Commercial Aquaponics for the Caribbean

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ABSTRACT

Aquaponics is the combined culture of fish and plants in recirculating systems. IntegratinRag fish and plant culture offers several advantages. Dissolved waste nutrients are recovered by the plants, reducing discharge to the environment and extending water use. The concentrated solid waste that is discharged can be used for associated land agriculture. A secondary plant crop, which receives most of its required nutrients at no cost, improves system profit potential. The plants purify the culture water and eliminate the need for separate and expensive biofilters. Savings are also realized by sharing operational and infrastructural costs. In addition, the intensive production of fish and plants reduces land requirements. Aquaponic systems do require a high capital investment, moderate energy inputs and skilled management. Niche markets may be required for profitability. In response to the need for more food fish and plant crop production in small Caribbean islands, an outdoor commercial aquaponic system was developed for the production of tilapia and leaf lettuce. It consists of fish rearing, solids removal and hydroponic components which utilize diffused aeration, solids removal, nitrification and direct nitrogen uptake by plants to maintain water quality. Annual average production during a 2.5-year trial was 3.1 mt of tilapia and 1,248 cases of lettuce on 0.04 ha of land. This system represents an intermediate technology that is ecologically stable and allows sustainable weekly harvests of fish and plants. The system is being modified with the goal of increasing production to 5.0 mt of tilapia and 1,700 cases of lettuce. In light of recent findings indicating that 24°C water temperature assures optimum lettuce production, two methods of regulating water temperature (chillers and evaporative cooling towers) will be investigated. Additional research will be conducted to determine the culture potential of other species such as ornamental fish, vegetables (e.g., tomatoes), culinary herbs, medicinal plants and cut flowers.

KEY WORDS: Aquaponics, tilapia, lettuce

INTRODUCTION

The fisheries sector of the U.S. Caribbean is in a state of decline (Caribbean Fishery Management Council 1985, de Graf and Moore 1987). The fisheries resources of the U.S. Virgin Islands and Puerto Rico supply only 10 to

20% of the local seafood demand, the balance of which must be imported. A similar situation exists on most islands in the Caribbean Region where 16,500 mt of seafood products, worth US$56 million were imported in 1987 (FAO Yearbook of Fishery Statistics 1987). Aquaculture is often proposed as a means of increasing fish supplies in the Caribbean. However, numerous obstacles have prevented the development of mariculture, and aquaculture has been limited to the larger islands where there are adequate quantities of fresh water and large tracts of level land for pond culture. Aquaponics, the combined culture of fish and plants in recirculating systems, is a production method with potential for widespread application throughout the Caribbean, including small islands that are mountainous or have limited freshwater resources.

In aquaponics, fish are reared intensively in tanks which are integrated with a hydroponic subsystem, and water is continuously circulated between these components. Aquaponic production greatly reduces water and land requirements, enabling systems to be established in areas that have been unsuitable for conventional pond aquaculture. Integrating fish and plants allows dissolved nutrients generated by the fish to be recovered by the plants, thereby reducing discharge to the environment and extending water use. The concentrated solid waste that is discharged can be used for associated land agriculture. A secondary plant crop, which receives most of its required nutrients at no cost, improves system profit potential. The plants purify the culture water and eliminate the need for separate and expensive biofilters. Savings are also realized by sharing operational and infrastructural costs.

The University of the Virgin Islands Agricultural Experiment Station (UVI-AES) has instituted a long-term program for the development of commercial aquaponic systems in the Caribbean. This paper will discuss the design, operation, productivity and economics of a commercial-scale aquaponic system, planned modifications to this system and some factors to consider for successful commercialization.

SYSTEM DESIGN

Aquaponic research at UVI-AES began with studies using small replicated experimental systems to learn the priciples of aquaponics and establish design criteria. Based on the results, a commecial-scale aquaponic unit was constructed and evaluated during a production trial of red tilapia and leaf lettuce from January 26, 1995 through June 30, 1997. The unit consisted of four fish rearing tanks (4.4 m^3 each, water volume), two cylindro-conical clarifiers (1.8 m^3 each), four filter tanks (0.7 m^3 each) containing orchard netting, six hydroponic tanks (11.5 m^3 each) and a sump (0.6 m^3) (Figure 1). The hydroponic tanks were 29.6 m long by 1.3 m wide by 0.4 m deep and had a combined surface area of 214 m^2. Total water volume was 91.6 m^3. Makup water was added by a float valve in the sump. A water meter recorded the daily additions. Rainwater was the sole source of water used in the unit.

