Trophic dynamics and energy flow in freshwater wetland ecosystems

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Abstract

On earth Freshwater wetlands are highly productive ecosystems and also provide complex trophic interactions as well as efficient energy transfer pathways. This study will aim at assessing the trophic processes and energy dynamics within freshwater wetlands ecosystems and more specifically the role of primary producers, consumers and decomposers in ensuring that the ecosystem is productive and stable. This analysis draws on a literature review and trophic modeling and trophic level analysis of the wetland biotic communities; macrophytes, phytoplankton, zooplankton, macroinvertebrates, fish, amphibians, and microbial decomposers. The conceptual trophic models and quantitative estimates of primary productivity, decomposition rates, and transfer efficiency of trophic models were used to study the energy transfer pathways. Other drivers of the environment like hydrology, nutrient supply, and light intensity were also analyzed to have insight into how it affect energy allocation in the ecosystem. It is established by the analysis that Primary producers contribute 60–65% of gross primary production (GPP), forming the base of the wetland food web. Grazing pathways produce about 60–90% of the energy flow whereas the detritus-based pathways produce about 10–40% of the energy flow underlining the preponderance of organic matter decomposition in the wetlands. The degradation rates of litter averaged at 3.0-3.5 g m^{-2} day^{-1}, indicating high rate of recycling

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of nutrients and high activity of microorganisms. Nevertheless, there was an efficiency of 8-12% trophic transfer across trophic levels with some deviation of the classical ecological efficiency rule with the complexity of structure of wetlands and the composition of lignocellulosic wetlands. Nutrient pollution, hydrological changes and the presence of invasive species in the ecosystem were also cited as anthropogenic stressors that were able to decrease the efficiency of energy transfer and destabilize trophic cascades. The general implications of the study are that balanced relationships between grazing and detrital processes are required to sustain the productivity of wetlands and ecological resilience, so there is a need to have sustainable management and conservation strategies of the wetlands.

Keywords: Freshwater wetlands, Trophic dynamics, Energy flow, Food webs, Primary productivity, Detritus pathways, Nutrient cycling

Introduction

Some of the most productive and ecologically important ecosystems on the planet are the freshwater wetlands which can be described as marshes, swamps, bogs and floodplains. Although wetlands cover a relatively small area in the world land, offer vital ecosystems services including water purification, nutrient retention, flood control, carbon sequestration, and homes to different biological communities. Such ecosystems sustain complicated communities of macrophytes, phytoplankton, invertebrates, fish, amphibians, birds, and microorganisms, which produce highly linked trophic webs (Yang and Chen, 2013). The key to the understanding of the working of the ecosystem and resiliency of the ecosystem is the knowledge of trophic dynamics and energy transfer in wetland ecosystems. The primary producers, i.e. aquatic macrophytes, algae, and phytoplankton, are the sources of energy that are mostly introduced into wetlands and convert solar radiation into organic biomass through their photosynthetic process (Belicka *et al.,* 2012). This energy is later transferred by various trophic levels as grazing and detrital information over supporting herbivores, carnivores and apex predators. The wetlands also possess a strong detritus-based food web, unlike most of the aquatic ecosystems which are dominated by direct grazing pathway due to the high levels of organic matter accretion and the low levels of decomposition in the wet logged environment (Fernandez *et al.,* 2025). Hydrological variability, nutrient availability, penetration, and heterogeneity of habitats are very important factors that determine the trophic interaction and energy flow pattern (Ma *et al.,* 2023; Khan *et al.,* 2024). The seasonal flooding and rising and falling of water govern the nutrition, deposition of sediments and the connection of habitats and therefore determines the structure of communities and the gain of the ecosystem. In addition to the anthropogenic stressors, which include nutrient contamination, hydrological change, intrusion, and climate change, have a colossal potential to destabilize the trophic relations as well as reduce the stability of the ecosystems (Sánchez-Hernández, 2023; Wang, 2025).

Key Contribution of the Paper

It is a study which provides a joint investigation of the trophic related dynamics through tracking the complex energy cycle of the primary producers through the various levels of consumers to the top predators of the wetland food webs.

