Rubber from the tropical rubber tree (Hevea brasiliensis). However, cost-effective field production is not yet possible because of slow growth rates, weed pressure, and a short growing season in the north.

**Methods**

The custom-built automated hydroponic system used in this study was originally built by Crop King (Crop King, Lodi, Ohio) and later modified by T.R. Fontana, Wooster, Ohio (Fig. 1). The hydroponic system was comprised of eight separate aerated nutrient tanks, each feeding eight cylindrical columns for a total of 64 plant positions in a fully randomized design (Fig. 1). Each well had a diameter of 8 cm and a depth of 40 cm.

Flexible vinyl tubing (1.3 cm inside diameter, 1.6 cm outside diameter, blue color to inhibit algal growth) was used to drain and fill each tank with a specified nutrient solution. Drain and fill cycles were automated, cycling in pairs of tanks (1&5, 2&6, 3&7, 4&8). Each set was filled with nutrient solution for 2 minutes, in sequence, with additional aeration through ceramic stones located at the bottom of each well, with air provided by an electric pump. Overflow tubes were set in each well to return excess solution to the appropriate tanks, maintain filled water levels and prevent overflow onto the table. After 2 minutes the tubes drained and roots were exposed to air for 6 minutes until the next refill cycle. During operation, the sides of the system were closed to inhibit algal growth. In addition, the system was outfitted with automated pH monitors, which added hydrochloric acid as needed to maintain pH at 5.7 ± 0.3. A modified, half strength, Hoagland’s solution (Hoagland and Arnon, 1950) was used, except where otherwise stated, to grow T. kok-saghyz in the hydroponics system, as follows: reagent grade Haifa 4 mM L-1 Ca(NO3)2, and 4 mM L-1 KNO3 (Haifa, Mata-m-Haifa, Israel); Innophos 1.3 mM L-1 KH2PO4 (Innophos, Cranbury Township, N.J.); Crop King 2.5 mM L-1 MgSO4, 22.5 /unicomm L-1 Fe, and a micro mix solution containing 0.09 /unicomm L-1 Zn, 0.02 /unicomm L-1 B, 0.075 /unicomm L-1 Cu, 0.17 /unicomm L-1 Mn, and 0.035 /unicomm L-1 Cu.

The hydroponics table was placed in a greenhouse in Wooster, Ohio. Temperatures were maintained throughout the year with set points ranging from 18-21°C during the day and 15.5-21°C at night. During the winter, artificial light was provided for 10 hours from a 50-50 mix of 1,000-watt high-pressure sodium and 1,000-watt metal halide bulbs. In the summer, light was dependent on natural conditions with a shade applied to the greenhouse to reduce light penetration by 30 percent. Several experiments were performed to address specific research questions.

**Experimental Summary**

Rubber dandelion (Taraxacum kok-saghyz), Rodin, TK produces natural rubber (cis-1,4-polyisoprene), almost identical to rubber from the tropical rubber tree (Hevea brasiliensis), in root latex vessels (laticifers).

Cost-effective field production is not yet possible because of low rubber content, slow growth rates, poor competition with weeds and short season when crops are established by economical direct seeding instead of expensive transplants. Controlled environment vertical hydroponic systems have no weeds or dirt, are not subjected to outdoor productivity limitations and plants can reach a productive size in weeks, not months.

Rubber yields on a dry weight basis are not significantly different between field grown roots and hydroponic roots. Roots can be harvested repeatedly from the same plants. A scalable, modular vertical farming hydroponic system is being developed to match or exceed growth rates attainable in the current research system.

**References**

Cornish serves as an internationally recognized expert and innovator in alternative natural rubber/latex crops, their processing and formulation technologies and byproducts, as well as in valorization of wastes. Her accomplishments include being elected as a fellow of the National Academy of Inventors, as well as of the American Association for the Advancement of Sciences; 25 issued or pending patents, from OSU and her prior career; and 265 publications, numerous worldwide lectures and considerable public and private funding.

Cornish recently won a hat-trick of innovator awards: Ohio State University’s 2018 Innovator of the Year, and 2019 Innovator of the Year for her college and for OSU’s Institute of Materials Research. She holds a bachelor’s in biological sciences and a doctorate in plant biology, both from the University of Birmingham in Edgbaston, England.
were root number (plants with 1 or 2 roots) and nutrient solution strength (¼ X and ½ X), with plants of both root morphologies randomly assigned to specific locations across nutrient strengths. Each individual well was tested daily to maintain nutrient solution conditions (pH of 5.7, 2 L of solution), and the dandelions were grown in the liquid media for four weeks. Total fresh plant weights were recorded at intervals to analyze growth patterns, and after eight weeks, root and shoot weights, and root rubber concentrations were separately determined in the pre-existing 10 cm of root and in the new hydroponically grown roots. Rubber concentrations were determined using accelerated solvent extraction (e.g. Ramirez-Cadavid et al. 2018).

