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Effect of water-saving technologies on productivity and profitability of tomato cultivation in Galapagos, Ecuador

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Abstract

We tested the effect of two water-saving systems (Groasis Waterboxx® and Hydrogel polymer), compared with conventional drip irrigation, on the productivity, profitability, and water efficiency of greenhouse tomato cultivation in the highlands of Santa Cruz Island, Galapagos. We measured the weight and volume of individual tomato fruits, along with biweekly production, over a typical growing cycle and found that tomatoes grown with water-saving systems were significantly heavier and larger than those produced with conventional drip irrigation, which led to a 28% average increase in tomato production using both technologies. Groasis and Hydrogel also reduced water use by 71 and 48%, respectively, compared to drip irrigation, and while both systems yielded a net profit, using Hydrogel was 51% more profitable than conventional drip irrigation. Water-saving systems such as Groasis and Hydrogel may provide more sustainable solutions for profitable tomato cultivation in environments with low annual rainfall and limited access to irrigation water, such as the Galapagos Islands.

Key words: Arid environments, water-saving technologies, Groasis Waterboxx®, hydrogel polymer, *Solanum lycopersicum*, Galapagos Islands-Ecuador

Introduction

Population growth and economic development increasingly strain the world's limited freshwater resources (Connor *et al.,* 2009). Agriculture already uses about 70% of freshwater globally, so it is important to find more efficient production methods to ensure long-term food security (Demir and Sahin, 2017). The Galapagos Islands, Ecuador, are a microcosm of these global issues. These islands, characterised by low rainfall and limited freshwater, harbour a rapidly growing population of residents and tourists (González *et al.,* 2008; Guyot-Téphany *et al.,* 2011). Agriculture in Galapagos relies on conventional irrigation methods that use water excessively and wastefully, and the islands depend on imported food to compensate for the growing demand (Cremers, 2002). These factors and the Galapagos Islands economy's small scale and distinct boundaries make them a model system for testing the applicability of new methods of conserving water and achieving food security.

Preliminary results in the Galapagos suggest that water-saving systems such as the Groasis Waterboxx® (Groasis, 2019) and Hydrogel polymer can increase the average growth rate and productivity of crops while using less water than conventional irrigation techniques (Jaramillo, 2015). The Groasis is a polypropylene container installed at the time of planting, which captures water from condensation, rain, or manual watering and provides this water to the plant at a continuous rate through a nylon rope wick while shading the plant from excessive solar exposure (Hoff, 2014; Tapia *et al.,* 2019). The Groasis is a "water-saving" system because it supplies water at a rate the plants can use rather than allowing water to drain rapidly through the soil. Hydrogel is a super-absorbent polymer powder which saves water when mixed with the soil by increasing water-holding capacity (Wang and Gregg, 1990, Islam *et al.,* 2011, Fernando *et al.,* 2013; Defaa *et al.,* 2015; Peyrusson, 2018). Although previous work has shown promising results with these systems, few empirical studies test their effect on agricultural production in environments with low water availability (Narjary *et al.,* 2013; Terranova *et al.,* 2014).

We tested these two systems with tomato (*Solanum lycopersicum*) because it is one of the commonest crops globally (Willcox *et al.,* 2003) and is in high demand in the Galapagos Islands (CGREG, 2014; 2016; Guzmán and Poma, 2015). We compared tomato cultivation using Groasis, Hydrogel and conventional drip irrigation to evaluate these systems' productivity, water use, and cost benefits.

Materials and methods

We conducted the experiment at five different farms in the agricultural area of Santa Cruz (0°40′32″S, 90°16′44″W). This zone is in the Transition vegetation zone, characterised by mixed vegetation of plants adapted to dry and humid conditions, annual rainfall of 800-1100 mm, and annual evapotranspiration of 400 mm (Hamann, 1975; Trueman & d'Ozouville, 2010; Watson *et al.,* 2010; Reyes *et al.,* 2017). The site is 200 m above sea level, with rocky clay and rocky-humiferous volcanic soils (Jaramillo *et al.,* 2015; Gerzabek *et al.,* 2019). Before planting, large rocks were removed and the soil was tilled and leveled. We used the

Miramar tomato cultivar because it is the most profitable and commonly grown in Galapagos.

