Agricultural Water Innovations in the Tropics (AgWIT)

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Executive Summary

The Agricultural Water Innovations in the Tropics (AgWIT) research consortium engaged in a range of research activities in order to evaluate crop water footprints in rainfed and irrigated cropping systems, and to evaluate potential impacts related to biochar additions to soil as a possible management option. Biochar is a charcoal made from organic material added to soil to increase carbon content and improve water retention capabilities.

A central finding from our efforts is that biochar additions to the soil can increase plant available water; however, there is much variability in response determined by unique geographical and climatic factors. Digging deeper into tropical agriculture in Costa Rica as a case study, we found that adding biochar allowed rice plants to access larger stores of water more consistently. This means that crops growing in biochar-amended soil could access soil water for seven extra days without irrigation relative to control treatments without biochar.

Methodological advances developed in the project included development of low-tech and inexpensive tools to extract water from plants—a necessary step for measuring “where from” plants take their water. These methods can be easily applied at locations with limited access to state-of-the-art resources and ultimately help manage water resources to fulfill agricultural and other competing water needs.

UAVs with hyperspectral and thermal imaging systems were employed to investigate the influence of biochar additions on plant water status and physiology. It also provided complementary information to in situ data regarding plant productivity to assess crop responses to biochar. For instance, increases in canopy chlorophyll and biomass estimates were found for rice grown in the biochar amended plots, along with increased crop water use efficiency, with differences depending on biochar type and application.

A large effort in AgWit concerned three aspects of technological development: (i) sensor integration and synergies exploitation (hyperspectral+thermal+RGB consumer grade cameras) on drones; (ii) data correction and calibration (e.g. cloudiness and turbulence effects); and (iii) modeling developments of energy, water and carbon fluxes, first tested on closeby pilot sites in Denmark and then in the field in Costa Rica. Applications of the above developments at the eddy covariance sites and biochar experiments are a first step to obtain “everywhere and all the time” estimates of crop water use and productivity, and to connect field and satellite estimates present at disparate scales.

Eddy covariance flux towers were operated in Brazil and Costa Rica throughout the project. This approach facilitated quantification of irrigation rates relative to crop water use (evapotranspiration), allowing a reduction in irrigation amounts by 20% by stakeholders. A plot based experiment in Brazil involving biochar addition to soils relative to an eddy covariance-monitored control is scheduled to be completed in June 2021. Also in Brazil, eddy covariance flux towers were operated on forest systems to provide a reference to agricultural sites. These forest flux towers provided the basis for several research advances regarding tree growth and mortality, as well as carbon and water implications due to forest degradation.

Introduction

Global food security through agricultural trade, exemplified by the doubling of grain imports to the EU over 2000-2010 (Eurostat 2015), depends upon the capacity of producing countries to sustain the hydrological and environmental foundations of agricultural production. Ideally, agricultural trade enables the provision of goods and services that are produced in less water-stressed regions via global virtual water trade patterns. For example, the EU as a unit is a net importer of virtual water (Steen-Olsen et al., 2012), defined as the sum of evapotranspiration by crops (the major component) and industrial water consumed from field to market. There is an urgent need to develop methodologies to increase water use efficiencies in both rainfed and irrigated agriculture locally in order to improve food and water security globally. In addition to the need for on-the-ground advancements in local contexts, more precise determinations of volumetric water footprints and impacts of water consumption are needed to assess agricultural sustainability, and to enable the inclusion of environmental impacts from water consumption in product life cycle assessments (Chenoweth et al., 2014) in a context of global trade. Innovations that comprehensively address the food-water-energy nexus across this local-to-global axis are required to meet human demands for food while maintaining water and energy security - a trilemma entailing some of society's greatest challenges. Given that most of the expansion and intensification of global agricultural production over the next several decades is projected to take place in tropical regions (Foley et al., 2011), innovations in tropical agricultural water management are particularly crucial. This need becomes more urgent when considering that the variability of tropical rainfall patterns is expected to increase due to climate change, particularly in terms of the arrival, duration and intensities of seasonal rainfall (Feng et al., 2013).