Rubber concentration and yield in field-grown and hydroponically grown roots:

A variety of TK dandelions were generated using root cuttings (Cornish et al. 2016) and placed in the hydroponic system. After 10 weeks of hydroponic growth, 20 vigorous, hydroponically grown dandelions were sorted into eight groups based upon plant size and leaf morphology. One plant within each grouping was designated as a control while the remaining dandelions harvested with a perpendicicular cut to the long axis of basilateral root growth leaving 10 cm of root attached to the crown. The dandelions were re-placed in the hydroponics system for eight weeks of additional growth. Final growth measurements and rubber quantification, through ASE, were obtained using protocols developed for initial harvest methods. Data were analyzed by analyses of variance and significance claimed at P < 0.05.

Results

Rubber concentration in field-grown and hydroponically-grown roots:

During the first four weeks, plants grew significantly more rapidly in ½ strength than in ¼ strength nutrient solution (Fig. 2, P = 0.056). After eight weeks, the plants had clearly distinct roots types (Fig. 3). Also, it was clear that some plants grew much better than others (Fig. 4 in hydronics), and this clearly hydroponic roots, were harvested with a perpendicicular cut to the long axis of basilateral root growth leaving 10 cm of root attached to the crown. The dandelions were re-placed in the hydroponics system for eight weeks of additional growth. Final growth measurements and rubber quantification, through ASE, were obtained using protocols developed for initial harvest methods. Data were analyzed by analyses of variance and significance claimed at P < 0.05.

Rubber concentration and yield in original and regrown hydroponic roots:

The demonstration that hydroponically grown roots produce similar rubber concentrations to field grown roots, opened the door to testing multiple root harvest potential in TK. After eight weeks post-root-cut, plants had regrown more root mass than they had accrued in the original 10 weeks of hydroponic production (Figs. 6 and 7), while rubber concentrations remained unchanged.

Discussion

The hydroponics research system proved highly effective at growing rubber dandelion roots containing rubber. The largest root system attained, under the same growing conditions, had a root fresh weight of 310 g, 30 g dry weight, and 80 mg/g rubber, contained 2.4 g of rubber. This indicates the potential of a TK hydroponic production system, which could contain millions of plants per acre, greatly exceeding the uncompetitive published rubber yields in TK field trials (Arias et al., 2016; Kreuzberger et al., 2016; Eggert et al., 2018).

However, the individual plant format of the research system reported here is poorly scalable. A new vertical farming system is needed which will be optimized to match or exceed the performance of the research system. Ohio State University and American Sustainable Rubber Co., L.L.C. are collaborating to develop and optimize such a system. It has already been proven that rubber produced by soil-grown rubber dandelions is very similar to that from Hevea brasiliensis (Ikeda et al., 2016; Junkong et al., 2017).

However, very little is known about the quality of rubber produced from hydroponic roots, beyond its similarity in appearance to rubber from soil-grown plants. Thus, it is essential to fully characterize the rubber from repeated harvests of the same plants, especially among treatments and new germplasm genetically modified to produce enhanced rubber yields. In addition, TK roots produce latex in laticles but these obviously cannot be tapped even if this were a cost-effective method. By harvest, much of the latex in hydroponically grown roots produce similar rubber concentra-tions to field grown roots, opened the door to testing multiple root harvest potential in TK. After eight weeks post-root-cut, plants had regrown more root mass than they had accrued in the original 10 weeks of hydroponic production (Figs. 6 and 7), while rubber concentrations remained unchanged.
that all latex is converted to the solid rubber form. Aquatic-based methods tend to retain non-rubber solids in the rubber fraction (Ramirez-Cadavid et al., 2017, 2018), failing the ASTM ‘dirt’ standard set for H. brasiliensis rubber, although it is not yet known if slight contamination with lignocellulosic root debris is as damaging as actual dirt.

Solvant-based methods tend not to extract the high molecular gel, reducing yield (McMahan et al., 2015). However, it seems possible that healthy hydroponically grown roots, never subjected to environmental or edaphic stress, may retain a greater fraction of their rubber in the latex. If this proves to be the case, then the latex extraction process, originally developed for guayule and recently improved (Cornish, 2018), would likely be the most efficient method to extract TK rubber. TK latex can be coagulated post-extraction to serve solid rubber applications, as is done to 89 percent of H. brasiliensis latex post-tapping (Thomas, 2010).

Hydroponecs also allow TK nutrient requirements to be optimized to maximize root growth and rubber concentration. These optimized parameters should also be applicable to fertigation requirements in different field settings. However, the variability in field TK means that hydroponically adapted selections also will be needed.

Hydroponec technology and economic assessment for growing TK was conducted in 2017 by a collaborative student team project by the University of Akron College of Chemical Engineering and Ecole Nationale Superieure du Petrole et des Moteurs (IFP) School in France. (Report June 19, 2017, “Definition of a 100 tons/year pilot plant based on 3D (Hydroponic) Dandelion technology to produce natural rubber”). Dependent on the variables, 1.5 ha of TK rubber would be required to produce 100 tons per year of TK rubber. Field grown dandelion (TK) have yet to exceed 0.1 t/yha.

Conclusions
Optimized vertical hydroponic farming, using 4D technology, integrating 3D indoor cultivation + 1D multiplication of harvest cycles from the same plants, indicates that TK rubber can be produced much more efficiently than in the field. This production system produces dirt and leaf-free rubber, which may be able to command a price premium in high value niche markets.

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