We randomly selected 29 farmers to estimate cost and water usage for locally used traditional irrigation systems. This poll was conducted at Santa Cruz Island's Puerto Ayora farmer's market in July 2017. The participants were interviewed using a structured questionnaire that covered important local crops, water tanker pricing, drip irrigation water volume utilisation, labour costs, infrastructural investments, and agricultural input costs.

The experiment was conducted in a greenhouse where we planted tomato seedlings were planted with three treatments: Groasis, Hydrogel, and conventional drip irrigation (control). Tomato seedlings were obtained directly from the owner of the farm, who germinated the seeds using conventional methods in a common seedbed. Seedlings were 10-15 cm tall and 20-25 days from germination when transplanted into randomly assigned treatments on 29 Aug 2017. Seedlings were planted in three parallel rows 1.2 m apart, one for each treatment. The seedlings in the Hydrogel and control treatments were planted 30 cm apart, but because two plants can be grown with one Groasis, the plants were 15 cm apart inside the Groasis, and each pair of plants within a Groasis was 50 cm apart. Despite the different distribution of tomatoes planted with Groasis, the overall density of tomato plants was similar between all treatments. In total, 54 tomato plants were used, 24 in Groasis, 10 with Hydrogel and 20 for control.

The plants were grown for 24 weeks until March 2018. At planting, each Groasis was filled with 15 L of water and then another 15 L three months later. For the Hydrogel treatment, 3 L of Hydrogel-water solution (comprising 15 g of Hydrogel powder in 3 L water) was mixed with the soil for each plant at the start of the experiment (Peyrusson, 2018; Rivera *et al.,* 2018). After three months, the Hydrogel treatments were supplemented with conventional drip irrigation for the remainder of the experiment (an additional 11 weeks) because the initial water supplied did not last beyond three months. Drip irrigation was applied using a centrifugal pump and polyethene piping with lateral lines parallel to the crop row. Irrigation water use supplied in the experiment was calculated from the farmer surveys: over the tomato production cycle of six months and for a tomato crop area of 1000 m^2 carrying an estimated 2778 plants, farmers used on average *c.* 4.8 tankers of capacity 5284 L per month = 25,363 L per month. This totals 152,179 L over six months (180 days) for 0.304 L per plant daily.

Beginning in December 2017 (14 weeks after planting), each plant's ripe tomatoes (evaluated by colour, taste and texture) were harvested and measured approximately once a week. Tomatoes were individually weighed with a digital balance (EatSmart Precision Pro Digital Kitchen Scale) and measured (height and maximum diameter) using a 150 mm caliper. We estimated fruit volume from height and diameter using the formula for the volume of an elliptical spheroid (Mutschler *et al.,* 1986).

All statistical analyses were conducted using R statistical software v3.5.1 (R Core Team, 2018), and means are given±1 SD. We tested the effect of treatment on four metrics of tomato productivity: mass (kg) and volume (cm^3) of individual tomatoes, number of tomatoes harvested every two weeks (biweekly count), and total mass of tomatoes harvested every two weeks (biweekly total mass, kg). For tomato mass, volume, and biweekly total mass, we used linear mixed-effect models and a generalized mixed-effect Poisson model for biweekly total fruit number. Models were of the form:

$$Productivity \sim \alpha + \beta_2 \times treatment + N(0, \sigma^2_{production\_age}) + N(0, \sigma^2_{individual\_ID}).$$

