Ecological Functions of Kelp Farming in the Integrated Multi-Trophic Aquaculture System of Sanggou Bay (Postprint)

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Abstract

The growth, photosynthesis, and nitrogen nutrient absorption characteristics of the large economic macroalga kelp (Saccharina japonica) were investigated using field and experimental ecological methods. Experimental results showed that within one growth cycle (approximately 200 d), the wet weight of kelp exhibited a significant power function relationship with cultivation days (W=1.3886 t^1.362, R2=0.9611), and the wet weight of kelp was a power function of length (W=0.0071 L^2.0882, R2=0.9392); the photosynthetic oxygen evolution rate of kelp (O2 mg/h) showed a significant linear correlation with wet weight (g) (R2 ranging from 0.950-0.981), with the slope of the regression line (reflecting the photosynthetic oxygen evolution rate per unit time per unit weight) varying from 0.096-0.195 (average 0.191); the photosynthetic oxygen evolution capacity per unit fresh weight was weaker in the early cultivation stage and stabilized later; the absorption rates of TIN by kelp thallus sections from different parts varied, with the upper middle section (60-110 cm) and base (20-50 cm) showing higher absorption rates than the lower middle section (150-200 cm) and margin; the highest TIN absorption rate (0.6 mol/g WW) occurred during the initial 0.5-1 h after nitrogen starvation, and after 24 h of culture, 64.2%-97.1% of TIN could be removed from the medium (initial concentration 24.2 mol/L, density 4 g/L); the absorption and removal rates of nutrients by thallus sections were greater at 10°C than at 4°C. The absorption rate of NO3-N by kelp thallus sections was greater than that of NH4-N, and the absorption rate of NO3-N stabilized after 24 h. The results demonstrate that kelp possesses high growth rates, photosynthetic oxygen production, and nutrient absorption capacities. During the late cultivation stage, kelp can increase oxygen by 28.8 g/m2 per day (based on a 14 h photoperiod); at harvest, the average carbon and nitrogen contents of kelp were 33.1% and 1.8%, respectively; based on the kelp cultivation yield of 84,500 t in Sanggou Bay, 28,000 t of carbon and 1,538 t of nitrogen

can be removed annually; kelp exhibits high ecological functions in integrated multi-trophic aquaculture systems.

Full Text

Preamble

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Ecological Functions of Kelp (*Saccharina japonica*) in Integrated Multi-Trophic Aquaculture in Sangou Bay, China

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Abstract

This study investigated the growth rate, photosynthetic activity, and nitrogen nutrient uptake characteristics of cultured commercial kelp (*Saccharina japonica*) using both field and experimental ecology methods. Throughout the entire growth cycle, the wet weight of kelp showed a clear power function relationship with culture days, and wet weight was also a power function of length ($W = 0.0071L^{2.0882}, R^2 = 0.9392$). There was a significant positive linear correlation between photosynthetic oxygen production rate (mg O /h) and wet weight (g) ($R^2 = 0.950$–0.981), with the slope (representing photosynthetic oxygen production rate per unit time and unit fresh weight) ranging from 0.096 to 0.195 (average 0.191). The photosynthetic oxygen production capacity per unit fresh weight was weaker in the early growth stage but gradually increased and stabilized after March. Different parts of the kelp blade showed varying absorption rates for total inorganic nitrogen (TIN). The upper middle band (60–110 cm) and basal portion (20–50 cm) had higher uptake rates than the lower middle band (150–200 cm) and marginal parts. The highest TIN uptake rate occurred within 0.5–1 hour after nitrogen starvation, with 64.2%–97.1% of TIN removed from the medium within 24 hours (initial concentration 24.2 mol/L, kelp density 4 g/L). Uptake and removal rates at 10°C were higher than at 4°C. The NO -N uptake rate was greater than NH -N and stabilized after 24 hours. The results demonstrate that kelp has relatively high growth rates, photosynthetic oxygen production, and nutrient uptake capacity, indicating valuable ecological functions in IMTA systems.

Keywords: *Saccharina japonica*; growth; photosynthesis; nitrogen nutrient uptake characteristics; ecological function

Introduction

Macroalgae as biofilter technology originated in the 1970s and has developed rapidly, establishing the foundation for integrated multi-trophic aquaculture (IMTA) systems combining seaweed with fish, shellfish, and multiple species. Large algae can absorb nutrients released by aquaculture animals into the water, converting them into algal biomass while producing oxygen. They can also serve as feed for economically important species such as abalone. IMTA models based on macroalgae have gained increasing attention from scholars worldwide. Cultivating large seaweeds is an effective measure for purifying aquaculture wastewater, controlling eutrophication, improving sea area utilization, and protecting the ecological environment [?, ?, ?, ?, ?].

