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A comparative life cycle assessment of flood and drip irrigation for guayule rubber production using experimental field data

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ABSTRACT

Guayule (*Parthenium argentatum*) is a woody, perennial desert shrub, native to the arid American Southwest. It produces natural rubber that can be used to replace Hevea natural rubber for U.S. domestic rubber demands. Irrigation water application and practices form an important component of its agricultural cultivation process. A comparative gate-to-gate lifecycle assessment (LCA) was conducted to examine two different irrigation practices in guayule rubber production-blocked furrow irrigation (denoted as flood) and sub-surface drip irrigation (SDI, denoted as drip). In flood irrigation, furrows are used to convey water flooded from one end of the field. In drip irrigation, the plant is irrigated more frequently with lighter amounts using drip tapes buried beneath crop rows. All relevant field data to conduct the LCA were obtained from experimental plots in Maricopa, AZ.

This study, the first of its kind for guayule, compares the metrics of energy consumption, lifecycle environmental impacts and irrigation water productivity. Drip irrigation showed a more efficient use of the applied water by generating higher rubber (46%) and bagasse (dry matter) yields (49%) compared to flood irrigation. Percent change calculations (with drip irrigation as the reference), showed that as a result of greater efficiency of water application in the drip irrigation system, it has between close-to-equal to 51% lower environmental impacts in various categories (with 23% lower impacts averaged over all impact categories). On the other hand, drip irrigation showed 13% higher energy consumption than flood because of the additional burdens of water pumping. Whereas water application was the foremost contributor to impact burdens in both flood and drip irrigations, the additional burdens of water pumping and sulfuric acid use for maintaining blockage-free drip tape were also noteworthy in the drip system. Experimental field operations were the central contributor to energy consumption in both irrigation methods. By separating a crucial stage of guayule production, namely irrigation, connections emerge between various key parameters in the two irrigation methods; accordingly, the outcomes from the evaluation of these two irrigation systems can assist with decision-making in the lifecycle framework of guayule rubber production.

1. Introduction

Natural rubber is an indispensable component in industries such as tire production and healthcare products (Rasutis, 2014) because of its greater resilience and durability compared to synthetically manufactured rubber (Sfeir et al., 2014). The United States (US) is the second largest importer of natural rubber, purchasing 10% of total world imports, next to China, which imports 27%. Thailand is the largest supplier at 33% followed by Indonesia at 27% (OEC, 2016) of a natural rubber produced by the rubber tree *Hevea brasiliensis*. Regions in Southeast Asia have changed their land use patterns in order to meet worldwide demands for natural rubber. For example Thailand has increased its land use for rubber plantations by 90% over the past five decades (Petsri et al., 2013), and such changes in land use may lead to the damage of diverse ecosystems. Consequently, these regions risk facing long-term detrimental environmental impacts (Mann December, 2015).

An alternative that could reduce the United States' dependence on rubber imports is another naturally occurring perennial rubber shrub, *Parthenium argentatum*, or guayule, which is native to northern Mexico and the U.S. Southwest (Soratana et al., 2014). The shrub

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has a rubber content that is typically 4–7% after about two years of growth, but with greater age may reach a much higher percentage (Thompson and Ray, 1989). Based on studies in literature, guayule biomass can reach about 13,600 kg/ha annually and rubber yields may approach 1000 kg/ha/yr, after several years of growth (van Beilen and Poirier, 2007; Rasutis et al., 2015). Its natural growth rate is low and can be improved with irrigation in arid regions. Applied water (irrigation and rainfall) for guayule has been reported to range from as low as 280 mm per year (NAS, 1977) to as high as 2135 mm annually (Bucks et al., 1985a). While guayule has much lower fertilizer and chemical requirements compared to other agricultural crops, its water productivity is also lower than most commercially produced crops (Foster and Coffelt, 2005). Therefore, the irrigation management of guayule cultivation forms an especially crucial component in its production. Currently available guayule irrigation research primarily conducted in the 1980s or earlier, has provided some understanding into its water requirement and management (Hunsaker and Elshikha, 2014). Irrigation studies conducted in central and southwestern Arizona have confirmed that economical guayule production requires at least 1500 mm of total water applied (irrigation plus rainfall) annually in the arid southwestern desert regions of the US (Bucks et al., 1985a,b). This amount of irrigation is significantly greater than believed prior to these studies. Development of improved irrigation management practices and comparisons between different irrigation practices are therefore needed to increase the water productivity and yield productivity of large-scale commercialized guayule efforts that are envisioned in the US Southwest.

