HortScience 59(8):1202–1206. 2024. https://doi.org/10.21273/HORTSCI17975-24

Sustainable Hydroponics Using Zero-discharge Nutrient Management and Automated pH Control

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Keywords. aeration, ammonium, manifold, nitrate, pH control

Abstract. **Here we review the 400-year history of hydroponic culture and describe a unique management approach that does not require leaching or discarding solution between harvests. Nutrients are maintained at a low and steady concentration by daily additions of a dilute solution that replaces the transpired water along with the nutrients that were removed in growth each day. A stable pH and a low steady-state concentration of ammonium are maintained through automated additions of a solution of nitric acid and ammonium nitrate. Ample solution volume (at least 20 cm deep) stabilizes nutrient concentrations, reduces root density, and improves uniformity. Gentle aeration at ≈100 mL·min^{-1}·L^{-1} maintains dissolved oxygen near saturation and increases uniformity throughout the rhizosphere. These practices facilitate a uniform, closed, root zone with rigorous pH control that provides the micromolar nutrient concentrations of N and P that are representative of field soils.**

The growth of plants without soil appears to have been first used in The Hanging Gardens of Babylon in the first millennium BCE (Hershey 1994) and later in the Aztec floating gardens (chinampas) of the 14th century (Ebel 2020) in modern day Mexico (Velazquez-Gonzalez et al. 2022). Francis Bacon, an English philosopher, was the first to compile a list of experiments in which plants were grown only in water. He concluded that soilless plants derived their mass solely from water in stating that: "It seemeth by these instances of water, hath for nourishment the water is almost all in all, and hath the Earth doth but keep the plant upright…" (Bacon 1627).

The Flemish scientist Jean Baptist van Helmont built on the ideas of Bacon by growing willow trees. He concluded that tree growth in a container was due only to the distilled water added over the course of 5 years as the soil mass remained the same (van Helmont 1652). John Woodward, an English medical professor dissatisfied with the conclusions drawn by Bacon and van Helmont, demonstrated that spearmint had a higher mass and lower transpiration rate when soil was added to the water compared with a tap water control (Stanhill 1986). Woodward (1699) concluded that "vegetables are not formed of water, but of a certain peculiar terrestrial matter."

Soilless culture began gaining traction as a research tool for plant physiology more than a century later. Jean-Baptiste Boussingault applied hydroponic principles by using containers filled with sand and concluded that nitrogen fixation was present in clover but absent in wheat (Boussingault 1838). One of the first fertilizer recipes for soilless culture was developed by Julius von Sachs in 1860 at his German agricultural experiment station (Hewitt 1952). Wilhelm Knop, a German agrochemist, published the first detailed plant nutrition studies using corn grown in soilless culture in his 1868 German textbook of agricultural chemistry (Knop 1868).

Soilless culture was used primarily as a research tool until the beginning of the 20th century. Gericke (1929) began a research program at the University of California, Berkeley to increase the scale from bench-top experiments to large-scale applications for agricultural producers. The term "hydroponics" was subsequently coined in 1937 by his colleague W.A. Setchell to differentiate the desire for crop production from the previously small-scale plant nutrition studies (Gericke 1937).

Gericke (1938) later built large hydroponic containers made of concrete, wood, sheet metal, or asphalt where he grew tomatoes and potatoes. One of the first large hydroponic systems grew food for Pan American Airlines passengers on Wake Island in the Central Pacific ("A Hydroponic Farm on Wake Island" 1938) using subirrigation methods adapted from R.B. Withrow (Walters et al. 2020). The US Army used the principles as early as 1945 to grow hydroponic vegetables in concrete basins filled with volcanic cinders on Ascension Island (Moore 1945) and in Japan after World War II (Thone 1947). Spurred by the growing interest in hydroponics, Dennis Hoagland and Daniel Arnon developed a standardized nutrient solution recipe for interested growers. Their seminal publication (Hoagland and Arnon 1938) has been cited more than 20,000 times.

Historical hydroponic systems can be classified as substrate or liquid water based. Plant growth in a relatively inert medium (e.g., mineral wool, perlite, or sand) that is irrigated with nutrient solution is referred to as substrate-based hydroponic culture. Plant roots in liquid hydroponic culture have no contact with a substrate after germination.

