ABSTRACT

Title of Dissertation:	SOCIOECONOMIC AND CLIMATE IMPACTS ON THE FUTURE OF WATER: AN INTEGRATED ASSESSMENT APPROACH TO DEMAND, SCARCITY, AND TRADE
	Neal Thornton Graham, Doctor of Philosophy, 2019
Dissertation directed by:	Professor Fernando Miralles-Wilhelm, Department of Atmospheric and Oceanic Science

Changes to socioeconomics and an evolving climate system are likely to play a vital role in how regions around the world use water into the future. Water projections for the future, while prolific, remain highly variable and dependent upon underlying scenario and model assumptions. In this study, the Global Change Assessment Model (GCAM) is used, where interactions between population, economic growth, energy, land, water, and climate systems interact dynamically within a market equilibrium economic modeling framework, to address how changing socioeconomic and climate conditions alter global water futures, and in turn, how water constrains the future of other systems. First, the impacts of efficiency changes are investigated with the addition of socioeconomically consistent water technologies across several sectors. Quantitative assumptions for the Shared Socioeconomic Pathways are extended to the water sector for the first time in a water constrained – Integrated Assessment

Modeling framework. It is found that significant water use reductions are possible under certain socioeconomic conditions, provided the ability to adopt appropriate technological advances in lower income regions. Secondly, the relative contributions of climate and human systems on water scarcity are analyzed at global and basin scales under the Shared Socioeconomic Pathway-Representative Concentration Pathway (SSP-RCP) framework. Ninety scenarios are explored to determine how the coevolution of energy-water-land systems affects not only the driver behind water scarcity changes in different water basins, but how human and climate systems interact in tandem to alter water scarcity. Human systems are found to dominate water scarcity changes into the future, regardless of socioeconomic or climate future. However, the sign of these changes has a significant scenario dependence, with an increased number of basins experiencing improving water scarcity conditions due to human interventions in the sustainability focused scenario. Finally, the reliance on international agricultural trade is analyzed to understand how future socioeconomic growth and climatic change will impact the dependency on international water sources. The differentiation between renewable and nonrenewable water sources allow for the quantification of the various water sources needed to produce enough agricultural goods to meet global demands. The first Integrated Assessment Model projection of the evolution of external water sources to meet domestic agricultural demands show that there will be an increasing international dependencies. China, the United States, and portions of South America are pivotal in providing the necessary exports to meet demands in water scarce or high demand areas of the Middle East and Africa.

SOCIOECONOMIC AND CLIMATE IMPACTS ON THE FUTURE OF WATER: AN INTEGRATED ASSESSMENT APPROACH TO DEMAND, SCARCITY, AND TRADE

by

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Dissertation submitted to the Faculty of the Graduate School of the University of Maryland, College Park, in partial fulfillment of the requirements for the degree of Doctor of Philosophy
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Dedication

I would like to dedicate this thesis to my wife Ashley. The support you have given me through this process is completely and totally unrivaled. Picking up and moving your entire life to allow me to pursue this goal is a debt I will never be able to repay. We have literally been through the highest of highs and the lowest of lows during this journey, but I could not envision doing this with a better person. I love you.

I would also like to dedicate this work to my mother Tracy. Being a single working mother while trying to raise a child is a task I cannot imagine undertaking. However, for so many years of my youth, you would have never known you were doing this all by yourself. You made my childhood memorable, even if it was the farthest thing from easy for you. You taught me everything I know, and there are no other words to say aside from I love you, mom.

Additionally, I would like to dedicate this work to my grandparents, Carol and William Storms. I walked into the University of Maryland with both of you ready to watch this journey, but I leave with neither of you still watching. The influence that you have had in this journey cannot be described. I love you both and miss you dearly.

Finally, I would like to dedicate this work, all of the hours spent on campus, and the numerous late nights to you, Baby G. You may not be here yet, but you have provided the motivation for this final push that has allowed me to complete this project. I have not even met you yet, but I love you more than anything son, thank you for this final push.

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Not to be forgotten, I could not have made it through this graduate school experience without the friends I have made, KB, STH, AK, DN, AS, TS, thank you all. And Gina and Cory, words cannot describe how much more enjoyable you made this process, from the bottom of my heart, thank you both.

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List of Abbreviations

AEEI	Autonomous energy efficiency improvement
AR5/6	Assessment Report 5 or 6
bcm	Billion cubic meters
BWC	Blue water consumption
BWW	Blue water withdrawals
CCS	Carbon-capture-storage
CH_4	Methane
CMIP	Coupled Model Intercomparison Project
CO_2	Carbon dioxide
EU	European Union
FAO	Food and Agricultural Organization of the United Nations
GCAM	Global Change Assessment Model
GCMs	General circulation models
GDP	Gross Domestic Product
GWC	Green water consumption
GWD	Groundwater depletion
IAM	Integrated Assessment Model
IAV	Impact, Adaptation, and Vulnerability
I_C	Relative climate impact on water scarcity
I_H	Relative human impact on water scarcity
IPCC	Intergovernmental Panel on Climate Change
ISIMIP	Inter-Sectoral Impact Model Intercomparison Project
LULCC	land-use land-cover change
N_2O	Nitrous oxide
NDCs	Nationally Determined Contributions
OECD	Organization for Economic Cooperation and Development
PV	Photovoltaics
RCPs	Representative Concentration Pathways
Ref_const	Refence SSP scenario run with water constraints
S_C	Water scarcity changes due to climate
SDGs	Sustainable Development Goals
S_H	Water scarcity changes due to humans
SLCF	Short-lived climate forcers
SPAs	Shared Policy Assumptions
SSPs	Shared Socioeconomic Pathways
S_X	Water scarcity changes due to humans and climate
TC	Technological change
Tech_const	SSP scenario run with water sector technological assumptions and water constraints
UN	United Nations
VBE	Virtual blue water exports
VBI	Virtual blue water imports

VBT	Virtual blue water trade
VGE	Virtual green water exports
VGI	Virtual green water imports
VGT	Virtual green water trade
VGWE	Virtual groundwater exports
VGWT	Virtual groundwater trade
VIC	Variable Infiltration Capacity
VWE	Virtual water exports
VWT	Virtual water trade
WMO	World Meteorological Organization
WSI	Water scarcity index

Chapter 1: Introduction

Water is essential to sustain life on Earth. Whether directly or indirectly, water is contained in everything that humans use on a day to day basis. The food and beverages that are consumed to fuel the human body contain water. Any form of transportation requires water to either manufacture the materials or to extract or create the fuel that runs the vehicle. The computer with which this thesis is being written required water to fabricate each of the components and requires water to provide the electricity allowing the battery to be charged each day. No matter where one looks, water surrounds them, but that water is becoming increasingly difficult for some people to access. Whether the demands are too high due to population increases, supplies are too low from climate change induced availability changes, the price is too high to afford clean water, water quality inhibits human consumption, or armed conflict has created competition between regions for water sources, the way in which humans use water is changing. It is extremely important to understand how the supplies and demands of water may change into the future in order to make policy-relevant decisions to combat the potential negative consequences. In order to accomplish this, projections into the future must consider how the human system will change the use of water, spatially and temporally, by considering population growth changes, economic growth rates, and technological advancements that increase efficiencies. In addition, these projections must also consider how the climate system will impact the availability of water by shifting precipitation patterns as a result of anthropogenic global warming.

Recent advances to select Integrated Assessment Models (IAMs) have allowed for the modeling of scenario-based 'what-if' statements to investigate the future of water. The studies that follow utilize the human-climate system feedback features of an IAM to gain an understanding of how the use of water might change into the future if human and climate systems evolve in predefined, yet dynamical ways. Investigations are conducted on how the demands of water change with socioeconomically viable efficiency improvements, how the evolving human and climate system interact to change the drivers of water scarcity, and how reliant the global trade market will be on the trading of water intensive agricultural goods across regional boundaries as a result of various socioeconomic and climate scenarios. These are assessed across a wide range of global futures which provide differences in the supply, demand, and access to water across global regions. These studies are conducted to provide a comprehensive first-step approximation to how, when dynamic human-climate feedbacks evolve in the future water use, scarcity, and the dependency on external sources of water change. Socioeconomic and climate system changes in the future are highly uncertain, but this thesis attempts to investigate a wide range of future outcomes to account for this uncertainty.

1.1Socioeconomics and Climate – Present State and Future Projections

1.1.1 Current State of the World

Socioeconomic and climate systems feedback each other in an evolving way with resultant changes to one system affecting the other in both global and localized fashions. In order to make assessments for the future growth of both socioeconomic and climate systems, it is important to understand how the historical evolution of each has allowed the human-Earth system to arrive at its current state.

According to the United Nations, the global population has tripled since 1950 to 7.5 billion people, recently climbing by 1 billion people between 2005 and 2017 alone (Figure 1.1). This increase can be attributed to high fertility rates in Asia and increasing fertility rates in Africa, whereas much of the remainder of the world has observed minor changes in fertility (UN, 2017).

In recent years the global economy has observed steady 3% per year growth in GDP, however smaller regions in developing countries are not observing such growth due to armed conflicts and an overall lack of diversification (UN 2019). This discontinuity between regions and income levels raises concerns about the ability to implement agreed upon nationally determined contributions (NDCs) in hopes of meeting the sustainable developments goals (SDGs) set forth in the Paris Agreement (Richards et al., 2016)

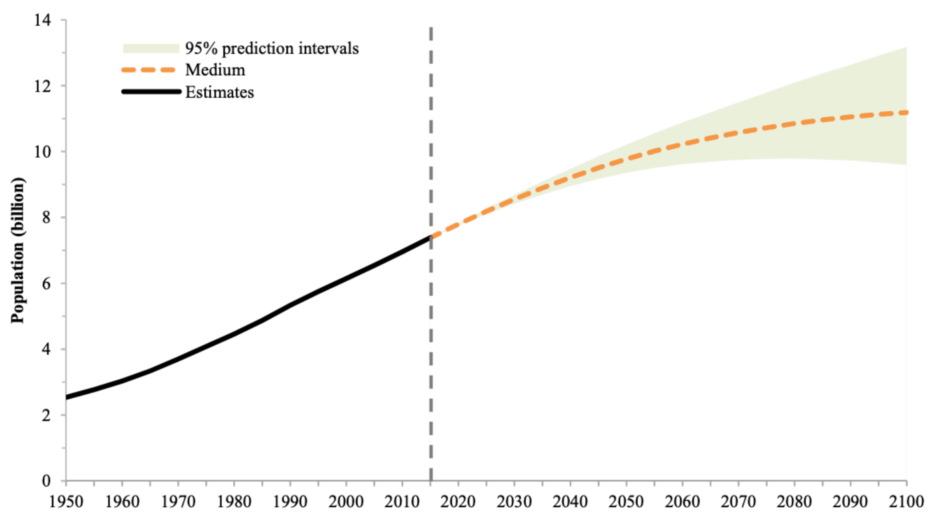

Figure 1.1 (UN, 2017) Global historical population changes from 1950 to 2017, with projections and uncertainties through 2100. Differences in fertility and death rates result in increasing uncertainty through the end of the century.

The state of the climate system is reported yearly through the World Meteorological Organization (WMO) in order to assess how a suite of climatic change indicators have changed in the most recent year. In 2018, the global mean temperature was the fourth highest on record, while atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), reached the highest observed values on record. The combination of these effects has a compounding impact on the climate system, resulting in, but not limited to, increased ocean heat content, sea level rise, ocean acidification, and increased atmospheric water vapor content (Vermeer and Rahmstorf, 2009; Held and Soden, 2006; Balmaseda et al. 2013; IPCC, 2014). There were also several areas around the world that experienced higher than average rainfall, such as Eastern North America and much of northern India during the summer monsoon. However, the precipitation and resultant water availability was much lower than historical average in areas of Europe, Australia, and southern India (WMO, 2019). While several of these results may be attributed to natural interannual variability, the trends of increasing greenhouse gas concentrations and global mean temperature are *virtually certain* to continue (IPCC, 2014), are likely have large impacts into the future, and must be understood in order to properly assess the future of the human-Earth system.

1.1.2 Future Changes to the Socioeconomic and Climate Systems

Future projections of the socioeconomic system consist of assumptions of how the population and economy will evolve over the course of the century. The United Nations makes projections through the end of the century of how fertility and death rate will change regionally and globally. Current projections of global population growth (Figure 1.1) result in an increase from 7.5 billion people today, up to 11.2 billion people in 2100 (UN, 2017). This is due to continued increases in the fertility rate in Africa while the population growth slows in much of Asia after 2050.

Changes to global, regional, and country level economics through the end of the century require an understanding of current trends. The Organization for Economic Cooperation and Development (OECD) use the ENV-Growth modelling framework to project how the global economy will evolve into the future. However, the results are typically assumed, through the conditional convergence hypothesis, that GDP among differing income regions will converge as lower income regions experience quick growth, while higher income regions are near the peak of their GDP potentials (Chateau et al., 2014). Other organizations make projections at smaller timescales based on current trends and without the conditional convergence hypothesis. Current UN projections have poor regions continuing to struggle in the global economy towards 2030 as trade policy disputes put the poorest regions at the forefront of the global economic struggle. Near term climate risks are also expected to create unfavorable economic prospects for island nations in the Caribbean, Indian Ocean, and Southwest Asia as precipitation extremes, sea-level rise, and decreases in freshwater availability, increase the dependence on imports, while potentially reducing the net exports and profitability from these nations (UN, 2019).

The climate system is nearly impossible to make projections for without the use of future scenarios and assumptions about how emissions, atmospheric concentrations of climate forcers, and land use land cover change (LULCC) will evolve into the future. The Intergovernmental Panel on Climate Change (IPCC) makes conditional statements on the likelihood of future changes to the climate system based upon the analysis of predetermined scenarios of the future (described in section 1.1.4). The agreement across studies allows for the IPCC to make assessments of the future, however most forward-thinking assessments merely provide trajectories from present day conditions.

1.1.3 Scenarios for Future Socioeconomic Development (the SSPs)

Understanding how the human system will evolve into the future is not a trivial task and requires significant assumptions on both global and regional scales. UN population projections typically use a "business-as-usual" methodology when projecting fertility and death rates based upon current observed trends, which result in a fairly small uncertainty range surrounding future projections (Figure 1.1). Combined with the OECD economic growth projections, these do not encompass a wide range of potential futures and leave the scientific community with nearly single projections. In order to account for a wide range of outcomes, scenarios are often developed with assumptions of how population, economic growth, and technological change will progress in the future by varying the projections made by such bodies as OECD and the UN. The most recent set of scenarios which have been adopted by the social and environmental science communities are the Shared Socioeconomic Pathways (SSPs) (O'Neill et al., 2017). The SSPs represent a set of five scenarios that are intended to span a set of futures to describe how socioeconomics result in making the mitigation of, or adaptation to, climate change harder or easier, with no direct consideration for climate change. Climate change considerations associated with the SSP framework are separated in order to account for human responses alone. The addition of climate change considerations are discussed in Section 1.1.5. The five scenarios have been placed on a 2D plane to emphasize the low or high magnitude of these challenges by scenario (Figure 1.2). Each of these scenarios have storylines which have been expanded into quantitative values across each of the SSPs for population (Samir and Lutz, 2017), economic growth (Dellink et al. 2017), and land use change (Popp et al., 2017). Further quantification of SSP assumptions has occurred within individual integrated assessment modeling teams based upon the applicability to each specific model. This has created an uncertainty range surrounding the potential outcomes of each SSP while also producing "marker" scenarios by different modeling groups. "Marker" scenarios were chosen based upon an individual model's ability to represent the distinct characteristics of the SSP storyline (Riahi et al., 2017). Scenario storylines for each SSP are provided below.