It explains that wetlands have outstanding geo-ecological importance of being high-productivity biological hot spots that are the most important mechanisms of nutrient recycling and carbon storage over long term.

The article evaluates the effects of the hydrological regimes, availability of nutrients, and the constitution of the habitat on the functionality of the ecosystem and identifies the anthropogenic threats and proposes active management strategies to ensure the ecological stability.

The rest of the paper is structured in the following way: Section I provides the ecological significance of freshwater wetlands and the notion of trophic dynamics. In section II, it is explained about primary production and basal energy sources. The various trophic levels among consumers and the flow of energy are described in section III. Section IV gives a description of decomposition and detrital processes in wetlands. In Section V, there is nutrient cycling and biogeochemical processes. The section VI looks at environmental and anthropogenic factors, and the section VII looks at the management and conservation plans. Lastly, the conclusion of the study is presented in the section of VIII.

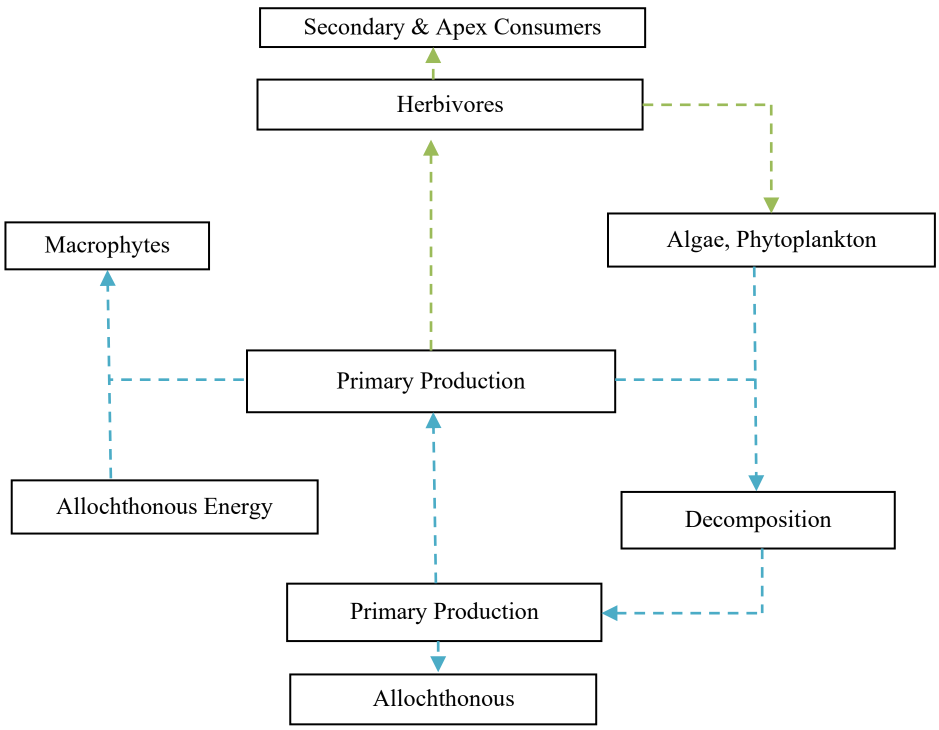

Figure 1: Trophic dynamics and energy flow in a wetland ecosystem.

Figure 1 illustrates that the flowchart depicts essential pathways of energy flow and trophic relationships of freshwater wetland ecosystems from the starting basal energy sources to the top trophic levels. At the bottom, both autochthonous energy (from wetland primary producers: macrophytes, algae, and phytoplankton) and allochthonous energy (from outside the wetland, e.g., leaf litter, runoff) fuel primary production. In the wetland detrital pathway, fungi and bacteria, supported by detritivores decomposing organic matter and liberating system nutrients, dominantly cycle and retain nutrients to support new primary production. The energy of herbivores is transferred to and then to secondary and apex consumers, top- and bottom-controlled by larger fish, birds, amphibians, and reptile predators, respectively, which exert top-down control of their prey.

