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Long-rotation sugarcane in Hawaii sustains high carbon accumulation and radiation use efficiency in 2nd year of growth

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ABSTRACT

Sugarcane has been a major agronomic crop in Hawaii with an unique, high-yield, two-year production system. However, parameters relevant to advanced, cellulosic biofuel production, such as net ecosystem productivity (NEP) and radiation use efficiency (RUE), have not been evaluated in Hawaii under commercial production. Recent demand potential has rekindled interest in Hawaiian grown biofuels; as such, there is a need to understand productivity under changing climate and agronomic practices. To this end, we established two eddy covariance towers in commercial sugarcane fields in Maui, Hawaii to evaluate the carbon balance and RUE of sugarcane under contrasting elevations and soil types. We combined the tower observations with biometric and satellite data to assess RUE in terms of net biomass accumulation and daily gross primary production. High, sustained net NEP was found in both fields (cumulative NEP 4.23–5.37 × 10^3 g C m^{-2} over the course of the measurement period). Biomass RUE was statistically similar for both fields (1.15–1.24 g above ground biomass per MJ intercepted solar irradiance). Carbon accumulated in both fields at nearly the same rate with differences in cumulative biomass due to differing crop cycle lengths; cumulative gross primary productivity and ecosystem respiration were higher in the lower elevation field. Contrary to previous studies in Hawaiian sugarcane, we did not see a large decrease in NEP or increase in ecosystem respiration in the 2nd year, which we attributed to suppressed decomposition of dead cane stalks and leaves due to drip irrigation and drought. Biomass RUE also showed little decline in the 2nd year. The results show that Hawaiian sugarcane has a higher productivity than sugarcane grown in other regions of the world and also suggests that a longer (>12 months) growing cycle may be optimal for biomass production.

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1. Introduction

Sugarcane is one of the most advantageous agronomic crops for biofuels due to its high productivity, efficiency, and return on energy investment (Goldemberg et al., 2008; Waclawovsky et al., 2010), which results in proportionally greater greenhouse gas reductions than other agronomic biofuels (De Vries et al., 2010; Davis et al., 2012). As with other crops, using sugarcane in advanced conversion techniques incentivizes different agronomic qualities (e.g., plant biomass accumulation and enhanced resource use efficiency) versus traditional traits (e.g., maximum sugar yield) (Muchow et al., 1996; Van der Weijde et al., 2013). Growth and efficiency properties that are advantageous for advanced biofuels, such as net biomass accumulation and radiation use efficiency (RUE), have been investigated for sugarcane using micrometeorological (Cabral et al., 2011, 2013), remote sensing (Portz et al., 2011), and field trial/biometric approaches (Inman-Bamber et al., 2011).

Hawaii is one region where cellulosic biofuel crops are being evaluated. The Hawaiian islands have been a significant, highly-productive, sugarcane region, but most of the commercial operations ceased in the 1980s and 1990s due to economic pressures (Heinz and Osgood, 2009). Following cessation of sugarcane cultivation, these lands have reverted back to pasture

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and forest and have been identified as potential source areas for biofuels (Keffer et al., 2006). Recent emergence of potentially large and stable consumers (e.g., the United States Navy) of advanced biofuels in Hawaii, (Closson, 2013; Steiner, 2012) has spurred renewed interest in growing sugarcane and other high biomass grasses. However, little research on the unique Hawaiian sugarcane system has been done since the decline of the industry and its research organization, the Hawaiian Sugar Planters' Association (Heinz and Osgood, 2009).

Hawaiian sugarcane production is distinguished by two major features compared to other regions. One is the extensive reliance on drip irrigation (Moore and Fitschen, 1990). The other is a much longer growing period (∼24 months) compared to other sugarcane growing regions (Allen et al., 1998). Previous studies have found that biomass accumulation (Evensen et al., 1997) and RUE (Muchow et al., 1997) decrease significantly during the 2nd year of growth. However, assessment of biomass and carbon accumulation in these highly productive environments is challenging, especially in the 2nd year, due to difficulties in recovering desiccated sugarcane leaves (trash) and accounting for stalk dynamics (Muchow et al., 1997). Assessment of sugarcane productivity and efficiency in Hawaii has relied on plot based studies often with narrower row spacing than commercial plantations (Evensen et al., 1997) that may affect the temporal growth dynamics of sugarcane. These studies have also had widely-spaced (>100 days) periodic sampling, which reduces the resolution of detecting changes in carbon accumulation and RUE in response to crop age and meteorological conditions. Furthermore, climate changes, including reduced frequency of trade winds (Garza et al., 2012) and decreased associated precipitation (Norton et al., 2011), and wide-spread adoption of disease resistant cultivars have occurred in Hawaiian sugarcane systems. The impacts of these changes on biomass accumulation and radiation have not been studied