Intensification of water use in agriculture, water pollution, and climate-induced changes in freshwater availability are all increasing vulnerability within the global food system. Strategies to maximize agricultural production and minimize environmental impacts through the large-scale deployment of negative-emissions technologies (e.g., technologies that result in the net removal of greenhouse gases (GHGs) from the atmosphere (Vuuren et al., 2013) are critical to improving agricultural sustainability. Biochar-based soil amendments (i.e., charcoal derived from waste biomass sources for use in soil) are exceptional in this context since, in addition to generally increasing crop yields (Liu et al., 2013) and improving the water holding capacity of agricultural soils (Omondi et al., 2016), they also represent a global negative emission potential of 0.7 Pg C yr^{-1} (Smith, 2016).

The Agricultural Water Innovations in the Tropics (AgWIT) partnership was established to test key agricultural management innovations that have the potential to lower impacts on water resources while improving climate change resiliency of irrigated and rainfed tropical agricultural systems that export crops to the EU. In particular, AgWIT sought to test the influence of biochar additions on rainfed and irrigated cropping systems located in two seasonally dry tropical countries. AgWIT incorporated eddy covariance towers in Brazil and Costa Rica established through two prior projects funded by the Freshwater Security Initiative of the Belmont Forum. Eddy covariance is the current gold standard for quantifying water vapour, carbon dioxide, and energy fluxes between the land surface and the atmosphere. Using this unique network of tropical agricultural water observatories, AgWIT investigated crop volumetric water footprints, carbon footprints, and water and carbon use efficiencies, providing sustainability benchmarks relative to resource appropriation indicators (i.e., environmental footprints).

AgWIT augmented the established agricultural water observatory platforms by adding (1) detailed measurements of crop light use efficiencies, photosynthesis and canopy stress dynamics using sensors integrated with Unmanned Aerial Vehicles (UAVs); (2) detailed assessments of plant water use and soil water dynamics via isotopic sampling and hydrologic modelling; (3) field-based cropping trials to assess biochar effects on plant, soil and water processes; and (4) detailed assessments of water, carbon and land footprints under rainfed and irrigated conditions (with and without biochar additions), permitting benchmarking of alternative production strategies relative to current crop performance. Overall, AgWIT efforts entailed measured and modelled research under irrigated and rainfed conditions, with and without biochar additions, for agricultural goods exported to the EU from two tropical producer countries.

Methodology

AgWIT incorporated a broad range of methodologies, including:

- Data synthesis of published studies to evaluate:
    - Impacts of biochar on soil physical and hydraulic properties;
    - Impacts of biochar on evapotranspiration;
- Eddy covariance flux towers to determine carbon, water and energy fluxes at the field-scale to empirically determine crop water footprints in rainfed and irrigated cropping systems;
- Field-based small-plot experiments to investigate:
    - Impacts of biochar on water fluxes in tropical agriculture using stable isotopes;
    - Effect of biochar and sugarcane filtercake as soil amendments on soil chemical, carbon stocks, and soil water retention;
- UAV flights to capture hyperspectral and thermal imagery to evaluate:
    - Upland rice growth and water use efficiency after biochar application.

Significant efforts were also directed towards methodological developments to support the broad-based methodologies listed above. These included:

- Innovation in biochar production
    - NTU developed a novel biochar production method involving residual biomass and ceramsite;

- Innovation in isotopic sampling
    - Development of plant water extraction methods for isotopic analysis using locally-sourced materials;
- Innovation in UAV-based remote sensing
    - Development of methods to determine stomatal conductance, transpiration, and photosynthesis for drought stressed crops using hyperspectral and thermal sensing.
- Innovation in remote sensing modeling
    - Determination of normalized spectral entropy from the power spectral density of vegetation indices to identify features related to the water stress. Spectral entropy was introduced as a means to quantify water stress.