The dependent variable *productivity* represents each of the four metrics of tomato productivity, and *treatment* represents Groasis, Hydrogel, or control. *Production_age* (based on farmers' experience and knowledge) and *individual_ID* were included as random effects to ensure that each value of fruit mass, volume, or number is statistically independent of other values during the same sampling period or from the same individual plant. Models were fitted with the "lme4" package in R (Bates *et al.,* 2019) and each model fit was evaluated by calculating conditional r^2 values (Nakagawa & Schielzeth, 2013) and by conducting likelihood-ratio tests against models that excluded the treatment effect. To assess differences between treatments, we used the "lsmeans" package (Lenth *et al.,* 2019) to calculate pairwise comparisons of significance within fitted models, comparing the effect of each treatment to each other treatment (*i.e.,* control *vs.* Groasis, control *vs.* Hydrogel, Groasis *vs* Hydrogel). A *post-hoc P*-value adjustment was applied using the Tukey method to reduce the possibility of Type I errors (false positives) due to the large number of tests between dependent variables.

To meet assumptions of normality, individual fruit mass, fruit volume and biweekly total fruit mass were log-transformed before analysis. Untransformed variables were used when plotting figures and 95% confidence intervals were generated using the "boot" package in R (Canty & Ripley, 2017).

We calculated the profitability of each treatment by extrapolating the productivity and costs of each treatment to an area of tomato production of 1000 m^2 carrying 2777 plants over five years (Carbo &Vidal 1978; Naika *et al.,* 2005), which is a temporal scale at which farmers can begin earning a profit after initial investments as discussed below (Rodríguez *et al.,* 2008). Costs and profits were estimated every six months, corresponding to the tomato cultivation cycle, and profitability was calculated as the profits-to-cost ratio (BCR). To calculate total costs per plant, we used the publicly available costs of each treatment. Groasis was calculated at $12.5 per plant since one Groasis for $25 can hold two plants (Groasis, 2019), and Hydrogel was calculated at $0.375 per plant for 15 g of powder (Ahmed, 2015; Montesano *et al.,* 2015; Peyrusson, 2018; Rivera *et al.,* 2018). A water truck of 12,000 L costs $30; therefore, the cost of water was calculated at $0.25 per 100 L based on the average water supply and transport on Santa Cruz Island at the time of this experiment. We included the costs of repaying a loan for the initial investments (Greenhouse infrastructure, geomembrane, irrigation system, seedling, labour and seeds) across five years with an annual interest rate of 10% (Aliaga, 2017; Banco Central del Ecuador, 2018). The depreciation of infrastructure and Groasis boxes was calculated using the "straight-line" method at 5% and 10% annual depreciation, respectively (Hood *et al.,* 2000). The annual price variation was 0.85% for the rainy season (January-June) and 0.44% for the dry season (July-December), the difference being due to the availability of rainwater for irrigation in the different seasons, which was used to adjust the costs of each tomato production cycle. These inflation rates were based on the monthly average rate in Ecuador over the three years 2016-18 (INEC, 2018). All other costs were estimated by averaging responses to farmer surveys (Table 1). The retail value of tomatoes produced by farmers in Santa Cruz in 2018 was obtained from the Ministry of Agriculture technical bulletin (MAG, 2018).

Table 1. Estimation of the fixed and variable costs of the initial investment for establishing tomato cultivation in 1000 m^2 under greenhouse with Groasis, Hydrogel, and Control treatments in Santa Cruz, Galapagos, Ecuador in 2017. Costs marked with asterisks (*) were generated from the average survey responses of 29 farmers in Puerto Ayora in 2017. All values were extrapolated to initial costs at a scale of 1000 m^2

Detail	Groasis ($ 0.1 ha^{-1})	Hydrogel ($ 0.1 ha^{-1})	Control ($ 0.1 ha^{-1})
Fixed costs			
Water saving technology	34,720.00	1,042.50	-
Installation cost	216.00	-	-
Irrigation system*	-	618.00	618.00
Agricultural inputs*	640.00	640.00	640.00
Tomato seed*	336.00	336.00	336.00
Geomembrane (160m^3)*	1,378.00	1,378.00	1,378.00
Greenhouse*	20,000.00	20,000.00	20,000.00
Plastic*	4,000.00	4,000.00	4,000.00
Tools*	150.00	150.00	150.00
Tutoring materials*	96	96	96
Fixed labor force*	2,782.44	2,782.44	2,782.44
Variable costs			
Soil preparation*	286.10	286.10	286.10
Offices supplies*	40	40	40
Post-harvest materials*	130.00	130.00	130.00
Fuel/Electricity*	30	30	30
Water*	315.42	555.88	1075.20
Transport*	300.00	300.00	300.00
Occasional labor*	180.00	180.00	180.00
Total	65,579.96	32,564.93	32,041.74

