Multifunctional Plant Protection Mat for Urban Forestry

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1. Introduction

Planting a tree is easy, but growing a tree is not, especially in places where irrigation is not available and natural rainfall is inadequate or in unison with a plant's needs. For instance, the average life of a city tree is seven years, according to the Richmond, Va, arborist, Mr. Luke McCall. Other sources suggest similar values of ~10 years.[1, 2] Re-planting young trees every 10 years cannot establish the desired canopy coverage for cities. One of the biggest factors contributing to the short life of city trees is the fact that irrigation systems serving public spaces (e.g. road median) are rare due to legal and physical constraints. As such, juvenile trees must be hand-watered by crews using water trucks. Hand-watering is costly due to the labor, fuel and equipment required (hundreds of dollars per tree) creating an inefficient operation. Tree establishment requires consistent soil moisture content to ensure growth.[3]

Slow release watering bags are used for urban tree cares to save water and help young tree survival. Watering bags require labor and resources to refill them frequently with irrigation water. However, it may take too many resources to ensure their replenishment during unexpected drought periods for urban foresters. For example, the dry weather in June and July 2014 put the newly planted trees in danger in Richmond area so that "*Richmond urging residents to help water trees*" appeared on all local news media in the middle of July, 2014.[4-9] Everything counted, each filling of 20 gallons of water to a watering bag cost James River Grounds Management Inc $65, according to Ms. Greta Hoyt, the Business Developer of the company. In addition, these bags can be easily damaged by lawn mowers and trimmers. Richmond City Arborist McCall said "Once they are broken, they are useless." With a continuously growing urban forestry industry (over 5 million deciduous shade trees are planted each year in the U. S.[10-12]), municipal arborists and landscape contractors are faced with the costly chore of ensuring that these plantings are sufficiently watered and weeded until they are established.

As the need for irrigation and weed control increases and the associated costs continue to rise, heavy demand is placed on providers of new and improved irrigation and weed control methods and products. Innovation in the area of irrigation products has been slow and a myriad of commercially available products impose extremely high cost for growers, because each, like the watering bags, focuses on a single aspect of tree and plant establishment. Currently, there is no product that delivers the combination of essential benefits that growers need to establish trees.

While establishing canopy coverage is difficult, the many benefits of trees may have on energy saving,[13-15] aesthetics, environmental protection, recreation and economic gains are universally acknowledged by urban planners and local communities around the world.[16] Sufficient water and weed control are two key parameters for tree care. Providing a consistent source of water, even during drought periods through irrigation or other water supplies, greatly enhances the likelihood of newly-planted trees reaching maturity and provides strength in older trees as well. Good weed control is also essential for successful establishment of newly-planted trees for quick initial growth. However, trees often struggle to survive, due to moisture and nutrient competition from weeds.

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In addition, a CBS news[17] report – "*Lake Mead in Nevada pushed to new low by drought*" – illustrates a serious underlying challenge for establishing and maintaining urban trees, orchards and vineyards: **water scarcity**. A news search of this subject yields hundreds of similar results from mainstream media. Many of these stories focus on how severely the water shortage will affect agriculture producers and the general population alike in the southwest states of the U.S.[18-23] As pointed out in these reports, water scarcity is an increasing issue for these states. In fact, California may lose 17,000 jobs and $2.2 billion in 2014 due to drought and water scarcity.[18] Although eastern states do not experience such severe droughts as frequently, seasonal droughts and water shortages are still a reality. For instance, a report titled "*North Carolina–Virginia Conflict: The Lake Gaston Water Transfer*" published in 2007 shows the severity of this problem nationwide.[24]

According to National Oceanic and Atmospheric Administration, 80% of the U.S. territory suffers at least a seasonal drought annually.[25] Water conservation by using novel irrigation methods must be a keystone to reducing water usage for landscape, which ranges from 40% to 70% of household water usages,[26] and almost all the agriculture usage. This is because plant and landscape survivability is directly linked to proper water management by municipalities, businesses, farms, and homeowners.

