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The Food–Energy–Water Nexus: A Framework to Address Sustainable Development in the Tropics

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Abstract

Interactions between agriculture, energy, and tropical environments occur within a larger, interconnected food–energy–water (FEW) system context. These interactions both affect and are shaped by the FEW nexus (connected FEW natural processes, engineering and infrastructure, and institutions and governance), motivating the collective inclusion of many processes and institutions in the discussion of any individual member. Moreover, the important role of the tropics in the global environment and global food security raises the stakes of management, providing further impetus for a thorough, FEW nexus approach. We herein discuss FEW issues which are key to proper FEW nexus management in the tropics, including fundamental earth system processes, agricultural expansion and deforestation, the potential benefits and drawbacks of hydropower development, and technology and policy advancements.

Keywords

sustainable, development, food, energy, tropics

Introduction

The tropics play an important role in global natural resource provision and ecosystems and face great conservation challenges (Singh & Sharma, 2009). As one illustrative example, tropical forests provide ecosystem services at a global scale, such as accounting for 70% of annual global forest carbon sequestration (Pan et al., 2011). Yet during 2000–2010, there was a net forest loss of 7 million hectares per year in tropical countries and a net gain in agricultural land of 6 million hectares per year, accounting for the majority of the world's new agricultural land over the period (Food and Agriculture Organization, 2016).

There are many such emerging and connected food, energy, and water (FEW) issues in the tropics which may benefit from a FEW nexus framework—one that addresses problems from these sectors in an integrated manner for the cobenefit of all stakeholders (Hoff, 2011). Irrigation is expected to increase considerably due to land expansion and climate change (i.e., increasing crop water requirement and reducing rainfall available in the crop growth season), which will put pressure on the supply of both water and energy (for pumping). Hydropower is a growing energy source in the tropics, and there have been intense debates on the impact of dam building in tropical rainforests on biodiversity, tropical rain forest ecosystems that provide humans with clean water, and contribution to greenhouse gas (GHG) emissions. Relationships between connected processes or institutions, such as those above, propagate up to impact the entirety of the interconnected FEW system (Ringler, Bhaduri, & Lawford, 2013). Likewise, interacting processes or institutions cannot be disentangled from the FEW context in which they exist (Kumar, 2015; Peters et al., 2004). As such, the relationships between commercial agriculture and tropical environments, specifically, cannot be isolated from their FEW context.

As resource and environmental constraints are realized at local and regional scales, trade-offs emerge among FEW provision, which can strain the livelihoods of

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those in poverty. On the other hand, positive FEW synergies can also arise for the cobenefits of these sectors. In the past, FEW systems were predominantly designed and evaluated in isolation; however, the complex interconnectedness of the respective systems, highlighted by these emergent trade-offs and synergies, mandates that they be analyzed together as part of a larger, more encompassing FEW system. The goal of FEW nexus research is to improve the understanding of processes, linkages, and feedbacks within the FEW system so that trade-offs may be minimized while synergies and efficiency of the overall system may be maximized (Ringler et al., 2013). In application, FEW nexus management has the potential to sustainably improve livelihoods via increased food, energy, and water security for vulnerable populations (Biggs et al., 2015).

An integrated, FEW nexus perspective is especially prudent in the humid tropics, a growing destination for outsourced global food and energy needs (Foley et al., 2011). Yet, significant knowledge gaps remain regarding critical earth system and FEW issues in the tropics. We herein discuss key FEW issues in the humid tropics, which require advancement in scientific understanding in order to properly manage the FEW nexus: fundamental earth system processes, the potential impacts of agricultural expansion and deforestation, and trade-offs in tropical hydropower development. In addition, before concluding, we briefly survey areas of ongoing technology and policy development relevant to managing the FEW nexus in the tropics.