The Benefit-Cost Ratio (BCR) was used as an indicator of the profitability of tomato production using each treatment and was calculated as the ratio of total income to total expenses. If BCR < 1, there are net losses; if BCR > 1, then there is a net profit (Muñante, 2002; Perdomo, 2002).

Results

All models converged successfully: individual fruit mass ($\chi2$ = 33.42, cond-R^2 = 0.37, P < 0.001), individual fruit volume ($\chi2$ = 35.06, cond-R^2 = 0.33, P < 0.001), biweekly fruit count ($\chi2$ = 2.62, cond-R^2 = 0.31, P > 0.05), and biweekly fruit mass ($\chi2$ = 8.91, cond-R^2 = 0.37, P < 0.05). The treatment effect was significant in all cases except biweekly fruit count. The mean mass of individual tomato fruits was significantly greater with the Groasis (0.165 kg; SE=±0.004) and Hydrogel (0.150 kg ±0.005) treatments, compared with the control (0.107 kg ±0.002) treatment (Tukey-adjusted means comparisons, t-ratio (52.1) = -6.53, P < 0.001 and t-ratio (48.8) = -4.188, P < 0.001, respectively), but no significant difference was found in the mass of individual tomato fruits between Groasis and Hydrogel treatments (Fig. 1a). The mean volume of tomatoes was also significantly greater with Groasis (142±2.904 cm^3) and Hydrogel (133 cm^3±4.196) treatments compared with the control (98 cm^3±1.575) treatment

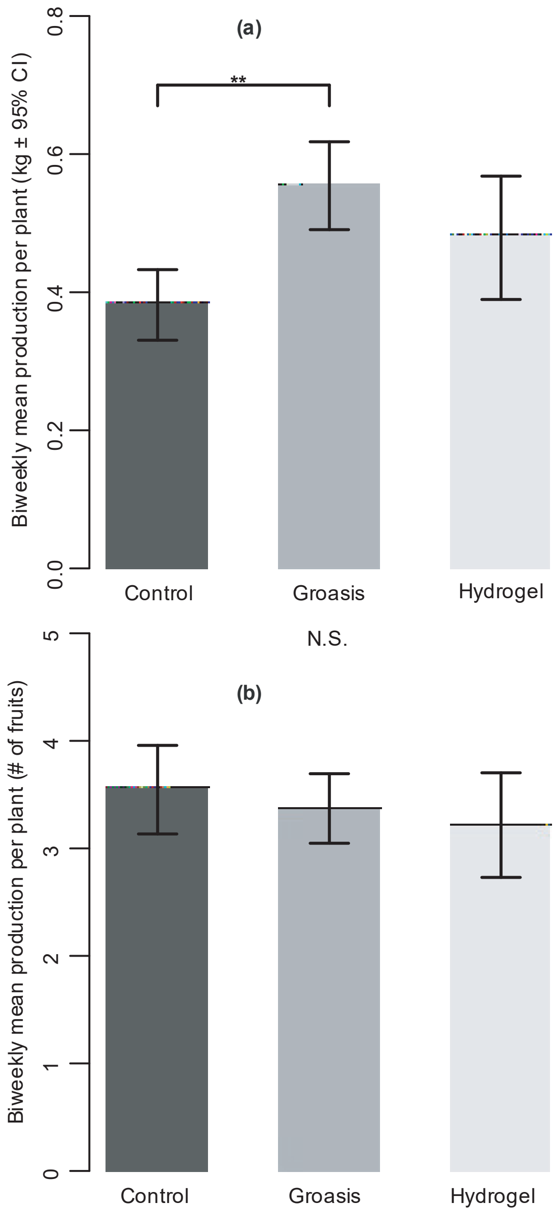

Fig 1. Effect of conventional drip irrigation (control) and water-saving technologies Groasis and Hydrogel on (a), individual fruit weight (kg), and (b), individual fruit volume (cm^3). Error bars represent bootstrapped 95% Confidence Intervals. Statistical significance is based on least squares pairwise comparisons with post-hoc P-value adjustment using the Tukey method. P < 0.001 = '***'; P < 0.01 = '**'; P < 0.05 = '*