A 1/5-hp in-line pump was used initially to move water at an average rate of 163 L/min from the sump to the fish rearing tanks (mean retention time, 1.8 h), from which effluent flowed by gravity through the solids-removal and hydroponic subsystems and returned to the sump. The pump was replaced on December 18, 1996 with a 2-hp in-line pump, which moved water at an average rate of 378 L/min from the sump to the rearing tanks (mean retention time, 0.8 hours). Effluent from the filter tanks was divided into three streams, each of which flowed through a set of two hydroponic tanks and returned to the sump.

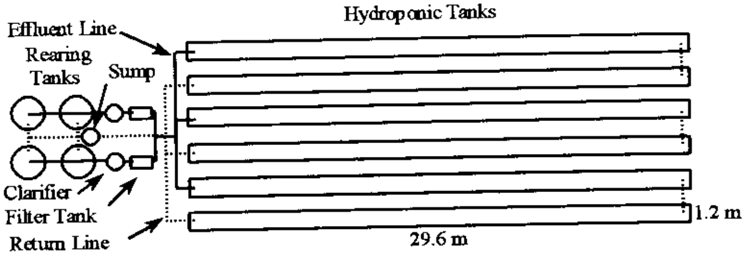

Figure 1. Commercial-scale aquaponic unit used for the production of tilapia and lettuce. Two additional filter tanks were added during the trial.

Each fish rearing and hydroponic tank was aerated by 10 (22.9 cm x 3.8 cm x 3.8 cm) and 24 (7.6 cm x 2.5 cm x 2.5 cm) air diffusers, respectively. A 1/20-hp vertical lift pump was used to supply additional aeration to the rearing tank in the last 12 weeks of the production cycle.

FISH PRODUCTION

Production of red tilapia was staggered so that one fish tank was harvested every six weeks. There were a total of 19 harvests. An initial stocking rate of 227 fish/m^3 was reduced to 182 fish/m^3 after harvest seven. Each batch of fish was fed for 24 weeks with a nutritionally-complete, floating ration (32% protein). The feed was delivered by demand feeders through harvest 12 and thereafter by 12-hour belt feeders, with which an initial feeding rate of 6% of body weight per day was gradually decreased to 1.2% by the time of harvest. The fish were kept slightly hungry to avoid feed wastage. The rearing tanks were covered with a black canopy to eliminate algal growth. Upon harvest, the rearing tank was immediately restocked with fingerlings.

Mixed-sex fingerlings were used in the first four batches of fish. The next 13 batches used male fingerlings that were manually selected. Manual selection of male fingerlings produced variable and unsatisfactory results (mean = 87.2% males). The final two batches used male fingerlings that were produced by sex reversal with 17α-methyltestosterone with excellent results (mean = 99.2% males). The mean weight of fingerlings per batch was 38.9 g (range = 25.9 to 106.1 g). Female red tilapia were only half as large as males at harvest and the mean weight during the first four harvests was 314 g/fish. A reduction in the stocking rate and the use of male populations significantly increased harvest weight to an average of 487 g/fish in the last 11 harvests.

Total harvest weight in the last 11 harvests averaged 81.1 kg/m^3 of rearing tank volume (range = 61.0 to 91.8 kg/m^3). Production was substantially greater than the general production range (30 to 40 kg/m^3) for tilapia in recirculating systems using diffused aeration (Losordo 1997) due to the high aeration rates in relatively small water volumes and the high quality of incoming water. Annual production, based on the last 11 harvests, was 3,096 kg.

The average growth rate during the final 11 harvests was 2.85 g/day (range = 2.55 to 3.29 g/day), which compares favorably with a range of results reported by Losordo (1997).

Survival in the last 11 harvests averaged 91.6% (range = 78.6 to 99.2%). The primary cause of mortality was an unidentified bacterial disease. During disease episodes, fish died at a rate of one or two per day while the majority of the fish in the tank fed vigorously and was not affected. Often fish died in just one of the four rearing tanks, which indicates that the disease was transmitted by direct contact. Mortality generally occurred during the warmer months (June - November) when water temperatures were above 28ºC.

