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The energy-water agriculture nexus: the past, present and future of holistic resource management via remote sensing technologies

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ABSTRACT

The nexus between energy, water and agricultural production is important to consider for effective resource management and risk mitigation. New data acquisition techniques, in conjunction with cheap storage applications, have facilitated the collection and analysis of massive datasets to holistically describe natural and built environments. However, the field of coupling energy, water and agricultural management through evolving remote sensing technologies is still nascent. We find that remote sensing technologies are being increasingly utilized for resource management, but there are still large opportunities to deploy these technologies to achieve integrated resource management goals. Thus, this article aims to bridge remote sensing and integrated resource management communities, which have largely developed in isolation, so that technologies can be developed to assist in achieving sustainable development. The opportunities and challenges highlighted in this article can guide technology development, research opportunities and create new interdisciplinary research partnerships.

1. Introduction

Energy, water, and agriculture share critical interdependencies that create grand challenges for sustainable resource management, especially in the current regime of population and economic growth, budgetary constraints, climatic changes, and technological shifts Biba (2015); Lawford et al. (2013). In the past, these resources have been managed and regulated, for the most part, individually, with little regard to these interconnections King et al. (2013). In recent years, there has been growing awareness that these interdependencies can be constraining when access to one resource inhibits access to another; but despite this realization, the holistic management of energy, water and agriculture resources is still thwarted by access to reliable data, siloed expertise, and siloed regulatory structures Ringler et al. (2013); Scott et al. (2011). Although there are trends toward governmental support for the public dissemination of data, many countries do not collect and disseminate robust datasets to the public or are selective in regards to who can access data resources Harris and Browning (2005). Datasets that are available are often poorly defined in terms of collection methods, unit definitions, or shortcomings, or are in inconsistent formats that can be difficult to manipulate and analyze US GAO (2009b); Mattmann (2013). However, access to advancements in remote sensing technologies and cheap data storage, which enable automated and high spatio-temporal resolution data collection, offer opportunities to overcome these barriers.

Despite these opportunities, the bodies of literature regarding integrated resource management versus remote sensing application development are still developing largely in isolation of each other. This manuscript is meant to bridge resource management and remote sensing research communities to enable innovation and efficiency into integrated resource management strategies, as these communities have developed largely in isolation. Thus, it fills a critical knowledge gap, bringing the insights being developed in the remote sensing community to integrated resource management community. This manuscript identifies the interconnections between energy, water and agricultural systems in Section 2, summarizes existing remote sensing applications that are being used to facilitate the management of these resources in Section 3, and offers suggestions for future opportunities and challenges facing the field of remote sensing for multi-resource management in Sections 4 and 5, respectively.

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2. The energy, water and agricultural nexus

The energy-water-agricultural nexus refers to the fact that energy, water and agriculture depend on one another for resource security Beck and Walker (2013); Beck and Villarroel Walker (2013). Thus, a constraint in one of these resources can inhibit access to another resource, which can negatively affect economic security, supply chain reliability and in some cases, human health Lawford et al. (2013). The water-energy-agricultural nexus has received increasing attention in recent years due to pressures from drought, climate change, natural disaster, and increasing competition over resources, which have contributed to existing tensions (e.g. in Syria Kelley et al. (2015); Kibaroglu and Gürsoy (2015), in Uganda Mugisha and Fenner (2015) and in Iran Madani (2014)) and will likely drive conflicts in regions that have not historically encountered resource tensions CNA Military Advisory Board (2014); Vorosmarty (2000).

Many existing tensions are derived from the fact that insufficient water or energy hurts crop productivity Pacific Institute (2015); Gleick and Christian-smith (2011). While some crops are rainfed and require no irrigation, in many regions, irrigation (and hence, a reliable water supply) is required for crop cultivation. In total, agriculture represents approximately 70% of global freshwater withdrawals, the majority of which are consumed (i.e., water displaced from its original source) Gleick and Christian-smith (2011). For many farming operations, energy is a requirement for pumping water to irrigated crops in addition to farm machinery and equipment utilized at the farm Plappally and Lienhard (2012). As surface water resources become more constrained, the rate of groundwater pumping, and consequently, the energy for supplying water, generally grows Famiglietti (2014); Sanders and Webber (2012). Over-pumping groundwater when surface water supplies are scarce can contribute to consequences such as seawater intrusion, ecosystem degradation, and land subsidence Famiglietti (2014). (While estimates for the total energy embedded in US agricultural systems vary in the literature, most estimates range from one to two percent of annual energy consumption Cuéllar and Webber (2010); Heller, Martin and Keoleian (2000); Sanders and Webber (2014).)