Cooper (1975) introduced the nutrient film technique (NFT) using sloped channels to allow a thin layer of nutrient solution to flow along the bottom of the root system. Dissolved oxygen and nutrient delivery can be challenging in NFT systems because the solution often begins to channel around roots as plants mature (Bugbee and Salisbury 1989; Burrage 1993).

Aeroponics was developed to increase oxygen transfer to roots by misting roots hanging in the air, but it is also difficult to deliver nutrients to the center of dense root systems using this approach.

Ebb and flow systems periodically flood and drain a substrate-filled container with nutrient solution, but they are not steady-state. Solution cycle times must be carefully controlled to avoid depletion of dissolved oxygen during flooding and low root zone water potential during periods of drainage.

Deep-water culture (DWC) is a widely used liquid culture system in which roots are continuously submerged in a nutrient solution. We have found that this approach provides the most uniform and steady-state root zone environment.

Regardless of system design, little consideration has historically been given to the long-term sustainability of hydroponic systems. Hewitt (1952) includes a review of more than 30 nutrient solution recipes developed since 1860 but none appear to be suitable for zero-discharge operation.

Trejo-Téllez and Gómez-Merino (2012) compared the solution developed by Hoagland with three more recent solutions and concluded that they were only based on empirical testing. These historical solutions were associated with a dump and refill approach to nutrient management, which wastes water and nutrients by discarding the entire nutrient solution and replacing it with fresh solution. This approach results in non–steady-state nutrient concentrations in solution. Smethurst (2000) showed that nitrogen concentrations

Received for publication 21 May 2024. Accepted for publication 13 Jun 2024.
Published online 30 Jul 2024.
This research was supported by the Utah Agricultural Experiment Station, Utah State University (approved as journal paper number 9780) and the National Aeronautics and Space Administration–Center for the Utilization of Biological Engineering in Space (grant number 80NSSC22K1474).
We acknowledge Hikari Skabelund for her work designing and 3D printing the tank lid inserts and Alec Hay for his assistance in helping procure and test the research-grade components used in this system.

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in the field are often less than 2 mM and phosphorus concentrations are often less than 0.02 mM. Every time a solution is replaced, the phosphorus is replenished back to ≈0.5 mM, which is 25 times the concentration in the field. Because field soils have low, steady-state nutrient concentrations, results from traditional hydroponic studies are not representative of field conditions.

Here we describe the development of a research-grade, zero-discharge, DWC hydroponic system with automated pH control that optimizes plant growth and approximates the nutrient availability and stable pH of field soils.

Design Considerations

Growth tank

Plastic is recommended for hydroponic containers because of its longevity and inertness. High-density polyethylene (HDPE) and polypropylene (PP) are the two most common plastics because they have good chemical resistance and are food safe. Polypropylene has higher rigidity and increased resistance to acids and bases compared with HDPE (Maddah 2016).

Most plastics absorb ultraviolet B (ultraviolet-B) radiation and degrade from extended exposure to sunlight (Andrady et al. 1998), but this degradation is minimized under low-ultraviolet-B electric lights and in greenhouses where nearly all ultraviolet-B radiation is blocked by plastic or glass roof coverings (Duarte et al. 2009). Degradation is also minimized by the addition of stabilizers to the plastic. We use 55-L gray PP containers (Quantub Nesting Tote; Quantum Storage Systems, Miami, FL, USA) that effectively block light transmission and eliminate algae growth (Pandey et al. 2009). We fill each container with nutrient solution to 90% to 95% capacity (1 to 2 cm head space) to minimize the splashing over the edges that is associated with aeration.

A deep container leads to a deep root zone, which improves solution circulation around roots and minimizes the channeling often seen in NFT systems. We have found a solution depth of at least 20 cm provides an ample root zone volume for many crops.

Container cover

The container cover holds plants above the nutrient solution and prevents light from promoting algae growth. Schwarz and Gross (2004) found a significant decrease in lettuce yield when algae was allowed to grow in the nutrient solution compared with when it was prevented. Floating the cover on the nutrient solution surface can also allow algae to grow in the gap between the cover and the tank sides. Kratky (2005) found that lettuce growth in nonaerated solutions was 19% lower when the tank cover was floated on top of the nutrient solution compared with when the cover was held above the solution. The small air gap (≈1 cm, Fig. 1) between the nutrient solution surface and the bottom of the cover allows vigorous root growth and increases oxygen transfer to the solution.