Based on data from the last 11 harvests, the average feed conversion ratio was 1.75 with demand feeders (four harvests) and 1.77 with belt feeders (seven harvests). Demand feeders were discontinued because they were less reliable. Often clumps of feed partially blocked the flow of feed or strong winds triggered the release of too much feed. Belt feeders provided a steady release of feed over 12 hours and any failure, which seldom occurred, was quickly detected. With belt feeders, it was also easier to assess feeding response.

With the initial pump (1/5 hp), the flow rate (163 L/min) and the water exchange rate (0.55 times/h) in the rearing tank appeared to be too low to achieve optimum production characteristics. However, after a new pump (2 hp) was installed, a higher flow rate (378 L/min) and exchange rate (1.25 times/h) did not improve total weight (81.4 kg/m^3 before vs. 80.9 kg/m^3 after), growth rate (2.97 g/day vs. 2.72 g/day), survival (91% vs 92.3%) or feed conversion ratio (1.74 vs. 1.80) appreciably, based on the last 11 harvests.

PLANT PRODUCTION

Five varieties of lettuce were cultured during the trial. They included red leaf (Sierra), green leaf (Nevada), romaine (Parris Island and Jerhico) and crisphead (Montello). In general, three varieties (red and green leaf and romaine) were cultured simultaneously. Production of lettuce was staggered so that one fourth of the lettuce being cultured was harvested every week. Lettuce transplants were produced from seed in a greenhouse in flats containing peat-based growing media. After 3 weeks in the greenhouse, the transplants were transferred to the aquaponic unit for a four-week growout period. The transplants were placed in net pots (5-cm diameter and height) that were inserted into holes in floating polystyrene sheets at a density of either 16 or 20 plants/m^2. The sheets were 2.44 m long by 1.22 m wide by 3.8 cm thick. Each hydroponic tank contained 12 sheets. Every Wednesday 18 sheets of lettuce were harvested at 0600 hours and the marketable plants were packed in cases at a rate of 24-30 heads/cs.

Total annual lettuce production averaged 1,248 cases. Using production data from the last six months, which was higher than average, projected annual production would increase to 1,700 cases. In 112 lettuce harvests, marketable production averaged 27 cases per week and ranged from 13 to 38 cases.

Of the 3,044 cases of lettuce harvested during the trial, there were 1,552 cases of Sierra, 1,030 cases of romaine (Parris Island and Jerhico), 410 cases of Nevada and 71 cases of Montello. The average weekly harvest weight of marketable plants during the last nine months of the experiment was 269 g for Sierra (range = 182 to 340 g), 327 g for Parris Island (181 to 446 g), 314 g for Jerhico (267 to 344 g) and 265 g for Nevada (149 to 360 g). The plants were weighed after the lower leaves were trimmed.

Production was greater in the cooler months (January-April) when water temperature averaged 25.1°C. Production of lettuce, which is a cool season crop, decreased during the warmer periods (April-November) when water temperature averaged 27.5°C and peak daytime canopy temperatures often reached 39°C.

There were no observable nutrient deficiencies during the 2.5-year trial. Direct nutrient excretion by the fish, mineralization of organic waste and supplementation with K, Ca and Fe provided sufficient amounts of the essential nutrients for normal plant growth.

During the April-August period of 1995, production also declined due to root damage caused by zooplankton blooms, comprised mainly of cladocera and ostracods. Plant growth was normal in areas near diffuser-induced currents, which dispelled the zooplankton, and was stunted in quiescent areas where the zooplankton flourished. Most damage was caused by ostracods, which clung to roots as they ate detritus and root hairs. More than 23,000 ostracods were dislodged from the roots of just one medium-sized lettuce plant. With the introduction of ornamental fish (tetras, swordtails, guppies, zebra danios), beginning in June of 1995, the problem gradually dissipated and the plants grew uniformly in size. As the swordtail population increased, they caused some minor root damage and were removed in June, 1996.

The tetras appeared to produce the best results because they controlled zooplankton and did not reproduce or cause damage to plant roots. The zebra danio populations declined, while the guppies reproduced excessively, causing incidental nibbling damage to the plant roots.