TreeDiaper™ mat designed and developed by Zynnovation LLC uses the same materials that come from diapers (virgin or recycled). These mats use the SAP found in disposable diapers to hold large amount of water (from precipitation and/or irrigation) and slowly release the water to the soil near the plants. Plastics covers/fabrics with porous texture are used to slow down evaporation of water from the top of the mats. These fabrics also serve as a weed barrier. Tree Diaper™ mat can reduce overall water usage by up to 97% versus commercially available products, while at the same time providing soil erosion control, automatic rainwater storage, weed control, and weather protection. TreeDiaper™ is the first and only landscaping irrigation product to combine these benefits into one low-cost package. It promises to promote plant health by reducing dependence on water supply during severe droughts, cut weed control maintenance, and increase survival rates.

2. Company

Zynnovation LLC is focusing on developing environmental technologies, biomedical and materials technologies. Zynnovation was established in 2010 by Hailing Yang, (Ph.D. in Chemistry). Hailing's technical expertise is in the area of polymer recycling, green products, polymer chemistry and physics, adhesives, and polymer processing. Zynnovation utilized the facilities at The Analytics Corporation, Ashland, VA for research and development.

Dr. Yang has designed and invented a novel **patent-pending (US20140230322**) Weed Control and Moisture Conservation (WCMC) tree mat, which is marketed as Treediaper™. The Treediaper prototypes have been tested in multiple commercial applications such as municipal landscaping and nursery production in greater Richmond regions. These field testing activities were partially funded by an NSF SBIR award (July-December 2013) and partially by Founders' contributions.

3. Research Outcomes

TreeDiaper™ mats were fabricated and evaluated for performances under various conditions. Controlled environment trials and field tests, on multiple sites, were carried out in greenhouses and in road medians, parks, landscaping grounds, vineyards, and nurseries. Field tests are still

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underway in central Virginia. The results show that the first generation of TreeDiaper™ mats can suppress weed control and alleviate planting stress of trees, especially in drought conditions. TreeDiaper™ mats have high potential for commercialization for reducing water usage, labor and other maintenance costs while increasing survival rate of trees for urban forest management, park and recreation, and forest restoration.

A. Water distribution test. This experiment was setup during the highest temperature period of the year in August 2013. It was designed to answer a few questions from two potential customers and our plant specialist: "does the water go down to the soil?", "how fast?", and "how much?". Potting soil was placed into flower pots that were under a rain exclusion shelter. The initial relative soil moisture was about 3-4 (on a scale from 1-10 with 1 being very dry and 10 being soaked). Prototype TreeDiaper™ (WCMC) mats with about 15 lbs absorbed water were placed on the top of potting soil. Soil moisture levels were measured at 4-inch deep for 6 weeks. The weight of the TreeDiaper™(WCMC) mat and the total weight of pot plus mat were recorded.

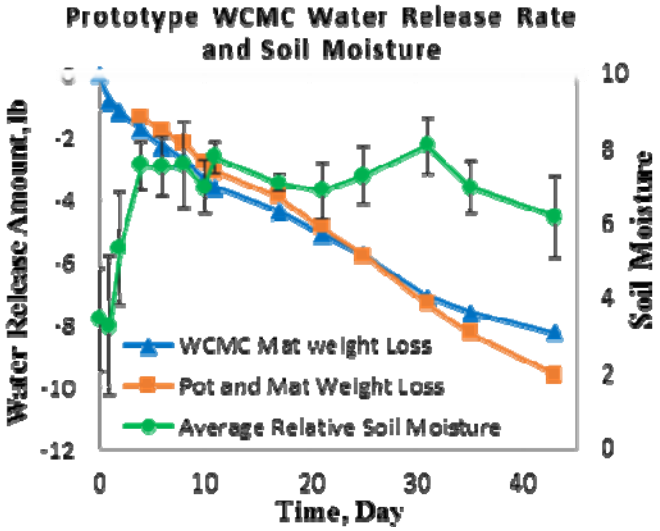

Figure 1. Water distribution test

The results are shown in Figure 1. It took 3 days for the soil moisture of 4 inches below surface rise from 3 to 6. Then in the following 40 days, the soil moisture was observed at a rather high level (6-8). Weight loss of mat was larger than the total weight loss initially; indicating water enters soil at the same time it evaporates from the mats and the potting soil. But the potting soil has a net gain in water. After 25 days, the total weight loss is larger than weight loss of the TreeDiaper™ mat. This suggests that the water in the mat became less available and there was more moisture evaporation than it obtained from the mat. At this point, more than half of the TreeDiaper™ (WCMC) mat's absorbency capacity became available for compensation of evaporation or movement down into the soil.

