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Exploring Water Use and Production Dynamics of Indigenous Protected Sikumi Forest in South Western Zimbabwe

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Exploring water use and production dynamics of indigenous protected Sikumi forest in south western Zimbabwe

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Key words: Indigenous forest; evapotranspiration; ecosystem functioning; climate change; measures of ecosystem stability

Abstract

Monitoring changes in carbon and water vapour fluxes over a landscape helps in understanding ecosystem functioning and improves vegetation management. To understand potential shifts in ecosystem functioning, MoDerate Resolution Imaging Spectroradiometer (MODIS) evapotranspiration (ET), net photosynthesis, gross primary production and net primary production data were explored in Sikumi forest dominated by three species clusters (Teak forest woodland, Miombo woodland and savannah, and *Vachellia*). Measures of ecosystem stability including water use efficiency (WUE), rainfall use efficiency (RUE), evaporative index, and carbon use efficiency (CUE) were assessed for trends and step changes together with rainfall and evapotranspiration data. Miombo woodland and savannah had significantly higher actual ET and production compared to *Vachellia* and Teak clusters. Ecosystem production was strongly coupled with precipitation as the *Vachellia* and Teak clusters became sources of carbon during the dry season. High production in the Miombo cluster even during the dry season could be linked to xylem rehydration and convergent evolution to harvest additional water and nutrients. Annual net primary production in Sikumi forest was 632±189 g C m^{-2}. Despite relatively small spatial coverage (12%), the *Vachellia* cluster contributed production similar to the Teak and Miombo woodlands clusters that covered 63 and 25% respectively of the forest area possibly due to soil fertility. Teak had the highest CUE (62%) but lowest NPP, possibly due to high respiration. The relationship between rainfall, NPP and measures of ecosystem stability was unimodal. This provided insights into the likely trajectory of these indices within the purview of climate change. The low RUE of the Teak cluster suggests that this cluster was more sensitive to disturbance. The study area was water limited as shown by a low ETa/PET ratio. Monitoring carbon and water flux dynamics help to identify the onset of ecosystem change and may inform requisite interventions to improve ecosystem functioning.

Introduction

Autotrophs produce new biomass via the process of photosynthesis. This process typifies the close coupling between the carbon and water cycles, which are essential for ecological functioning and provision of ecosystem services (Murray et al. 2019). During photosynthesis, plants release water vapour through evapotranspiration (ET), in exchange for atmospheric carbon. For vegetated land surfaces, ET rates are closely related to the carbon fixation rates of plants and can be used as an indicator of plant ecological functioning. Net primary production typifies this new biomass created over a given time and is critical in evaluating ecosystem functionality. Evapotranspiration is the combined process of water loss from the soil, surfaces and transpiration. Transpiration relates to loss of water vapour via the small pores on leaf surfaces called stomata. Through links between stomatal conductance and carbon exchange, plant ET serves as a regulator of key ecosystem processes. It provides insights into ecologically important aspects of climate linked to energy supply, water balance and plant productivity. Within the context of global environmental changes, it is vital to evaluate the performance of each landscape in terms of plant – atmosphere exchanges as it helps to predict earth system processes (Murray et al. 2019).

Forests are critical in attenuating global warming since they sequester carbon via the process of photosynthesis. In addition, they play an important role in producing and regulating the world's temperatures, fresh water flows and other ecosystem services. Therefore, the maintenance of healthy forests is critical for human wellbeing. Globally, indigenous forests are under pressure from degradation, climate change, and human appropriation of net primary production. As a result most patches of indigenous forests have been transformed. Zimbabwe prides itself as a country with remarkable quantities of indigenous forest. In Zimbabwe, the dynamics in water vapour and carbon fluxes have not been adequately described especially over indigenous forests. Even in neighbouring Zambia there is a dearth of studies that focus on water vapour and carbon fluxes and hence it is important to investigate these dynamics at the lower rainfall end gradient of the indigenous forest belt of Southern Africa. The Zimbabwean situation is also unique in that buffer zones that had been left around gazetted forests have been compromised by resettling people during the watershed fast track land reform programme in 2000. This has consequently increased disturbances in protected forests and consequently affecting water vapour and carbon dynamics.

