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The impact of climate change mitigation on water demand for energy and food: An integrated analysis based on the Shared Socioeconomic Pathways

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ABSTRACT

Climate change mitigation, in the context of growing population and ever increasing economic activity, will require a transformation of energy and agricultural systems, posing significant challenges to global water resources. We use an integrated modelling framework of the water-energy-land-climate systems to assess how changes in electricity and land use, induced by climate change mitigation, impact on water demand under alternative socioeconomic (Shared Socioeconomic Pathways) and water policy assumptions (irrigation of bioenergy crops, cooling technologies for electricity generation). The impacts of climate change mitigation on cumulated global water demand across the century are highly uncertain, and depending on socioeconomic and water policy conditions, they range from a reduction of 15,000 km^3 to an increase of more than 160,000 km^3. The impact of irrigation of bioenergy crops is the most prominent factor, leading to significantly higher water requirements under climate change mitigation if bioenergy crops are irrigated. Differences in socioeconomic drivers and fossil fuel availability result in significant differences in electricity and bioenergy demands, in the associated electricity and primary energy mixes, and consequently in water demand. Economic affluence and abundance of fossil fuels aggravate pressures on water resources due to higher energy demand and greater deployment of water intensive technologies such as bioenergy and nuclear power. The evolution of future cooling systems is also identified as an important determinant of electricity water demand. Climate policy can result in a reduction of water demand if combined with policies on irrigation of bioenergy, and the deployment of non-water-intensive electricity sources and cooling types.

1. Introduction

Future water systems are confronted with multiple challenges emerging from the interplay of the complex and interrelated set of forces often referred to as the water-energy-land-climate nexus. Agriculture is the largest user of the world's freshwater resources, consuming yearly 70% of all abstracted water (Rost et al., 2008) and resulting locally in severe water scarcity. Water is also a key input of most energy production and conversion processes, and in particular cooling for electricity generation. Electricity sector abstractions can be in the range of 40% of abstracted freshwater resources in industrialized countries (Byers et al., 2014) and insufficient water availability for energy supply systems is already apparent in various locations, such as the US (Feeley III et al., 2008). A world population expected to grow to 8.5–10 billion[1] by 2050 (KC and Lutz, 2014; UN, 2015) and ever increasing economic growth will increase the pressure on energy, land, and water systems and add to the challenge.

In addition, as the energy and agricultural sectors are major greenhouse gas emitters, a substantial reduction of their emissions in order to mitigate climate change requires systems transformations that can pose further challenges regarding the use of water, land, and energy resources. Large scale bioenergy production, identified as an important option for reaching ambitious

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[1] Future population projections range due to differences in the employed narratives and methods. The UN 2015 revision reports a projection of 9.7 billion of global population by 2050, while KC and Lutz (2014) project this to be about 8.5, 9.2 or 10 billion depending on the adopted narrative.

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climate change mitigation goals (Rose et al., 2014), can put significant pressure on land and water resources (Beringer et al., 2011; Berndes, 2002; Bonsch et al., 2014). Further, the role of electricity is likely to become more prominent under climate change mitigation (Williams et al., 2012), resulting in increased water demand for power plant cooling purposes. The technology mix for achieving decarbonization of electricity systems consists of a combination of technologies, such as nuclear, fossils or biomass with carbon capture and storage (BECCS), and renewable sources (Krey et al., 2014; Luderer et al., 2014) characterized by diverse water requirements and thus impacts on water resources (Kyle et al., 2013).

Given the importance of the water-energy-land-climate nexus for sustainable climate and water resources planning, several studies have made attempts of its exploration. Some studies analyse water demand across sectors and socioeconomic scenarios (e.g. Alcamo et al., 2007; Hanasaki et al., 2013) using hydrological models with detailed representations of water resource systems and stylized representations of water demand. Another category of studies use integrated assessment models (IAMs) with detailed explicit representations of energy and land use systems. These models, by including comprehensive descriptions of energy carriers and conversion technologies, and potentially also land use dynamics, can better capture the underlying structural patterns of changes in energy and agricultural water demand. Several IAM studies focus on the energy-land use (e.g. Klein et al., 2014; Popp et al., 2014a), the water-land use (e.g. Bonsch et al., 2014; Chaturvedi et al., 2015) or the water-energy interactions (Davies et al., 2013; Kyle et al., 2013; Bijl et al., 2016; Fricko et al., 2016), yet the implications of combined socioeconomic and mitigation assumptions across the full nexus is underexplored. One exception is the study of Hejazi et al. (2014), which investigates changes in water demand across the nexus under different socio-economic conditions, but does not explore the implications of such conditions under stringent mitigation scenarios.