Primary Production and Basal Energy Sources

Primary production is the most basic source of energy in freshwater wetland ecosystem, and the foundation of all the interactive value chains. The main producers are aquatic macrophytes, phytoplankton, and benthic algae, which play varied roles in the productivity of the ecosystem and the energy flow mechanisms.

Aquatic macrophytes like emergent, floating and submerged plants are known to dominate most wetland systems by stabilizing the sediments, offering complexity to the habitat and creating significant biomass. It is also their structural tissues that help in the detrital organic matter after senescence. Phytoplankton and periphytic algae, on the contrary, have a high rate of growth and are easy targets of herbivorous zooplankton and invertebrates where it constitute the base of grazing-based food webs (Atkinson *et al.,* 2017; Mustapha, 2017).

Environmental factors such as availability of light, depth of water, turbidity and nutrient concentration are very influential of the productivity of these primary producers. Nitrogen (N) and phosphorus (P) are especially relevant limiting nutrients in freshwater systems and many times their presence is the defining factor of primary production. The hydrological conditions also control the nutrient transportation, resuspension of sediment and the build-up of organic matters, therefore, altering the patterns of energy flows.

Wetland system derives energy through both autochthonous (generated within the system) and allochthonous (brought into the system through leaf litter, run-off, etc.) (Yuan *et al.,* 2024). Although the production in the autochthonous part is easily assimilated by herbivores, the autochthonous production will provide a valuable addition to the detrital pools and contribute to the process of decomposition of microbes. The energy pathway of most wetlands with plant litter and organic debris leads to a detritus-based energy cycle supporting high populations of microorganisms and benthic invertebrates. This two-energy system increases the complexity of trophic processes and leads to carbon storage in the sediments of the wetlands in the long run.

Consumers and Trophic Levels

Herbivores

Herbivores play an important intermediate role in freshwater wetland food webs in that help to transport energy to the higher trophic levels through the primary producers (Gavrilaș *et al.,* 2025).

The important groups of herbivorous organisms are zooplankton, grazing snails, and insect larvae herbivores.

As primary consumers, the zooplankton filter phytoplankton and suspended organic material through the water column and therefore primary production becomes biomass that can be fed upon by fish and other predators. Snail grazing and benthic invertebrate grazing of periphyton, biofilms and algal growth on submerged surfaces controls the abundance of algae and is a source of nutrient recycling. The insect larvae are Herbivorous insects such as mayflies and caddisflies which feed on plant tissues and algae as well as on detrital matter interconnecting grazing and detrital food chains within wetland food webs. By having varied feeding behaviors like; filtering, scraping, shredding, and browsing, herbivores enhance trophic connectivity and the transfer of energy within the ecosystem (Wu *et al.,* 2021).

- *The Microbial Loop: An Intermediate between Trophic Gaps*

Another aspect of wetland trophic dynamics that is critical and can be neglected frequently is the Microbial Loop. Although the grazing food chain removes the energy of living plants to the herbivores, the most energy is stored in Dissolved Organic Matter (DOM) and particulate detritus. The main cause of the translocation is bacteria and fungi, which feed on this DOM and transform it into microbial biomass. This is done through incorporation of carbon that would otherwise be wasted to the system into the food web. Then protists and rotifers eat these microorganisms which are further consumed by bigger zooplankton and micro-invertebrates. In the absence of this kind of microbial mediation, the energy contained in the enormous detrital pools of the wetland would be inaccessible to the primary carnivores that will be discussed in the next section. This cycle guarantees the high primary productivity in Section II is recycled thus ensuring the high biological density of the ecosystem.