Sangou Bay is a semi-enclosed bay located at the eastern tip of the Shandong Peninsula with an area of 144 km². Aquaculture methods include raft, coastal pond, and intertidal cultivation [?]. Kelp cultivation has been the main aquaculture activity in Sangou Bay since its inception as one of China' s earliest mariculture bays, with production exceeding 100,000 tons annually. The bay also cultivates abalone and sea cucumber, and has conducted research on cultured organism physiology and ecology, aquaculture environmental impact assessment, and carrying capacity evaluation [?, ?, ?, ?]. The IMTA model has gained worldwide recognition [?], and the water quality environment remains in excellent condition, likely due to large-scale seaweed cultivation.

Saccharina japonica is an important economic seaweed in China, originally cultivated only in northern coastal areas such as Shandong and Liaoning. In recent years, high-temperature tolerant varieties have been developed, gradually expanding cultivation to Jiangsu, Zhejiang, and Fujian coastal areas. In 2015, China' s kelp production reached 1.411 million tons, accounting for 67.6% of total seaweed production. However, few studies have reported on its ecological functions. This study measured the growth and photosynthetic characteristics of cultured kelp in Sangou Bay and conducted laboratory simulations of nutrient uptake by kelp discs, including temporal changes in nutrient absorption, differences among various blade parts, and selectivity for different nitrogen sources (NH -N and NO -N). The seasonal variation in carbon and nitrogen content was also analyzed to understand the ecological regulation role of kelp in mariculture ecosystems and provide theoretical basis for IMTA systems.

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1. Field Experiments

Field experiments were conducted in the kelp cultivation area of Sangou Bay, Rongcheng (122°34 42 E, 37°8 21 N).

1.1 Kelp Growth Measurement

Five to ten individuals were randomly collected from the same cultivation raft every 15-20 days throughout the entire growth cycle for length and wet weight measurement. Kelp growth was measured in situ, with marked individuals measured periodically. The growth initiation time was determined as November 15-20 each year when kelp seedlings were approximately 15-20 cm long. Seedlings are released from nurseries in late October, moved to sea for temporary cultivation, and then transplanted in mid-to-late November. Harvesting is basically completed by mid-to-late June, with a growth cycle of about 200 days. A growth model was established within this timeframe.

1.2 Kelp Photosynthesis Measurement

Photosynthetic oxygen production rate was measured in situ in January, March, May, and July. Large kelp individuals were collected from the experimental sea area each month. High-transmission polyethylene tubes (perimeter 25-50 cm, light transmittance >80%) were used as containers, customized to accommodate whole kelp plants. The tube was tied at one end, filled with site water, and a whole kelp plant was placed inside with the stipe tied to a rope. The other end was then tied securely and suspended in the kelp farming area. Water samples were taken using a siphon method for dissolved oxygen and nutrient analysis. The photosynthetic oxygen production rate was calculated as:

$$PR = \frac{(O_t' - O_t) - (O_c' - O_c) \times V}{W \times t}$$

where PR is the photosynthetic oxygen production rate (mg O /g/h), O_t' and O_t are initial and final dissolved oxygen in treatment groups (mg/L), O_c' and O_c are initial and final dissolved oxygen in control groups (no kelp), V is the volume of the experimental bucket (L), W is the fresh weight of kelp (g), and t is the experimental time (h).

1.3 Kelp Tissue Carbon and Nitrogen Content Measurement

Kelp samples used for length and weight measurement were cleaned with seawater, refrigerated, and transported to the laboratory. They were divided into three groups based on size, dried in a constant temperature oven, and then crushed and sieved. Carbon and nitrogen contents were determined using a German Elemental Analyzer (Vario EL cube).

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2. Laboratory Experiments

2.1 Kelp Collection and Disc Preparation

Healthy, mature kelp was selected and cleaned to remove surface epiphytes. The blade was divided into three sections by length and position: basal part (20–50 cm), upper middle band (60–110 cm), and lower middle band (150–200 cm). Discs were punched using a cork borer (1.0 cm diameter), placed in 400 mL conical flasks, and temporarily cultured in illumination incubators at different temperatures (4°C and 10°C) under 40 mol m ² s ¹ light intensity.