Results and Discussion

Data synthesis: Our analysis of literature-derived observational data showed that while biochar additions to soil generally increase the soil water holding capacity, it can have variable impacts on soil water retention relative to control conditions. Our modelling demonstrated that biochar increases plant water availability, and therefore long-term evapotranspiration rates, by increasing soil water retention capacity – especially in water-limited regions. Empirical evidence indicates that biochar amendments generally increased crop yields (75% of the compiled studies) and, in several cases (35% of the compiled studies), simultaneously increased yield and water use efficiencies. Hence, while biochar amendments are promising, the potential for variable impact highlights the need for targeted research on how biochar affects the soil-plant-water cycle. For more details, please see Fischer, B.M.C., S. Manzoni, L. Morillas, M. Garcia, M.S. Johnson, S.W. Lyon (2018). Improving agricultural water use efficiency with biochar - A synthesis of biochar effects on water storage and fluxes across scales, *Science of the Total Environment*, 657:853-862 https://doi.org/10.1016/j.scitotenv.2018.11.312.

Stable isotopes: From a methodological perspective, we observed that the application of isotopic analysis to soil-plant systems is hampered by the high-energy and specialized materials required to extract water from plant materials. Therefore, we developed novel low-tech approaches using locally-sourced materials for plant water extraction. These low-tech methods allow extracting plant water consistently and comparably to what can be done with state-of-the-art methods. These results are methodologically promising for the rapid expansion of isotopic investigations, especially for citizen science and/or school projects, or in remote areas. For more details, please see Fischer, B.M.C., Frentress, J., Manzoni, S., Cousins, S.A.O., Hugelius, G., Greger, M., Smittenberg, R.H., Lyon, S.W. (2019). Mojito, anyone? An exploration of low-tech plant water extraction methods for isotopic analysis using locally-sourced materials, *Frontiers in Earth Science*, 7, 150, https://doi.org/10.3389/feart.2019.00150.

Stable isotopes (continued): Focusing on upland rice as a case study, we collected hydrometric and isotopic data to quantify plant available water and uptake across the growing season under variations in biochar amendment. Soil water retention curves for biochar treated soils shifted, indicating that rice plants had 2% to 7% more water available relative to the control plots. The stable water isotope composition of plant water showed that the rice plants preferentially utilized water from the top 20 cm of the soil instead of using the deeper and more reliable sources of water. Our results indicated that rice plants in biochar amended soils could access larger stores of water more consistently and thus could withstand dry spells better than rice grown in non-treated soils. However, supplemental irrigation was required to facilitate plant growth during extended dry periods. Therefore, biochar amendments can complement, but not necessarily replace, other water management strategies. A paper detailing these results is in progress [Fischer, B., L. Morillas, J. Rojas Conejo, R. Sánchez-Murillo, A. Suárez Serrano, J. Frentress, C.H. Cheng, M. Garcia, S. Manzoni, M.S. Johnson and S.W. Lyon. Investigating the impacts of biochar on water fluxes in tropical agriculture using stable isotopes.]

Water footprints: We empirically quantified total crop water use (CWU) and water footprints (WFs) of rainfed upland rice (wet season) and groundwater-irrigated melons (dry season) grown sequentially as a double cropping system, one of the major cropping systems in the seasonally dry province of Guanacaste in northwestern Costa Rica. Data for this study were measured with a state-of-the-art eddy covariance water and carbon flux station. Upland rice only consumed green water (CWUgreen = 383 L/m2), while melons only consumed blue water (CWUblue = 177 L/m2). Irrigation was found to be 1.5 times larger than the actual melon water consumption, with better irrigation efficiencies than reported for melon farms in Brazil but slightly inferior to farms in Spain. Melon WFblue was 79 m3/t, a much lower value than global and regional estimates reported but similar to values reported for melons produced in Brazil or Spain. Upland rice WFgreen (681 m3/t) was reported for the first time and was proven to be much lower than flood irrigated-rice WFblue-green. Our results demonstrated lower overall water demand for upland rice-melon double crop compared to the two other major monocultures of the region (flood-irrigated rice and irrigated sugar cane). For more information, please see Morillas, L., S. V. Hund, and M. S. Johnson (2019). Water use dynamics in double cropping of rainfed upland rice and irrigated melons produced under drought-prone tropical conditions, Water Resources Research, 55(5), 4110-4127, https://doi.org/10.1029/2018WR023757. Further results are forthcoming as field research on the small plot experiment at Fazenda Nascente in Mato Grosso Brazil are continuing through mid-2021.