Primary Carnivores

Small fish, predator (invertebrate) fishes, and amphibian larvae are all vital components of primary carnivores in freshwater wetland food webs, and control the populations of herbivorous species and ecological stability. Invertebrate predators, including the dragonfly larvae, water beetles, and backswimmers, are effective predators that regulate the zooplankton, insect larvae, and small detritivores, thus structuring the community at lower trophic levels (Peel *et al.,* 2019). Small fish- minnows, killifish, and juvenile perch- are intermediate trophic levels and are predators of invertebrates though also preyed upon by predators of a larger size and, therefore, contribute to the vertical movement of energy. Amphibian larvae, particularly carnivorous tadpoles and salamander larvae, are also known to be predators of insect larvae, and also other small aquatic organisms, and are also known to play a role in nutrient cycling (Baker *et al.,* 2013). All these communities combine to form dynamic and interacting trophic relationships which dictate the species composition, energy movement and the general degree of wetland ecosystem functioning owing to complex interactions, such as predation pressure, rivalry, and habitat-imposed feeding behaviors.

The first level of energy concentration by herbivorous secondary producers is taken up by primary carnivores in a wetland ecosystem, e.g., predatory aquatic insects and small fish. In order to measure the energy transfer between these levels, used the Trophic Transfer Efficiency model (TTE):

$$L_n = \frac{P_n}{P_{n-1}} \times 100 \qquad (1)$$

In equation (1) where, L_n : The efficiency of energy transfer to the current trophic level.

P_n: The net production at the current trophic level.

P_{n-1} : The net production at the preceding (lower) trophic level.

Although in open-water pelagic systems tending to take the formal 10% Rule, freshwater wetland systems frequently have lower efficiencies, usually between 2 and 5%. The main reason why the biochemical composition of the basal resource attenuates this is because of the biochemical nature of the resource. High lignin and cellulose levels of the emergent macrophytes dominate wetland primary production. Such complicated polymers are not subject to direct herbivory and demand much metabolic energy to be conditioned by the microbes before the energy can pass up the detrital pathway to higher trophic levels. This results in a huge loss of energy to metabolic heat during decomposition as opposed to storing the energy in consumer biomass.

Secondary & Apex Consumers

With respect to larger fish, mature amphibians, birds, reptiles, and numerous lesser vertebrates, are secondary and primary regional consumers, maintaining important, top-down regulatory control pertaining to the composition and stability of the food webs within freshwater marshes. These top consumers control the population of smaller fish and amphibian larvae and detritivores, macroinvertebrates, and herbivores, thus keeping the trophic relationships in balance and avoiding overgrazing and detrital accumulation. Energy redistribution is facilitated by mobile birds, especially herons, egrets, and ducks, and their migratory and resting habits often interlink wetland food webs with the surrounding ecosystems. Apex predator reptiles, in particular the turtles and crocodilians, and pike and catfish as predator fish add to both the community composition and structure of prey and also stabilize trophic pathways by having a long predatory lifespan. All these apex consumers together regulate trophic cascades and make the ecosystem more resilient by supporting biodiversity and ecosystem functional integrity of the wetlands.

Decomposition and Detrital Pathways

The processes of decomposition play a vital role in the circulation of energy in freshwater emergent wetlands, as vascular vegetation litter abounds in large amounts due to the extensive primary productivity. Macrophyte senescent leaves, stems, and other tissues accumulate over time in the wetland sediments as an extensive pool of detritus which is the major microbial activity substrate. In contrast to other water bodies where food chain is mainly composed of grazing food, wetland food chains tend to have detritus food chain due to the accumulation of organic matter which outpaces the herbivore consumption rate. This leads to detritus becoming the significant source of energy in the ecosystem which sustains a complex web of microbial decomposers, and detritivores organisms. Such detrital food webs are critical in the control of nutrient availability, energy flow and storage of carbon long term in the wetland environments.

The process of breaking down accumulated organic matter is started by microbial decomposers especially bacteria and fungi through enzyme degradation of complex substances like cellulose, hemicellulose and lignin that are found in plant tissues. In the same process, microorganisms break down organic nutrients into inorganic nutrients in a process known as mineralization and hence making the essential elements like nitrogen and phosphorus to be released back to the ecosystem. Not only does this microbial activity maintain primary productivity but the nutrient retention of the wetland system is also increased. Besides microbial processes, soil invertebrates and detritivores such as annelid worms, insect larvae, amphipods and other benthic macroinvertebrates are also important contributors of plant litter fragmentation into smaller particles. It is this mechanical degradation which maximizes the surface area to which microbes can colonize and hastens rates of decomposition thus enhancing the flow of organic matter and nutrients to higher trophic levels.