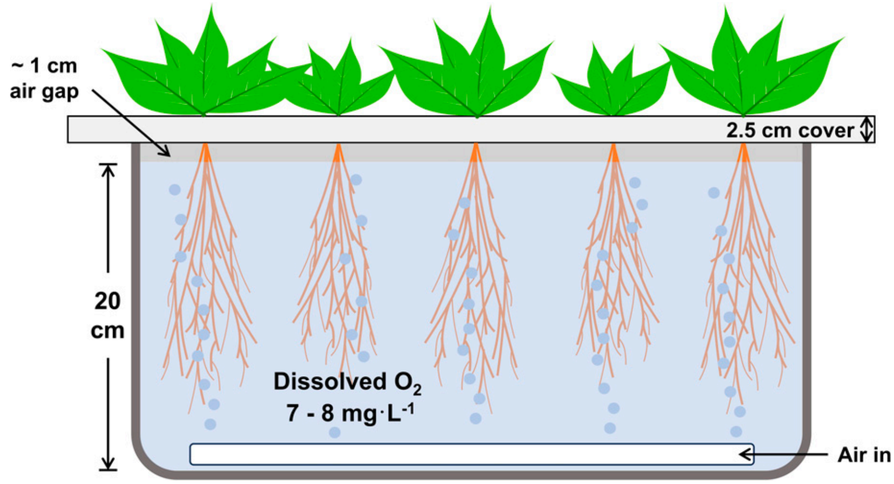

Fig. 1. A profile view of a deep-water culture hydroponics system. The 1-cm air gap below the cover facilitates oxygen transfer to the solution. Continuous aeration helps maintain a dissolved oxygen concentration near saturation at 7 to 8 mg·L^{-1} (0.25 mM O_2).

A lightweight, sturdy cover can be made from closed cell foam. Extruded polystyrene (XPS) is food safe and is preferred over expanded polystyrene because it is smoother and more rigid. We have used 2.54-cm-thick XPS covers (FOAMULAR 150; Owens Corning, Toledo, OH, USA) for more than 6 years without noticeable degradation.

To maximize light reflection, we apply adhesive ultraviolet-resistant white vinyl (Oracal® 651, ORAFOL, Oranienburg, Germany) to the top. Vinyl that is wider than the cover ensures a single piece can be used to eliminate seams. White tape can be used to seal the edges of the vinyl around the cover, but taping over the bottom of the cover should be avoided. We cut a 1.27-cm-deep slot into the bottom of the foam cover to facilitate better contact with the growth tank (Supplemental File 1). The holes and slot can be cut using a computer numerical control router or a palm router. A design file for the cover is included as Supplemental File 2.

Plant spacing considerations

The morphology of the crop determines plant spacing. We have grown wheat (*Triticum aestivum*) at a density of 2000 plants per m^2 (700 plants per container), lettuce (*Lactuca sativa*) at a density of 23 plants per m^2 (eight plants per container), and tomato (*Solanum lycopersicum*) at 11 plants per m^2 (four plants per container).

Cover inserts

Firm neoprene cloning collars are used to hold plants in the cover above the solution. Soft neoprene degrades faster than firm neoprene and has a shorter life span. The collars can be placed directly in the cover holes or placed in inserts to improve cleaning and minimize wear on the edges around the holes. We 3D-print inserts from white polylactic acid (PLA) plastic to have an outer diameter of 5.08 cm to fit snuggly into the holes of the cover. The PLA should be food safe to be used in a hydroponics system. A file for 3D printing the inserts is included as Supplemental File 3.

Collars with a diameter of 4.76 cm are a common size and fit into the inserts. Brighter collar colors are beneficial for increased light reflection. The growing stem base can easily expand the hole at the center of the collar. We have reused collars for more than 1 year (more than 12 crop cycles) with only a light cleaning after each harvest.

Aeration

Aeration helps maintain a high level of dissolved oxygen (DO) in the root zone and is highly beneficial in systems with rapid plant growth.