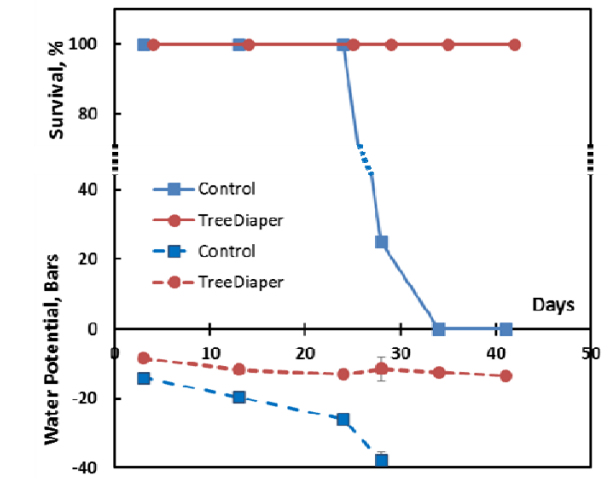

Figure 2. Western redcedar seedlings water potential (lower chart) and survival rate (upper) in sandy soil.

B Exposure to drought in sandy soil. Sandy soil is known to have poor water retention property and usually

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more frequent watering is required for planting. This experiment was defined whether the WCMC mat provides water retention and release that are necessary for seedlings being exposed to drought in sandy soils. In this bioassay, the Control condition is seedlings without WCMC mats. Each group of eight seedlings was exposed an extended drought cycle.

The results show (Figure 2) that the seedlings in control group had much lower water potential (i.e. higher water stress) than that in WCMC group. This suggests the poor water retention capability in sandy soil exposed the Control seedlings to extreme drought conditions. Six out of eight seedlings died before 26 days and none survived for 34 days. The seedlings in two TreeDiaper (WCMC) groups all survived the trial period. The Control group had minimal height growth and no diameter growth and no root growth during the dry down treatment. The WCMC group had root growth throughout the soil profile that helped the seedling survive the experiment period. A larger-sized and more sophisticated experiment is needed to be conclusive, but it is clear from this trial that WCMC mats can provide protections for trees against severe drought.

C. Field trials. During the Phase I period, several field trials were setup in a nursery farm, public parks and road median in the greater Richmond area of Virginia. All of these field trials are still on-going.

Urban Forestry (Richmond, VA) The Urban Forestry department of the City of Richmond, VA is mandated to plant more than 2,000 trees every year. External contractors are hired to plant these trees but the department does maintenances including watering, de-weeding, pruning, and removing dead trees. They use watering bags for every newly planted trees, and they are supposed to keep watering them for two to three years. The department has ten 200-gallon tanks on 6 diesel trucks (gas mileage: 15 MPG). A full tank of water allows them to water 10 trees. Then the trucks have to return to the station for refilling. Average round trip back to watering site takes 15 miles and 40 minutes. So each day one truck plus two crew members can water 80 trees. Consider equipment service time and other duties of the trucks and crew members, watering all first year trees as frequent as needed is impossible, let alone the second and third year trees. Actually, the city Arborist, Mr. Luke McCall told us that he has difficulties just to water them once a month, while the requirement to use watering bags is to refill at least once per week.

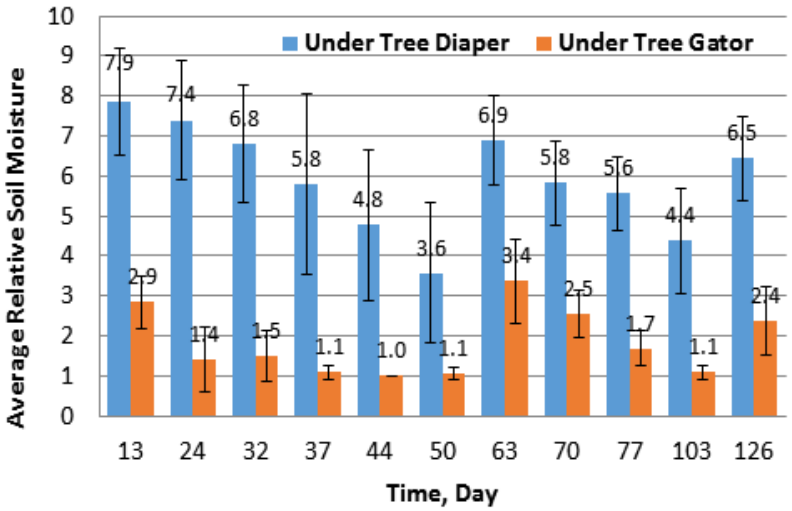

Figure 3. Soil moisture of TreeDiaper mats compared to watering bags in the road median of Jefferson Davis Hwy, Richmond VA.

