher it stands on the food chain, especially in the ocean (Potapov et al., 2019). These large predators can have a "top-down" impact on the animals in the lower layer, and the stability of the ecosystem is in the left and right. But if an alien species enters, such as fish or other animals that do not belong here, this balance may be broken. This may cause some animal populations to skyrocket or decrease, ultimately destroying the entire food chain (Gallardo et al., 2016).

4 Energy Flow and Material Cycling

4.1 The “10% rule” of energy transfer and its impact

In the ecosystem, there is a rule called the “10% rule”. It means: When energy is transferred from one trophic level to the next, only about 10% of the energy can be used, and most of the others are consumed. This process is not very efficient. If the environment changes, such as the temperature rises, the energy transfer efficiency may become worse. Studies have found that in freshwater ecosystems, when the temperature rises by 4 °C, the energy transfer efficiency decreases by 56% (Barneche et al., 2021). This affects the entire food web, especially for animals in the upper layer of the food chain (Barneche et al., 2021; Mooney, 2024).

4.2 Biomass changes between trophic levels

4.2.1 Construction and significance of the biomass pyramid

The biomass pyramid is a graph that shows how the number (or weight) of organisms at different trophic levels are distributed. Generally speaking, the higher the trophic level, the less biomass there is. This structure tells us how energy flows through an ecosystem. Because energy is lost a lot every time it increases, there can be too many creatures in the upper layer (Schramski et al., 2015).

4.2.2 Biomass differences between primary producers and consumers

Primary producers like phytoplankton generally have more than consumers. This is because they absorb sunlight, make organic matter, and are the energy source of the entire system. However, this relationship is not fixed. Some factors, such as excessive nutrition in water (eutrophication), can change the feeding position of invertebrates, thus breaking this balance (Van et al., 2020). In the ocean, if temperatures rise or water becomes acidic, phytoplankton may become more numerous, but the number of higher-level animals will decrease (Ullah et al., 2018).

4.2.3 Biomass and population dynamics of apex predators

Top predators, such as large fish or marine mammals, have their biomass and population changes that are important to the entire ecosystem. These changes are related to energy flow efficiency. Because the energy will be transferred upwards less and less, the top predators can get little energy. In some experiments, different environmental treatments (such as heating or acidification) have different effects on energy flow. At the bottom layer, that is, the phytoplankton layer, the energy changes little. This shows that they are relatively stable to environmental changes. When it reaches the second layer, that is, the zooplankton layer, heating or heating and acidification will increase their energy utilization, perhaps because their metabolism is accelerated. But to the third level, which is the top predator, the impact of different treatments on energy is obvious. For example, under the “OAT processing” conditions, they obtain less energy and are also inefficient. This may be because they do not eat enough food, or they have too little prey, or they may be because they lose too much energy during the transfer process. Together these factors lead to their reduction in numbers and decreased biomass (Figure 1) (Ullah et al., 2018; Mooney, 2024).

4.3 The role of decomposers in aquatic ecosystems

In aquatic ecosystems, decomposition is important. They can break down dead plants and animals into simple nutrients. These nutrients are then used by phytoplankton and other plants to create new energy. In this way, energy and matter can continue to circulate and the entire system can remain active. The efficiency of the decomposed person will also be affected by temperature, nutrients, etc. These factors determine whether they metabolize quickly and affect the speed of circulation throughout the ecosystem (Atkinson et al., 2017).

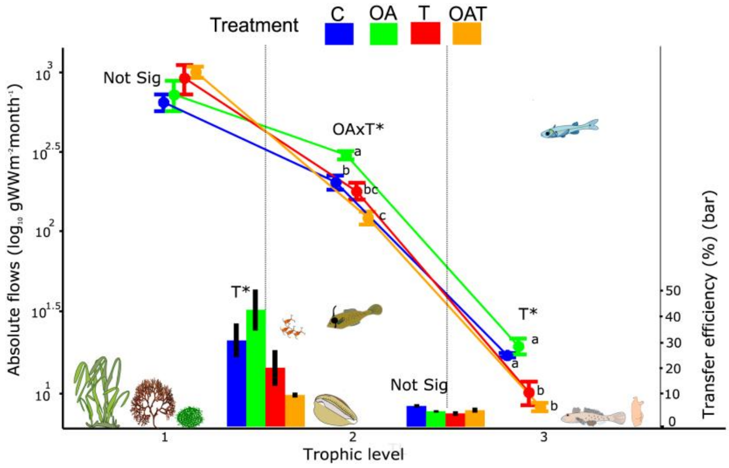

Figure 1 The effects of future climate on absolute flows and transfer efficiency between successive trophic levels of the mesocosm food web (Adopted from Ullah et al., 2018)

5 Food Web Structure in Aquatic Ecosystems

5.1 Examples of simple food chains

Simple food chains in aquatic ecosystems typically involve a linear sequence of organisms, where each is a food source for the next. A classic example is the phytoplankton-zooplankton-fish chain, where phytoplankton serve as primary producers, zooplankton as primary consumers, and fish as secondary consumers (Feitosa et al., 2019). In some ecosystems, such as the Amazonian floodplain lakes, the microbial food web (MFW) plays a significant role, with microbial interactions contributing substantially to the total plankton biomass (Huang, 2024). This highlights the importance of both classical and microbial food chains in different aquatic environments.