Some of the unifying concepts in terms of diagnosing ecosystem stability include water use efficiency (WUE) or rainfall use efficiency (RUE), evaporative index and carbon use efficiency (CUE). In southern Africa, there is paucity of ecological observation infrastructure to effectively monitor ecosystems functioning. However, with growing availability of satellite data to support ecosystem monitoring, it becomes possible to analyse spatial-temporal dynamics in these measures of ecosystem stability. The study seeks to explore water vapour and carbon dynamics in Sikumi protected indigenous forest in south western Zimbabwe. The study employs ET, NPP and GPP data from MoDerate resolution imaging spectroradiometer (MODIS) sensors as well as rainfall derived from Tropical Application of Meteorology Using Satellite data and Ground Based Observations (TAMSAT). Such spatio-temporal studies are critical to monitoring ecosystem to help decipher any shifts in ecosystem functioning.

Methods and Study Site

Study site

The study area encompasses the entire 54 400 ha Sikumi forest in Matabeleland North province, Zimbabwe. The study area is an indigenous forest which is gazetted and protected under the auspices of the Forest Act Cap 19:05. The Forestry Commission of Zimbabwe conveniently divided the forest reserve into clusters based on species dominance. These include the *Baikaiaea plurijuga* or Zambezi teak woodland forest cluster (63%), followed by Miombo woodland and savana cluster (25%), and the *Vachellia* spp cluster (12%). An important feature is that Sikumi forest lies predominantly on Kalahari Sands geological formations which are characterised by deep sandy soils. The *Vachellia* cluster occupies extensive areas within the forests that have eutrophic soils that are developed from base-rich geological formations.

Evapotranspiration and rainfall data

We accessed the MOD16 ET product from the DAAC website (https://lpdaac.usgs.gov/) to compute ET. The Tropical Applications of Meteorology Using Satellite Data and Ground-Based Observations (TAMSAT) (Tarnavsky et al., 2014) was also used to compute rainfall. The data was accumulated into annual sums and 8 day sums to be consistent with MODIS products to facilitate easy analysis. Annual pattern of ET and rainfall data were tested for the presence of trends using the Mann-Kendall trend test and step change using the Pettitt or median change point between the year 2000 and 2018. Detecting changes in ET data is useful in determining ecosystem functioning in terms of water vapour fluxes.

Net primary production and water use efficiency

We also accessed the MOD17A2 and MOD17A3 products (https://lpdaac.usgs.gov/) to determine carbon sequestration in the vegetation stand. The correlation between rainfall and net photosynthesis (PsnNet) and the MOD17A3 were explored to help uncover the influence of rainfall on carbon capture. Subsequently, the WUE, RUE, CUE were computed

Measures of ecosystem stability

To determine ecosystem resilience, WUE, RUE, evaporative index, and CUE were determined. Subsequently, the Mann-Kendall trend test and Pettitt tests were applied on these indices. In addition the relationship between these indices and precipitation was explored. The Kruskall Wallis test was applied to test for any significant differences at 95% confidence interval.