2.2 Effects of Temperature and Blade Position on Inorganic Nitrogen Uptake

Kelp discs from the three positions were placed in 500 mL conical flasks at a density of 2 g/L with 400 mL of medium containing 50 mol/L TIN (nitrate:ammonium ratio   9:1, based on actual Sangou Bay concentrations) and KH PO (f/2 concentration). Other conditions matched the temporary culture conditions. After the experiment, discs were removed, surface water was absorbed with filter paper, and they were dried to constant weight in an oven. Inorganic nitrogen (nitrate, ammonium, and nitrite) concentrations were measured before and after the experiment according to marine monitoring standards (GB 17378.4-2007). The nutrient uptake rate (NUR) was calculated as:

$$NUR = \frac{(C_0 - C_t) \times V}{W \times t}$$

where NUR is the uptake rate (mol/g/h), C_0 and C_t are initial and final concentrations (mol/L), V is the experimental water volume (L), W is the wet weight of kelp (g), and t is the culture time (h).

2.3 Temporal Variation in Nitrogen Uptake by Kelp Discs

Kelp discs were placed in 800 mL triangular flasks at 2 g/L density. The medium contained 50 mol/L TIN (nitrate:ammonium   9:1) and f/2 micronutrient solution. Control flasks without kelp discs were prepared simultaneously. Flasks were sealed with breathable paper and cultured in a 10°C illumination incubator. Samples were taken at 0, 0.5, 1, 2, 5, 10, and 22 hours to measure nutrient concentrations and calculate uptake rates, including cumulative uptake rate (NUR) and stage-specific uptake rate (NUR) between sampling intervals.

2.4 Uptake of Different Nitrogen Sources by Kelp Discs

The middle band of kelp was used to measure uptake rates under different NH -N:NO -N ratios (3:1, 2:1, 1:1, 1:2, 1:3). Total nitrogen concentration was 50 mol/L. The medium was placed in 500 mL flasks (400 mL volume), sealed, and cultured at 10°C for 24 hours. Initial and final concentrations of NH -N and NO -N were measured in each treatment.

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3. Results

3.1 Kelp Growth Characteristics

The growth initiation time was set at November 15–20 each year. Over the 200-day growth cycle, both wet weight and length followed power functions of culture days. Wet weight variation was more stable than length variation. At harvest (150 days), average length was (313 ± 26.6) cm with maximum recorded length of 365 cm, and wet weight was (1586 ± 130) g with maximum of 1838 g.

The relationship between wet weight and length followed a power function ($W = 0.0071L^{2.0882}, R^2 = 0.9392$) [Figure 3: see original paper]. The exponent >1 indicates that wet weight increases faster than length, consistent with kelp growth characteristics. However, length growth slowed or ceased when exceeding 300 cm due to tip shedding.

3.2 Kelp Photosynthesis

Photosynthetic oxygen production showed significant positive correlation with wet weight, described by linear equations $PR = a + bW$. The slope b (photosynthetic rate per unit fresh weight) was lower in early growth stages (0.096 in January) but stabilized after March (0.187–0.195), indicating stable photosynthetic capacity. The average slope across all months was 0.191, with R^2 values of 0.950–0.981.

3.3 Nitrogen Uptake by Different Blade Parts

Natural seawater TIN concentration was 24.2 mol/L. After 24 hours, remaining concentrations varied by position: upper middle band (60–110 cm) < basal part (20–50 cm) < lower middle band (150–200 cm) < marginal part. Uptake rates followed: upper middle band > basal part > lower middle band. Removal efficiencies were 64.2%–94.2% at 4°C and 78.0%–97.3% at 10°C [FIGURE:5, FIGURE:6]. Uptake rates at 10°C were slightly higher than at 4°C across all positions.

3.4 Temporal Variation in Nitrogen Uptake

Kelp discs showed rapid TIN absorption within 0.5–1 hour after nitrogen starvation, with stage-specific uptake rates (NUR) of 2.1 mol/L. Cumulative uptake rates remained high at 1-2 hours but decreased over time. After 10 hours, absorption slowed or stagnated, with slight concentration increases observed. After 22 hours, uptake rates were low [Figure 7: see original paper].