Zynnovation installed 20 TreeDiaper™ mats in the road median of Jefferson Davis Highway in August 2013. Luke's team manages more than 200 newly planted trees and shrubs on this site.

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Before the installment of TreeDiaper™ mats, all had been installed with watering bags. Figure 3 shows the soil moisture level under TreeDiaper™ compared to that under watering bags (randomly selected from nearby trees). For most of time in an unusually wet summer with a late drought, soil moisture level under TreeDiaper™ was from 4 to 8, which was most suitable for most plants to grow. It was at least 2 times higher than that under watering bags. Soil moisture data from two field tests set up in the parks of Hanover County agrees with the data shown in Figure 3.

In a seasonal drought in City of Richmond in June-July 2014, the performance of TreeDiaper™ after 11 month was demonstrated with a "**live** *vs* **dead**" comparison (Figure 4) against the City's standard operations. Trees installed with TreeDiapers are all green and strong, while trees installed with watering bags (removed early in 2014) are all dead.

Figure 4. Performance comparison of TreeDiaper mats (upper) compared to watering bags (lower) in the road median of Jefferson Davis Hwy, Richmond VA. Pictures were taken on July 18th, 2014 during a seasonal drought.

The other problem Mr. McCall has with the watering bags is that they can be easily damaged by lawn mowers and trimmers. The broken bags are no longer effective since they lose the slow release function. After TreeDiaper™ mats were installed, the same issue was quickly brought to our attention as some of them were broken. Intended to observe how these damaged TreeDiaper™ mats perform, they were not replaced. Some SAP materials came out of the mats, but the majority SAP remained in mats to perform the designed function: catch and slow release precipitations as well as suppress weed growth. Water evaporation from the damaged sections was visually observed to be faster, while weed control was not apparently affected.

Urban Orchard (Chesterfield, VA) In June 2013, the grounds supervisor of Chesterfield County, Virginia, Ms. Stacey Arnold started an urban orchard project for demonstration and recreation purpose for the county residents. Zynnovation had a chance to install 10 TreeDiaper™ mats for half of the fruit trees while watering bags were used for the other 10 trees. The selection of tree species was done before Zynnovation was involved in this project and it included a variety of different fruit trees. Although it cannot be considered as a scientifically sound experimental design of experiment, it was a chance to test TreeDiaper™ mats on different fruit trees. Fruit tree care is one of the markets Zynnovation intends to penetrate. Ms. Arnold and her staff were on schedule in filling the watering bags whenever there was less than one inch rain during a 7-day period. TreeDiaper™ mats were not watered throughout the year in 2013. Despite their diligence, the average relative soil moisture level under TreeDiaper™ mats (~7.7) was still higher than that under Watering bags (~7.5).

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With the accurate watering record and the precipitation record from weather.org, we could calculated the amount of water received by each tree. Watering bags were manually filled 4 times with total of 60 gallons for each tree. From June to December, 2013, Treediaper™ mats received total of 26 inches of rain since they were planted, this corresponds to 50 gallons during this period using 24 inch diameter mat and 4-inch diameter tree hole. We assume all the rain water were collected and stored since runoff could not be estimated. Because the cone shape (estimated diameter at bottom is 12 inches) of watering bags, rain drops are excluded from entering underneath soil. The total excluded rain water is estimated to be 11 gallons of rain water per tree. The accumulative water amount available for each tree is shown in Figure 5. Although the numbers are not supported by actual measurements, the total water amounts are about same at the end of the 180 days period. It is in good agreement with the soil moisture level measurements. A few things might have been missed in the calculation: runoff rainwater from TreeDiaper™ mats, runoff irrigation water from watering bags, and rainwater flows into the area covered by watering bags. Better estimation could be derived by including the measurement of runoff water amount.