The prevalence of detritus-based pathways in wetland can be greatly explained by the high input of organic matter as well as the nature of hydrology that is saturated soil and low oxygen supply. When anoxic or hypoxic, the breakdown of plant matter is slowed down and this enables organic matter to accumulate and support long-term detrital food webs. The microbial and invertebrate-mediated processes are interconnected and increase nutrient recycling efficiency and favor high levels of microbial respiration in the sediments of wetlands. As such, the wetlands harbor high numbers of invertebrates and microorganisms which are highly productive in the ecosystem as well as in terms of the trophic stability. Detrital pathways through these processes serve as an important process of sustaining energy in the ecosystem, biodiversity, and biogeochemical cycling in freshwater wetlands.

Table 1 demonstrates that the presence of detritus and decomposition is among the characteristics of freshwater wetland energy budgets. The detrital pathway supplies a total of 10–40% of the total energy flow, required to stabilize the trophic structure compared to the 60-90% of the same which is supplied by grazing channels. The observed decomposition rates of vascular plant litter (3.2 g/m^2/ day) provide a stable supply of the organic material to the system, which leads to the elevated metabolism of microbes. These rates of mineralization of nitrogen and phosphorus ensure that the released nutrients are recreated into the system at a constant rate to sustain the primary production, which underpins the potential of wetland in nutrient storage and conversion of biomass.

Table 1: Decomposition rates and detrital pathway contributions in freshwater wetlands.

S. No	Ecological Component / Process	Description	Representative Numerical Value	Unit
1	Annual Detritus Input	Accumulation of plant litter forms a detrital base	500–4,000	g/m²/yr
2	Microbial Decomposition Rate (Bacteria + Fungi)	Breakdown of organic matter under saturated conditions	3.2	g detritus decomposed/g /g biomass/day
3	Relative Energy Flow	Contribution of Detrital vs. Grazing	60–90:10–40	%
4	Nitrogen Mineralization Rate	Release of inorganic N through microbial activity	8–15	mg N/m²/day
5	Phosphorus Mineralization Rate	Release of bioavailable P from organic matter	1.0–2.5	mg P/m²/day
6	Detritivore Density	Invertebrates contributing to fragmentation & nutrient transfer	2,500–6,000	individuals/m²

Nutrient Cycling and Biogeochemical Processes

Transformations of nitrogen, phosphorus, and carbon drive productivity and energy flow and govern nutrient cycling in the freshwater wetlands. Nitrogen enters wetlands from the atmosphere, surface runoff, and biological nitrogen fixation, supporting plant uptake and microbial metabolism through nitrification/ denitrification. Phosphorus bound to sediment is released via primary induction through reducing conditions, available to primary producers. Wetlands also have a significant role in carbon dynamics with enormous quantities of carbon sequestered in the long term due to the slow decay of the plant production in the form of organic matter. These processes are mediated by hydrology in which the availability of oxygen, redox potential, sediment deposition, and nutrient mobility in the system are dependent on the varying water levels. The rates of mineralization and immobilization of nutrients also depend on the texture and content of moisture in soil, the presence of organic matter, and the activity of microbes. It permitted to store large amounts of carbon or peat and sediment in wetlands and store carbon as greenhouse gases; and thus, are able to regulate their climate and ecosystem processes.

Environmental and Anthropogenic Influences

One of the hydrological changes that characteristically defines the trophic interactions in wetland habitats is seasonal flooding and water level variation that influence the distribution of nutrients, connectivity, and ground changes of nutrients to the aquatic organisms. However, human action like dams and water diversion project is likely to disrupt the natural flow regime leading to habitat fragmentation and reduced transfer efficiencies. Pollution and eutrophication are also additional threats to the stability of wetlands because agricultural runoff, which is full of nitrogen and phosphorus, industrial pollutants, elicit algal blooms, oxygen losses, and drastic changes in trophic structure that destabilize food-web interactions (Giraldo *et al.,* 2024).