(Tukey-adjusted means comparisons, t-ratio (52) = -6.62, P < 0.001 and t-ratio (48.4) = -4.22, P < 0.001, respectively), but no significant difference was found in the volume of tomato fruits between Groasis and Hydrogel treatments (Fig. 1b). The mean biweekly total production of tomatoes by weight was significantly greater for the Groasis (0.556 kg) treatment, compared to the Hydrogel treatment and the control (Tukey-adjusted means comparisons, t-ratio (52.8) = -3.03, P < 0.01), but no significant difference was found in the mean biweekly production weight of tomatoes between Groasis and Hydrogel (0.482 kg) and Hydrogel and control (0.384 kg) treatments (Fig. 2a). The total biweekly number of tomatoes was not significantly different between any of the treatments (Tukey-adjusted means comparisons, P > 0.05) (Fig. 2b). The average production per tomato plant during the six-month production cycle was: 3.41±0.88 kg for Groasis, 3.57±0.88

kg for Hydrogel, and 2.73±0.98 kg for the control group. If we project these yields onto an area of 1000 m^2 for a single growth cycle, the Groasis treatment is estimated to yield 9.46±2.45 t of tomatoes, the Hydrogel treatment to yield 9.91±2.45 t, while the control group would produce 7.57±2.72 t (refer to Fig. 3).

The Benefit-Cost Ratios for Groasis, Hydrogel and controls were 1.14, 1.61 and 1.37, respectively (Table 2). Across the 24 weeks of the experiment, Groasis used a total of 15 l of water per plant, Hydrogel 26.4 l and controls 54.8 l. Groasis saved 71% (= 10,037 l per 1000 m^2) of the water used in controls and Hydrogel saved 48% (= 6,860 l per 1000 m^2) of the water used in controls (Table 3).