Aeration rate. We continuously aerate the root zone at a rate of ≈100 mL·min^{-1}·L^{-1}. Lower aeration rates can still provide ample oxygen, but it is difficult to uniformly distribute smaller volumes of air. Higher aeration rates may cause water to splash from containers and can be damaging to young roots because of excessive solution agitation. Aerating with pure oxygen increases the DO concentration in solution, but Goto et al. (1996) showed no benefit to lettuce growth at DO concentrations above saturation at 25 °C (8.4 mg·L^{-1}).

Aeration control. Aeration rate can be accurately measured and controlled using a rotameter. Manifolds can also be used, but flow rates to different tanks may become uneven. We have found rotameters (RM Rate-master®; Dwyer Instruments, Michigan City, IN, USA) to require minimal maintenance and be more robust and reliable than manifolds.

Air distribution. Air should be dispensed across the tank bottom to evenly circulate the nutrient solution and deliver oxygen to roots. A manifold with small holes (we use 1-mm-diameter holes) can be made from 2.54-cm-diameter schedule 40 PVC tubing that is friction fit together. The manifold can be attached to the bottom of the tank using aquarium heater suction cups, which have a long service life. A suction cup will only stick to the bottom of the tank for a few hours on its own and super glue will only last a few weeks, so we use a two-part epoxy to create a permanent bond.

Refilling the nutrient solution

The solution used by plants in transpiration is replenished without discarding the remaining solution. The refill is the same composition and concentration as the initial solution, which is determined using a mass balance approach described in Langenfeld et al. (2022). The volume used is dependent on transpiration rate: replenishment is less than 0.1 L per day when plants are young but may be more than 5 L per day when plants are mature, which is 10% of a 50-L volume. If the solution electrical conductivity (EC) is 0.40 mS·cm^{-1} and the refill is 1.00 mS·cm^{-1}, the EC will increase from 0.40 to 0.46 mS·cm^{-1}. Solution refill can be automated with a float mini-switch connected to a reservoir containing nutrient solution, but we have not found it difficult to manually refill the containers.

pH control system

The pH can be automatically controlled by using a pH electrode, pH controller, and solenoid valve. The electrode continuously monitors pH, and when it exceeds a set point, the controller triggers the solenoid to open. This releases a solution from a reservoir to push the pH back toward the set point. The pH changes, and the cycle then repeats itself with a frequency dependent on plant growth rate.

The pH control solution can be gravity-fed from reservoirs located above the nutrient solution surface (Fig. 2). Only a small head (5 to 10 cm) is needed. A low point in the tube connecting the pH control solution to the nutrient solution should be avoided to eliminate the chance of creating a siphon in the event of tubing failure, which could allow back flow and deplete the main nutrient solution. Active pumping is an additional failure point and is often more expensive.

Selection of a pH electrode and controller. We use a pH controller (Model 931700-0; Hanna Instruments, Woonsocket, RI, USA) connected to a single junction combination pH electrode (Oakton pH electrode; Cole Parmer, Vernon Hills, IL, USA). Langenfeld and Bugbee (2022a) describe how to interface the pH controller and electrode with a datalogger for continuous pH monitoring. We have never had to replace pH controllers but have found that even well-cared-for pH electrodes begin to drift after ≈1 year of continuous use and require replacement. The electrodes should be recalibrated at least once a month and reconditioned (30-min soak in 0.4 M HCl) if response times become slow.

Selection of a solenoid valve. The pH control solution is dispensed into the tank using a solenoid valve. We use a time delay relay (Droking, Guangzhou, China) in line between the controller and valve to open the solenoid for only 5 s after triggering. Our system overdosed on acid on two occasions before the relay was installed due to an electrode failure, which compromised the studies. We previously used 1-s dosing times but found they could not keep up with acid demand as plant growth rate increased. For many years, we used acid-resistant flow-through solenoid valves but found they corroded and began to leak in less than a year. We now use pinch valves (PG-PV solenoid pinch valve; Preci-Genome, San Jose, CA, USA), which prevent the solenoid components from contacting the solution. These valves compress the tubing to stop flow and release to allow flow. The spring inside the valve compresses over time, but the Allen screw on the top of the valve can be adjusted to compensate for changes in spring compression.