This paper adds to the literature by providing a systematic exploration of the impact of socioeconomic assumptions and selected water policies on the effects of climate change mitigation on water demand, using an IAM approach across the water-energy-land-climate nexus. This allows us to consider explicitly the most important determinants of the effects of climate change mitigation on water use, namely demand patterns, the supply composition, and the water use intensity of electricity and agricultural systems. We investigate these effects with the use of three alternative Shared Socioeconomic Pathways (SSPs)[2] (O'Neill et al., 2015), encapsulating profound differences regarding the underlying food and energy demand and supply dynamics, and therefore the associated challenges to mitigation. We explore the combined social and biophysical aspects of the nexus focusing on key systems interactions, such as water demand for electricity and agricultural production, and bioenergy and electricity demand for climate change mitigation. Further, we investigate the effects of two important dimensions of water policy: the irrigation of bioenergy crops and the shares of cooling technologies for power generation. By combining socio-economic and water policy assumptions we demonstrate the uncertainty associated with the impacts of climate change mitigation on water use.

2. Methodology

2.1. The LPJmL-MAgPIE-REMIND framework

Our analysis uses the LPJmL-MAgPIE-REMIND integrated modelling framework (Popp et al., 2011; Fig. 1), based on three coupled models representing different aspects of the water-energy-land-climate nexus. LPJmL (Rost et al., 2008) is a global dynamic vegetation and hydrology model. MAgPIE (Biewald et al., 2014; Popp et al., 2014b) is a land use model representing costs of agricultural production, food and bioenergy demand, and land and water constraints. The REMIND model (Luderer et al., 2013; Mouratiadou et al., 2016) is a multi-regional model incorporating the economy, the climate system and a detailed representation of the energy sector. The MAgPIE-REMIND models are coupled in order to establish equilibrium of bioenergy[3] and greenhouse gas emissions markets in an iterative procedure (see Bauer et al., 2014; Kriegler et al., 2016 for details). Establishing the simultaneous equilibrium of bioenergy and emissions markets allows addressing, beyond model boundaries, the trade-off between emissions savings from bioenergy in the energy sector and potential additional emissions from bioenergy production in the land use sector. More generally, it allows identifying the optimal combination of land- and energy-based mitigation options, including the optimal extent of bioenergy production which has important implications for water demand. The climate outcomes of the resulting emission pathways of the two models are estimated by the MAGICC model (Meinshausen et al., 2011).

The grid-based dynamic vegetation model LPJmL provides the agro-economic land and water use model MAgPIE with several biophysical inputs. Crop yields under rainfed and irrigated conditions are provided for 16 food crops and two bioenergy crops. Also, available water and the amount of irrigation water that needs to be applied to a field are provided on a 0.5° grid basis. Irrigation water requirements are estimated as the soil water deficit below optimal plant growth (Rost et al., 2008) and corrected for losses from source to fields. For each river basin, surface, lateral and seepage groundwater runoff are added to grid cell runoff and subsequently are available for downstream reuse, routed along the river network (Jägermeyr et al., 2015).

Agricultural water demand for irrigated crop and bioenergy production is determined endogenously in MAgPIE based on irrigation cost-effectiveness and water availability. Irrigated crop production requires irrigation infrastructure for water distribution and application. The initial pattern of area equipped for irrigation is taken from the AQUASTAT database (Siebert et al., 2007). During the optimization process, the model can endogenously deploy additional irrigation infrastructure (not including building reservoirs). Irrigation costs comprise investment costs for the deployment of additional irrigation infrastructure as well as annual costs for operation and maintenance of irrigation systems.

The REMIND model features an elaborate representation of water demand for electricity production, taking explicitly into account the age structure of thermal power plants and power plant thermal efficiencies. Our estimate of water demand for electricity represents requirements associated to cleaning, cooling, and other process related needs (e.g. flue gas desulfurization) (Macknick et al., 2011), and is based on the mix of electricity production technologies, the shares of cooling technologies, the water withdrawal and water consumption intensities, the vintage structures and the power plant thermal efficiencies. All four

[2] The SSPs reflect the socioeconomic component of the new scenario framework for climate change research (van Vuuren et al., 2014). This framework aims to facilitate the production of shared scenarios among the community carrying out research on climate change impacts, adaptation, and mitigation, and combines pathways of socioeconomic development with pathways of future radiative forcing and climate changes (van Vuuren et al., 2014). Further details are provided in Section 2.3.

[3] In the REMIND-MAgPIE scenarios, future bioenergy demand is dominated by second generation purpose-grown biomass.