FEW Nexus Issues and Knowledge Gaps in the Humid Tropics

Fundamental Earth System Processes

The earth system processes of the humid tropics are somewhat less understood than other biomes around the globe. The hydrologic processes of the humid tropics are characterized by greater magnitude, interannual variability, and spatial gradients than are generally found elsewhere, each of which can be obstacles to prediction (Bonell & Bruijnzeel, 2005; Wohl et al., 2012). As temperatures and atmospheric water carrying capacity in the tropics increase due to climate change, some hydrological processes are expected to quicken and potentially exacerbate the aforementioned characteristics (Wohl et al., 2012). At a global scale, precipitation and evapotranspiration are expected to increase with increasing air temperatures; however, it is unclear what trends will emerge from complex atmosphere–land surface interactions at continental and regional scales (Wang & Dickinson, 2012). The distinct hydrologic character of the tropics and unknown features of future climate present difficultly for modeling and prediction, which is compounded by the relative lack of research investigation within the humid tropics in comparison with systems of temperate regions (Wohl et al., 2012). For instance, little is definitively known regarding the functioning and hydrologic contributions of tropical montane cloud forests (Bruijnzeel and Proctor, 1995) or the sensitivity of tropical forests to drought (Samanta et al., 2010). Understanding earth system processes in the tropics is particularly critical given the important role the tropics play in the global earth system. Modeling exercises have shown profound teleconnections between tropical forests and distant geographic regions; for instance, land clearing in the Amazon basin was shown to result in significant temperature increases in Western Europe and Central Asia (Rockström et al., 2009). Responsible FEW system management hinges on understanding these fundamental earth system processes, particularly as vital ecosystems in the humid tropics are subjected to climatic and anthropogenic changes.

Agricultural Expansion and Deforestation

Much of the global need for increased food production is being met via agricultural intensification and expansion in the humid tropics, often at the expense of tropical forest (Foley et al., 2011). In addition, agricultural land is expanding to meet the demand for biofuels in countries such as Brazil, Indonesia, and Malaysia (Gibbs et al., 2010). Food, energy, and the natural environment are intertwined via competition for land and water. Single-sector analysis may lead to ignorance of the impacts of one sector on others (for instance, biofuel development with an energy-only perspective may have undesirable impacts on food prices or forest cover), and a full FEW system analysis must be undertaken. The stakes for the humid tropics are high, as deforestation cannot be easily or quickly reversed should surprises arise.

However, agricultural expansion operates in a highly complex FEW system, hindering thorough understanding and management. While biofuels theoretically offer a route to simultaneously increase energy supply and curb climate change, it can take several decades for carbon savings to be realized in locations where biofuel crops replace carbon-storing forests (Gibbs et al., 2008). In addition, the ecological community is still only beginning to understand the ability of tropical forests to recover from disturbance. How quickly forests recover from land clearing and how biodiversity losses affect forests' ability to withstand future disturbances are ongoing fields of inquiry (Cole, Bhagwat, & Willis, 2014; Sakschewski et al., 2016). Further insight is vital to ensure that large swaths of tropical forest, and all their accompanying services, do not catastrophically switch to a state of savanna—a FEW system tragedy comparable with the shrinking of the Aral Sea due to unsustainable irrigation practices and hydropower development in Central Asia (Cai, McKinney, & Rosegrant, 2003; Hirota, Holmgren, Van Nes, & Scheffer, 2011). Answers to what degree agricultural expansion is sustainable, or even advantageous for the present, require that carbon-payback time and forest resilience concepts, among others, be applied to evaluate tropical FEW systems.

Hydropower Versus Fish and GHG Emissions

Due to typically high runoff within humid regions, there is great potential for hydropower in much of the humid tropics. In fact, Brazil, one of the more developed tropical countries, trails only the United States and China in developed hydropower capacity, and hydropower provides nearly 80% of the nation's electricity (Soito & Freitas, 2011). However, building dams for hydropower is a complicated FEW nexus issue. In addition to energy provision, positive benefits of dams include water storage for irrigation (a critical element of food provision infrastructure) and periods of drought, flood regulation, and recreation. Conversely, dam construction often inhibits fish migration (also critical to food provision, via fisheries), disrupts sediment transport, and eliminates other ecosystem services (Gunkel, 2009). Tropical cold-water fish are an important source of nutrition and food security in many regions. According to Winemiller et al. (2016), as many as 450 new hydroelectric dams are planned or in construction on the Amazon, Congo, and Mekong rivers, and species extinction and basin-wide declines in fisheries may accompany these new hydropower projects. Moreover, 54% of global installed hydropower capacity—an amount totaling 507 Gigawatts—directly competes with irrigation, meaning that increased hydroelectricity production might reduce food security in many regions, although hydropower development can also support irrigation through timely availability of irrigation supplies (Zeng, Cai, Ringler, & Zhu, 2017). Thus, research and practice should encompass the full scope of FEW system impacts of dam construction and operation.