5.2 Interactions in complex food webs

Compared to a simple line, a complex food web is like a large interlaced web. There is not only one kind of relationship between “eating and being eaten”, but there are many kinds of organisms intertwined with each other and the trophic levels often overlap. In this complex network, energy still starts from the lowest phytoplankton. They turn solar energy into organic matter through photosynthesis and are then eaten by various zooplanktons, such as mesozooplanktons and protozooplanktons. But that's not all. In some systems, there is also a “mixplankton”. They are special, both photosynthesis like plants and prey on other plankton like animals. In this way, they break the traditional layer-by-layer food chain structure, making the flow paths of energy more complex and diverse. Because of the addition of these organisms, the connection between different trophic levels is closer, the energy flows more frequently, and the entire food web becomes more stable and is not easily broken (Figure 2) (Glibert and Mitra, 2022). For example, in Chishui River, research has found that the food species varies greatly between fish, indicating that there are several different energy transmission paths here and the ecological structure is relatively stable (Qin et al., 2021). In the Arctic lagoon, the food that organisms eat will also change according to season and location, which may be organic matter from land, phytoplankton, or plants at the bottom of the water. These changes make the structure of food webs more varied (McMahon et al., 2021). The consumer’s “position” and “eating method” will directly affect the flow direction of these energy and nutrients.

5.3 The concept of keystone and dominant species

In an ecosystem, although some species are not large in number, they have a particularly large role. These are called “key species”. They can affect the structure and balance of the entire food web. In marine systems, we can judge which key species are based on their living location, range of activities and other characteristics (Endrédi et al., 2021). In freshwater systems, small animals like Daphnia are typical examples. They eat algae while being eaten by fish, connecting the upper and lower trophic levels. This creates a “nutritional cascade” effect, that is, their presence affects the dynamics and balance of the entire food web (Rakowski and Leibold, 2022). If these key species disappear from the system, it may cause a chain reaction that will make the water unstable. Therefore, protecting these species is very important to maintaining ecological balance.