Remote sensing: A field campaign using hyperspectral and thermal cameras from an unmanned aerial system (UAS) was conducted on a biochar experimental site planted with upland rice (Oryza sativa L.) during a dry-spell period prior to harvest in Costa Rica. The experiment consisted of two treatment groups with bamboo biochar and sugarcane biochar amendments, and one control group without biochar application. Rice canopy biophysical variables were estimated by inversion of a canopy radiative transfer model on hyperspectral data. Soil moisture content was estimated using a temperature-vegetation dryness index derived from UAS, and plant evapotranspiration (ET) using energy balance and aerodynamic equations form UAS-derived land surface parameters and the weather data at the site. Variations in gross primary production (GPP) and WUE across treatments were estimated from the variations in normalized difference vegetation index (NDVI), canopy chlorophyll content (CCC), and ET. We found that CCC and NDVI were significantly higher in both biochar groups than in the control, which resulted in higher GPP by 41.9±3.4 % when using bamboo biochar and 17.5±3.4 % when using sugarcane biochar respectively. These higher GPP values were probably due to higher soil moisture in the biochar-amended plots, and led to significantly higher WUE by 40.8±3.5 % in bamboo biochar and 13.4±3.5 % in sugarcane biochar applications. This study demonstrated the use of hyperspectral and thermal sensing from drone to quantify biochar effects on tropical dry cropland by incorporating with ground point samples and physical models. A paper detailing these results is in progress [Jin H., B.M.C. Fischer, J. Rojas-Conejo, C.J. Köppl, M.S. Johnson, L. Morillas, S.W. Lyon, A. Duran-Quesada, A. Suárez-Serrano, S. Manzoni, M. Garcia. Quantifying upland rice growth and water use efficiency after biochar application with drone-based hyperspectral and thermal imagery. In review at Agriculture, Ecosystems and Environment.]

The results above are mainly related to AgWIT's central hypothesis that biochar additions increase water availability by increasing soil water retention capacity without altering the pools of water available for plants, resulting in improved crop water use metrics. In addition to these primary results, the project facilitated a number of related scientific advances. These are briefly summarized below:

- Development of a novel evapotranspiration model facilitated through AgWIT eddy flux tower data demonstrating that near-surface atmospheric relative humidity (rh) fundamentally coevolves with rh at the land surface. The new model expresses the latent heat flux as a combination of thermodynamic processes in the atmospheric surface layer. This approach builds on the Penman-Monteith equation but uses only routinely measured abiotic variables, avoiding the need to parameterize surface resistance. The results also demonstrate that the latent heat portion of available energy (i.e., evaporative fraction) at local scales is mainly controlled by the vertical rh gradient. By demonstrating how land surface conditions become encoded in the atmospheric state, this study will improve our fundamental understanding of Earth's climate and the terrestrial water cycle. [Paper currently in open review in *Hydrology and Earth System Science*, https://hess.copernicus.org/preprints/hess-2020-643/]
- Investigation of non-structural carbon storage strategies in tropical trees in relation to growth and mortality.
    - Herrera-Ramirez, D., Sierra, C., Römermann, C., Muhr, J., Trumbore, S. E., Silvério, D., Brando, P. M., Hartmann, H. (2021). Starch and lipid storage strategies in tropical trees relate to growth and mortality. New Phytologist, 230(1), 139-154. https://doi.org/10.1111/nph.17239. [open access]
- Evaluate of the influence of prolonged tropical forest degradation due to compounding disturbances on CO_2 and water fluxes
    - Brando, P. M., Silvério, D., Maracahipes-Santos, L., Oliveira-Santos, C., Levick, S. R., Coe, M. T., Migliavacca, M., Balch, J. K., Macedo, M. N., Nepstad, D. C., Maracahipes, L., Davidson, E., Asner, G., Kolle, O., Trumbore, S. E. (2019). Prolonged tropical forest degradation due to compounding disturbances: Implications for CO_2 and H_2O fluxes. Global Change Biology, 25(9), 2855-2868. http://doi.org/10.1111/gcb.14659.