Furthermore, the validity of hydropower as a form of "green" energy has come into question in recent years. Carbon dioxide and methane emissions are both natural products of decomposition within a lake, and recent findings suggest that emissions from reservoirs are substantially higher than previously believed (Fearnside & Pueyo, 2012; Winemiller et al., 2016). GHG emissions are particularly high for shallow, tropical reservoirs, where decomposition occurs more rapidly (Gunkel, 2009). In fact, for some tropical reservoirs, the initial surge in GHG emissions due to decomposition of the inundated upstream vegetation may outweigh the GHG savings of fossil fuel reduction for several decades (Gunkel, 2009). At this stage, a great deal more data is needed to confidently quantify GHG emissions of tropical reservoirs (Rosa, dos Santos, Matvienko, dos Santos, & Sikar, 2004), and to do so in comparison with their natural state alternatives. Emerging insights must be continuously tested and incorporated into FEW system analysis to ensure that tropical dam construction, an enormous investment, is not misguided regarding its potential benefits.

Cross-Sectoral Technological and Policy Innovations

Improvements in technology and system design are building blocks for synergistic solutions to FEW demands. In much of the humid tropics, fruits and other food require a great deal of energy to be stored and transported at their necessary temperature and humidity (Wardlaw, 1939). Harnessing renewable energy sources such as solar powered refrigeration may allow tropical food economies to flourish without placing such a burden on the energy market (Sarbu & Sebarchievici, 2013). Meanwhile, in water scarce tropical regions such as islands and deserts, wind or solar powered desalination and water pumping may alleviate trade-offs between water and energy by supplying water while putting less pressure on exhaustible energy resources (Kalogirou, 2005; Omer, 2001). Given the intermittent nature of wind and solar energy production, they may be especially suitable to applications such as desalination and pumping, which may be more tolerant to intermittent energy supply than a region's electrical grid (Webber, 2015). Technological development, guided by FEW system analysis insights, may lead to significant gains in FEW security for tropical communities.

There are opportunities for institutional reforms in the context of FEW systems in the tropics. In particular, policies can be redesigned or initialized to balance economic interests and ecological sustainability in tropical agricultural landscapes (Drescher et al., 2016) and to account for social equity (Calvet-Mir, Corbera, Martin, Fisher, & Gross-Camp, 2015), especially for underrepresented groups (Biggs et al., 2015). Given that the majority of additional food production to satisfy the world food demand will come from the tropics, international food market and prices will also play a role in the environmental sustainability of the tropics.

Summary

Management of the FEW nexus in the humid tropics is not only essential for local livelihoods but also impacts those across the globe. Yet, numerous knowledge gaps exist that must be resolved to ensure responsible stewardship of FEW resources in the tropics and of the ecosystems which provide them. Here, we summarize uncertainty regarding fundamental earth system processes, highlight two phenomena—agricultural expansion and hydropower development—and review some promising technological synergies; each of these areas warrant significant scientific effort. Bridging these knowledge gaps will be essential in avoiding unforeseen consequences, meeting local and global needs for FEW, and improving livelihoods. Interactions of agriculture, energy, and tropical environments cannot be disentangled from the complex FEW context. The FEW nexus provides a framework to optimize the cobenefit of all FEW sectors and the sustainability of the tropical environments. In addition, local contexts and priorities will shape specific implementations, such as the food security focus in tropical African countries and zero-deforestation goal in tropical South American countries.

Declaration of Conflicting Interests

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