The United States Department of Agriculture (USDA) estimates agriculture as accounting for 80–90% of the total consumptive water-use of ground and surface water in the US (USDA-ERS, 2015). For this reason, more efficient water management practices in crop cultivation need to be developed. Two irrigation methods were considered in this study: the first method was blocked furrow irrigation (also called simply furrow or flood irrigation), where furrows are made in the soil usually at 1.02 m (or 40 in.) spacing to distribute water applied by flood irrigation to the plant rows. In blocked furrows, border dikes are formed at the bottom end of the furrows, so that there is no water runoff from the plot. The second method was sub-surface drip irrigation (SDI denoted as drip in this study), where plants are irrigated more precisely along rows using drip tape that is buried about 0.20–0.25 m below the soil surface in the plant row. While flood irrigation may providing easier seedling establishment than drip, the seasonal water application efficiencies for some furrow systems can be as low as 50–60% (Dasberg and Or, 1999), whereas overall application efficiencies of >90% for drip can often be attained (Skaggs, 2001). However, some flood irrigation systems, e.g., level basins, may sometimes attain application efficiencies closer to those for drip, particularly if the systems are well-designed and are precisely graded with laser-leveling equipment (Dedrick, 1984). The higher application efficiency and lower water applied attributed to drip irrigation generally comes from eliminating deep percolation and runoff, reducing soil evaporation, and minimizing weed growth (Schwankl, 1997) (though blocked-furrow and level basin irrigation do not have runoff). The reduced irrigation water use commonly associated with drip versus flood irrigation does not have a negative effect on yield (Roth et al., 1995; Sharmasarkar et al., 2001), and it has been shown that crop yields using drip are equal to or better than yields realized with other irrigation methods (Camp et al., 2016; Patel and Rajput, 2008). Radin et al. (Radin et al., 1992) reported daily drip irrigation for cotton increased irrigation water productivity (lint yield per unit irrigation applied) by 48% compared to furrow irrigation applied from 10 to 14 day intervals in Arizona. The higher frequency irrigation with drip contributes to the boost in yields. The farm and ranch irrigation survey for five southwestern US states relevant to guayule production (AZ, CA, TX, CO, NM) shows that the number of farms in the United States using drip/trickle irrigation systems increased from 16,382 to 22,432 (USDA, 2013b) between 1998 and 2008, whereas those using gravity irrigation systems decreased from 43,375 to 35,786 (USDA, 2013a), indicating that agricultural practices may be shifting towards the adoption of more efficient irrigation techniques. Agriculture in these states included high value crops such as lettuce, pecans, almonds, grapes, cotton, forage crops, onions, and wheat (ERS, 2016; Owen, 2008). However, drip irrigation has rarely been used for irrigating guayule except for a few studies that were conducted on very small plots (Benzioni et al., 1989; Abrahams et al., 1984; Ostler and Martineau, 1983). Therefore, the effectiveness of drip irrigation has not yet been tested in guayule cultivation.

Additionally, there is an absence of life cycle analyses (LCAs) in literature comparing the impacts of flood vs. drip irrigation in agriculture-particularly so in guayule production. The goal of this study, which to our knowledge is the first of its kind, is to conduct a gate-to-gate comparative LCA to evaluate the energy use and environmental impacts of the two aforementioned irrigation methods for guayule production. This study is a 'gate-to-gate' LCA since it considers only a specific portion of the lifecycle of guayule rubber, i.e., irrigation. LCA is an important tool in assessing the sustainability of a product or process, especially in the early stages of the product's establishment. LCA is commonly used to categorize the life-cycle environmental impacts through the different stages of a product or process in a methodological approach as follows: (a) defining the processes that will be included in the LCA and establishing a system boundary, (b) establishing an inventory of life-cycle data (LCI), (c) assessing individual and cumulative impacts (including energy use) of various process stages (LCIA), (d) interpreting these results in the context of the system being evaluated. The International Organization for Standardization (ISO) 14,040 (International Organization for Standardization, 2006) is the standard that describes methods to conduct LCAs and report environmental impacts. In an LCA, a functional unit specifies the measure of the function of a given system to ensure comparability of results on a common basis- in this case a kg of guayule rubber, which is the product of interest. All inputs and outputs in the LCI and LCIA stages are related to the specified functional unit (International Organization for Standardization, 2006). Centering LCA efforts, as in this study, on an important stage in guayule production supports environmental decisions; this study will form a part of a larger cradle-to-grave LCA of guayule rubber and its use.

2. Methods

In this section, the two irrigation systems and experimental plots are described briefly. Water application quantities on plots, and resulting rubber and dry matter yields are presented. Primarily, a depiction of the LCA system boundary, model setup, data collection, and establishment of the life-cycle inventory, as well as details of impact assessment are also discussed. Lastly, model limitations are considered.

2.1. Guayule irrigation techniques on experimental plots

While some of the methodologies and certain results (such as first year yields) of the flood and drip experimental field setups have been previously described by co-authors (Hunsaker and Elshikha, 2014; Hunsaker and Elshikha, 2016), a summary of the pertinent methodologies and results of the field experiments are described in this section as these were used to develop and conduct the LCA – these descriptions provide context for the present LCA study.