Invasive species have a combination of these effects: by changing native trophic interactions, invasive plants, in some cases, can be more competitive than native macrophytes, which alters the base of energy, and in many examples, introduced fish species interfere with predator-prey interactions. Climate change exacerbates these forces by changing patterns of productivity, reorganizing species, and changing food-web interactions with rising temperatures, shifting regimes of precipitation, and an increase in extreme event occurrences. All of these combined environmental and anthropogenic processes promote radical ecological changes that question the sustainability and climatic viability of freshwater wetland ecosystems.

Moreover, the anthropogenic changes in water flow that include building of dams and water-diversion systems interfere with the seasonal flooding processes that are critical in the nutrient transportation and primary productivity. The physical barriers cause habitat fragmentation and a quantifiable loss in the trophic transfer efficiency. Alongside these, the process of the invasion of the invasive species only serves to destabilize these systems even further; the non-native macrophytes tend to hoard the light and nutrients, and exotic-prey fish species can cause cascading events that rearrange the predator-prey structure of the water body entirely.

Management and Conservation Strategies

Multi-tiered management structure is needed to maintain the ecological resilience of freshwater wetlands to increasing levels of anthropogenic stress. These plans aim at preserving the integrity of the trophic pathways and the energy transfer efficiency:

- **Re-establishment of Natural Hydrology:** Hydroperiod is the major stimulating factor of wetland productivity. The management should be focused on eliminating or adjusting the restrictive structures like levees and dams in order to restore the natural flood pulses. Through the introduction of managed floods, there is the provision of a lateral connectivity, which is necessary in the exchange of nutrients between the river channel and the floodplain, aiding in the autochthonous and allochthonous energy inputs.
- **Riparian Buffers:** The Riparian Buffers should be set up to address the effects of eutrophication and these buffer areas must be vegetated with a minimum width of 30m in the areas surrounding the wetlands. These buffers serve as biological filters which intercept agricultural runoff which is full of nitrogen (N) and phosphorus (P). Buffers inhibit algal blooms which are known to destabilize the grazing food web, resulting in hypoxia.
- **Invasive Species Reduction:** There should be Integrated Pest Management (IPM) measures to manage the non-native macrophytes and predatory fish. Many invasive species usually form monocultures which shade native primary producers and invasive fishes may initiate top-down troic cascades which extinction of zooplankton populations. The attack on these species

reinstatement of the natural basal source of energy and predatory balance within the ecosystem.

- **Carbon Credit Integration and Sequestration:** Since wetlands are known to be important players in the world carbon cycle, preservation of peat-forming marshes is an important climate mitigation measure. International carbon credit markets as a way of incentivizing conservation offer the financial resources that would be required in the long run to monitor the conservation. The preservation of these valuable carbon sinks will keep the detrital form of pathway as a carbon sequestration pathway but not a source of greenhouse gases.