Eddy covariance (EC) has been used to make non-destructive, highly temporally-resolved, field-scale observations of sugarcane carbon accumulation and controls on growth in rain-fed systems in Australia (Denmead et al., 2009) and Brazil (Cabral et al., 2013). However, to the best of our knowledge, no EC observations have been reported for either irrigated or Hawaiian sugarcane systems. In this study, we used two EC towers in commercial sugarcane fields in Maui, Hawaii with contrasting elevations and soil types in combination with remote sensing and biometric approaches. Our objectives were two-fold. First, we evaluated whether recent climatic changes in Hawaii have changed the temporal pattern of sugarcane RUE and carbon/biomass accumulation. We hypothesize that the drier locations in our study would result in larger biomass accumulation and higher RUE into the 2nd year of production than previously found due to lower stalk mortality and reduced decay of detritus (also known as trash in sugarcane production literature). Second, we assessed whether the adoption of drip irrigation reduced the impact of soil type and elevation on sugarcane growth and biomass accumulation. Higher-elevation Hawaiian fields have historically had sugarcane rotations up to 36 months to maximize sucrose accumulation (Heinz and Osgood, 2009). Additionally, higher elevation fields tend to have greater slopes which make furrow irrigation practices difficult. We hypothesize that drip irrigation and associated fertigation would enable more precise, site-specific irrigation and fertilization to meet sugarcane growth needs, thus reducing biomass accumulation differences between locations with different soil types and elevations as well as reducing inaccessible below ground biomass growth. Answering these two objectives will help update life cycle analyses (e.g., Davis et al., 2009) for comparison of sugarcane with alternative potential biofuel crops and cultivation practices in Hawaii and elsewhere.

2. Methods

2.1. Study site and cultivation practices

Our study sites were located on a ∼15,000 ha commercial sugarcane (*Saccharum officinarum* L.) plantation (hereafter referred to as "the farm") in Central Maui, Hawaii, USA (Fig. 1). More details of the farm and experimental setup can be found in Anderson et al. (2014) and Anderson and Wang (2014). Per common practice in Hawaii (Evensen et al., 1997; Heinz and Osgood, 2009), the farm grows sugarcane on a 24-month cycle. The sugarcane is grown from a seed cane crop and is not ratooned. Many areas of the farm have been in continuous sugarcane cultivation for over 100 years. Due to its predominantly Leeward location, the farm uses drip irrigation (Moore and Fitschen, 1990) to supplement highly spatially variable precipitation that ranges from less than 300 to more than 1200 mm year^{-1} across the plantation (Giambelluca et al., 2013). Prior to planting, the soil is tilled to a depth of approximately 60 cm and soil amendments, including lime, mill mud, and sand, are added to balance soil pH and to fertilize according to commercial practice. Drip irrigation lines are laid out

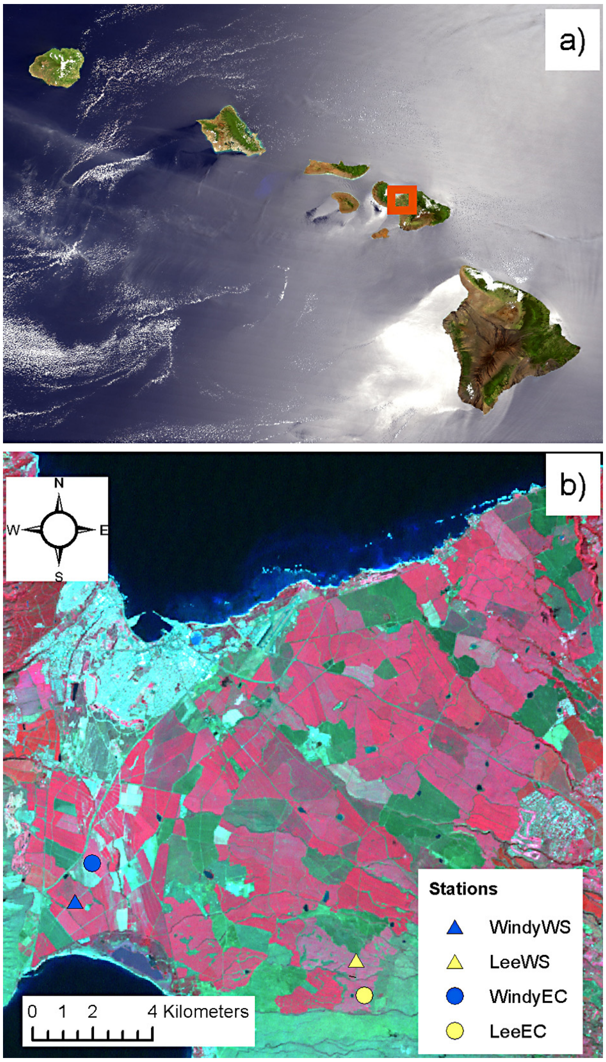

Fig. 1. (a) True color image of the Hawaiian Islands from MODIS – Terra. Study area inset in red box. (b) Landsat 8 false color image (bands 6, 5, and 4 corresponding to red, green, and blue) showing eddy covariance (EC) and weather station (WS) in relation to the farm. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)