Recommendations

In terms of reducing crop water footprints, water balance accounting can help target if current practices are overly water intensive. The water balance approach needs to consider drainage requirements so that salts do not build up in soils. For the double cropping system investigated in Costa Rica (irrigated melons during the dry season followed by rainfed upland rice grown during the rainy season), the annual wet season provides adequate soil water fluxes to sufficiently flush out any salts that accumulate during the dry season. For this system, monitoring of irrigation amounts and soil moisture in the root zone can be sufficient to ensure that irrigation amounts are appropriate. Our detailed measurements of dry season evapotranspiration (i.e., crop water use) found that irrigation practices could be reduced without any impact on crop growth. The stakeholder partner hosting AgWIT field work reduced irrigation amounts by 20%, saving money and water, and reducing the crop water footprint.

Biochar additions to tropical agricultural systems appears to be a promising management strategy for improving drought resiliency for rainfed systems and reducing irrigation requirements for irrigated systems. However, biochar use requires further research before best practices can be broadly disseminated. This is because can be produced from a wide range of feedstock materials, resulting in biochars with differing physical and physical characteristics. Potential biochar users should evaluate the influence of a specific biochar within their cropping system on an exploratory/research basis (e.g., small plot trial) to ensure compatibility with soils and crops for the particular biochar and at a specific application rate before using biochar to a significant level. We note that for a good match between cropping system characteristics and the biochar (e.g., resulting soil pH and micronutrient levels at desired levels following biochar additions), biochar additions may be considered on a long time scale such as one application every 10 years or as conditions suggest.

In the AgWIT project, we followed up on a study of candidate biochars before moving to the small plot stage. Details on this screening stage are available at Speratti et al. (2017, https://onlinelibrary.wiley.com/doi/full/10.1111/gcbb.12489). This resulted in biochar produced from sugarcane filtercake residuals as the material of choice based on availability in tropical regions and without competing beneficial uses. This biochar was applied in the small plot trials in Costa Rica and Brazil, the latter of which are ongoing through June 2021. In Costa Rica, biochar produced from bamboo residues was also used in the study based on local knowledge of suitability for use in Costa Rican cropping systems (J. Quesada, personal communication).

Our research found that improved plant water availability resulted from biochar additions. Due to difficulty in obtaining biochar in sufficient quantities plus logistical considerations, our field trial in Costa Rica was limited to fewer plots than those planned in the initial design. We recommend that our results therefore be considered as a proof-of-concept that should be built upon through further research.

At the time of this report, scientific contributions from the project related to small plot experiments are still under peer review (Costa Rica for UAV-based measurements and isotopic analyses) and still underway (Brazil). We will update the project website as project results are finalized.

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Annexes

1. Fischer, B.M.C., S. Manzoni, L. Morillas, M. Garcia, M.S. Johnson, S.W. Lyon (2018). Improving agricultural water use efficiency with biochar - A synthesis of biochar effects on water storage and fluxes across scales, *Science of the Total Environment*, 657:853-862, doi: https://doi.org/10.1016/j.scitotenv.2018.11.312.
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10. Brando, P. M., Silvério, D., Maracahipes-Santos, L., Oliveira-Santos, C., Levick, S. R., Coe, M. T., Migliavacca, M., Balch, J. K., Macedo, M. N., Nepstad, D. C., Maracahipes, L., Davidson, E., Asner, G., Kolle, O., Trumbore, S. E. (2019). Prolonged tropical forest degradation due to compounding disturbances: Implications for CO_2 and H_2O fluxes. Global Change Biology, 25(9), 2855-2868. http://doi.org/10.1111/gcb.14659. [open access]