3.5 Uptake of Different Nitrogen Sources

Regardless of ratio, NO -N uptake rates were consistently higher than NH -N. The highest NO -N uptake rate (0.98 mol/g/h) occurred at NH -N:NO -N ratio of 1:2. After 24 hours, NH -N uptake rates decreased significantly as NH -N proportion decreased, while NO -N uptake remained stable at 1.03-1.06 mol/g/h [Figure 8: see original paper].

3.6 Seasonal Variation in Kelp Tissue Carbon and Nitrogen Content

Carbon content in cultured kelp ranged from 31.7%-36.1% (average 33.9%), showing relatively high but stable seasonal variation. Nitrogen content ranged from 1.59%-2.99% (average 2.24%). The C/N ratio varied from 11.6-20.2 (average 15.5) [Figure 9: see original paper].

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4. Discussion

4.1 Kelp Growth

Kelp is a major cultivated macroalgae in China, accounting for about half of total seaweed production. The main cultivation method in northern China uses rafts 4-6 m long with 2.5 m spacing, employing horizontal cultivation at 1.0-1.2 m depth. Based on cultivation area of approximately 7,500 hm^2 and average harvest weight of 1.6 kg/m^2, fresh kelp yield is estimated at 120,000 tons, comparable to actual production in Sangou Bay [11].

Sangou Bay kelp reaches average length of 313 cm at 150 days, with average growth rate of 1.95 cm/day from initial 20 cm seedlings. Length growth slows in later stages or shows negative growth due to tip shedding, while wet weight continues increasing during the thickening period [11]. The growth model established in this study did not use the punch-hole method, and our kelp showed greater wet weight and length than reported by Zhang et al. [11], possibly due to cultivar differences.

4.2 Kelp Photosynthesis and Oxygen Production

Macroalgae produce oxygen through photosynthesis, a function often overlooked due to seawater oxygen supersaturation. However, global coastal hypoxic zones are expanding exponentially, with the East China Sea hypoxic area reaching 10,000 km^2 and summer hypoxia reported in the Bohai Sea [12]. This study shows kelp photosynthetic rate is positively correlated with wet weight. Based on 1.5 kg/m^2 cultivation density and 12:12 hour light:dark cycle, kelp produces approximately 28,800 mg O /m^2/day, significantly higher than terrestrial plants. This exceeds the oxygen production of *Cinnamomum camphora* (11,374 mg C/m^2/day) in northern Zhejiang [13], shrubs like *Lantana camara* and *Duranta erecta* (8,272 mg O /m^2/day) [14], and temperate coniferous forests like *Cryptomeria japonica* [15].

With average cultivation depth of 5 m, kelp increases dissolved oxygen in farming areas where summer DO often remains low (1.9 mg/L) due to biological oxygen consumption [16]. Kelp carbon content averages 33.1%, with carbon fixation rate of 2,185 g C/m^2/year, exceeding that of boreal and temperate old-growth forests (0.4 t C/hm^2/year) [17].

4.3 Nitrogen Uptake by Kelp Discs

Rapid nutrient absorption within 10–60 minutes after nitrogen starvation was first observed in the 1970s as an adaptation to environmental nutrient fluctuations [18]. This phenomenon is widespread in macroalgae. Pedersen [19] reported that *Ulva lactuca* absorbed ammonium exceeding its nitrogen demand by 15-fold when transferred from field to high-concentration indoor conditions. Chapman [20] found *Laminaria longicruris* could store nitrogen up to 150 mol/g in winter, allowing growth supplementation when external nutrients are scarce.

In this study, kelp showed high uptake rates within 0.5–1 hour, likely due to small intracellular nitrogen pools under nitrogen limitation. The initial rapid absorption fills internal nutrient pools, followed by feedback inhibition causing rate stabilization, then concentration-controlled uptake [19]. Different blade parts showed varying uptake rates, with higher rates in the basal and upper middle bands where meristematic tissue is located, consistent with kelp growth characteristics [21].

The NO -N uptake rate exceeded NH -N, consistent with Xu et al. [22], reflecting inherent macroalgal traits. This characteristic makes kelp suitable for Sangou Bay cultivation, as NH -N concentrations increase after kelp harvest [23]. With average nitrogen content of 1.82% and annual production of 120,000 tons fresh weight, kelp removes approximately 1,538 tons of nitrogen annually, demonstrating significant ecological function as a biofilter.

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Note: Figure translations are in progress. See original paper for figures.