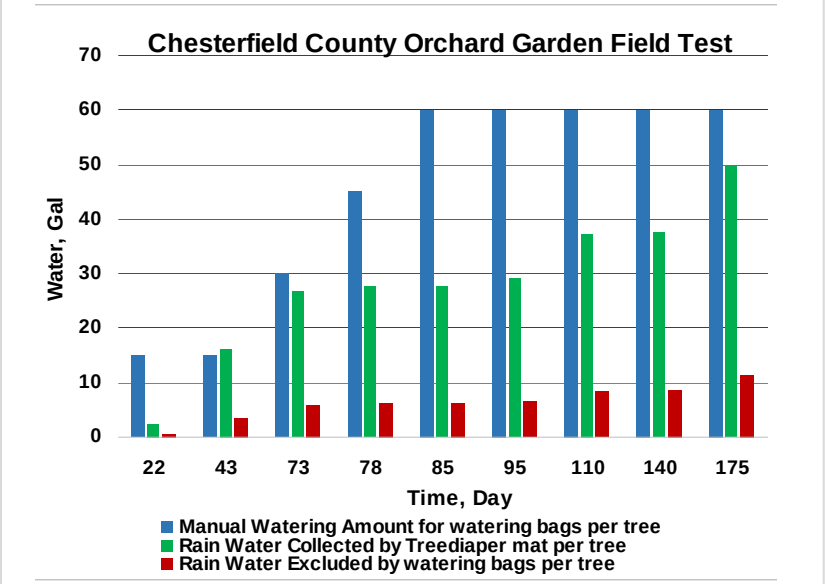

Figure 5. The accumulated rain water collected by TreeDiaper mats, irrigation water and rain water shielded by watering bags per tree in the Urban Orchard field test (rain record obtained from weather.org for zip code 23832)

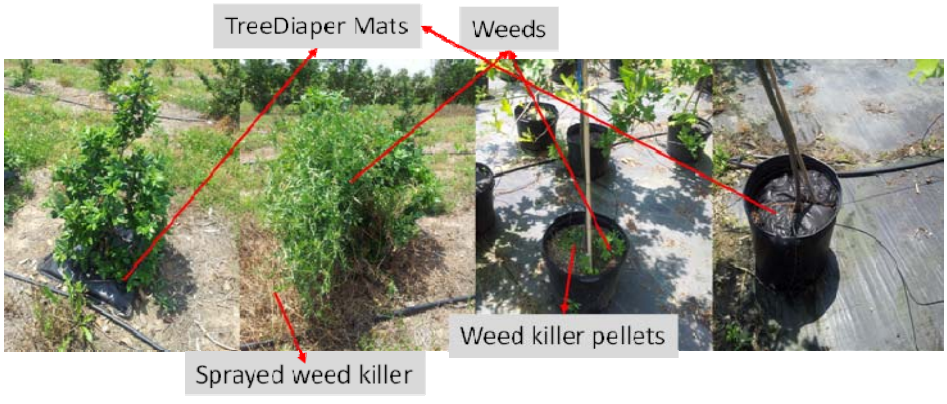

Figure 6. The weed control effects on local nursery farms

D. Weed Management. The overall weed control results of our Treediapers are very good. First, the fabrics used to make the prototypes are commercially available weed barrier fabrics. Second, the swelled SAP secures the WCMC mat on the ground so that air and sunlight cannot reach

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weeds, which would die without photosynthesis. The weight of mats also provides extra pressure to prevent grass penetrating, which happens to single layer of weed fabrics. Figure 6 shows comparison of weed control effect on local nursery field and pot farms.

E. Soil Temperature Measurement. During a field trip to one testing site in October 2013, researchers noticed a big temperature difference above and under the TreeDiaper mats. A literature review on the temperature effects on root growth as well as plants winter protection showed that 5-30 ^{o}C is the temperature range for root growth for most plants on this planet. Therefore, an experiment was designed to measure soil temperatures during winter 2013. Soil temperatures were measured in the road median of Jefferson Davis Highway in City of Richmond from January to February of 2014. Sensors were buried 3" below soil surface. In Figure 7, daily mean or high temperatures (weather.org), air temperature on site when measurements were done (some were taken in early morning when temperature was close to the min temperature of the specific day), soil temperature under TreeDiaper™ mats and watering bags are reported. The results showed that the soil temperature under TreeDiaper™ mats remained around 5 ^{o}C in one of the coldest days in January, while the temperature under watering bags was about 1-2 ^{o}C. For a continuous cold period, the results showed the soil