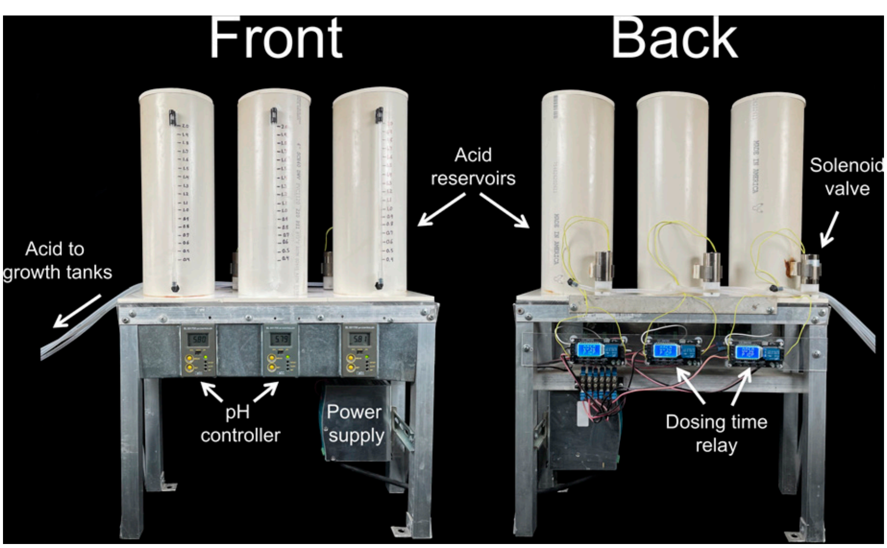

Fig. 2. The automated pH control system described in this paper. Each PVC tower holds the pH control solution that is automatically dispensed through a solenoid pinch valve when needed. The system pictured can independently control the pH in three hydroponic containers.

Selection of tubing. We have found polyethylene tubing (trade name Bev-A-Line IV®) to be durable, ultraviolet, and chemical resistant for long-term use in aeration of pH control. Silicone tubing is used with the solenoid pinch valve due to its lower durometer, but it will temporarily bond together if continuously pinched for more than a few days. Air can also be pulled into the silicone tubing through small pores from the constant tension due to the gravity-fed nature of the system. Air is difficult to draw through the tube, which can lead to blockages and a failure of the control system. This is a potential problem when plants are younger and there is no pH control requirement. These issues can be eliminated by not enabling pH control until it is required, and dosing is more frequent.

Selection of fittings. The acids used for pH control can cause many types of plastic fittings to become brittle, leading to small cracks and leaks. We have found polyvinylidene fluoride (PVDF, trade name Kynar®) fittings to be chemical and acid resistant and have a long service life in the hydroponics system.

Example cultural procedures

Harvest results from a typical crop of lettuce (*Lactuca sativa* cv. Grand Rapids) grown using these principles are summarized in Table 1. We used the dicot solution from Bugbee and Langenfeld (2022) to prepare a nutrient solution with an EC of 1.00 mS·cm^{-1}. The pH control solution for each tank was composed of 50 mM nitric acid and 25 mM ammonium nitrate.

The system was placed in a glass greenhouse in Logan, UT, USA, and maintained at 28/25 °C day/night. Supplemental light from LED fixtures maintained a 16-h photoperiod with an average daily light integral of 29 mol·m^{-2}·d^{-1} from 25 Jan 2024 to 22 Feb 2024. The daytime carbon dioxide concentration averaged 500 µmol·mol^{-1} CO_2 and the relative humidity averaged 50%.

We planted seeds on a slant board for 7 d using the methods described in Langenfeld and Bugbee (2022b). After 7 d, eight seedlings were transplanted into the hydroponics system. The lettuce was harvested after 28 d in the system, for a total growth time of 35 d. Shoots and roots were separated and dried at 80 °C to a constant mass.

Results

Lettuce growth in the hydroponics system. The roots were easily separated from the shoots, which allowed us to calculate harvest index. This allowed us to dry the shoots and roots separately to determine a percent dry mass. We rigorously tracked the volume of nutrient solution and pH control solution used throughout the lifecycle of the crop. This allowed us to calculate water-use efficiency in grams of dry mass per volume of solution used.

Long-term results. We have optimized our system over the past 40 years [Bugbee (2004)

Table 1. Harvest data for eight lettuce plants (*Lactuca sativa* cv. Grand Rapids) grown in the deep-water culture hydroponics system described in this paper. Plants were grown for 28 d after transplanting in the system (35 d total).