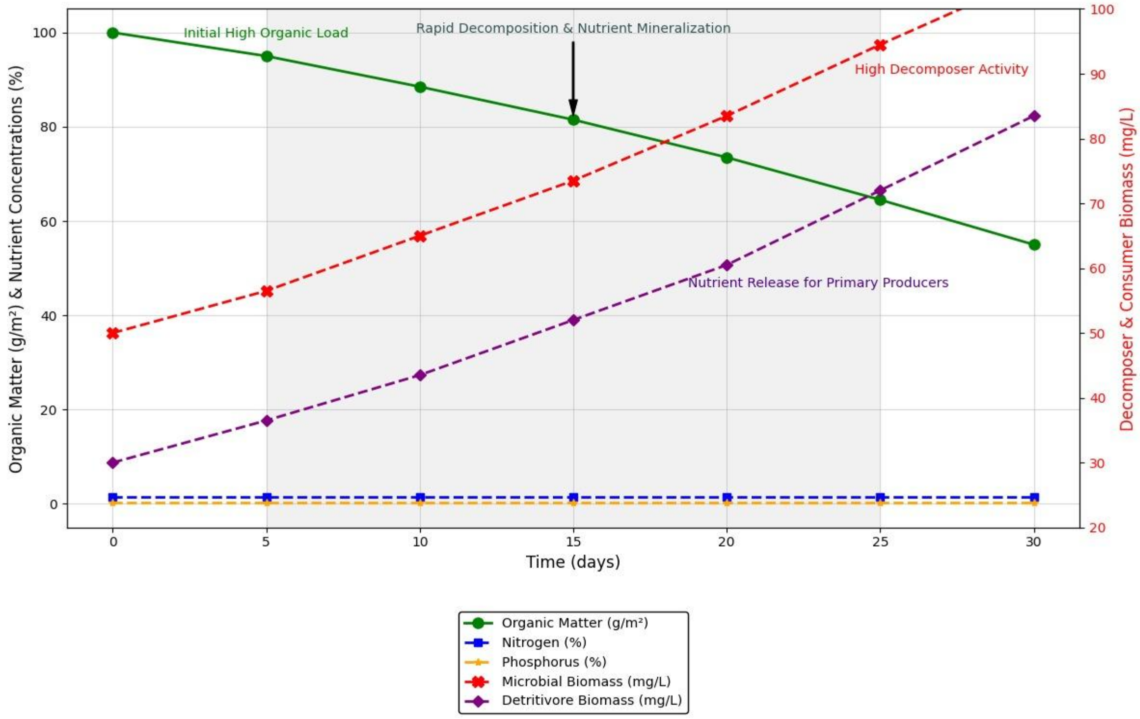

Figure 2: Critical dynamics of decomposition and nutrient cycling in freshwater wetlands.

Figure 2 illustrates that the inverse relationship between the variable Organic Matter (Green Line) and Microbial Biomass (Red Line), and Detritivore Biomass (Purple Line) is predicated upon the depletion of organic matter due to microbial-led decomposition. The dry matter and carbon of the detritus turn into decomposers, and, hence, revitalize the bottom of the food web. The stability of the Nitrogen and Phosphorus (Blue and Orange Lines) concentrations implies that since these nutrients are released by the decay process, are instantly consumed by the generated population of microbes and plants. This process of quick absorption and internalization of nutrients characterizes the ability of wetlands to retain and biochemically filter nutrients, which is a characteristic feature of an ecosystem wellness and productivity.

Conclusion

The freshwater wetlands are the most productive ecosystems and complex networks of trophic interactions, energy transfer processes govern the biodiversity, nutrients cycling, and ecological stability. In the current research, the authors discussed the trophic and energy flow patterns within the freshwater wetland ecosystems in order to learn about the distribution of energy among the primary producers, consumers, and decomposers. As the findings show, primary producers like macrophytes and phytoplankton provide a contribution of about 60 to 65 % of total energy input into the ecosystem which is the foundation of wetland food web. The trophic pathways analysis indicates that approximately 60–90% of the energy transfer exists in grazing food chains, and almost 10–40% of the energy transfer is in the detritus-based pathways, which highlights the significant contribution of decomposed organic matter to the higher trophic levels. The litter decay rate of 3.2 g m^{-1} day^{-1} is known to be high and organic matter decomposing and nutrient cycle is efficient supporting the endless primary productivity of the ecosystem. Moreover, trophic transfer efficiency across two consecutive trophic levels was calculated to be between 8-12%, marginally going against the 10 %ecological efficiency canon, as a result of the complexity of the structure and lignocellulosic composition of wetlands vegetation. Such statistical results demonstrate the important role of microbial decomposers and detrital pathways in the process of keeping the energy circulation and ecosystem productivity. Nevertheless, the growing human impacts, including nutrient pollution, hydrological changes, invasive species, and climate change can impair the trophic balance and cause the decrease in the efficiency of energy transfer. This may result in species composition and ecosystem functioning alterations. Conservation and sustainable management of freshwater wetlands, such as protecting biodiversity, natural hydrological regimes and good pollution management, is therefore necessary in maintenance of stability and productivity of ecosystems as well as sustainability of long-term ecological services supplied by wetland environments.

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