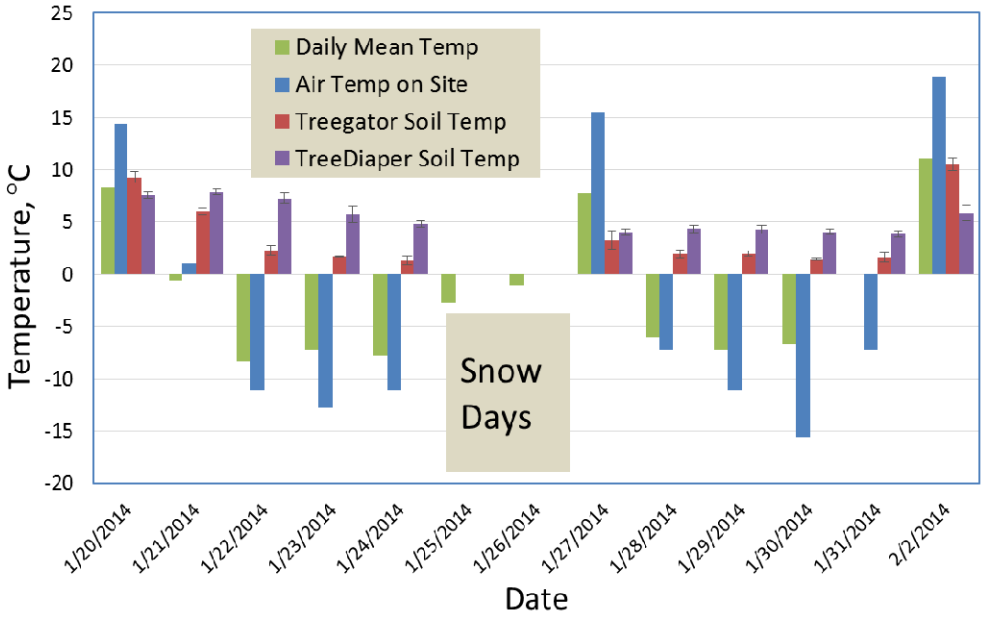

Figure 7. Soil temperatures (3" below soil surface) on Jefferson Davis Highway of City of Richmond in January-February 2014

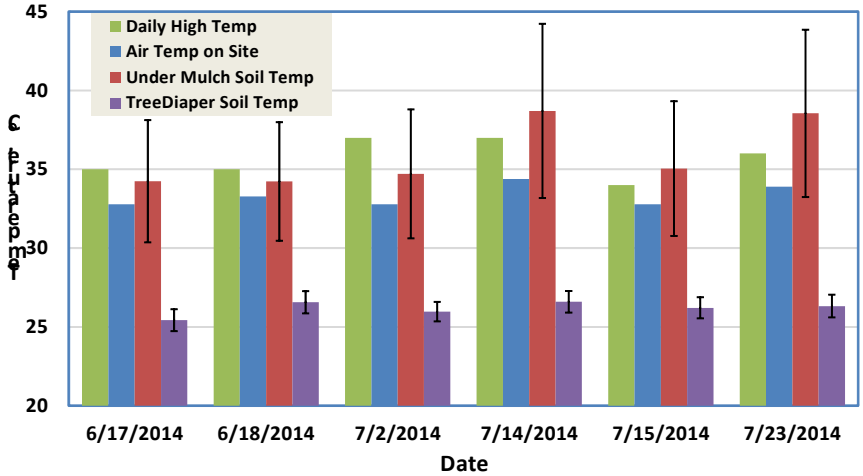

Figure 8. Soil temperatures (3" below soil surface) in the parks of Poor Farm and Taylor in Hanover County in June and July 2014.

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temperature under Treediaper™ mats were also 3-5 ºC higher than that under watering bags.

In some of the warm days of winter (i.e. February 2, 2014), the temperature under TreeDiaper™ mats was lower than the temperature that under watering bags. This indicates that in the very hot summer days, soil temperature under TreeDiaper™ mats will be lower than that under watering bags to offer hot weather protection for trees. A summer intern student from VCU was recruited to perform the summer temperature experiment. However, temperature data could not be collected in the road median of the City of Richmond because of vandalization of temperature sensors. Therefore, temperatures were only collected from the two parks in Hanover County in the days with high temperature above 90 F (32 ºC). Data is shown in Figure 8. In the hottest days, the soil temperature under TreeDiaper was lower than 27 ºC. Much higher average temperatures, 34-38 ºC (as high as 45 ºC), were recorded for trees covered with mulch only. The direct sun exposure does contribute much to the soil temperature.