Figure 1.2 (From O'Neill et al., 2017) Representation of the five SSP scenarios and the characteristics of each with respect to climate change adaptation and mitigation.

SSP1 (Sustainability) assumes that throughout the century the population becomes more educated while shifting focus to meet development goals and adopting sustainable lifestyles through infrastructure efficiency improvements and diet changes. Population growth slows, leading to overall population declines in the second half of the century. Renewable energy becomes increasingly desirable while environmentally friendly technologies are adopted on a grand scale. Population declines and global-first mentality allow from decreases in the demands for water intensive goods and the ability to freely trade in a global market. The focus on sustainability and willingness to invest in renewables allow for minimal challenges to future climate change mitigation and adaptation (O'Neill et al., 2017; van Vuuren et al., 2017).

SSP2 (Middle of the Road) assumes that throughout the century technological change rates, population growth, and economic growth do not change drastically from historical values. Population levels off towards 2100 while educational and economic differences remain across regional boundaries. Global demands follow population projections and trading remains in the global market. As socioeconomic changes are small compared to today, this business-as-usual scenario represents a future with moderate challenges to both mitigation and adaptation (O'Neill et al., 2017; Fricko et al., 2017).

SSP3 (Regional Rivalry) assumes that an increasing focus on meeting domestic needs, with little cooperation across regional boundaries, drives an increasingly fragile global economy. Limitations to future trade result in a need for an intensification of fossil fuel use, particularly in developing countries. Education is limited and population growth increases throughout the century, resulting in a global population over 12 billion people by 2100. The struggling economy, drastic increase in global demands of goods and services, a regional market and lack of a globally thinking society, results in an inability to invest in mitigation technologies and adaptation measures creating large challenges to both future climate mitigation and adaptation (O'Neill et al., 2017; Fujimori et al., 2017).

SSP4 (Inequality) depicts a divergence in economic performance between regions as the century progresses, creating an increasing gap between the rich and poor. Higher income regions invest in efficient technologies and become increasingly educated, while in poor regions, people are forced to live in a labor-intensive environment and utilize a low technology economy. Global demands for goods and services remain highly dependent upon income level and trading with and between the poorest regions is almost non-existent. Therefore, the investment in, and adoption of, mitigation technologies is very high, due in large part to the wealthiest countries, but adaptation is more difficult particularly in the lower-income regions (O'Neill et al., 2017; Calvin et al., 2017).

SSP5 (Fossil-fuel Development) includes strong economic development throughout the century, particularly in poor regions. This leads to a globalization of trade and an increasingly successful global economy. Education increases, yet the success of the economy leads to an energy-intensive lifestyle and a continued exploitation of fossil-fuel resources. However, population declines and educational increases lead to lowering demands while a booming economy allows for a global trade market. This dependency on fossil fuels makes mitigation efforts difficult, but high incomes lead to low challenges to adaptation (O'Neill et al., 2017; Kriegler et al., 2017).

While important to understand, the qualitative assumptions are implemented in slightly different ways across modeling groups. For the purposes of the following studies, quantitative assumptions of each scenario are shown in Chapter 2 and in Calvin et al. (2017). These assumptions have been made for several non-water sectors (Table 2.2) and are expanded to the water sector to better represent socioeconomic impacts on water technologies (Chapter 2 and Graham et al. 2018). Future projections of global population and GDP, as implemented in GCAM (Section 1.3), are shown in Figure 1.3.

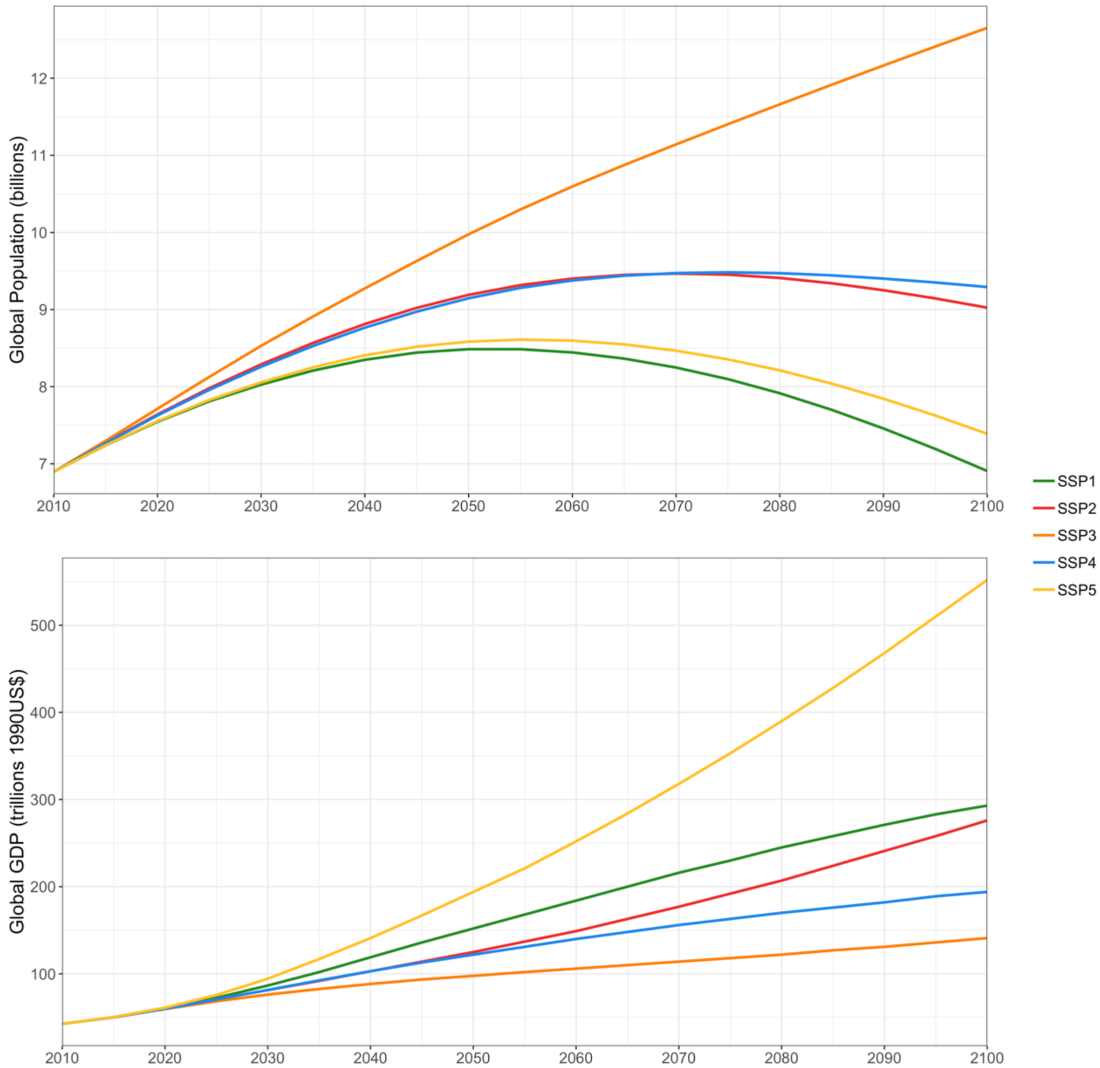

Figure 1.3 Population and GDP projections for each of the 5 SSP scenarios as represented in GCAM. Population declines are observed in SSP1 and SSP5 after 2050 while GDP continues to rise throughout the century.

1.1.4 Scenarios for Future Climatic Change (the RCPs)

The scientific community use climate change scenarios as a basis for modeling projections of the future, impact, adaptability, and vulnerability (IAV) analysis, and to investigate mitigation strategies. The process of creating these scenarios follows a similar path as that of the socioeconomic scenarios described earlier. The International Panel on Climate Change (IPCC) has been using climate change scenarios since the release of The First Assessment Report (1990). Since this time, scenarios have evolved to include increasing levels of detail about future emissions to best estimate climatic impact. The most recent set of climate change scenarios are the Representative Concentration Pathways (van Vuuren et al., 2011). The RCPs consist of differing land-use change, atmospheric greenhouse gas emissions, and short-lived climate forcers (SLCF) concentrations derived from previous literature in the IAM community (Riahi et al., 2007; Fujino et al., 2006; Hijioka et al., 2008; Clarke et al., 2007; Smith and Wigley 2006; Wise et al., 2009; van Vuuren et al., 2007; van Vuuren et al., 2006). This data from the IAM community was harmonized for use in climate models in order to obtain a set of consistent futures for each RCP scenario (Lamarque et al., 2010; Hurtt et al., 2011; Meinshausen et al., 2011). These scenarios span a set of four end-of-century increases in climate forcing from 2.6 W/m^2 to 8.5 W/m^2. The RCPs are prescribed to climate models in order to provide analysis of how the earth system will change by following these four emissions pathways and make up the basis for the IPCC Assessment Report 5 (AR5).

1.1.5 The IPCC and Scenarios of the Future

The IPCC is currently divided into three distinct Working Groups that have differing focuses with regards to climate change. Each Working Group creates a report on 1) the physical science behind the past, present, and future changes to the climate system, 2) the impacts, adaptation, and vulnerability associated with climate change, or 3) mitigation of climate change, respectively. The analysis that is completed, and the literature reviews that make up the reports for the IPCC are based upon a set of scenarios consistent across modeling communities. In the most recent report, the RCPs provided the basis for analysis.

For Assessment Report 6 (AR6) from the IPCC, a new set of scenarios will be used for future climatic change analyses. Following the work of Moss et al. (2010), the scientific community continues to evolve scenarios to include more detailed information about socioeconomics and climate change. For this reason, the SSPs and RCPs are being combined to form a set of future global change scenarios (Figure 1.4) that allow for comprehensive socioeconomic assumptions to be matched with future radiative forcing pathways to achieve future global warming targets (O'Neill et al., 2016; Eyring et al., 2016). Each scenario is then matched with specific Shared Policy Assumptions (SPAs) in order to account for differences in adaptation and mitigation strategies across the SSPs (Kriegler et al., 2014; Calvin et al., 2017). These scenarios have been developed by the IAM community with greenhouse gas emissions, atmospheric concentrations of greenhouse gases, and land-use changes once again being provided to the climate modeling community for implementation into general circulation models (GCMs).

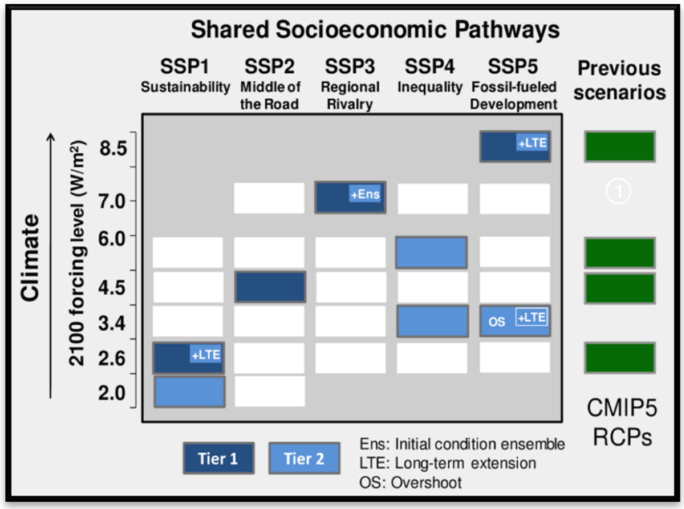

Figure 1.4 (From O'Neill et al., 2016) Scenario matrix for the SSP-RCP framework set to be used in the upcoming IPCC AR6. Previous scenarios are shown to the right in green, with extensions to the SSPs shown as the white and blue boxes. All dark blue boxes, entitled Tier 1, are set to be the main, initial set of scenarios used by the IPCC in order to capture plausible future scenarios in which the socioeconomics and climate system combine to reach an end-of-century radiative forcing target.

1.2 Water Usage – Supply, Demand, and Projections of Change

1.2.1 Overview of Relevant Water Cycle Components

The water cycle consists of several components that define the amount of water in the Earth system at any given time. These components are often represented in a water budget as shown in Equation 1.1, adopted and modified for these studies from Eagleson (1978), where P represents the precipitation, E_T the evapotranspiration, Q_R the available renewable surface runoff and groundwater extraction, W_d the available water withdrawn for human use, S_G the nonrenewable groundwater extracted from deep aquifer storage, and ΔS_T as the change in total water storage.

$$P - E_T + (Q_R - W_d) - S_G = \Delta S_T \qquad 1.1$$

For the purposes of this research, the focus will be placed on four components of Equation 1.1, explained hereafter with their GCAM (Section 1.3) definitions: E_T, or the amount of evapotranspiration that occurs during crop growth, also referred to as green water consumption (Hoekstra et al., 2011). W_d, or the amount of surface runoff or groundwater recharge that is withdrawn in the production of all global goods and services, referred to as blue water (Hoekstra et al., 2011). S_G, or the amount of nonrenewable groundwater that is extracted from deep aquifers in the production of global goods and services, an extension of blue water. Finally, Q_R is the total renewable runoff and groundwater recharge that is available for use in global production. Q_R represents the total amount of blue available water. Each of these values changes yearly dependent upon both human and climate systems and understanding how much, and which mechanisms cause these changes is the purpose of the following studies.

1.2.2 Current Use and Availability on Global Scales

The availability of water around the world relies heavily on the precipitation in a region providing enough surface runoff for human consumption. Recently, extreme precipitation events (i.e. floods and droughts) have been shown to be the worst since 1950 (Arndt et al., 2010). This has been attributed to increases in anthropogenic global warming (Zhang et al. 2007). Available surface water has seen decreases in low and mid-latitudes over the period 1940-2004, whereas areas where most winter precipitation has historically fallen as snow, are seeing increasing wintertime rainfall and increased water availability. This has been increasing the water availability at these locations, particularly in sub-seasonal timescales (Dai, 2013).

The global use of water has been increasing, largely due to increases in GDP and population in developing regions (Shiklomanov, 2000; Alcamo et al., 2007; WWAP 2015). It is estimated that the global demands for water are increasing at 1% per year due to population growth, economic development and technological advancements changing global consumptive patterns (WWAP, 2018). It is estimated that roughly 3850 km^3 of freshwater are withdrawn for human use each year (FAO, 2016). Of this, 69% is used for agricultural purposes, 19% for industrial uses, and 12% for domestic needs. When considering the consumption of freshwater, nearly 90% of the water that is not returned to streamflow is used for agricultural purposes (FAO, 2016).

As a result of the drying of low to mid-latitude regions, water scarcity is increasing and causing increased stress on the ability to meet demands for water intensive products. In recent years, countries around the world have become increasingly reliant on imports of water intensive crops to meet demands. This process, known as virtual water trade (VWT) (Allan, 1998) has evolved as socioeconomic and climate conditions have created deficits in many countries around the world. Over the last three decades, the United States, Argentina, and Brazil represent some of the largest virtual water exporters (VWE) in the world, while China, through population increases and an increasing demand for soy products, has become the largest importing region for virtual water (Hoekstra and Chapagain, 2006; Dalin et al., 2012a; Carr et al., 2013). While country-to-country dynamics change with evolving socio-environmental conditions, global VWT over the 1986-2007 time period has more than doubled (Dalin et al., 2012a; Carr et al., 2013) to combat these human and clime influences.