Results

Water flux

Over the 18 year study period, 8 day mean ETa ranged from 11 to 22.5 mm across different species cluster while average 8 day rainfall was 1.82 mm. The average ETa for the Miombo cluster was significantly higher ($p < 0.001$) than that of the *Vachellia* and Teak clusters while ETa from the latter two were similar. Rainfall was similar across species types and it was the most variable water flux followed by ETa from the Vachellia, Teak and finally that of the Miombo cluster. The averaged 8-day ETa followed the pattern of rainfall, although a significant amount occurs during the long winter dry spell, particularly for the Miombo woodland and savannah cluster. ETa for Teak woodland ranged from 2.5 to 23.3 while that for the Miombo woodland and savanna cluster ranged from 11.7 to 37.7 mm and that of *Vachellia* cluster ranged from 1.5 to 28.7 mm per 8-day period. On an annual basis, average ETa for the Teak forest and woodland cluster (503.2±106 mm) was significantly ($p < 0.05$) lower than that from that of Miombo woodland and savannah cluster (572.71±116) and marginally ($p < 0.1$) different from that of the *Vachellia* cluster (563±111. PET was consistently higher than ETa with an average ETa/PET of 0.22 over the eighteen year study period. Annual ETa was relatively low during periods of high (>750 mm) rainfall and relatively higher during periods of lower (< 750 mm) rainfall.

Pattern of carbon fluxes

Despite marked seasonality in the long-term rainfall pattern, production occurred throughout much of the year. V*achellia* and Teak woodland became sources of carbon by DoY 273 while the Miombo wodlands and savannah cluster remained productive with a minimum of 6.8 g C m^{-2} 8 day^{-1} period. Average Net photosynthesis for the Miombo and savannah woodlands (26.3±11) was significantly higher ($p < 0.01$) than that of the *Vachellia* (16.4±11) and Teak (15.8±100) clusters. The coefficient of variation for Miombo (41%) was relatively lower than that of Teak (63%) and *Vachellia* (67%). On an annual basis, average NPP for Sikumi forest was 632± 189 g C m^{-2}. Production from Miombo (645.4±192 g C m^{-2}) was higher than that of *Vachellia* (631.6±194 g C m^{-2}) and Teak (619±181 g C m^{-2}). The annual rate of change in NPP for Vachellia and Miombo cluster was 14 g while that for Teak forest, it was 13 g C m^{-2}. Over the study period, Miombo woodland and savannah (12.3 C Kg m^{-2}) contributed the highest amount of carbon, followed by *Vachellia* (12 Kg C m^{-2}) and finally Teak forest and woodland (11.8 kg C m^{-2}) . Across all the studied species clusters, rainfall and NPP displayed a polynomial relationship. Beyond annual rainfall of 700 mm, NPP began to decline.

Measures of ecosystem stability

The Teak and woodland forest had a relatively lower evaporative index compared to Miombo and Vachellia species clusters. During the study period, Teak forest had the highest WUE ($p < 0.05$) compared to Miombo woodland and savannah and *Vachellia* cluster. No trend was detected in the evaporative index of clusters though Kindall's *tau* was positive. The CUE of Teak forest and woodland were significantly higher ($p < 0.001$) than that of Miombo woodland and savannah but similar to that of the *Vachellia* cluster. WUE, CUE, and RUE were strongly coupled to rainfall. However, when rainfall exceeded 700 mm, they all began to decline.

Discussion and Conclusions

Influence of species cluster on water and carbon dynamics

Despite marked seasonality of rainfall, a significant amount of ETa, especially for the Miombo cluster took place during the dry season when rainfall was negligible. This suggests that such vegetation could be accessing ground water or has high water storage potential to support ecosystem processes. However, given the very low water table in the Kalahari Sands, not all trees may access groundwater. The apparent pre-rainfall greening in the savannah could suggest that additional water comes from plant storage system or ground water (Ryan et al. 2017). This pre greening could be explained by vegetation convergent evolution linked to xylem rehydration at the height of the dry season owing to the long distance xylem transport (Vinya et al. 2018). The ETa/PET ratio was 0.22, indicating that the area was water limited.