Two species of pathogenic root fungi (*Pythium myriotylum* and *P. dissoticum*) caused production to decline noticeably from March through November of 1996. *P. myriotylum* causes root rot while *P. dissoticum* causes general retardation in the maturation rate of the plant. There was evidence that microbes in the system were antagonistic to these plant root pathogens. The *Pythium* infection was worse in four of the hydroponic tanks after removal of organic matter from the tank bottom. In the final 6 months, losses resulting from *Pythium* decreased, possibly due to the gradual accumulation of organic matter on the bottom of the hydroponic tanks. However, *Pythium* was still present as the plants were relatively small at harvest (265 to 327 g) compared to previous unpublished data (>500 g).

Minor losses of lettuce were caused by caterpillar (fall armyworm and corn earworm) and aphid damage. Caterpillars were controlled by twice-weekly sprays with *Bacillus thuringiensis*. During wet periods (September-November), more frequent spraying was sometimes required.

Since the lettuce plants were grown outdoors in an unprotected environment, they were hardened and were not affected by heavy rainfall (less than hurricane strength) or extended periods of wetting. There were no observable leaf diseases, which wetting often promotes. The plants were affected by intense solar radiation and air temperature during the warmer months. Wilting often occurred between 1000 and 1600 hours.

WATER QUALITY

The aeration, solids removal and hydroponic components maintained good water quality. Dissolved oxygen (DO) levels averaged 6.2 mg/L in the rearing tanks (range = 2.4 to 8.6 mg/L), 4.0 mg/L in the effluent from the filter tanks and 6.9 mg/L in the effluent from the hydroponic tanks. Total ammonia-nitrogen (TAN) averaged 1.47 mg/L in the rearing tanks (0.08 to 4.25 mg/L), 1.25 mg/L in the effluent from the filter tanks and 0.61 mg/L (a 51% reduction) in the effluent from the hydroponic tanks. Nitrite-nitrogen averaged 0.52 mg/L in the rearing tanks (0.07 to 1.51 mg/L), 0.68 mg/L in the effluent from the filter tanks and 0.42 mg/L (a 38% reduction) in the effluent from the hydroponic tanks. The hydroponic tanks treated the water through direct ammonia uptake by the lettuce roots, nitrification on the tank surface area, and through sedimentation and filtration (by the roots) of solids. A previous study showed that raft hydroponics, using lettuce, provides adequate and sustainable waste treatment up to a feeding rate of 180 g/m^2 of hydroponic growing area/day, which is three times higher than the average feeding rate (56 g/m^2/day) in this trial (Gloger *et al.*, 1995). Therefore, there was a wide margin of safety in regards to water quality.

The solids removal subsystem initially consisted of two clarifiers and two filter tanks containing orchard netting. The effluent from two rearing tanks flowed through one clarifier and one filter tank. Thirty male tilapia fingerlings were placed in each clarifier to graze settleable solids from the sides of the cone and concentrate them at the base. A drain line was opened twice a day to remove sludge from the clarifier. Fine particulate solids in the effluent from the clarifier adhered to the orchard netting mesh in the filter tank. Once or twice a week the netting was washed with a pressure sprayer and the entire water volume in the filter tank was discharged. All solids were discharged through drain lines into two lined 16-m^3 ponds, which were continuously aerated with diffused air. As one pond was being filled over a 2 to 4-week period, water from the other pond was used to irrigate and fertilize field crops. On July 27, 1995, two additional filter tanks were installed in series with the initial filter tanks.

After installation of a larger pump, the flow rate increased by 132%, which significantly altered solids removal and nutrient levels. There was a decrease in clarifier retention time from 22 to 9.5 minutes. As a consequence, less solids were removed by the clarifier and significantly more solids accumulated in the filter tanks, which increased rates of denitrification and mineralization. Nitrate-nitrogen levels decreased dramatically while concentrations of Mg, PO_4, SO_4, Cu, Zn, B and Mo increased. When the frequency of solids removal from the first filter tank was increased to twice a week, the NO_3-N concentration increased.

The average water temperature was 26.6°C (23.8 to 29.0°C). Total alkalinity and pH averaged 55.0 mg/L as $CaCO_3$ and 7.2 (range = 6.4-7.6), respectively. An average decrease in total alkalinity by 4.6 mg/L on passage through the hydroponic tanks indicated the occurrence of nitrification, an acid-producing process that reduces alkalinity. In response to nitrification, pH and total alkalinity constantly declined. pH was monitored several times weekly, and whenever pH decreased to less than 7.0, base was added. It is important to maintain pH near 7.0 because nitrification efficiency decreases at lower pH values and nutrient solubility decreases at higher pH values.