1.2.3 Projected Changes to Water Use and Supply

With projections of future GDP and population uncertain, future water demands remain highly uncertain. Several studies have investigated the effects of changing socioeconomics on future water demands with various results. Socioeconomic systems affect freshwater demands through population changes and economic growth by 1) increasing the number of people who require water and 2) affecting the affordability of reliable access to water and technological improvements to increase water sector efficiencies. In addition, socioeconomics affect what people demand (i.e., manufactured goods, food, domestic needs) which cause changes to the amount of water demands around the world. Alcamo et al. (2007) found that water stress will increase as a direct result of increasing income and higher per capita water use in the future, while population acts as a secondary source of changes. Hanasaki et al. (2013 a, b) have estimated that across a set of pre-release SSPs, between 39% to 55% of the population in the period 2071-2100 would be under severely water-stressed conditions due to future population, demand changes in the municipal and industrial sectors, and changes in irrigated crop intensity, irrigation efficiency, and irrigated area. Hejazi et al. (2014b) found that future water demands will increase by 31% to 242% by 2095 under a set of six future socioeconomic scenarios. Changes to water demands will alter the future stress placed upon the water availability of a location. Water scarcity is defined as the ratio of water demanded to the available water. Future changes to water scarcity have been attributed to population changes, economic growth, and resultant demand increases more so than to climate system impacts (Vörösmarty et al., 2000; Arnell, 2004; Alcamo et al., 2007; Hanasaki et al., 2013b; Arnell and Lloyd-Hughes, 2014; Schewe et al., 2014; Schlosser et al., 2014;

Shen et al., 2014; Wada et al., 2014; Kiguchi et al., 2015). All results indicate that socioeconomic changes will be significant driving forces into the future, and that consequences will vary considerably by scenario.

Water use is not just a local problem. Socioeconomic growth and future changes to the climate system lead to changes in food demand and shifts in global production causing changes to the global dependence on VWT (D'Odorico et al., 2014; Distefano et al., 2018). An increasing emphasis is likely to be placed on the trading of goods across regional boundaries, particularly from water abundant regions to water stressed regions, as water availability decreases and demands cannot be met by domestic production alone (Hoekstra and Chapagain, 2008; Carr et al., 2013). Konar et al. (2013) found that total VWT is likely to decrease towards 2030 as climate change induced agricultural productivity increases cause the amount of water required to grow crops, or the virtual water content, to decline. Current VWT is determined to be unsustainable under worsening water scarcity into the future without shifts in global production (Orlowsky et al., 2014). Various future socioeconomic conditions are found to result in an increase of global VWT (Distefano and Kelly, 2017; Ercin and Hoekstra, 2016), likely driven by the five main drivers of change identified by Ercin and Hoekstra (2014): population growth, economic growth, consumption patterns, global production and trade, and technological development. However, these analyses have thus far have not attempted to project future changes based upon the features in an IAM (Section 1.3).

While future human dynamics are likely to cause the most significant impact to water use and scarcity around the world, the availability of water is likely to be altered by anthropogenic global warming driven hydrological changes. Climate system warming is expected to cause precipitation shifts across regions (Figure 1.5) and therefore alter regional water availability, while increases in evapotranspiration and reductions in soil moisture will lead to an increased demand for irrigation water in certain areas of the world (Arnell 1999; Döll 2002; Diaz et al. 2007; Fischer et al. 2007; Kang et al, 2009; Wada et al., 2013). Surface runoff is expected to increase in the northern high latitudes and in current rainforests while decreasing in most dry tropical regions following the notion of ‘wet get wetter, dry get drier”. The Xanthos (section 1.3.3.1) derived changes to water supply, or the amount of water available for human use, from 2005-2100 for each RCP is shown in Figure 1.6. Increases in water supply are observed in all RCP scenarios, particularly in northern high latitudes and northern Africa. Reductions in water availability increasingly occur within higher radiative forcing scenarios and are located over much of southwestern North America, northeastern South America, and southern Europe in RCP8.5. Future climate mitigation scenarios have been found to decrease the impact of climate factors (Blanc et al., 2014; Hanasaki et al., 2013; Wada et al., 2013; Arnell and Lloyd-Hughes 2014), but the increased demand for bioenergy to reach such targets will likely increase water demands (Hejazi et al. 2015; Yamagata 2018).

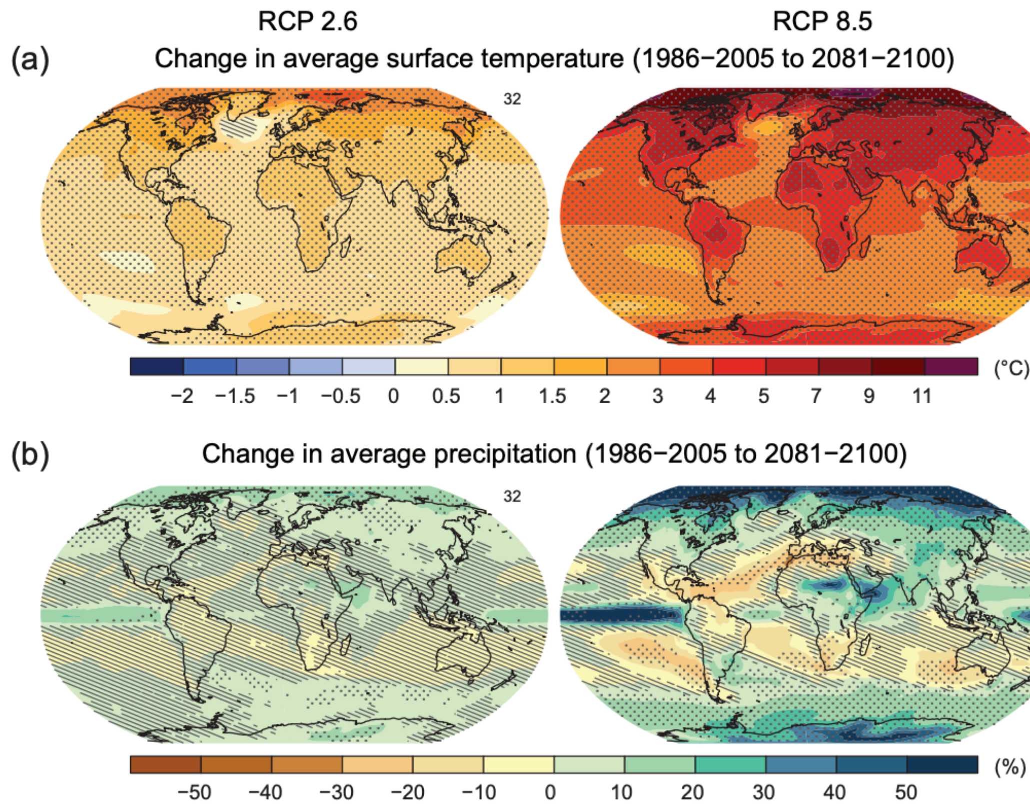

Figure 1.5 (From IPCC, 2014) Temperature and precipitation changes based upon two RCP scenarios. Precipitation extremes are observed under RCP8.5 with increases in the northern high latitudes and along the tropics. Values for warming and precipitation are dampened under a RCP2.6 scenario showing the impact of future anthropogenic global warming.

1.3 The Global Change Assessment Model (GCAM)

1.3.1 What is Integrated Assessment Modeling?

Integrated Assessment Modeling is the process by which interdisciplinary sets of models are combined to analyze the interactions between human and Earth systems. In broad terms, this means linking agriculture, the economy, energy systems, and more recently the water cycle, to the carbon cycle in a consistent manor to allow these systems to coevolve and interact with one another (Calvin et al., 2019). This provides a unique opportunity to capture interactions between highly nonlinear systems outside of singular disciplinary framework. Historically IAMs have been used to provide greenhouse gas emissions, concentrations of short-lived climate forcers, and LULCC to the suite of Coupled Model Intercomparison Project (CMIP) GCMs that are then forced by these variables to create comprehensive Earth-system analyses (As in Section 1.1.4). IAMs are also used to provide decision support for policy-makers by asking 'what if' questions about the future and providing potential outcomes in order to answer these theory questions. IAMs, much like climate models, are not meant to be used for fine temporal resolution decision making, rather these models are often used to analyze suites of scenarios in decadal time horizons.

While IAMs have several similarities amongst one another, there are also several differences. All IAMs have a global perspective that accounts for all anthropogenic sources of emissions and some representation of the climate system. However, across the family of IAM models, differences arise in the sophistication of the climate system, representation of land and agriculture, available spatial resolution, and sector specific representations (e.g. differences in economies, energy systems, etc.). For the purposes of the studies that follow, an IAM which has been used for the RCP and SSP scenarios (Wise et al., 2009; Calvin et al., 2017) has been chosen that has additional water sector capabilities, described in the sections that follow.

1.3.2 The Global Change Assessment Model

These investigations use the Global Change Assessment Model (GCAM) version 5.0, with updates to include water constraints and water technology assumptions (discussed below). GCAM is a global community Integrated Assessment Model that links socioeconomics, the energy system, land-use change, climate, and the water sector. GCAM has 32 energy-economy regions, 384 land regions, and 235 global water basins (Calvin et al., 2019). GCAM uses the simple global system carbon cycle climate model, hector (Hartin et al., 2015; Hartin et al., 2016) to track greenhouse gas emissions. GCAM tracks the emissions of 16 greenhouse gas that are then used as inputs into the CMIP suite of GCMs ex facto. As such, GCAM has been the primary model for the emissions suite for RCP4.5 (Thomson et al. 2011) and SSP4 (Calvin et al. 2017). GCAM has a historical spin-up period from 1975-2010 solving at 15-year time steps through 2005 and then at 5-year time steps from 2005 through 2100. GCAM is a market-equilibrium model that allows for prices to be adjusted within each time step to ensure that the supply and demand of goods and services remains equilibrated at each time step allowing for simultaneous market clearing across sectors. As mentioned earlier, GCAM is an RCP-class IAM which has been used for several previous international climate assessments (Edmonds and Reilly, 1985; Brenkert et al., 2003; Kim et al., 2006; Clarke et al., 2007; Thomson et al., 2011).

1.3.3 Modeling water in GCAM

As discussed in Section 1.2.1, water within GCAM is modeled for available surface runoff, blue water withdrawals and consumption, green (biophysical) water consumption, nonrenewable groundwater supply and extraction, and to a lesser extent desalination. Sections 1.3.3.1 – 1.3.3.2 describe the processes by which each are modeled and how historical supply values have been reconstructed and calibrated.

1.3.3.1 Water Demand

Water demand is modeled within GCAM across 235 individual basins. Six individual sectors generate water demands – agriculture, electricity generation, manufacturing of goods and services, municipal (domestic), primary energy extraction and processing, and livestock (Hejazi et al., 2014b) – which are calculated based on cost and availability of supply (Kim et al., 2016, Turner et al. 2019a). Agricultural water demands in GCAM are modeled across each of the 235 major river basins for twelve crop commodities (Chaturvedi et al. 2013) and two biomass types and are disaggregated into rainfed and irrigated production. Agricultural blue water demands are driven by the extent of irrigated land, irrigated crop mix, irrigation efficiency, climate and weather, and several other lesser factors. The extent of irrigated land and irrigated crop mix are determined endogenously in GCAM and depend solely on economics, as explained in Calvin et al. (2017). Regionalized estimates of three main irrigation systems exist and are employed in GCAM (Rohwer et al. 2007). Electricity generation water demands are calculated based on cooling system types; once-through cooling systems, which account for 86% of the withdrawals in the energy sector in GCAM; recirculating cooling systems, which represent the largest water-consumption cooling process; and dry cooling systems, in which water usage is minimal. Manufacturing water demands are calculated based upon the energy required by the manufacturing sector. This value represents an aggregate of all goods and services produced in the manufacturing sector, as GCAM does not separate manufacturing into subsectors. Municipal water demands are calculated based upon population and per-capita income across all GCAM regions. Primary energy demands encompass oil production and refining, coal mining, gas production and processing, ethanol production and coal-to-liquids fuel production. Finally, water demands for the livestock sector represent the drinking water requirements for five livestock types (beef, dairy, sheep & goats, pigs, and poultry), as well as water for cleaning and servicing them. Detailed methods on water demand modeling within GCAM are described in Chaturvedi et al. (2013), Hejazi et al. (2013b), and Hejazi et al. (2014b).

1.3.3.2 Water Supply

Water supplies in GCAM exist in three distinct categories: renewable water, non-renewable groundwater, and seawater. GCAM employs cost resource curves across all 235 basins that follow a logit formulation, a statistical representation of the competition between multiple objects (Clarke and Edmonds, 1993), to determine the share of each water source needed to meet the water demands within all basins (Kim et al., 2016, Turner et al., 2019a). As accessible water within a basin decreases, the price of water within that basin increases until higher cost options – non-renewable groundwater or seawater – are used to meet demands. Rising water prices in a basin lead to a compounding price increase on the goods and services that require higher-priced water sources. In response, a corresponding change occurs in demands for agricultural production, energy resources, and all remaining goods and services within the basin. The inclusion of water constraints within GCAM has resulted in changes to regional agricultural production in water scarce regions, leading to increased dependency on international trading of goods to water scarce regions (Kim et al., 2016). As nonrenewable groundwater is increasingly depleted, expansions in rainfed agriculture and shifts of irrigated agriculture from scarce regions occurs (Turner et al. 2019b).

Future available surface runoff supply is calculated by use of the global hydrologic model, Xanthos (Li et al. 2017, Liu et al., 2018; Vernon et al. 2019). This is completed by using bias-corrected hydrologic data derived from GCMs. With temperature and precipitation data, Xanthos calculates the potential evapotranspiration using the FAO Penman-Monteith method (Monteith, 1965; Allan et al., 1998). From the potential evapotranspiration calculation, information regarding soil moisture capacity allows for runoff generation within a single grid cell. Within Xanthos, an accessible water module calculates the amount of water available for human use dependent upon the total runoff generated. This is aggregated to the 235-basin level for implementation in GCAM. For the purposes of these studies, 5-year moving averages will be considered as the water supply (available runoff) to tease out interannual variability, while leaving the general trend of water supply evolution. Historical water supplies are also calculated by Xanthos for the 1975-2010 period. Xanthos has undergone extensive verification for the historical reconstruction of potential evapotranspiration and runoff generation. Xanthos has been calibrated to the Variable Infiltration Capacity (VIC) model runoff projections that have been forced with observation data in the WATCH dataset (Weedon et al., 2011; Vernon et al., 2019).