F. Environmental Impacts. To check if there was contaminations from the mats, water samples were collected from runoff water from WCMC mats and soil samples were collected from under mats. Water samples were tested for the routine of chemicals (water pH, hardness, Pb, N) and total carbon amount (TOC). Results are shown in Table 1. Soil tests included the routine chemicals (analysis for soil pH, P, K, Ca, Mg. Zn. Mn, Cu, Fe and B), organic matter, and soluble salts (pesticides and fertilizer), as shown in Table 2. Nothing abnormal was found. The results also show that the mats did not take up any nutrients from soil that would be essential for trees.

Table 1. Analytical results for leaching water samples

Leaching water sample	New WCMC Mat	WCMC Mat on field for 10 months	Partially Decomposed Mulch
Cyanuric acid, ppm	0	0	-
pH	6.8-7.2	6.5-6.8	-
Total Alkalinity, ppm	100	80	-
Free Chlorine, ppm	0	0	-
Total Hardness, ppm	50	50	-
Total Chlorine/Bromine, ppm	0	0	0
Total Organic Carbon, mg/L	111	515	779

Table 2. Soil sample tests results

Analysis results			Soil pH	Soluble Salts	Est.-CEC,%	Organic Matters, %	Micronutrients (Zn, Mn, Cu, Fe)
Chesterfield	Site 1	0	7.6	Low	4.2	2.3	SUFF
		10	7.3	Low	7.2	3.5	SUFF
Richmond	Site 1	0	6.5	N/A	5.8	N/A	SUFF
		8	7.3	Low	6.8	6.7	SUFF
	Site 2	0	6.4	N/A	5.3	N/A	SUFF
		8	6.8	Low	5.7	2.9	SUFF
Colesville	Site 1	0	6.8	Low	6.8	4.9	SUFF
		6	6.6	Low	7.3	4.6	SUFF
Hanover	Site 1	0	5.4	Low	4.9	3.1	SUFF
		9	5.8	Low	3.6	2.9	SUFF
	Site 2	0	6.6	Low	7.2	4.4	SUFF
		6	6.6	Low	9.2	14.4	SUFF
	Site 3	0	5.7	Low	3.5	2.4	SUFF
		6	6.9	Low	6.6	5.9	SUFF

4. Commercial Impacts

Tree Diaper is an advanced plant hydration system. It is the first and only landscaping product to combine the functions of slow release irrigation that automatically

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recharges during rain storms. It also provides weed control and insulates the root structure from temperature extremes. All these features are incorporated into this one, low cost package that is like an insurance policy for the survival of young trees or plants. This product can serve the needs of urban foresters, nursery/greenhouse owners, orchard and vineyard growers and backyard gardeners.

Commercially available slow release watering bags such as Tree Gator®, Arbor Rain™, Hippo Bag™, and Ooze Tube® are also used for tree care. The use of these products saves water and helps the survival of young trees. But they also require labor and resources to refill periodically. It is very costly to bring water to hard-to-reach areas and perform maintenances. Arborists have been looking for a product that can eliminate the need of watering and maintenance for trees in these areas.

TreeDiaper™ was designed to have at least two functions in weed control and slow irrigation. The rain collection feature dramatically reduced water usage. In regions that have only seasonal droughts like Central Virginia, irrigation can be eliminated. The water-filled TreeDiaper™ mats also effectively control weed growth because it blocks sunlight and oxygen. The wholesale and retail prices of competitive products like Tree Gator®, Arbor Rain™, Hippo Bag™, Ooze Tube® are roughly same in the range from $16 to $25 for a 15-gallon bag. They do not have weed control functions. Mulch and weed control rings are either made from recycled tire rubber or natural fibers with retail prices ~ $20 each for 3' diameter ones. They do not offer more functions than conventional wood chip mulching except that they may last longer.