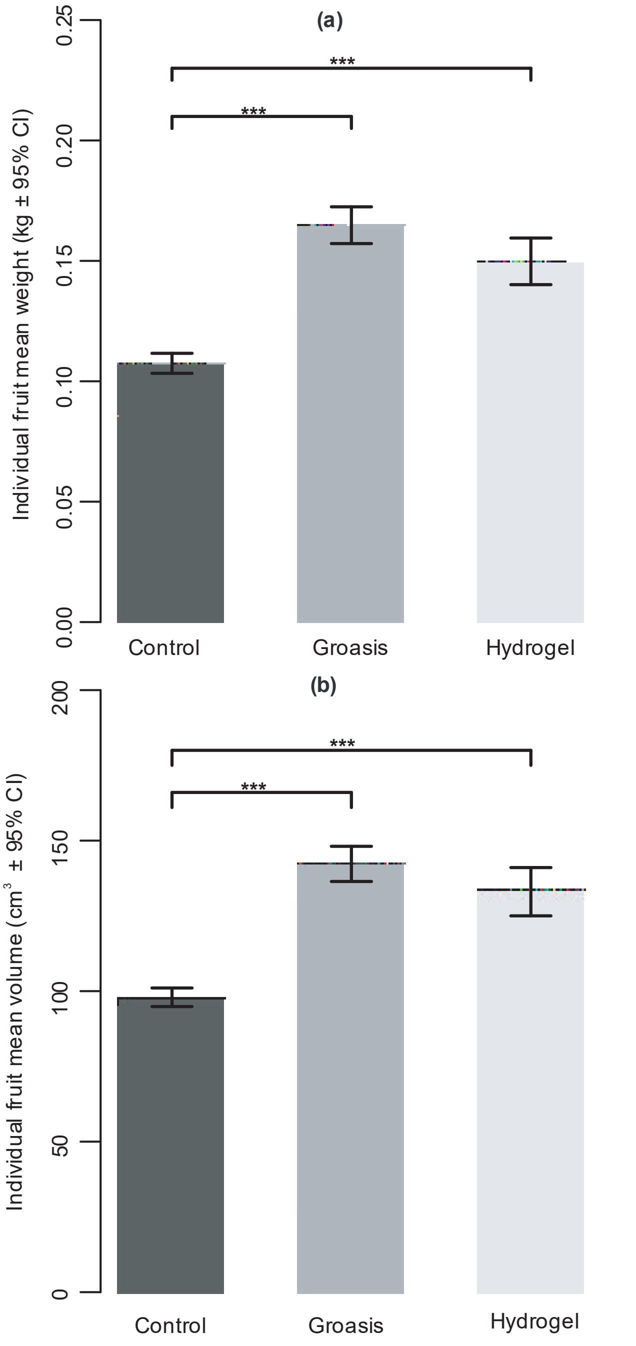

Fig 2. Effect of conventional drip irrigation (control) and water-saving technologies Groasis and Hydrogel on (a), biweekly mean total production (kg), and (b), biweekly mean number of fruits. Error bars represent bootstrapped 95% Confidence Intervals. Statistical significance is based on least squares pairwise comparisons with post-hoc P-value adjustment using the Tukey method. $P < 0.001$ = '***'; $P < 0.01$ = '**';

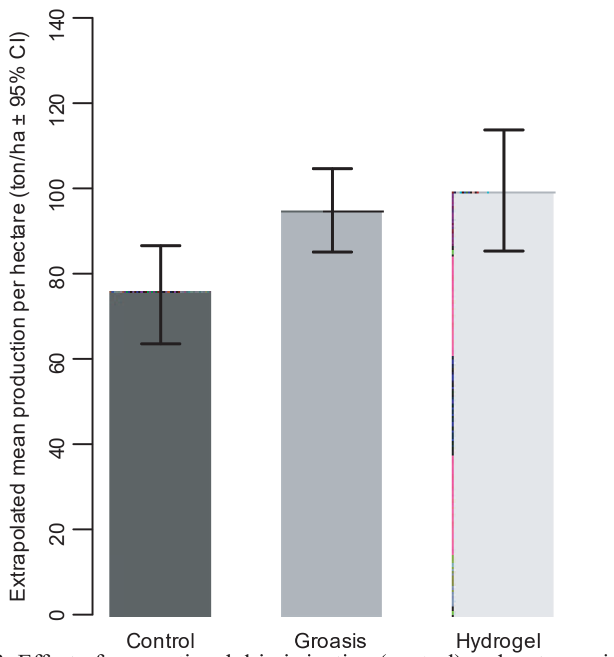

Fig 3. Effect of conventional drip irrigation (control) and water-saving technologies Groasis and Hydrogel on extrapolated total mean tomato production (metric ton ha^{-1}). Error bars represent bootstrapped 95% Confidence Intervals. Statistical comparisons were not conducted due to the low sample size (20 control, 24 Groasis, and 10 Hydrogel).

Table 2. Total costs, income, profit, and benefit-cost ratios (BCR) of tomato production under greenhouse conditions using Groasis, Hydrogel and Control treatments. Values are extrapolated to ten production cycles (five years) on 1000 m^2. Total production costs include 10% annual loan interest and infrastructure and Groasis yearly depreciation of 5 and 10%, respectively, across five years.

Parameter	Groasis	Hydrogel	Control
Total production cost ($ 0.1 ha^{-1})	197,064.44	146,645.57	131,463.65
Total income ($ 0.1 ha^{-1})	224,958.98	235,514.24	180,099.12
Gross profit ($ 0.1 ha^{-1})	27,894.54	88,868.67	48,635.47
Benefit-Cost Ratio (BCR)	1.14	1.61	1.37

Table 3. Amount of water and percentage of savings per 1000 m^2 per cycle (6 months) of tomato cultivation under greenhouse conditions with Groasis and Hydrogel treatments compared to conventional drip irrigation (control).