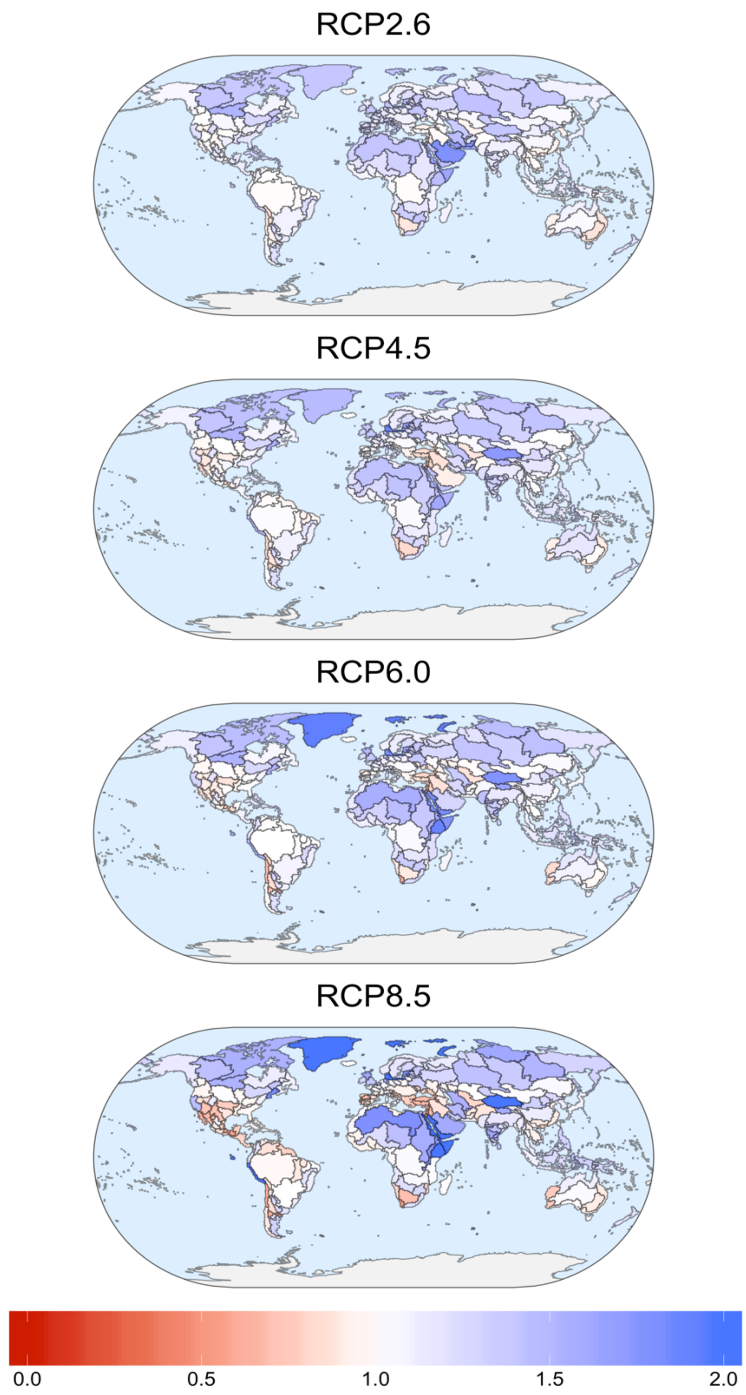

Figure 1.6 Intensification of water supply from 2005 to 2100 as calculated from Xanthos (Section 1.3.3.2). Values consider the average water supply as calculated from five GCMs for each RCP scenario. Values below 1, depicted in red, represent decreases in available surface runoff from 2005 values, while values above 1, depicted in blue, represent relative increases in the amount of available water from 2005 values. Intensification calculation provided as ${Q_{R_{2100}}}/{Q_{R_{2005}}}$.

1.4 Noted Research Gaps and Objectives

The evaluation of water futures has increased significantly in recent years by studying the effects of human systems, climate systems, and projecting how the use of water will change in the future. However, there remain significant research gaps which the studies that follow aim to address. Due to the recent advancements to the modeling of the water sector in GCAM, the following studies are able to capture the interactions between the human and climate system, and the resulting effects on water use and availability. A unique component of this research is the ability to constrain the amount of water that is available for use from all sources. This inclusion allows for more accurate representations of water use and are a critical aspect of these studies.

Three key areas of potential knowledge improvement have been found which will be the focus of the following studies. 1) There is currently a lack of understanding regarding the implications of adding socioeconomically viable water technologies to the set of SSP scenarios released by the IAM community and used for the upcoming IPCC report. Several studies have offered glances at how socioeconomics may change water use, but none have been able to capture both the human-energy-land feedbacks as well as account for limiting supplies of water. 2) Future water scarcity is widely believed to be driven by human interactions, however there remains a clear lack of knowledge regarding the codependence on the climate system as well as how the interactions between each may alter scarcity, positively and negatively, in the future. The use of the IAM framework allows for these interactions to be captured. 3) The concept of virtual water trade is gaining additional recognition in the sociohydrological community, however very little is known about how it will change in the future. Even less is known about the reliance on nonrenewable groundwater use for meeting global demands. GCAM allows for trade evolution, specifically as a response to socioenvironmental forcings. As such, this provides a platform to evaluate, for the first time, the temporal evolution of virtual water trade.

In general, this work aims to gain a better understanding of the interactions between the human and climate systems on the future of water around the world. To do this, three research questions are posed to evaluate the noted research gaps:

(i) How do quantitative assumptions for the water sector across the five Shared Socioeconomic Pathways scenarios change global water demands in a water constrained world?

(ii) How does the coevolution of human-energy-water-land-climate systems affect the driver of water scarcity changes and how do human and climate systems interact to alter water scarcity attributions both spatially and temporally?

(iii) How will future changes in socioeconomics and climate affect the amount of water embedded in international agricultural trade and what are the implications for nonrenewable groundwater extraction?

In order to answer these three questions, the following methods are used to examine the future of global water:

(i) Establish qualitative and quantitative water demand assumptions for the Shared Socioeconomic Pathway scenarios and analyze the associated impacts

- Develop qualitative technological change assumptions for four water demand sectors, based upon previous literature and current advancement rates, consistent with the storylines of each SSP scenario.
- Implement quantitative assumptions in GCAM and evaluate the impact on 21st century global water demands across each SSP scenario and individual sectors under basin level water constraints.
- Document the reliance on different income regions towards reaching observed demand changes.
- Demonstrate the differences between technology assumptions and water constraints on global water demands throughout the century.

(ii) Analyze how future water scarcity will change spatially and temporally across a set of changing socioeconomic and climate conditions.

- Establish GCM derived climate impacts on water supply, agricultural productivity, hydropower expansion, and building energy demands.
- Combine climate impacts with each SSP scenario following the SSP-RCP modeling framework and use GCAM to establish water demands through 2100.
- Document the relative contributions of both the human and climate systems to water scarcity changes at the GCAM basin level.

- Analyze in which basins human systems or climate systems have a larger impact and establish whether these systems are increasing or decreasing scarcity over time.
- Document the dependence of the observed results on the socioeconomic and climate assumptions contained within each scenario.

(iii) Establish, for the first time, a virtual water trade projection through the end of the century when considering feedbacks between the human and Earth system.

- Using a single SSP-RCP combination, estimate, through 2100, the reliance on global trading of water intensive agricultural goods.
- Estimate the amount of green, blue, and nonrenewable groundwater that must be consumed in the crop growth process for crops that are traded in the global market.
- Downscale the virtual water exports to the GCAM basin to estimate location of exports.
- Document how virtual water trading of all water sources progresses through 2100 by aggregating by crop type and GCAM energy-economy region.
- Demonstrate locations of increased reliance on nonrenewable groundwater extraction to meet global agricultural demands.

This thesis is organized as follows. Chapter 2 depicts the implementation of quantitative water sector assumptions in GCAM in the absence of climate change. Chapter 3 introduces the climate change impacts to the socioeconomic assumptions established in the previous chapter to investigate how human and climate systems drives future water scarcity changes. Chapter 4 establishes how both climate and socioeconomic impacts change the reliance on traded water intensive agricultural goods to meet changing demands by the end of the century. These chapters are organized to capture the results from Graham et al. (2018), Graham et al. (2019a, *submitted*), Graham et al. (2019b, *in prep*). Concluding remarks and future directions are provided in Chapter 5.

Chapter 2: Water Sector Assumptions for the Shared Socioeconomic Pathways in an Integrated Modeling framework (published as Graham et al., 2018)

2.1 Introduction

In order to present results consistent with the next generation of socioeconomic scenarios, we employ the Shared Socioeconomic Pathways (SSP). These scenarios have been quantified using a set of global integrated assessment models (IAM), where each model has been used to produce the marker scenario (Riahi et al., 2017) for one SSP scenario (Calvin et al., 2017; Fricko et al., 2017; Fujimori et al., 2017; Kriegler et al., 2017; van Vuuren et al., 2017) and provide uncertainty ranges for the other SSPs. The IAM results provided alternative projections of the evolution of the economy, energy systems, land systems, emissions, and climate.

Initially absent from the scenario descriptions have been assumptions for the water sector. Therefore, studies have begun to investigate the complete water sector response under different socioeconomic scenarios. Several studies (Hejazi et al., 2014b; Hanasaki et al., 2013a, b) predate the multi-sector SSP assumption implementation in the global IAMs (Calvin et al., 2017; Fricko et al., 2017; Fujimori et al., 2017; Kriegler et al., 2017; van Vuuren et al., 2017); however, since their release, others have incorporated assumptions for water sectors within the SSP framework. For example, the Water Futures and Solutions initiative (WFaS) combined the hydro-economic classification system (Fischer et al., 2015) with the socioeconomic assumptions of the SSP scenarios to create varying degrees of technological change in the agricultural, municipal, and industrial sectors, which were then applied to a set of three global hydrological models (Wada et al., 2016). Other studies have focused on sector-specific assumptions (Fujimori et al., 2016; Mouratiadou et al., 2016) or on a subset of the five SSP scenarios (Bijl et al., 2016). Despite recent efforts, water demand changes as a response to both SSP storyline and limited water supply have not been addressed as of the submission of this thesis. Table 2.1 lists recent studies that have explored future technological changes within specific water sectors associated with changing socioeconomic scenarios. The use of an IAM is necessary for the inclusion of intersectoral and subsectoral feedbacks, incorporated through several sectoral water demand models, allowing for the endogenous calculations of water demand while considering both the cost and availability of various water sources (Hejazi et al., 2014a; Kim et al., 2016). All previous studies that modeled water in the SSPs have calculated water assuming unlimited supply and therefore have the potential to both overestimate water demands and exclude important feedbacks resulting from a constrained basin-level supply of water (Kim et al. 2016). Also absent from the discussion thus far is the magnitude of changes in water demands that result from the inclusion or exclusion of future water technology changes.

Table 2.1 A comparison of previous studies which have looked at technological change with the SSPs and the resulting effects on future water demands

	This Study	Hanasaki et al. (2013a, b)	Wada et al. (2016)	Fujimori et al. (2016)	Mouratiadou et al. (2016)	Bijl et al. (2016)
SSP Scenarios	1-5	1-5[a]	1-3	1-5	1, 2, 5	2
Water Constraints	X					
Use of IAM	X			X	X	X
Agriculture	X	X	X[b]		X	
Manufacturing	X	X	X	X		X
Electricity	X	X	X	X	X	X
Municipal	X	X	X			X

[a] Hanasaki et al. (2013a, b) predates the release of O'Neill et al. (2014) and the recently released SSP marker scenarios in which SSP assumptions were input into various IAMs. (Calvin et al., 2017; Fricko et al., 2017; Fujimori et al., 2017; Kriegler et al., 2017; van Vuuren et al., 2017)

[b] Wada et al. (2016) provide qualitative assumptions of agricultural changes that are not currently implemented into the Global Hydrologic Model used.

In this study, we employ GCAM to explore future water use and the effects of technological advancements in the water sector, following the SSP framework. Specifically, we explore a comprehensive set of water sector assumptions for each of the SSP scenarios that 1) quantifies the implications of technological change in the water sector and 2) considers the effects of limiting the supply of water across all sectors. Changes that are consistent with each SSP scenario are simulated within the agricultural, manufacturing, municipal, and electricity generation sectors in terms of water withdrawals, as driven by technological advancements and associated efficiency changes. Further, we investigate the impact that these water technologies have on global water demands and note 1) when advanced technologies can result in substantial reductions in water use (SSP1 & SSP5) and 2) under which circumstances end-of-century water demands are reduced below base-year values. As different regions undergo technological changes at different rates, the resulting withdrawal changes vary by scenario and region. Finally, in combining socioeconomic and water sector assumptions with water constraints, we can both advance the SSP scenarios and assess their implications for other sectors, e.g., agriculture, energy, manufacturing, municipal, livestock and primary energy production. The effects of climate change on water are not explored in this study, as our focus is an exploration of demand changes by SSP scenario.

2.2 Methods

GCAM has developed a set of qualitative and quantitative assumptions for the five SSP scenarios after being chosen as the marker model for the SSP4 scenario

(Calvin et al., 2017; top portion of Table 2.2). For this study we have developed a set of qualitative assumptions for each water sector, shown in the bottom portion of Table 2.2. The assumptions represent varying degrees of change in individual sectors based on future storylines of the SSP scenarios. The development of qualitative assumptions is intended to aid other modeling groups in exploring various quantitative changes while remaining true to the SSP storylines. We have categorized each sector and SSP using three levels of change, high, medium and low, for which quantitative assumptions are later derived. The specifics for all non-water sector assumptions are discussed in detail in Calvin et al. (2017). For future water demand changes, the assumptions developed here consider two factors, the desire for sustainable futures and the ability to invest in the technological advances required to produce varying degrees of sustainability. For the former, we consider the degree of sustainability of each SSP storyline in O'Neill et al. (2017). For the latter, we use the future global economic conditions (such as GDP per capita) as a proxy. SSP1 and SSP5 are thus assumed to have high degrees of progress for most water sector variables due to high income, as well as the sustainability focus of SSP1. SSP3 experiences low degrees of progress because of low GDP growth. SSP2 includes a medium degree of progress in the water sector, consistent with its middle-of-the-road narrative. SSP4 is split between three income regions, where the high-income regions follow closely the assumptions from SSP1 and SSP5, the medium-income regions generally follow SSP2, and the low-income regions generally follow SSP3 assumptions. From these assumptions, the quantitative responses to future technological change for each SSP scenario are derived and applied to the respective water sectors in GCAM, as described below.

Table 2.2 Qualitative assumptions for the SSP scenarios within GCAM. All non-water sector assumptions adopted from Calvin et al. (2017).

		SSP1	SSP2	SSP3	SSP4			SSP5
					High-income	Medium-income	Low-income	
SSP Prescribed Challenges	Challenges to Mitigation	Low	Medium	High	Low			High
	Challenges to Adaptation	Low	Medium	High	High			Low
Socioeconomics	Population in 2100	6.9 billion	9 billion	12.7 billion	0.9 billion	2.0 billion	6.4 billion	7.4 billion
	GDP per capita in 2100	$46,306	$33,307	$12,092	$123,244	$30,937	$7,388	$83,496
Fossil Resources (Technological Change/Acceptance)	Coal	Med/Low	Med/Med	High/High	Med/Low	Med/Med	Med/ High	High/High
	Conventional Gas & Oil	Med/Med	Med/Med	Med/Med	High/Low	High/Low	High/ Low	High/High
	Unconventional Oil	Low/Med	Med/Med	Med/Med	Med/Low	Med/Low	Med/ Low	High/High
Electricity (Technology Cost)	Nuclear	High	Med	High	Low	Low	Low	Med
	Renewables	Low	Med	High	Low	Low	Low	Med
	CCS	High	Med	Med	Low	Low	Low	Low
Fuel Preference	Renewables	High	Med	Med	High	High	High	Med
	Traditional Biomass	Low	Low	High	Low	Low	High	Low
Energy Demand (Service Demands)	Buildings	Low	Med	Low	High	Med	Low	High
	Transportation	Low	Med	Low	High	Med	Low	High
	Industry	Low	Med	Low	High	Med	Low	High
Agriculture & Land Use	Food Demand	High	Med	Low	High	Med	Low	High
	Meat Demand	Low	Med	High	Med	Med	Med	High
	Productivity Growth	High	Med	Low	High	Med	Low	High
	Trade	Global	Global	Global	Regional	Regional	Local	Global
Water Use (Efficiency Improvements)	Irrigation	High	Med	Low	High	High	Low	High
	Manufacturing	High	Med	Low	High	Med	Low	High
	Energy	High	Med	Low	Med	Med	Med	High
Water (Technological Change)	Shift to Recirculating and Dry Cooling	High	Med	Low	High	Med	Low	High
	Municipal	High	Med	Low	High	Med	Low	High
	Municipal Water Price	Med.	Med	High	Low	Med	High	Low

2.2.1 Water Technology Assumptions for the Agricultural Sector

Agricultural withdrawals for irrigation purposes account for nearly 70% of all global water withdrawals (FAO, 2011). The efficiency with which water is delivered to crops and the extent and geographic location of irrigated land significantly affect withdrawal values. Because GCAM calculates both crop mix and extent of irrigated land endogenously, we do not implement any SSP-specific preferences for these factors and instead allow the relative profitability of irrigated and rainfed crops to determine the irrigation shares. According to the FAO, irrigation systems can be categorized as one of three types, each possessing different field application efficiencies. Surface irrigation (crop flooding) practices generally have a maximum efficiency of 60%, sprinkler irrigation systems (center pivot) have a maximum efficiency of 75%, and drip irrigation systems have the highest maximum efficiency at 90% (Brouwer, 1989). Unfortunately, historical values of global and regional irrigation efficiencies are not currently well documented. Country-level values are available from the FAO database (AQUASTAT, 2016); however, several countries have little to no data available. More recently, studies have incorporated increased biophysical dependencies as a result of spatially variable irrigation systems derived from AQUASTAT and applied based upon individual crop functional types (Jägermeyr et al., 2015, 2016, 2017). Several recent studies have also investigated future changes in irrigation efficiency. Schmitz et al. (2013) calculated irrigation efficiency improvements of 2% to 12% from 2005-2045, using regional GDP per capita as the driving force. Fischer et al. (2007) assigned universal irrigation efficiency improvements of 10% per decade, and Chaturvedi et al. (2013) prescribed field application efficiency changes through 2095 closely based on regional GDP and assumed a maximum field efficiency of 85%.