In terms of carbon, the Miombo woodland and savannah cluster remained productive during extremely dry conditions while the *Vachellia* and Teak and woodland became carbon sources. The high productivity of the Miombo cluster suggests that the trees could have been accessing additional water by deploying a number of strategies such as deep roots as well as lateral roots that enable it to effectively harness water and nutrients (. The mean annual NPP was lower than the 9 to 12 tons ha^{-1} reported for Miombo woodlands of Zambia (Day et al. 2014). Despite that the Vachellia cluster covered only 12% of the area, it contributed average cumulative NPP similar to Miombo woodland and savanna and Teak over the 18 year period, suggesting that the species cluster was critical in the water and carbon dynamics of Sikumi forest.

Many studies have found a positive relationship between rainfall and NPP since increased rainfall improves water supply and the process of photosynthesis. Admittedly, temperature influences NPP but in the study area, temperature was not limiting as shown by the low ETa/PET ratio as well as the consistently higher PET compared to ETa. The unimodal relationship between rainfall and NPP suggests convergent evolution of the trees species in this area to reach optimal production at around 700 mm of annual rainfall. We postulate that beyond 700 mm high nutrient leaching in these Kalahari Sands derived soils undermine plant nutrient absorption.

Ecosystem stability

The relationship between ETa and rainfall was consistent with the well-established theoretical framework that during periods of low rainfall the evaporative index tends to be relatively higher compared to times of high rainfall (Zhang et al. 2001). The fact that the evaporative index was occasionally > 1 or even at unity suggest that the plants had access to additional moisture probably from underground or moisture stored in the plant system in the deep Kalahari Sands. Governments should consider commercial cultivation of teak given its high WUE than to leave it to grow naturally in demarcated forests. Relatively lower amount of rainfall falling on Teak was used in plant biomass production compared to the Miombo woodland and savannah and *Vachellia* clusters. Hence, besides rainfall, other factors (anthropogenic, nutrients) had more impact in vegetation production with respect to the Teak cluster than the *Vachellia* and Miombo clusters. This suggests that teak could be more sensitive to disturbance than other clusters.

About 55% of photosynthetic production was assimilated into new plant biomass in the Sikumi forest. This was higher than the global average of 45% (He et al., 2018). The Teak cluster had the highest CUE, suggesting that it had the higher carbon conversion efficiency and therefore critical in attenuating global warmings. We found relatively high CUE (0.43 – 0.62) and this was similar to results reported elsewhere (0.47 – 0.6) (Chen and Yu 2019). In a context of increasing atmospheric CO_2, teak would be critical in carbon sequestration. Hence, Teak could play a more important role in attenuating global warming. Therefore, maintenance of the vegetation will be critical not only for the timber industry but also for global change science. However, the relatively lower NPP of Teak compared to other clusters suggests a potentially higher respiration in Teak

Neither trends nor step changes were detected in the evaporative index, WUE, RUE and CUE in Sikumi forest, suggesting that the ecosystem remained relatively stable during the study period. The stability of these ecosystem indicators suggests that the ecosystem is resilient and no marked changes are taking place. Rainfall was strongly coupled with water vapour and carbon fluxes in the study area. However as soon as rainfall reached 700 mm, WUE, CUE and RUE began to decline, because optimum productivity conditions will have been surpassed.

In conclusion, water use and carbon assimilation at Sikumi forestry were strongly coupled with the rainfall input. However, production especially for Miombo woodlands cluster continued even during the dry season possibly due to xylem rehydration and access to ground water. Despite a high carbon conversion efficiency by the Teak cluster (62%) and large spatial coverage, it contributed the least in terms of NPP owing to a possibly high respiration in the cluster. The anticipated reduction in mean annual rainfall in the study site is likely to result in a decline in these ecosystem indicators and a deterioration in ecosystem services at Sikumi forest since the relationship between measures of ecosystem stability and rainfall was unimodal. The stability of these measures of ecosystem stability suggests that the ecosystem was resilient during the study period. The Teak cluster was more sensitive to disturbance than other clusters as shown by low rainfall use efficiency. It is critical to continuously monitor carbon and water flux dynamics in the study to help identify the onset of ecosystem change and make requite interventions to improve ecosystem functioning.

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