Agriculture can also have large consequences on water quality, which can have energy repercussions if extra treatment is required to remediate water for other uses Twomey et al. (2010). Agricultural crop production and livestock operations often degrades water quality via the mobilization of salts, pathogens, and toxic runoff that can transport chemicals, pesticides and herbacides to adjacent water bodies Twomey et al. (2010); Scanlon et al. (2007). Excessive nutrients, from sources such as nitrogen fertilizers, that build up in aquatic ecosystems can prompt the proliferation of algal blooms that reduce the oxygen content of water as they die (a condition referred to as "hypoxia" and eutrophication) Twomey et al. (2010); Costello et al. (2009); Pimentel et al. (2005). Agricultural crop and livestock production represent the largest fraction of anthropogenic nitrogen loading to the environment Billen et al. (2013). The upstream production of synthetic fertilizers also contributes to energy consumption and water pollution Zhang et al. (2012a). In addition to surface water, groundwater can also be contaminated by chemical inputs such as inorganic fertilizers and synthetic pesticides Bexfield (2008); Foster and Chilton (2003). Thus, natural water resources, which often serve other anthropogenic water uses, are heavily affected by the presence of agricultural production.

While crop production can affect the water quality of water used by downstream users in an interconnected water supply, water quality also affects crop cultivation. Saline or brackish water reduces the productivity of most plant species Bouwer (2002); Sabo et al. (2010). As water becomes more constrained, water salinity often increases as a result, exacerbating these interdependencies. Worldwide, salinity and soil erosion are growing threats to the sustainability of irrigated agriculture and have already contributed to a significant loss in arable land Sabo et al. (2010); Pimentel and Pimentel (2003).

Trends in the US energy sector are increasing these resource tensions. Agricultural feedstocks are becoming an increasingly important aspect to energy production Erb et al. (2012). In addition to food, a growing percentage of crops and agricultural waste is now being used as primary energy sources in the transportation and electricity generation sectors US Energy Information Administration (2015). These additional agricultural feedstock demands are intensifying agricultural production practices and have resulted in significant water quality impacts downstream Pimentel and Patzek (2005); Evans and Cohen (2009); Fingerman et al. (2010). While using food crops for energy production competes with food production, agricultural waste products and buffer grasses (e.g., switchgrass, miscanthus) can provide energy without affecting the food supply if these sources require no additional arable land Cherubini et al. (2009); Zhuang et al. (2013). Water quality benefits might also be incurred if riparian buffer grasses are utilized for energy feedstocks since these grasses serve to block chemicals from entering surface water sources Wu et al. (2014); Costello et al. (2009).

There are also examples where water and energy tensions occur in isolation of the agricultural sector. In addition to biofuels feedstocks, water is required in the production, refining, and conversion of primary fuels such as petroleum, natural gas and coal. Most forms of mining require substantial amounts of water for primary energy production Liphadzi and Vermaak (2015). Refining and processing primary energy sources into forms consistent with desired end use also requires substantial amounts of water Maupin et al. (2014). Consequently, water management can be a costly part of primary energy production Mauter and Palmer (2014); Walker et al. (2013). For example, in many mining processes, energy-intensive centrifugal pumps are used to dewater them mine so that ore can be extracted Norgate and Haque (2010). Energy is also required to manage wastewater produced during energy production, processing and refining. For example, large quantities of wastewater are generated during the production of oil and gas resources and must be remediated or pumped into injection wells for disposal Gregory et al. (2011).

In the power sector, water is necessary to transform mechanical energy into electrical energy via hydroelectric facilities or thermoelectric power plants. Hydroelectric power plants utilize water as a fuel to turn hydroelectric turbines, while thermoelectric power plants utilize high-pressure steam to turn steam turbines. Although the volume of water contained within the closed steam loop used to move steam turbines at thermoelectric power plants is relatively small, large volumes of water are typically required to cool the steam exiting the turbine to reduce backpressure Sanders et al. (2014); Sanders (2015). Ensuring cooling water supplies at sufficiently cool temperatures (to ensure adequate power plant efficiency and safety) and volume is important to the US power sector. Moderating the temperature at which cooling water is discharged to the receiving reservoir is also important for protecting aquatic ecosystems Sanders (2015); US Environmental Protection Agency (2014); Scanlon et al. (2013). In fact, when cooling water resources become too hot, thermal power plants are required to curtail operation to mitigate impact to the receiving reservoir Sanders (2015); Madden et al. (2013). Although shifts towards solar photovoltaics and wind will reduce the coupling between power generation and water resources, these resources still represented less than 4% of US electricity generation in 2012 Sanders (2015).

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