Previous SSP studies have implemented changes in agricultural water demands through efficiency changes and crop yield improvements. Mouratiadou et al. (2016) addressed crop yield improvements, but these were only applied to bioenergy. Wada et al. (2016) held irrigation efficiency constant at base year values for the three SSP scenarios they analyzed, while Hanasaki et al. (2013a) assumed maximum irrigation efficiency of 100%. This study assumes differing rates of efficiency change (described here and shown in Graham et al., 2018) for future irrigation practices, using maximum efficiency values in line with the upper bounds shown in the literature (Rohwer et al. 2007; Sauer et al. 2010; Jägermeyr et al. 2015). Specifically, we use current-generation irrigation technologies and the efficiencies that are currently obtainable as a basis for technological improvements.

In the high technological-change scenarios of this study (SSP1, SSP5, and high- and medium-income regions of SSP4) GCAM regions are assumed to invest in the most efficient irrigation technology. The result is that, beginning in 2015, all regions begin linear yearly efficiency improvements with the goal of reaching drip irrigation efficiency, 90%, by 2100. The adoption of universal drip irrigation systems is assumed to require significant regulations, investments, and cultural changes (Jägermeyr et al., 2015) at a global scale; therefore, we have assumed that field application efficiency will only reach a midway point between sprinkler and drip irrigation systems, 83%, in 2100. The direct cost of adding drip irrigation systems across all GCAM regions has not been considered. In the medium technological-change scenarios, regions will linearly adopt the next attainable technology from

2015 to 2100. This means that regions below the threshold of crop flooding will approach a field application efficiency of 60% by 2100. The same holds true for all other irrigation systems, with no individual region attaining field application efficiencies above 75%. Finally, in the low technological-change scenario, all regions are assumed not to invest in technological advances for irrigation efficiencies; therefore, all field application efficiencies remain at 2010 values throughout the century.

2.2.2 Water Technology Assumptions for the Electricity Sector

Three scenarios that combine changes in power-plant cooling system shares and efficiency improvements were adapted from Davies et al. (2013) for use in this study. The water efficiency improvements, originally described in Feeley et al. (2008) for coal and non-coal plants, result in up to a 48% reduction in water withdrawal and 39% reduction in consumption, while the shifts in cooling systems vary regionally but converge to similar values in most regions by 2035, as described in Davies et al. (2013), and are then held constant through the remainder of the century. In this study, the medium technology change scenario assumes 50% of new power plants built after the year 2015 invest in the water savings technologies described in Feeley et al. (2008), and cooling system shares move from once-through cooling to recirculating and dry cooling at the same rate as in Davies et al. (2013); the assumptions therefore match a “median_midtech” scenario in Davies et al. (2013). The high technology scenario differs from the medium technology case in assuming 100% adoption of water savings technologies (“hitech”) and a 10% increase in the share of dry-cooling power plants and a corresponding 10% decrease in the share of recirculating systems (“+10% Dry”). Finally, the low scenario is new for this study, and assumes no water efficiency improvements and a 25% reduction in adoption of recirculating and dry cooling technologies, as compared with the other scenarios. Table 2.3 provides water efficiency and cooling system share changes in coal and non-coal power plant withdrawals.

2.2.3 Water Technology Assumptions for the Manufacturing Sector

In GCAM, water use for manufacturing goods and services is calculated separately from the water used to cool power plants during electricity generation. However, because the manufacturing sector is not broken into individual goods and services, GCAM uses an estimate of technological changes for the sum of all manufacturing branches. Therefore, following the aggregate manufacturing efficiency improvements found in Fujimori et al. (2016), we assume that the water withdrawals in the manufacturing sector decrease at a constant rate of 1.1% per year in the high technological-change scenarios, SSP1 and SSP5, by 0.55% per year in the medium technological-change scenario, SSP2 and by 0.275% per year in the low technological change scenario, SSP3. SSP4 has withdrawal decreases of 1.1% in high-income regions, 0.55% in medium-income regions, and 0.275% in low-income regions.

Along with withdrawal improvements, Bijl et al. (2016) investigated withdrawal to consumption ratio improvements in the manufacturing sector. They created three technological advancement scenarios with varying degrees of reductions in manufacturing water consumption. Here, we apply 0.5% consumption reduction per year (Bijl et al., 2016 medium scenario) to the scenarios with high qualitative assumptions, 0.25% per year to medium scenarios, and no change in consumption (Bijl et al., 2016 high scenario) to low qualitative assumption scenarios. A summary of withdrawal changes is located in Table 2.3 and consumption changes can be found in Table 2.4.

2.2.4 Water Technology Assumptions for the Municipal Sector

Hejazi et al. (2013b) described the modeling of municipal water demand in GCAM. Changes made in the municipal sector for the SSP scenarios are based on technological advancement and the influence of price on water demand. Technological change in SSP2 uses the same technological change rate, represented by AEEI in Table 3, originally prescribed by Hejazi et al. (2013b), 5% per year, which accounts for efficiency improvements. In the high technological-change scenarios, SSP1 and SSP5, and the high-income regions of SSP4, technological change is assumed to progress 25% faster than the base value of 5% per year; in contrast, SSP3 experiences a 25% reduction in the rate of technological change, leading to a decrease in the adoption of water-efficient practices.

Price changes alter municipal water use, based on the GDP of a particular region, through their effects on the numbers of people with access to water-using appliances (Hejazi et al., 2013b). Here we base all future price elasticity changes within the municipal sector on GDP per capita characteristics (Table 2.2). In SSP1, SSP2, and the medium-income regions of SSP4, the price elasticity remains the same as in Hejazi et al. (2013b). In SSP5 and the high-income regions of SSP4, the price elasticity of municipal water withdrawals (percentage change in withdrawal for a percentage change in price) is decreased by 10%. SSP3 and low-income regions of SSP4 experience a 10% increase in price elasticity. Increases in price elasticity will result in an increase in adoption of water conservation strategies driven by higher prices for municipal water, and lead to a decrease in overall municipal water demand. Decreases will allow people to use more water for municipal purposes.

2.2.5 Water Technology Assumptions for the Livestock and Primary Energy Sectors

In GCAM, water withdrawals for the livestock sector represent the drinking water requirements for five livestock types (beef, dairy, sheep & goats, pigs, and poultry), as well as water for cleaning and servicing them. The demand for livestock varies both by region and SSP (see Table 2.2). We have assumed that the livestock water demands (per head) into the future are unlikely to change greatly; therefore, the differences in livestock water withdrawals across SSPs are based on differences in livestock numbers alone and, within this study, include no future technological changes.

Finally, water use for the production and processing of primary energy was discussed in Hejazi et al. (2014b), who assumed no technological change would alter future water withdrawals in primary energy production in future periods, and that withdrawals would therefore scale with energy sector activities. In this study, we employ the same assumptions.

Table 2.3 Quantitative withdrawal changes applied to the various water sectors within GCAM

		SSP1	SSP2	SSP3	SSP4			SSP5
					High-income	Medium-income	Low-income	
Water Use (Efficiency Improvements)	Irrigation	83% Field Efficiency by 2100	Increase by one efficiency level	Remain at 2010 Values	83% Field Efficiency by 2100	83% Field Efficiency by 2100	Remain at 2010 Values	83% Field Efficiency by 2100
	Manufacturing	1.1% per year Withdrawal Reduction	0.55% per year Withdrawal Reduction	0.275% per year Withdrawal Reduction	1.1% per year Withdrawal Reduction	0.55% per year Withdrawal Reduction	0.275% per year Withdrawal Reduction	1.1% per year Withdrawal Reduction
	Electricity (By Power Plant Type)	Coal: 45.7% Non-Coal: 47.7%	Coal: 22.9% Non-Coal: 23.9%	No Change	Coal: 22.9% Non-Coal: 23.9%	Coal: 22.9% Non-Coal: 23.9%	Coal: 22.9% Non-Coal: 23.9%	Coal: 45.7% Non-Coal: 47.7%
Water (Technological Change)	Electricity (Power Plant Cooling Systems)	10% increase in dry cooling over current values	Davies et al. (2013) median midtech	25% reduction in recirculating and dry cooling from current	10% increase in dry cooling over current values	Davies et al. (2013) median midtech	25% reduction in recirculating and dry cooling from current	10% increase in dry cooling over current values
	Municipal	AEEI[a] = 0.0625	AEEI = 0.05	AEEI = 0.0375	AEEI = 0.0625	AEEI = 0.05	AEEI = 0.0375	AEEI = 0.0625
	Municipal Water Price	Price Elasticity = -0.32619	Price Elasticity = -0.32619	Price Elasticity = -0.35881	Price Elasticity = -0.29357	Price Elasticity = -0.32619	Price Elasticity = -0.35881	Price Elasticity = -0.29357

[a]AEEI, or autonomous energy efficiency improvement, represents the technological change rate (%/year).

Table 2.4 Quantitative consumption changes made to various sectors within GCAM

		SSP1	SSP2	SSP3	SSP4			SSP5
					High-income	Medium-income	Low-income	
Water Use (Efficiency Improvements)	Manufacturing	0.5% per year Consumption Reduction	0.25% per year Consumption Reduction	2010 Values remain	0.5% per year Consumpti on Reduction	0.25%per year Consumpti on Reduction	2010 Values remain	0.5% per year Consumpti on Reduction
	Energy (2035 Coefficient Reductions)	Coal: 38.9% Non-Coal: 41.2%	Coal: 19.5% Non-Coal: 20.6%	No Change	Coal: 19.5% Non-Coal: 20.6%	Coal: 19.5% Non-Coal: 20.6%	Coal: 19.5% Non-Coal: 20.6%	Coal: 38.9% Non-Coal: 41.2%

2.2.6 Non-Water Sector SSP Assumptions

The non-water SSP-related assumptions in GCAM can be broken into five main components: socioeconomics, energy demand, agricultural productivity and growth, energy supply, and non-CO_2 emission changes. These five components have qualitative assumptions shown in Table 2.2 and are described in detail in Calvin et al. (2017). Socioeconomic assumptions for the SSPs include population growth, GDP per capita changes, and associated income elasticities. Energy demand assumptions alter the cost, performance, and preference for energy demand technologies (e.g., vehicle efficiency or preference for walking/biking). Agricultural productivity and growth assumptions specify future crop yield improvements and assumptions about trade of crops and bioenergy. Energy supply includes assumptions about the cost and performance of energy generation technologies, the cost of energy extraction, and the cost and availability of carbon dioxide capture and storage. Finally, non-CO_2 emission assumptions adjust the emissions factors for various technologies to reflect differing assumptions about air pollution controls. Unless otherwise noted, it is assumed that these five components are included within each SSP simultaneously; however, an assessment of their individual impacts on water demands across SSP scenarios is undertaken below.

2.2.7 Scenario Description

In this study, we investigate the effects of both water constraints and water technologies on future global water demands across the SSP scenarios. To organize the results, we have developed a scenario naming system that differentiates SSP scenarios based on the assumptions used. Scenario names therefore refer to both water technologies (Ref and Tech) and water constraints (const and unconst) and are provided in Table 2.5. In these scenarios, Tech assumes that all water technological advances and efficiency changes shown in Table 2.3 are implemented. In the Ref scenarios, all non-water sector SSP assumptions are present and water sector values are based on Hejazi et al. (2014b) and are consistent across all SSPs. Water constraints introduce water markets as described in Kim et al. (2016), while unconstrained scenarios assume that water is freely available in each basin, and therefore the amount required to meet the demand of any good or service can be provided. Results shown below compare the effects of water sector technology changes under a constrained water supply (Ref_const and Tech_const), unless otherwise noted.

Table 2.5 Scenario names and components added to each of the five SSP scenarios

	Ref_unconst	Tech_unconst	Ref_const	Tech_const
Existing SSP Assumptions [a]	X	X	X	X
Water Technologies [b]		X		X
Water Constraints [c]			X	X

[a] Existing assumptions for the SSP scenarios are adopted from Calvin et al. (2017) and are outlined in Table 2.2 which include all non-water sectors.
[b] Assumptions for the water sector developed in this study and shown in Table 2.3.
[c] Water supply is limited for renewable water only (Kim et al. 2016)

2.3 Results

2.3.1 Total Global Water Withdrawals

Total global water withdrawals increase through 2050 in all scenarios; however, despite declines in water withdrawals in the second half of the century of several scenarios, only in SSP1 are withdrawals less than 2010 values by 2100. Across all scenarios, declines in withdrawals are due to the inclusion of large changes in irrigation practices and significant efficiency improvements across other sectors.

Changes in global withdrawals from 2010 to 2100 range from a decrease of 8% (SSP1) to an increase of 71% (SSP3). All results shown throughout Section 2.3 include water constraints unless otherwise noted.

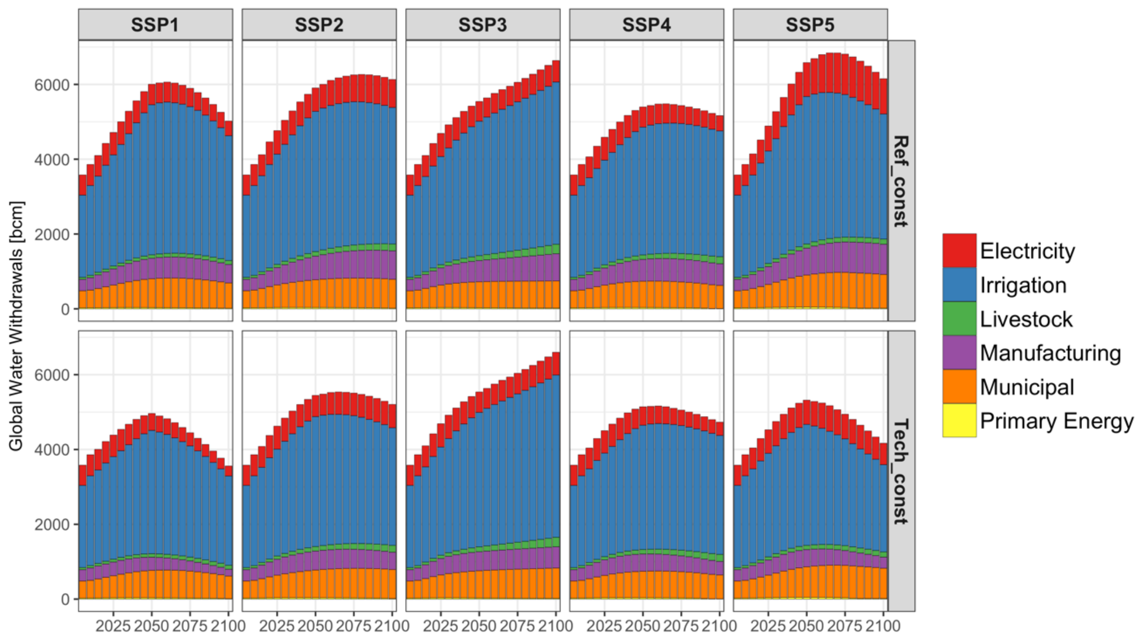

Figure 2.1 Global yearly water withdrawals by SSP scenario and sector (bcm/year). The top row shows scenarios run without technological change in the water sector, while the bottom row includes technological change in the SSP storylines.