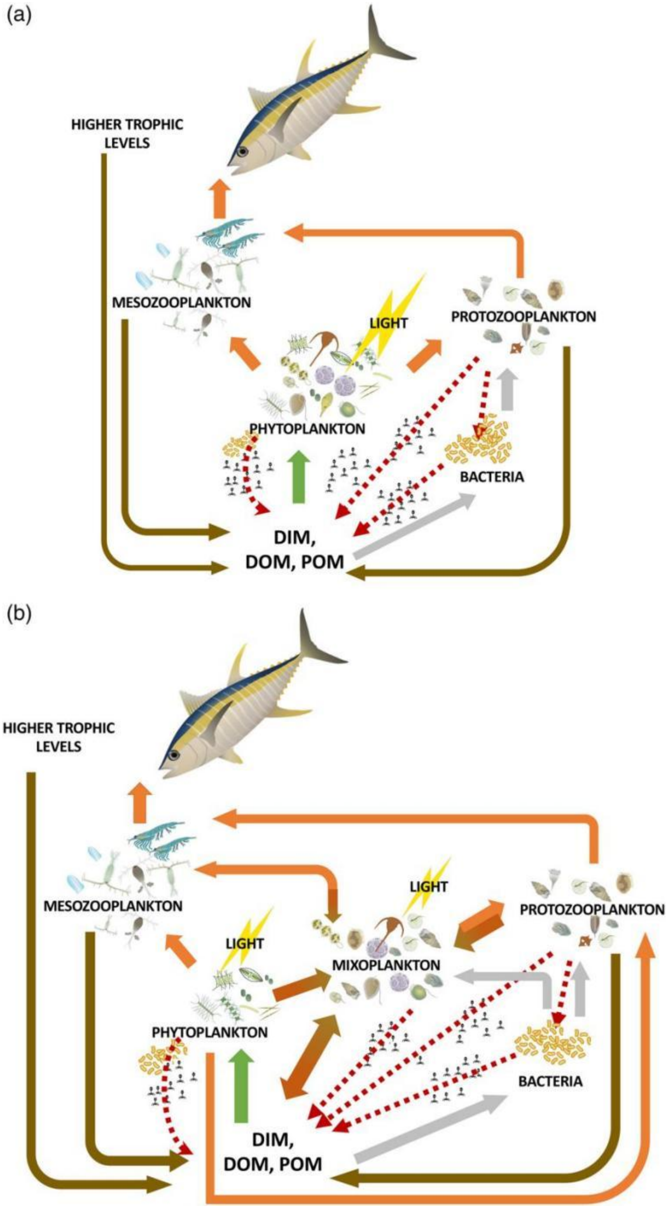

Figure 2 Conceptual understanding of microbial interactions and the oceanic food web (Adopted from Glibert and Mitra, 2022)

6 Case Studies of Aquatic Ecosystems

6.1 Nutritional relationship between krill and whales in marine ecosystems

Krill is a very important small animal in the ocean. They connect to the middle part of the food web and are the main food source for many cetaceans.Whales eat krill, while krill eats phytoplankton. This chain is easily affected by environmental changes. If phytoplankton decreases, krill may go hungry and the number decreases, and whales will be affected by not eating enough food. In addition, issues such as ocean warming and changes in nutrient supply will also affect the stability of the entire food chain (Wu et al., 2021; Glibert and Mitra, 2023). So, understanding these relationships will help us better protect the ecosystems in the ocean.

6.2 Impact of carp populations on zooplankton in freshwater lakes

In freshwater lakes, carp, especially exotic species like big-headed carp, have a great impact on the ecosystem. These fish filter the zooplankton in the water in large quantities and eat them as food. Once the zooplankton decreases, the phytoplankton that they originally ate will increase in a large number. This will cause the water to turn green and turbid, which is eutrophication. After the water quality deteriorates, the ecological balance in the lake may be disrupted. Therefore, controlling carp populations, especially invasive species, is an important step in protecting lake ecology (Razlutskij et al., 2021; Hochstrasser and Collins, 2024).

6.3 Multi-trophic interactions in coral reef ecosystems

There are many kinds of organisms living in coral reef ecosystems, and the nutritional relationship is also very complex. From the bottom phytoplankton to the grass-eating fish to the top vegetarian predators, everyone depends on each other. If the environment changes, such as too much nutrients in the water or too much temperature fluctuation, these relationships are easily broken. Community structure may change, and the entire ecosystem may become unstable (Lomartire et al., 2021).

Here, zooplankton plays a very critical role. They eat phytoplankton and are eaten by more advanced animals, such as coral fish and some filter feeders. The fatty acids and sterols in the body of zooplankton are very important to their own growth and also affect the nutritional status of the upper animals. These nutrients are also different, they will vary depending on the type of zooplankton, what they eat and living environment. For example, some zooplankton eat specific types of food, so their nutrition will be different in their bodies. When coral reefs are under external pressure, such as rising water temperatures or excessive nutrients in the water, the nutrient structure of zooplankton also changes. This change may affect the operation and balance of the entire food web (Figure 3) (Thomas et al., 2022).

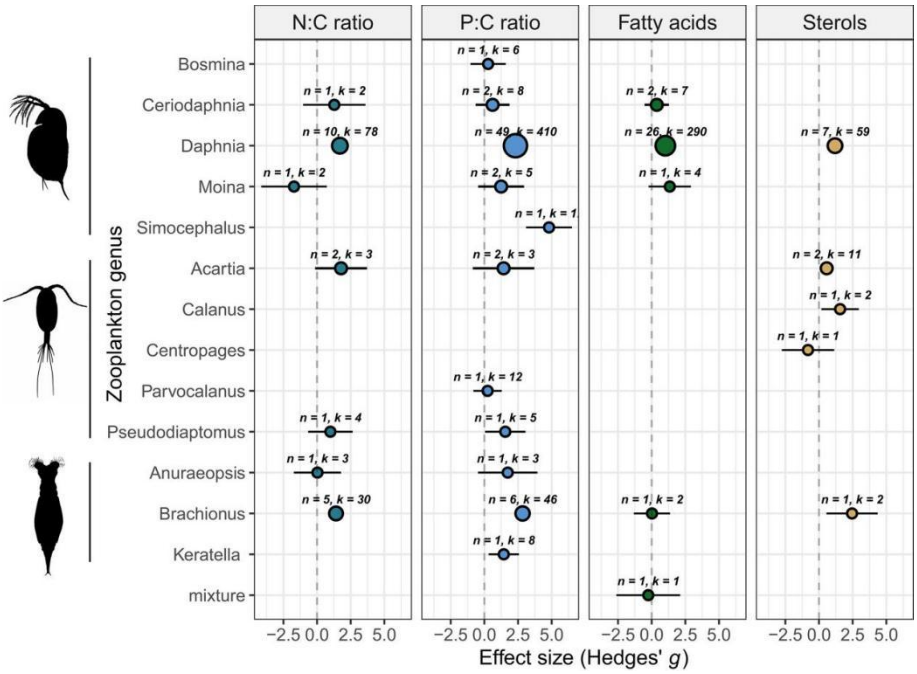

Figure 3 Effects of nutrient manipulation differ based on zooplankton genus and broad nutrient type (Adopted from Thomas et al., 2022)