Bases (generally ranging from 300 to 1,000 g per addition) consisted of potassium hydroxide (KOH), calcium oxide (CaO), or calcium hydroxide [$Ca(OH)_2$]. Calcium oxide was replaced with calcium hydroxide beginning August 22, 1995 because it was too expensive. Potassium and calcium bases were added alternately in equal amounts. Iron chelate (13% Fe) was added to the unit every 3 to 4 weeks at a rate of 1,360 g through July 17, 1995 and thereafter at a rate of 1,832 g.

Total feed application during the trial was 10,440 kg and the daily feed input averaged 12.0 kg. The average feed input was equivalent to 56 g/m^2 of plant growing area/day, very close to the design ratio of 57 g/m^2/day, which was determined to be optimum for lettuce production (Rakocy, 1997). During the trial, 168.48 kg of KOH, 34.48 kg of CaO, 142.9 kg of $Ca(OH)_2$ and 62.668 kg of iron chelate (13% Fe) were added to the system, which was equivalent to the addition of 16.1, 3.3, 13.7 and 6.0 g, respectively, for every kilogram of feed added to the system.

The average Na concentration was 36.0 mg/L (5.6 to 62.6 mg/L) and the average Cl level was 55.3 mg/L (8.5 to 102.2 mg/L). The accumulation of Na is a concern in aquaponic systems because Na levels higher than 50 mg/L in the presence of Cl are toxic to plants (Resh, 1995). Soluble salt (NaCl) levels in fish feed, associated particularly with the fish meal fraction, are relatively high. Special feed formulations with reduced salt levels are needed for aquaponics. Until low-salt diets are developed, partial dilutions may be necessary to reduce Na levels. Rainwater was used in this trial because the groundwater of semiarid islands such as St. Croix contains too much salt for aquaponics.

Accumulation of nitrates is a concern with aquaponic systems. The discharge from one experimental system contained 180 mg/L of NO_3-N (Rakocy, 1994). On the final sampling day the NO_3-N concentration was 11.9 mg/L and the unit contained only 1.8 kg of total inorganic nitrogen (approximately 0.6 kg of nitrogen was added to the system daily in the feed). The main difference between the experimental system and the commercial unit was the presence of filter tanks in the commercial unit. Large quantities of organic matter accumulated on the orchard netting between cleanings. Denitrification most likely occurred in anaerobic pockets that developed in the sludge. The entire water column moved through the accumulated sludge, which provided good contact between nitrate ions and the denitrifying bacteria. In other areas of the system where organic matter accumulates, such as the clarifier and hydroponic tanks, it forms a layer on the tank bottom, has much less contact with the overlying water and mediates less denitrification, as in the experimental unit. Now it appears that through manipulation of organic matter in the filter tanks (i.e., adjusting the cleaning frequency) nitrate levels can be controlled and excessive buildup can be avoided, thereby reducing the environmental impact of water discharged from the system.

WATER CONSUMPTION

Total water consumption during the trial was 1,444 m^3. Average daily makeup water was 1.4 m^3 or 1.5% of the system volume. In the last 6 months of the trial, water loss through sludge removal from the clarifiers averaged 36 L/day. When all the filter tanks were cleaned once per week, average water loss from the filter tanks was 301 L/day. Therefore, sludge removal accounted for 24% of the water loss from the system. Splashing, evaporation and transpiration accounted for the remaining water loss. In the last month, the filter tanks adjacent to the clarifiers were cleaned twice per week, which brought average water loss from the filter tanks to 468 L/day. Water use was 0.25 m^3/kg of total tilapia production and 0.29 m^3/kg of net fish production. This aquaponic unit ranks among the top systems for water use efficiency (Cole *et al.*, 1997; Losordo, 1997). In addition, each cubic meter of water produced 2.1 cases of lettuce or approximately 50 heads.