Table 2.6 Global water withdrawals by sector (bcm/year). Values are given both for total withdrawals in water constrained scenarios with and without technological change (TC).

Sector	**2010**	**2050 with TC**					**2100 with TC**				
		SSP1	SSP2	SSP3	SSP4	SSP5	SSP1	SSP2	SSP3	SSP4	SSP5
Agricultural	2402	3297	3474	3596	3323	3234	2387	3145	4338	3180	2333
Manufacturing	332	352	506	508	461	461	182	463	568	362	299
Electricity Generation	562	453	566	546	493	650	268	624	609	354	573
Municipal	474	735	742	730	710	816	604	774	811	638	808
Total [a]	3861	4964	5446	5583	5142	5320	3560	5207	6600	4731	4168
Sector	**2010**	**2050 without TC**					**2100 without TC**				
		SSP1	SSP2	SSP3	SSP4	SSP5	SSP1	SSP2	SSP3	SSP4	SSP5
Agricultural	2402	4012	3749	3596	3416	3943	3073	3649	4338	3363	3345
Manufacturing	332	548	631	568	583	718	493	760	728	578	808
Electricity Generation	562	546	627	526	540	905	392	750	574	408	942
Municipal	474	772	742	694	704	857	676	774	725	619	903
Total [a]	3861	6004	5906	5543	5398	6583	5021	6134	6639	5166	6153

[a] includes Livestock and Primary Energy withdrawals not depicted in table.

While there are potentially significant scenario-based changes in future water withdrawals, the changes resulting from the inclusion of future water technologies are just as significant. Figure 2.1 shows total global withdrawals in scenarios with and without future water technological change. Significant reductions in post-2050 water withdrawals in SSP1 and SSP5 clearly result from technological change in the water sector, and stem largely from irrigation system improvements in low-income regions (see Section 2.3.6). All scenarios, aside from SSP3, show higher estimations of global water demand in 2100 in the absence of SSP-specific water technology adoption. Using 2100 with technological assumptions considered as a baseline, reductions in water withdrawal range from <1% in SSP3 to 32% in SSP5.

2.3.2 Agriculture and Livestock

Irrigation water withdrawals depend on the extent and geographic distribution of irrigated land, which in turn depends on agricultural demand, commodity prices, competition for land, etc. Irrigated land area differs across SSPs, even absent water-related technological change as shown in Figure 2.2. Specifically, irrigation withdrawals increase steadily into the mid-century for all scenarios, at which point all scenarios excluding SSP3 begin to see either small decreases or a leveling-off of withdrawals (Figure 2.3, top panel, absent water technologies), or large decreases in withdrawals (Figure 2.3, bottom panel, including water technologies), depending on the exclusion or inclusion of technological change. Population declines in the second half of the century in SSP1 and SSP5, which leads, in combination with the newly-implemented high-efficiency irrigation applications globally, to declines of more 900 bcm (billion cubic meters) by 2100 from 2050 values. These results show that technological change may result in lower future irrigation water withdrawals in the

SSP scenarios than those observed by previous studies (Figure 2.4). The results here are contingent upon the extent of irrigated land (Figure 2.2) not changing drastically over the course of the century as implied in previous studies (Hanasaki et al. 2013a). In contrast, SSP3 does not invest in more efficient technologies, and therefore does not experience a decline after 2050.

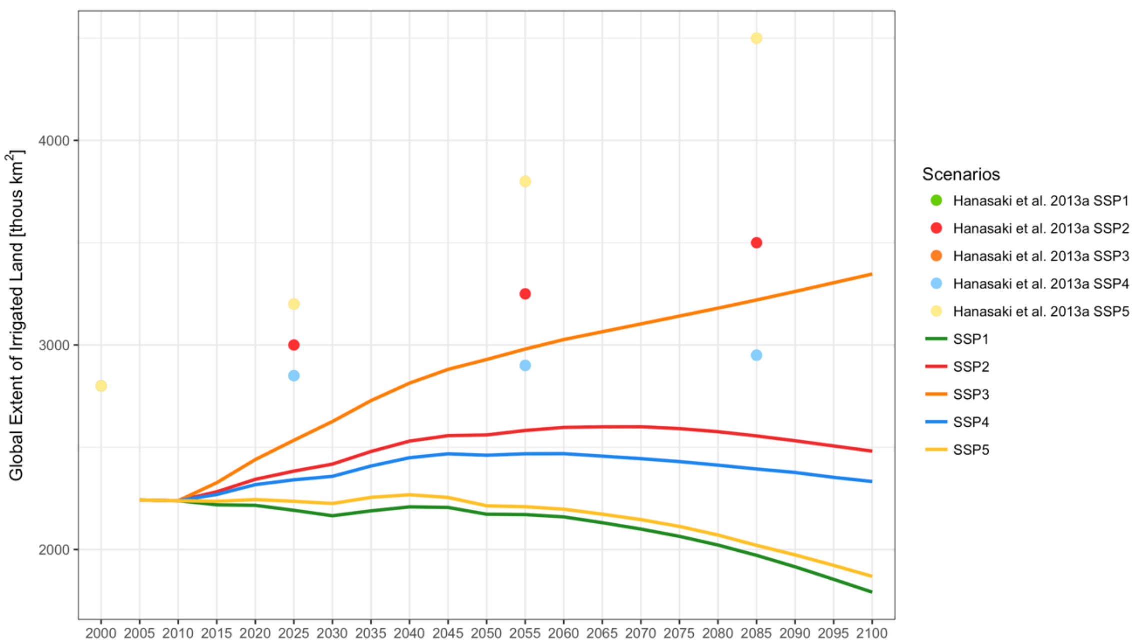

Figure 2.2 Extent of irrigated land within GCAM across the five SSP scenarios. Values shown here represent the extent of irrigated land in the Tech_const scenario. The extent of irrigated land is determined endogenously in GCAM and depends solely on economics in our analysis, as explained in Calvin et al. (2017). In GCAM we allow the relative profitability of irrigated and rainfed crops to determine the irrigation shares and geographic location and extent of irrigated land.

Table 2.6 shows that when water-efficiency technologies are included, global irrigation withdrawals in 2100 for SSP1 and SSP5 are lower than the 2010 values. In contrast, SSP3 shows a 81% increase in irrigation withdrawals by the end of the century. Agricultural water withdrawals have historically accounted for 70% of all water withdrawals globally. Incorporating the irrigation efficiency improvements of

SSP5, along with the emphasis on non-renewable energy sources, causes the share of agricultural water withdrawals to drop to 56% in 2100. In all other SSPs, agriculture represents between 60% (SSP2) and 67% (SSP1 & SSP4) of total global water withdrawals. Under our assumptions (no change in field efficiency between 2010 and 2100 in SSP3), SSP3 has no differences in agricultural withdrawals with technological change. The significant decrease in the share of irrigation water withdrawal found in SSP5 illustrates the potential for future changes in irrigation practices to affect the global water withdrawal footprint dramatically, provided that socioeconomic conditions are viable and that there remains a high reliance on manufacturing and electricity water needs.

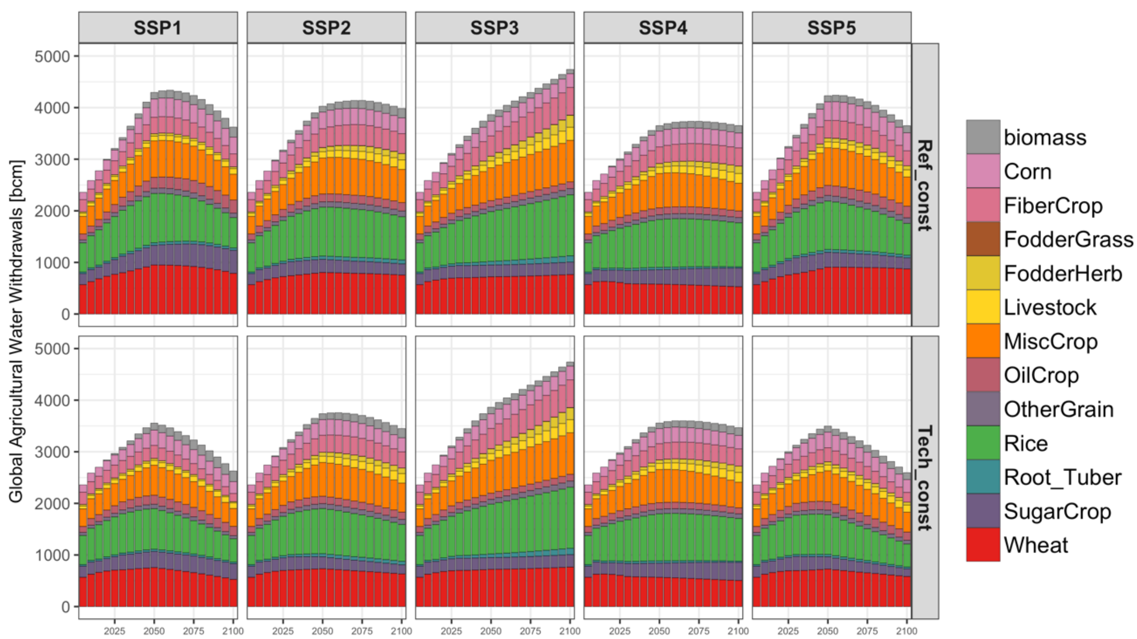

Figure 2.3 Global water withdrawals from irrigated agriculture and livestock production (bcm/year). The top panel shows scenarios run without technological change in the water sector while the bottom panel includes technological change.

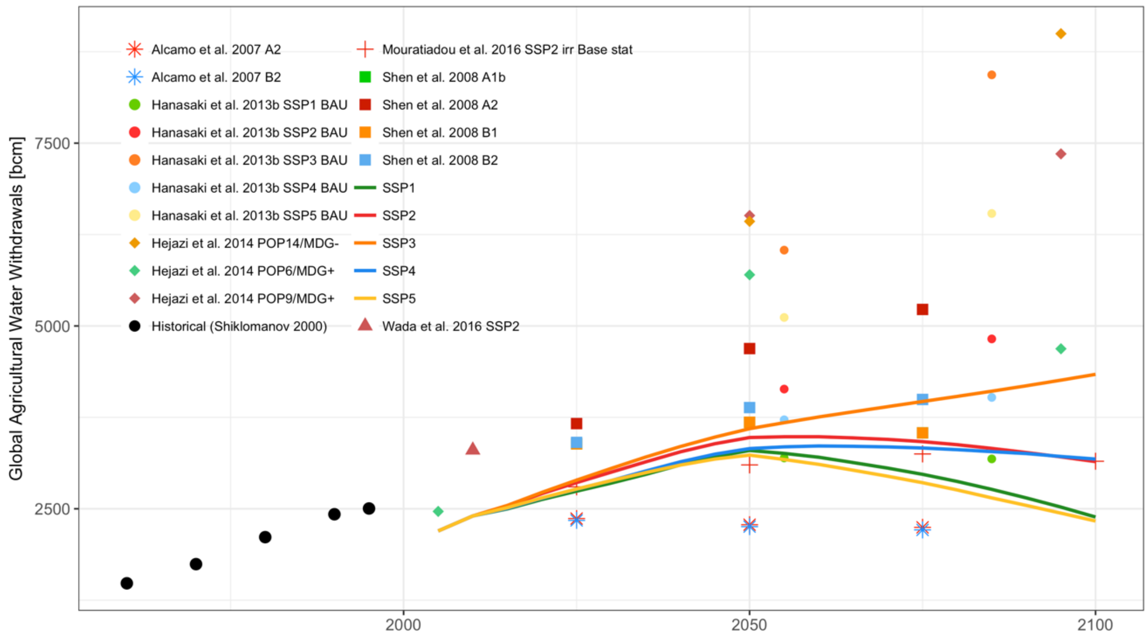

Figure 2.4 A comparison of future irrigation water withdrawals (bcm/year) across several studies. The figure shows studies that have attempted to account for future socioeconomic changes on the agricultural sector; not all of these have provided future sectoral changes as applied in this study. The values from this study, shown as solid colored lines, account for future technological change and are the same values seen in the Tech_const panel of Figure 2.3. Studies shown in this comparison have several differences in underlying assumptions and are shown here to represent a comparison between different socioeconomic impacts on agricultural withdrawals. (Alcamo et al., 2007; Wada et al., 2016; Hanasaki et al., 2013b; Hejazi et al., 2014b; Shiklomanov, 2000; Shen et al., 2008)

Livestock withdrawals are based on dietary patterns in each SSP scenario and are therefore lowest in SSP1, where diet is expected to shift away from ruminants and towards other food sources. All remaining SSP scenarios have very similar withdrawal values for livestock. While SSP3 has the highest end-of-century population, livestock withdrawals are similar to the other scenarios because of the low per-capita meat demands associated with low income levels.

2.3.3 Electricity Generation

Water withdrawals for electricity generation depend largely on the fractional share of once-through cooling for power plants and the type of fuel used. Within the

Tech_const scenario, bottom of Figure 2.5, SSP1 experiences water withdrawals in 2100 that are less than half of 2010 values, due to a shift away from coal, an increase in power plant water use efficiency, and a shift to less water-intensive cooling systems (e.g., recirculating and dry cooling). In SSP5, water efficiency improvements offset the large increase in non-renewable power sources, resulting in nearly identical withdrawal values in 2100 as in the base year. In SSP2, withdrawals do not change significantly throughout the century, because of smaller water-efficiency improvements and a lack of cooling-system share changes. All withdrawal increases due to electricity-demand increases are nearly negated by the assumed changes in water efficiency. SSP3 experiences an increase in withdrawals throughout the century, as efficiency changes are assumed not to occur. SSP4 is unique for the large decrease in water withdrawals in the second half of the century, which occurs as high-income regions shift towards higher percentages of recirculating cooling systems and adopt water-efficient power plants as in SSP1 and SSP5. These regions typically have the highest electricity generation and the increase in recirculating cooling and efficiency results in a decrease in withdrawals. The differences between regional reductions are discussed further in Section 2.3.6. Figure 2.5 shows the influences of once-through cooling on water withdrawals and the movement away from this cooling technology.

Comparison of scenarios with and without technological change reveals that the relatively small shift away from once-through cooling in combination with greater electricity generation increases water withdrawals in SSP3, while all other scenarios see decreases in water withdrawals. Reductions in withdrawals in SSP1, the high-income regions of SSP4, and SSP5 are a result of increasing dry cooling and efficiency changes in power plants, while lower withdrawals in SSP2 are a direct result of the efficiency changes.