7 Challenges Facing Aquatic Ecosystems

7.1 Impact of overfishing on trophic balance

Catching too many fish in the water, especially catching the top predators, will break the original nutritional balance of the ecosystem. If these predators are gone, the number of prey they originally controlled will increase rapidly. In this way, some species may be too many, while others will become less, causing chaos in the entire food web. Such changes may make ecosystems unstable and may also reduce biodiversity (Mao et al., 2020). Moreover, the disappearance of top predators may also cause the number of phytoplankton and zooplankton to be out of control and cannot maintain the “top to bottom” regulation. The result may be that algae grow wildly, and algae blooms appear, which makes the water quality worse (Su et al., 2021).

7.2 Water pollution and eutrophication issues

Water pollution is a big problem, especially when nutrients flow into water from farmland or cities, which can cause eutrophication. When there is too much nitrogen and phosphorus in the water, algae and cyanobacteria will reproduce in large quantities. They grow too fast and consume oxygen in the water, which eventually leads to the inability of fish and other organisms in the water, forming the so-called "dead zone" (Briland et al., 2020; Zhang et al., 2024). Too much harmful algae can also damage the original food web. For example, they will prevent fish from finding enough or suitable food, affect their nutritional intake, and also change the relationship between different organisms.

7.3 Disruption of aquatic food webs by climate change

Climate change is also a major problem for aquatic ecosystems. Rising temperatures, changing rainfall distribution, and even increasing extreme weather will affect the lives of organisms in the water. These changes may reduce some species and others increase, causing food webs to become less balanced. For example, rising water temperatures will make phytoplankton grow faster, thereby amplifying the original "nutritional cascade effect" and may also make the eutrophication problem worse (Bouraï et al., 2020). Climate change may also make pollution worse and may also make alien species more prone to invasion. Once these pressures are added together, ecosystems are more prone to losing stability (Gallardo et al., 2016; González-Olalla et al., 2023).

8 Conservation and Management Strategies

8.1 Ecosystem restoration measures

To keep the aquatic ecosystems in balance, we need to take some restoration measures. This is especially important today when global environmental changes are becoming increasingly obvious. Most recovery efforts start by reducing nutrient pollution in the water. Because too much nitrogen and phosphorus in the water will cause eutrophication and disrupt the original nutritional relationship. Some research has specifically analyzed some ecological restoration projects in China and found that long-term monitoring is very important. This can help us judge whether animals, plants and environments return to normal (Fu et al., 2022). However, the study also found a problem: Although water quality (such as nitrogen and phosphorus) improves quite quickly, biodiversity (such as fish and aquatic plants) recovers slowly. Another point is very important, different methods should be used in different places. Measures such as intercepting sewage and building artificial wetlands will have more obvious results if the location is selected well, especially in river systems (Wang, 2024).

8.2 Policies for sustainable fisheries development

In order to prevent fish from being caught and ensure that fishermen can get a harvest, we must implement sustainable fishery management. It's not just about limiting the number of fishing. We also need to understand the relationships of the entire food web, such as the effects of phytoplankton and zooplankton on fish populations (Stock et al., 2017; Lomartire et al., 2021). In some places, such as the Celtic Sea and the Bay of Biscay, scientists use nutritional models to simulate ecosystems. They found that focusing on only one species may ignore the chain reaction of the entire ecosystem. For example, overfishing of large fish can affect the number and relationship of lower organisms (Moullec et al., 2017). Therefore, relevant policies should find a balance between "protecting the ecology" and "ensuring fishery development". We must not only allow people to live fishing, but also not let the ecosystem hurt..

8.3 Public engagement and awareness in ecosystem protection

It is not enough to rely solely on experts and governments, and the participation and environmental awareness of ordinary people are also important. For example, if you know how important zooplankton is to replenish fish, you will be more willing to protect the water environment. Similarly, letting more people understand that phytoplankton regulates climate and purifies water quality can also help promote better management policies (Tweddle et al., 2018). If the public participates, such as participating in environmental protection activities and supporting ecological policies, the effect will be better. Only by working together can we maintain a good water environment and promote sustainable development (Funge-Smith and Bennett, 2019).

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Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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