ECONOMICS

An economic analysis was performed for an operation of 6, 12 and 24 production units using data from this trial, actual sales prices and an estimate of overall costs (Bailey et al., 1997). Capital and infrastructure costs were $285,134, $540,268, $1,030,536 for 6, 12 and 24 production units, respectively. Returns to risk were $30,761, $131,519 and $278,038 and internal rates of return were 11.1%, 17.9% and 21.7%, respectively. The results showed that aquaponics, though capital intensive, would be profitable in the U.S. Virgin Islands and that larger operations would be more profitable than smaller operations due to economies of scale.

DISCUSSION

Based on experience with the system, a number of modifications are being made to increase fish and lettuce production and ease management. The rearing tank density (182 fish/m^3) appeared to be too high for maximum growth. Total daily feed to each rearing tank generally peaked near 5 kg midway through the trial. As the fish continued to grow they did not consume more feed. Therefore, a higher percentage of the daily ration went to maintenance, which increased the feed conversion ratio. Larger fish rearing tanks (7.8 m^3) are being installed to decrease maximum density to 154 fish/m^3 and increase fish production (target: 577 kg/harvest; 5 mt/year).

The belt feeders will be replaced with manual feeding twice per day to gauge feeding response better, to reduce the capital expense of the feeder and its associated support structure and to eliminate maintenance and periodic failure, whereby a day's feeding is missed.

Although effective, the vertical-lift pumps presented problems. With a change in water level, the pumps became less efficient. The pumps had to be secured correctly, a difficult procedure, or else they would wobble and produce a surge. Dead fish would impinge on the pump casing and escape detection, and the plastic propellers often broke. The vertical-lift pump will be replaced with additional air diffusers (22 in total, 15.2 cm x 3.8 cm x 3.8 cm) that are arrayed along the perimeter of the tank. A 1-hp blower will be allocated for the four rearing tanks.

The clarifiers will be enlarged to 3.8 m^3 to increase retention time to 19 minutes and thereby remove more settleable solids. Removing a larger portion of the settleable solids in the clarifier will reduce the number of filter tank cleanings and the associated labor.

Adding base to the system has been problematic in that base addition creates high-pH zones which are harmful to fish and plants. Therefore, a small tank (0.15 m^3) will be installed adjacent to the sump for base addition. The tank will be well aerated and supplied with a continuous flow (2 L/min) of system water that will discharge into the sump, thereby slowly neutralizing acid buildup while avoiding pH swings.

A 0.7-m^3 rectangular degassing tank will be placed between the second filter tanks to receive their discharge. This tank will be aerated vigorously to vent gases (carbon dioxide, methane, hydrogen sulphide) into the atmosphere that are created in the anaerobic microzones of the filter tanks.

A number of design changes will be made to lower water temperature to increase lettuce survival and growth. Thompson et al. (1998) showed that the effect of water temperature on lettuce production was more important than air temperature. At a water temperature of 24°C, lettuce grew optimally regardless of air temperature, and disease symptoms, caused by *Pythium,* disappeared. In the UVI system, *P. myriotylum* becomes a problem when water temperature exceeds 26.7°C. Therefore, a temperature decrease of 1 - 2°C will reduce the incidence of *P. myriotylum.* To lower water temperature, the canopy covering the rearing tanks will be extended to also cover the clarifiers and filter tanks so that no tanks other than the hydroponic tanks are exposed to direct sunlight. All water distribution lines will be buried or shaded from the sun. A series of large heat dissipating pipes will be attached to the blowers. The portion of the black hydroponic tank liners that is exposed to the sun will be painted white. Small evaporative cooling towers, which are currently being tested along with chillers on UVI=s experimental aquaponic systems, may be added to the hydroponic tanks and operated at night. With evaporative cooling, the water temperature will approach the wet bulb temperature, which is 24 - 25°C at night during summer in St. Croix.

After renovation, the system will be tested in production trials. In addition to rearing red tilapia to approximately 500 g for the whole fish market, Nile tilapia (*Oreochromis niloticus*) will be grown to 1,000 g for the fillet market using lower stocking densities. The culture of lettuce will be continued to assess growth at lower temperatures, to screen varieties for resistance to *Pythium* and to evaluate production at different planting densities. Additional research will be conducted to determine the culture potential of other species such as ornamental fish, vegetables (e.g., tomatoes, cucumbers, peppers), culinary herbs (e.g., sweet basil, chives, mint), medicinal plants and cut flowers.

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