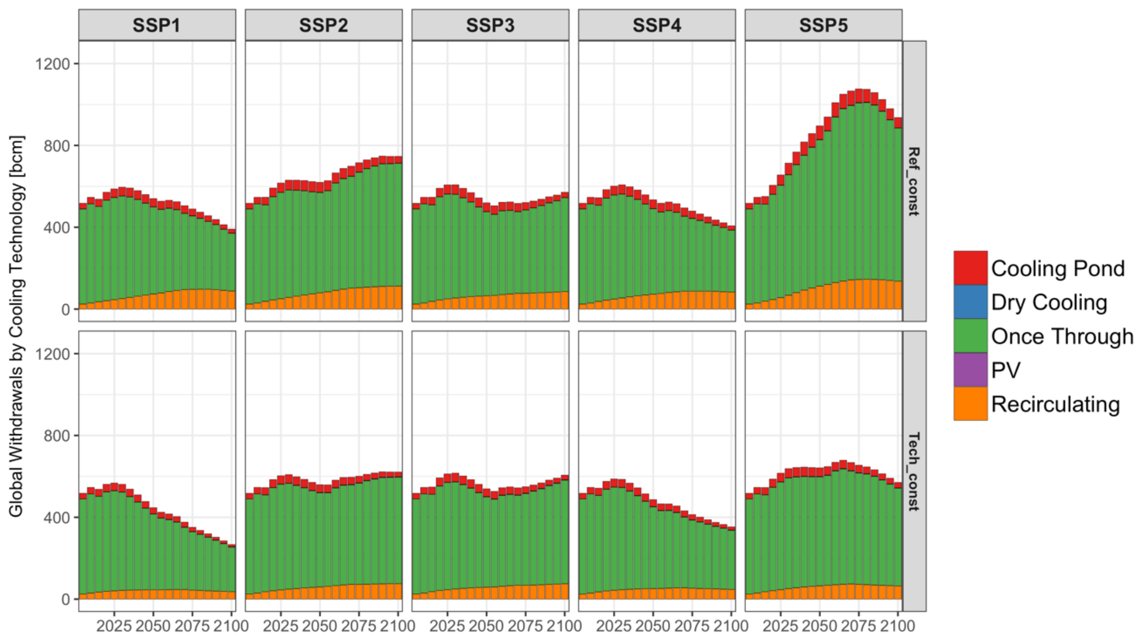

Figure 2.5 Water withdrawals by power plant cooling technology (bcm/year). The top panel shows scenarios run without technological change in the water sector while the bottom panel includes technological change.

2.3.4 Manufacturing and Primary Energy Production

In the base year (2010), manufacturing withdrawals account for 9% of the global water withdrawals. Withdrawals for manufacturing goods and services follow a similar pattern to the irrigation withdrawals, with most scenarios reaching a maximum near the middle of the century and decreasing in the second half of the century. In scenarios with high technological change (1.1% per year decrease in withdrawals), end-of-century demands are lower than the 2010 levels. For example, in Tech_const, SSP1 has a reduction of 45% from 2010 values by 2100, while SSP5 sees a slight reduction (seen in the bottom of Figure 2.6). SSP4 ends the century near the 2010 starting value because the high-income regions represent a large proportion of the global manufacturing market and achieve the greatest technological change. Overall, the share of global water withdrawals from manufacturing decreases across all scenarios except for SSP3, with SSP1 reaching 5% of total global withdrawals by the end of century, the lowest share among scenarios. When technological change is included, all scenarios see reductions in water withdrawals, with magnitudes ranging from 22% in SSP3 to 63% in SSP1.

The largest amounts of water used in primary energy production and processing are in SSP5, due to its focus on future fossil fuel use; however, these withdrawals are still a rather small portion of the global total and these decrease below that of other scenarios in 2100 due to the high efficiency improvements prescribed. As described in Section 2.2.5, we have assumed that water demands for primary energy extraction will not change due to the SSP storylines, and rather will remain to be driven by the energy demand of each SSP scenario. Therefore, we observe no differences between Ref_const and Tech_const scenarios.

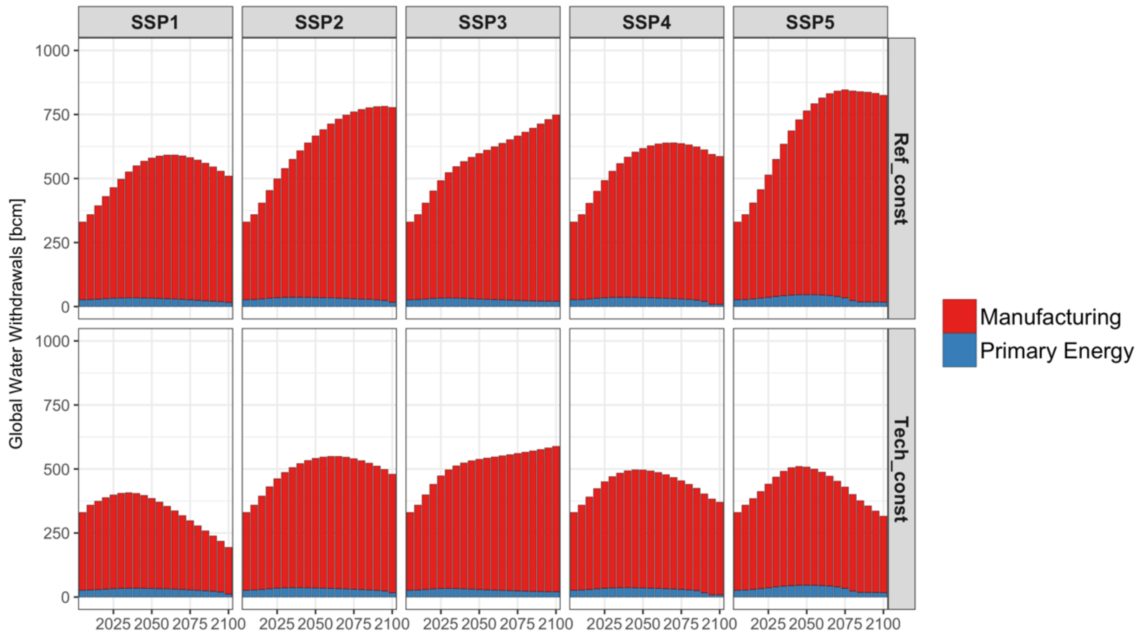

Figure 2.6 Water withdrawals from manufacturing and primary energy sectors (bcm/year). The top row shows scenarios run without technological change in the water sector, Ref_const, while the bottom row includes technological change in the SSP storylines, Tech_const.

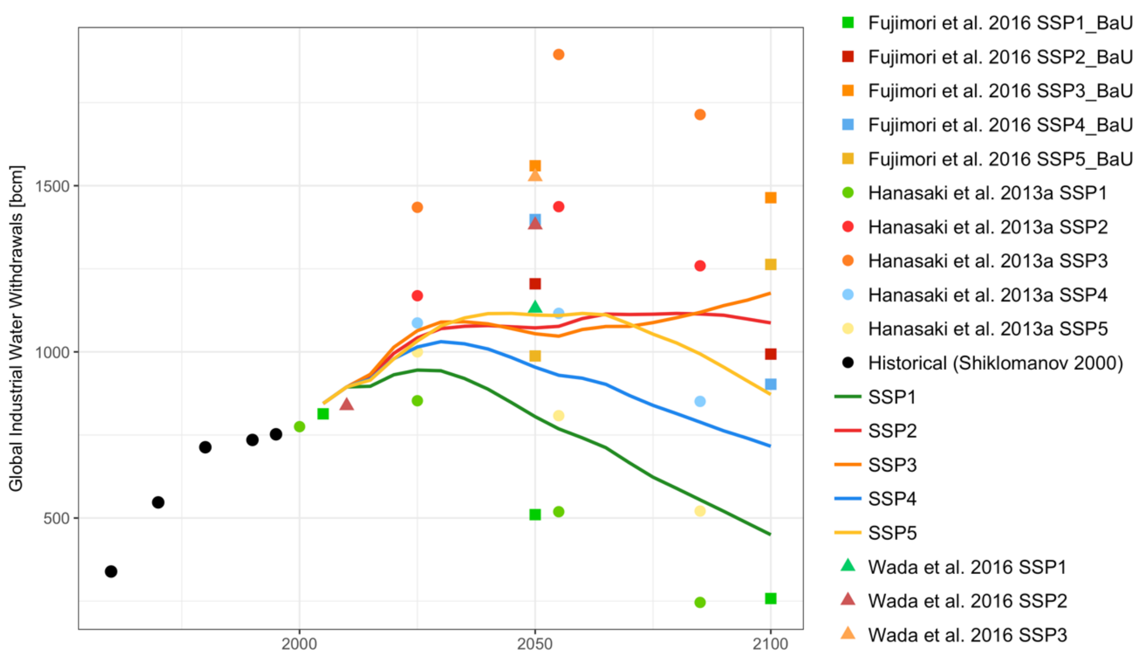

Figure 2.7 Comparison of industrial water withdrawals across several studies (bcm/year). GCAM does not explicitly model Industrial water demand, instead, a combination of water demands for electricity generation and manufacturing goods and services are used to allow for comparison to other studies. Values from this study, as solid colored lines, are shown for the Tech_const scenario. (Wada et al., 2016; Fujimori et al., 2016; Hanasaki et al., 2013a; Shiklomanov, 2000)

2.3.5 Municipal

Municipal water demand was estimated to account for 12% of the total global water withdrawals in 2010 (FAO, 2011). Municipal demand in GCAM is driven by water price, the regional GDP per capita, and the technological improvement rate, which captures changes in the efficiency of appliances. The results in Table 2.6 show that scenarios such as SSP5 have high withdrawals due to a lower price elasticity, resulting in a higher demand of water for municipal purposes, such as for appliances and lawn watering; in contrast, withdrawals are high in SSP3 due to future population growth and a lack of efficiency improvements. All scenarios see smaller technologically-induced water changes than those in other sectors because of smaller expected efficiency improvement rates within the municipal sector when compared to the period-to-period changes in other sectors. Changes to the municipal sector lead to less-drastic declines, or in some cases an increase, in post-2050 withdrawals. This leads to an overall change in the balance of global water withdrawals. For example, municipal water use in SSP1 increased from 12% of the total global water withdrawal in 2010 to 17% in 2100.

Differences between simulations with and without technological change are less than 20% for all SSPs. For SSP3 and SSP4, an increase in withdrawal values in 2100 is observed due to slow technological progress (SSP3 and the low-income regions of SSP4), resulting in large percentage-based increases in water withdrawals. In SSP3, a difference of 86 km^3 $year^{-1}$ is observed globally in 2100.

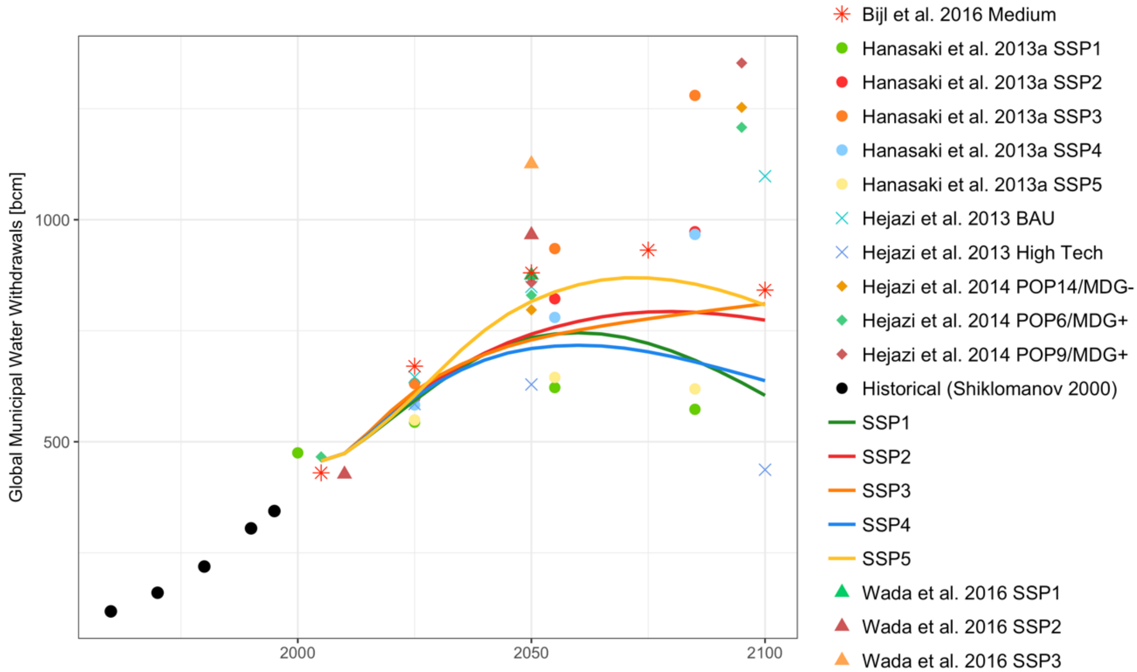

Figure 2.8 Comparison of municipal water withdrawals across several studies (bcm/year). Studies shown in this comparison have offered the potential for socioeconomics to influence future demands within the municipal water sector. Values depicted from this study, shown in solid colored lines, are depicted for the Tech_const scenario. (Bijl et al., 2016; Wada et al., 2016; Hanasaki et al., 2013a; Hejazi et al., 2013b; Hejazi et al., 2014b; Shiklomanov, 2000)

2.3.6 Income Region Differences

In SSP4, technology adoption rates differ across regions with differing income levels. This means that in SSP4, differences in adoption rates of higher-efficiency technologies are based on the starting efficiencies in each region. Regional groupings, based on income levels in SSP4, were described in Calvin et al. (2017) and are included in Table 2.7.

When all five SSP scenarios are analyzed in terms of the three income regions of SSP4, a pattern of technological improvements emerges (Figure 2.9). For most SSP scenarios, the largest-magnitude changes occur in low-income regions (bottom panel), where the irrigation systems are assumed to change by the largest amount. This results in savings of over 1000 billion cubic meters (bcm) in SSP5, more than double the savings of the medium-income regions (middle panel) and triple the high-income regions (top panel). The sector that experiences the largest reductions from technological change varies by income region. In high-income regions, in all scenarios but SSP3, a reduction in manufacturing and electricity withdrawals dominates annual withdrawal changes because of the relatively high industrialization and power generation in each of the high-income regions. For example, 78% of the total high-income SSP5 reductions in 2100 are found in the manufacturing and electricity sectors. In contrast, SSP3 experiences slight increases in mid-century water withdrawals because of higher electric-sector water withdrawals in high-income regions, which are associated with increases in once-through cooling.

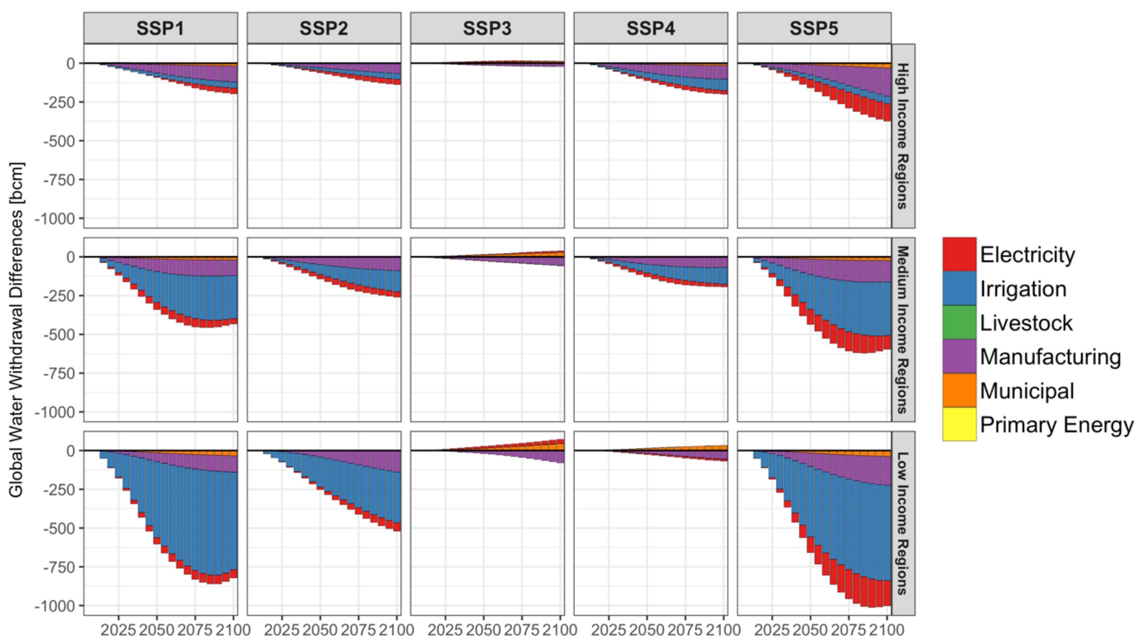

Figure 2.9 Global water withdrawal differences by income region and sector in each SSP scenario (bcm/year). High-income regions are shown in the top panel, medium-income regions in the middle panel, and low-income regions in the bottom panel. Income regions are defined in Table 2.7. Differences shown represent reductions due to technological change and are calculated as Tech_const minus Ref_const.