Parameter	Measurement
Fresh shoot (g)	2051.0
Fresh root (g)	357.5
Dry shoot (g)	106.1
Dry root (g)	14.7
Harvest index (%)	88.7
Percent dry mass (%)	5.0
Solution used (L)	28.0
Acid used (L)	0.89
Water-use efficiency ($g \cdot L^{-1}$)	4.2

and Langenfeld et al. (2022)] to grow lettuce, cucumber, spinach, tomato, wheat, corn, sunflower, and *Cannabis*. We recently expanded the system to include 12 replicate growth tanks each with independent pH control (Fig. 3). Root zone factors that can be controlled include aeration rate, pH set point, pH control solution composition and concentration, and nutrient solution composition and concentration.

Discussion

The form of nitrogen in solution dictates pH changes. Nitrate is taken up by roots along with a proton, which increases rhizosphere pH. Ammonium uptake releases a net proton from roots and the rhizosphere pH decreases (Bittsánszky et al. 2015; Hachiya and Sakakibara 2016). Because many hydroponic nutrient solutions include only nitrate-nitrogen, the pH increases over time and an acid is added to maintain pH. Sulfuric acid is low cost, readily available, and widely used, but sulfate accumulates in recirculating solution. Phosphoric acid addition can help buffer pH, but it contributes excess phosphorus (P), which is a serious environmental pollutant and can lead to luxury uptake rates without any beneficial effect on yields (Penn et al. 2022). Nitric acid is less common, but it provides a slow, steady source of nitrogen to plants and is actively taken up from the solution. Some hydroponic systems can include both an acid and a base injector, but these will often counteract each other, and a stable equilibrium will be difficult to reach.

Many crops produce higher yields when ammonium is provided along with nitrate (Li et al. 2013), but a high ammonium percentage can lead to toxicities (Britto and Kronzucker 2002). A low and steady ammonium concentration can be achieved by adding an ammonium salt in the pH control solution, which also reduces pH, as discussed earlier. Ammonium sulfate contributes excess sulfate to the solution, which is undesirable. Monoammonium phosphate increases the P concentration, which can result in elevated P levels in solution. Ammonium nitrate delivers both ammonium and nitrate into solution and avoids overdosing undesirable anions. Our optimized pH control solution is composed of 50 mM nitric acid and 25 mM ammonium nitrate, which is a 3:1 M ratio of nitrate to ammonium. We have seen higher ammonium concentrations lead to a rapid decrease in solution pH. A typical lettuce crop may receive less than 4% of its water from the pH control solution, but more than 20% of its total nitrogen. The nitrate-to-ammonium ratio over the lifecycle averages about 20:1.

This management approach can be used with tap water, but the nutrients and pH must be adjusted during the solution preparation stage to account for elements in the tap water. Bicarbonate in tap water is converted to CO_2 by adjusting pH to 6 before adding the refill solution. These adjustments result in little to no variation in pH control among source water alkalinities.

We have not found the need for sanitization of the system components or nutrient solution. Following good agricultural practices and using dilute nutrient solutions keeps the organic carbon content low, which minimizes microbial growth and disease and reduces the need for sanitization. Any algae growth on the lid can be removed with a soft brush. A light scrub of system components with a clean sponge followed by a rinse with tap water are the only cleaning methods we use between crop cycles. Although we have not found a drawback to more rigorous sanitization, we have also not found a benefit.

Fig. 3. Lettuce (*Lactuca sativa*) growing in the recirculating deep-water culture hydroponic system with automated pH control described in this paper. The pink hue is due to the overhead LED supplemental lighting.

Conclusions

The principles of this DWC hydroponics system with automated pH control are designed to optimize root zone conditions for plant growth. The cover holds the plants above the nutrient solution to increase oxygen transfer to the solution. Continuous aeration in the nutrient solution helps to maintain a uniform, aerobic rhizosphere. The automated pH control with nitric acid and ammonium nitrate facilitates a pH that varies less than 0.1 pH units. Consistent refills of dilute nutrient solution enable a zero-discharge system that helps to maintain a low and steady nutrient concentration that is representative of field soils. The optimized, steady-state root zone conditions facilitate extrapolation to field agriculture.

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