Treatment	Water used (L)	Water saved compared to control (L)	Savings (%)
Control	142,033.92	0	0%
Hydrogel	73,432.21	68,601.71	48.3%
Groasis	41,666.67	100,367.25	70.7%

Discussion

Water-saving systems such as Groasis and Hydrogel may provide a profitable solution to help ensure food security with the limited annual rainfall and high cost of irrigation in the Galapagos archipelago. Compared with the conventional drip irrigation used locally, we found that Groasis and Hydrogel-supplemented systems increased tomato production by 25 and 31%, respectively, while using 71 and 48% less water. The extrapolated yield of tomatoes grown with Groasis or Hydrogel (9.46 and 9.91 t per 1000 $m^{2,}$ respectively) approached the minimum yield expected in mainland Ecuador (10-14 t per 1000 m^2), which has greater rainfall and cheaper irrigation water than the Galapagos Islands (Villavicencio and Vásquez, 2008).

Although Groasis used the least water, using Hydrogel for three months, followed by drip irrigation, was the most profitable treatment, yielding an 80% net return on investment, a 51% greater return than that provided by conventional drip irrigation alone (Table 2). The Groasis treatment provided a net return of 25%, which was only about half the return yielded with conventional drip irrigation (Table 2), largely due to the higher cost of Groasis at $12.50 per plant compared to $0.375 per plant for Hydrogel. Furthermore, the initial investment in Groasis required for a large area of tomato production may be cost-prohibitive for most farmers (Table 1). Another advantage of Hydrogel over Groasis is that it is much easier to use and can be applied directly to the soil of existing conventional irrigation systems without needing equipment changes. Hydrogel is thus currently the better system for reducing water consumption in conditions found in the Galapagos Islands. Groasis is also a valuable system but may be most profitable where subsidies are available to offset the initial costs or where water conservation is prioritized and a higher cost of water makes Groasis more profitable. Additionally, Groasis may be best suited for small-scale farms or home gardens, where it can altogether replace the need for otherwise costly irrigation systems.

The greater overall yield with water-saving systems was primarily driven by the production of heavier (by about 51 g) larger (by about 40 cm^3) tomatoes (Fig. 1), while the number of fruits produced did not differ between treatments. Larger, heavier fruit may trade off against fruit quality, with a lower ratio of tomato dry matter and nutrients to water (Patanè & Cosentino, 2010). In other words, the increased weight and size of tomatoes may be due to a greater water content of the fruit. Water availability can be and has been used to influence fruit quality in tomato cultivation by reducing the ratio of dry matter and nutrients to water (Mitchell *et al.,* 1991). However, the right amount of water should ideally be used to ensure good fruit quality while maintaining a profitable yield (Hanson *et al.,* 2006, Topcu *et al.,* 2007, Chen *et al.,* 2013, Zheng *et al.,* 2013, Wang *et al.,* 2015). It may be that Groasis and Hydrogel technologies are so efficient at supplying water to the tomatoes that the plants were effectively over-watered despite how little water these systems used.

Hydrogel polymer is potentially profitable by increasing tomato yield and reducing water consumption for a minimal initial investment of only $0.375 per plant per cycle. We suggest that farmers in the Galapagos begin to test our Hydrogel protocol within their own tomato crops since our results suggest that tomato production may be profitably increased by around 31% (Tables 1, 2 and 3 calculated for 0.1 ha of tomato production). Future studies should measure fruit quality, vary the amount of water used, and test these systems both inside and outside a greenhouse to determine the ideal watering regime under the range of agricultural conditions found in the Galapagos. Future work should also examine other crops grown in the Galapagos, measuring the nutritional value of produce grown using these systems and varying the amount of water applied with them at additional sites and larger scales. These results would produce valuable information for farmers in Galapagos, where irrigation water is limited and profitable, and local production is essential for long-term food security.

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