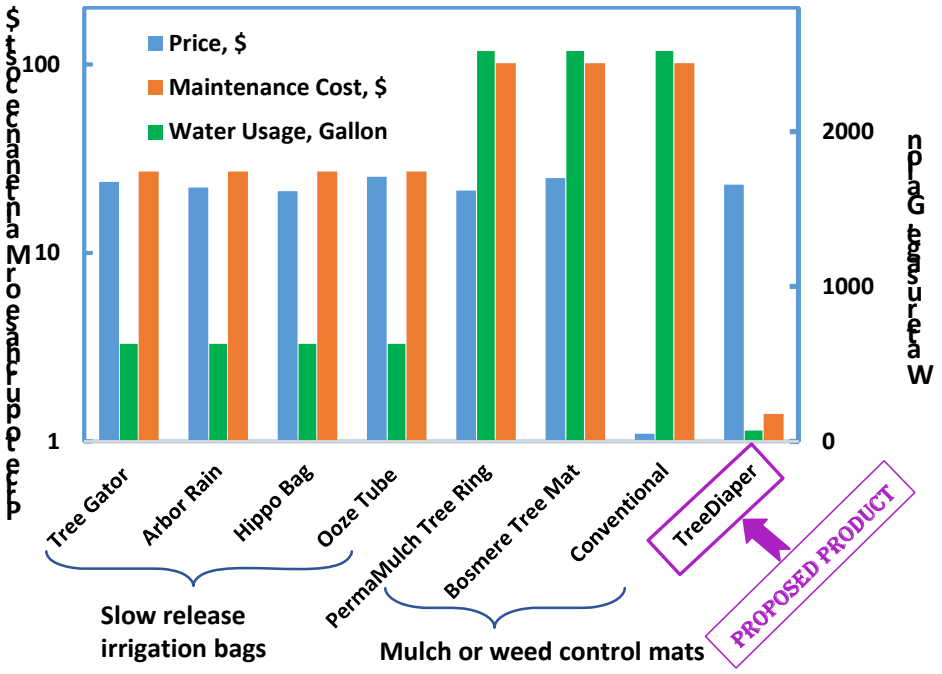

Figure 9. Competitive products are compared with TreeDiaper on purchase / maintain costs (left, Logarithmic Scale) and water usage (right) for each newly planted trees during the first 3 years

For conventional tree planting using wood chips mulching, watering twice a week with roughly 40 gallons each time is the professional standard. For slow release watering bags, the specified watering frequency is also very similar at once a week, which takes about ~20 gallons of water each time. TreeDiaper mats only require irrigation once per month only if there is less

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than 2 inches of rain during that period. Cost analysis revealed significant saving on water usage and maintenance cost. The maintenance cost includes labor for watering and weed control, water, herbicides, transportation, and other materials / supplies. TreeDiaper can save up to 97% of water usage compared to wood mulches and conventional watering method and up to 90% water over the slow release watering bags. A maintenance cost saving of 95% can be realized. The performance of the prototypes are superior to competitors' products in both water conservation and weed control, as illustrated in Figure 9 and Table 4.

Table 4. Comparison of current innovation with competitons[(a)]

Competing Products	% Water Savings	Weed Control	Accept & Store Rainwater	Recycled Components	Weather Protection	Soil Erosion Control	% Cost Saving[(b)]
Mulch	0	Neutral	Neutral	Green Waste	Neutral	Neutral	0
Tree Gator	75	Negative	NO	None	No	No	73
Arbor Rain,	75	Negative	NO	None	No	No	73
Ooze Tube	75	Negative	NO	None	No	No	73
Rubber Mat	0	Positive	NO	Tire	Neutral	Yes	0
Coco Fiber Mat	0	Neutral	NO	N/A	Neutral	Yes	0
TreeDiaper	**97**	**Positive**	**YES**	**Diaper**	**Yes**	**Yes**	**99**

(a) The products are compared to mulch with conventional watering and weed control.
(b) Cost saving on maintenance including labor and materials for watering and de-weeding.

With WCMC mat, urban foresters can reduce cost and expand tree canopy coverage while staying within shrinking budgets of many local governments. The WCMC mats are proven to increase the survival rates of trees during severe droughts with less or no irrigations. Costs for tree planting and after-planting care can be dramatically lower. It will also significantly improve potential tree survival by increased moisture level in the soil near root systems. It will benefit US agriculture products and reforestation programs, as well as help conserve global forest and water resources. Owners of land, household, orchards, vineyards, and nurseries can benefit from increased survival and growth rate and reduced irrigation / weed control cost.

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