Table 2.7 Income level classifications by GCAM region, as defined in Calvin et al. (2017).

Aggregate Region	GCAM Regions Included	Countries
High Income	Australia_NZ	Australia, New Zealand
	Canada	Canada
	EU-15	Andorra, Austria, Belgium, Denmark, Finland, France, Germany, Greece, Greenland, Ireland, Italy, Luxembourg, Monaco, Netherlands, Portugal, Sweden, Spain, United Kingdom
	European Free Trade Association	Iceland, Norway, Switzerland
	Japan	Japan
	South Korea	South Korea
	Taiwan	Taiwan
	USA	United States
Medium Income	Argentina	Argentina
	Brazil	Brazil
	Central America and the Caribbean	Aruba, Anguilla, Netherlands Antilles, Antigua & Barbuda, Bahamas, Belize, Bermuda, Barbados, Costa Rica, Cuba, Cayman Islands, Dominica, Dominican Republic, Guadeloupe, Grenada, Guatemala, Honduras, Haiti, Jamaica, Saint Kitts and Nevis, Saint Lucia, Montserrat, Martinique, Nicaragua, Panama, El Salvador, Trinidad and Tobago, Saint Vincent and the Grenadines
	China	China
	Colombia	Colombia
	EU-12	Bulgaria, Cyprus, Czech Republic, Estonia, Hungary, Lithuania, Latvia, Malta, Poland, Romania, Slovakia, Slovenia
	Europe_Eastern	Belarus, Moldova, Ukraine
	Europe_Non_EU	Albania, Bosnia and Herzegovina, Croatia, Macedonia, Montenegro, Serbia, Turkey
	Mexico	Mexico
	Middle East	United Arab Emirates, Bahrain, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Palestine, Qatar, Saudi Arabia, Syria, Yemen
	Russia	Russia
	South Africa	South Africa
	South America_Northern	French Guiana, Guyana, Suriname, Venezuela
	South America_Southern	Bolivia, Chile, Ecuador, Peru, Paraguay, Uruguay
Low Income	Africa_Eastern	Burundi, Comoros, Djibouti, Eritrea, Ethiopia, Kenya, Madagascar, Mauritius, Reunion, Rwanda, Sudan, Somalia, Uganda
	Africa_Northern	Algeria, Egypt, Western Sahara, Libya, Morocco, Tunisia
	Africa_Southern	Angola, Botswana, Lesotho, Mozambique, Malawi, Namibia, Swaziland, Tanzania, Zambia, Zimbabwe
	Africa_Western	Benin, Burkina Faso, Central African Republic, Cote d'Ivoire, Cameroon, Democratic Republic of the Congo, Congo, Cape Verde, Gabon, Ghana, Guinea, Gambia, Guinea-Bissau, Equatorial Guinea, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone, Sao Tome and Principe, Chad, Togo
	Central Asia	Armenia, Azerbaijan, Georgia, Kazakhstan, Kyrgyzstan, Mongolia, Tajikistan, Turkmenistan, Uzbekistan
	India	India

	Indonesia	Indonesia
	Pakistan	Pakistan
	South Asia	Afghanistan, Bangladesh, Bhutan, Sri Lanka, Maldives, Nepal
	Southeast Asia	American Samoa, Brunei Darussalam, Cocos (Keeling) Islands, Cook Islands, Christmas Island, Fiji, Federated States of Micronesia, Guam, Cambodia, Kiribati, Lao Peoples Democratic Republic, Marshall Islands, Myanmar, Northern Mariana Islands, Malaysia, Mayotte, New Caledonia, Norfolk Island, Niue, Nauru, Pacific Islands Trust Territory, Pitcairn Islands, Philippines, Palau, Papua New Guinea, Democratic Peoples Republic of Korea, French Polynesia, Singapore, Solomon Islands, Seychelles, Thailand, Tokelau, Timor Leste, Tonga, Tuvalu, Viet Nam, Vanuatu, Samoa

2.3.7 Impact of SSP Assumptions and Water Constraints

In this section, we have added the five SSP assumptions discussed in Section 2.2.6 and water technology changes in a step-wise manner to investigate the compounding impacts on global water demands. The assumptions have been added in this order: socioeconomics, energy demand, agricultural productivity and growth, energy supply, non-CO_2 emissions, and water technologies. It is important to note that the following results are independent of the order of addition. Here we have assumed that the socioeconomic assumptions provide the minimal additions to be considered among the SSP scenarios; therefore, the changes in Figure 2.10 represent changes from the SSPs run with only socioeconomic assumptions. Values based on subsequent assumptions represent changes from the preceding assumption set. The solid black line represents net water demand change from the socioeconomic assumptions to the water technology assumptions.

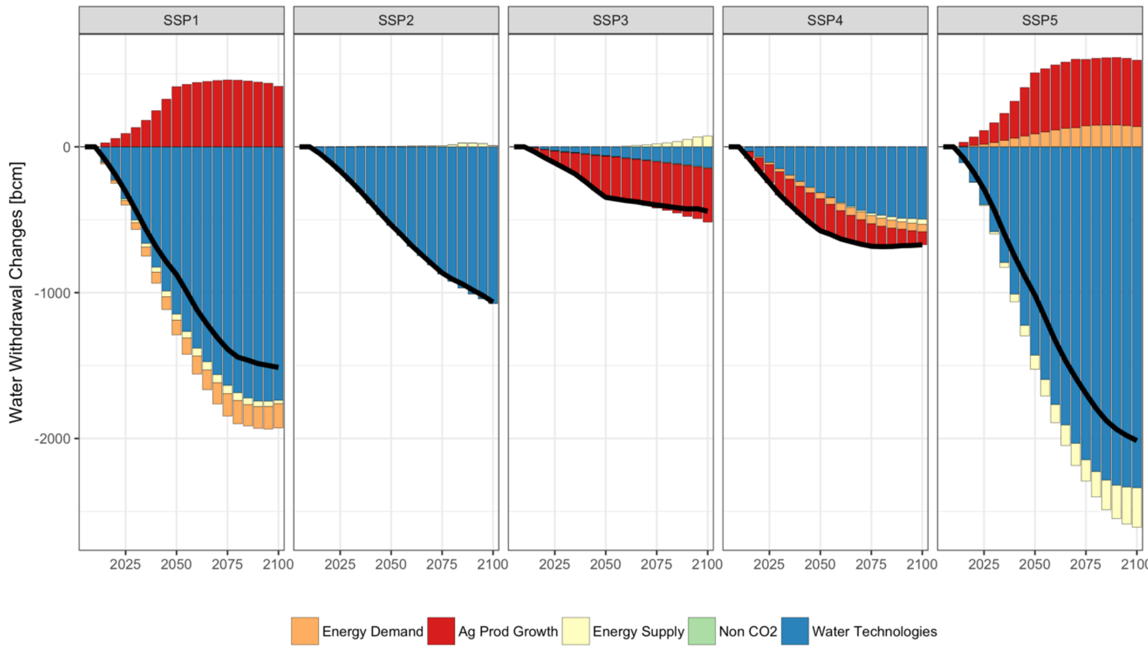

Figure 2.10 Global water withdrawal changes (bcm/year) as a result of step-wise addition of SSP assumption components. The net impact on global water withdrawals is represented as the solid black line.

In particular, agricultural productivity growth and change is shown to have differing effects across the SSP scenarios, resulting in increases in water withdrawals in SSP1 and SSP5, and decreasing demands in SSP3 and SSP4. This is caused by changing crop yields and cropping intensities in each SSP (Calvin et al., 2017). Specifically, as crop yields improve and cropping intensity increases, water withdrawals increase (as in SSP1 and SSP5). Energy demand also has a clear, but opposite, effect on water demand in both SSP1 and SSP5. This is due to significantly different transportation practices; SSP5 experiences increases in the movement of goods by freight resulting in higher demands for fuel and water needed for fuel extraction, whereas in SSP1 investments into hybrid fuels and a reduction in fossil fuel consumption lead to decreases in demand. The introduction of water technologies has the largest impact on global water demand across all SSP scenarios as efficiency improvements, particularly within the agricultural sector, provide a large potential demand reduction. It can be seen that when all SSP assumptions are combined, every SSP experiences a net decrease in global water demands, however the magnitude and sign of each component differ by SSP. The net changes in SSP2 are minimal aside from water technologies as the assumptions for SSP2 make up the base GCAM model scenario.

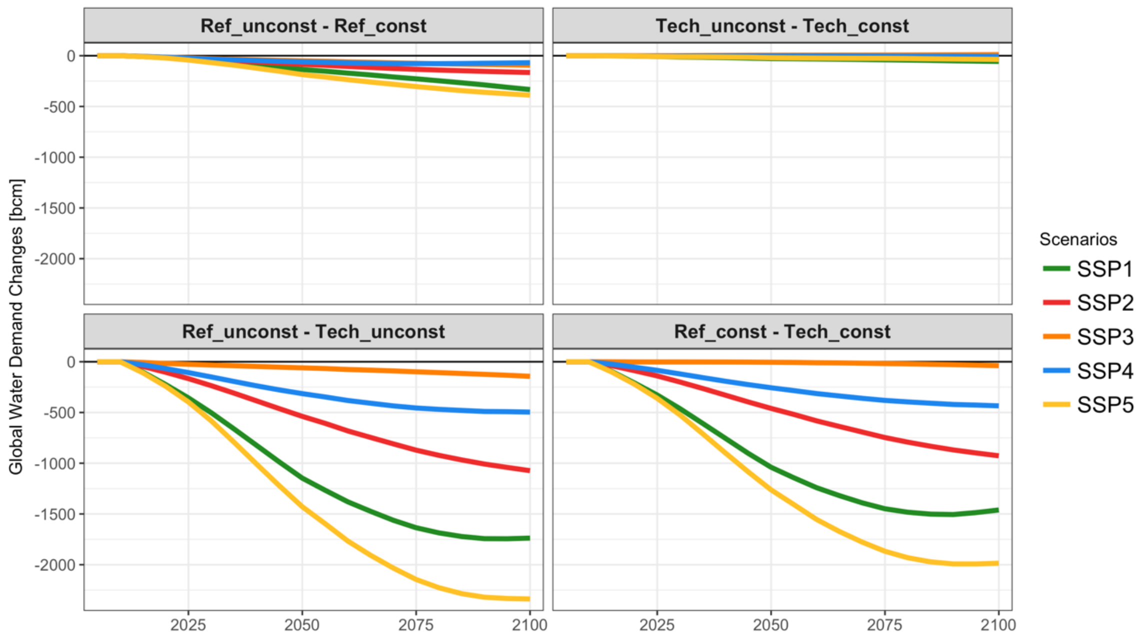

Figure 2.11 Change in global water withdrawals as a result of water constraints (top row) and water technologies (bottom row). Top left figure represents the impact of adding water constraints to the SSP scenarios run with the existing set of SSP assumptions for GCAM (Calvin et al., 2017). The top right figure represents the impact of adding water constraints to the SSP scenarios run with the assumptions from this study. The bottom left panel represents the impact of adding the water technology changes outlined in this study to an unconstrained water set of scenarios. The bottom right figure represents scenarios with added water technologies while under water constraints.

Water constraints in GCAM limit the amount of available water in river basins by using cost resource curves that increase the cost of water as the supply decreases (Kim et al., 2016). Water sector technology advances result in various efficiency changes due to changing infrastructure and prices across the SSP scenarios (This study). Both of these factors affect water demands and are shown in Figure 2.11. The impact of water constraints on the SSPs is shown in the top panel. SSP scenarios that do not consider advancements in water technologies (top left) experience water demand decreases of up to 400 km^3 by the end of the century, in line with values shown in Kim et al. (2016). Constraints have far less of an impact on SSP scenarios that include future water technology changes (top right), as water demands decrease by around 100 km^3 across all scenarios. The bottom panel analyzes the impact of water technologies in the SSP scenarios. Water technologies added to SSP scenarios in which water is assumed to be in unlimited supply (bottom left) have the largest water demand reduction of all scenarios with reductions reaching almost 2000 km^3 by 2100 in SSP5. When water technologies are added to scenarios with water constraints (bottom right), the differences are slightly smaller than those in unconstrained supply scenarios; however, technological advancements still clearly have a significant impact on future water demands. These results demonstrate that advancements in water use efficiency, infrastructure changes across the energy sector, and price changes of all water and non-water markets and commodities will lead to lower water demands in future scenarios than the inclusion of water constraints alone. The reductions shown would act to decrease water scarcity across the globe.

2.4 Discussion

The incorporation of water sector futures into SSP scenarios relies on assumptions for each of the agricultural, electricity, manufacturing, and municipal sectors. The evolution of these individual sectors to the end of the century has the potential to be highly variable among scenarios, regions, and economic characteristics. In order to account for the high variability of future sectoral changes, this study has introduced varying technological changes based on the defined characteristics of each SSP scenario. In all scenarios except for SSP4, we have assumed that the adoption of prescribed technological changes (Table 2.3) do not vary by region (2100 efficiency goal is uniform across regions, but adoption rates differ based upon base year starting efficiency). This results in a wide range of changes that depend on starting economic levels, as low-income regions transition to more-efficient technologies from lower base year values than is the case in the medium and high-income regions, which leads to advancement rates being very high for agriculture in particular. Results show similar patterns of water use across sectors due to the underlying assumptions of the SSPs within GCAM, expressed in Table 2.2 and discussed in Calvin et al. (2017). Changes in population growth, particularly in SSP3, yield near-linear increases in water demands across all sectors, as there are minimal improvements in the water sector. In the SSP1 and SSP5 scenarios, similar water demands result in large part from the significant water sector improvements that have been discussed in this study and applied to GCAM, leading to noticeable changes in all sectors. Similar explanations apply for SSP2, as population levels off in the second half of the century and water sector improvements produce a leveling off of demands across most sectors.

The change rates and assumptions applied in this study attempt to follow values currently existing within the literature; however, in the scenarios in which economic conditions allow for sustainable improvement, they offer a new perspective on potential benefits of future changes in the water sector. High water savings that arise from increased agricultural and infrastructure efficiencies can provide scientists and policy-makers alike, global water savings potentials of sustainable futures. In sectors where historical data are limited, such as irrigation-efficiency improvements, we have assumed that technological progress throughout the century will vary significantly based on the willingness to invest in efficient technologies, as represented in the assumptions of the different SSP storylines.

The introduction of water constraints in the SSPs presents a novel look at various global futures under a limited water supply. Our results showed that while technological change accounts for the largest impact on global water demands, the inclusion of water constraints also causes a noticeable decrease. The inclusion of water constraints also allows for better representation of global production in the SSPs and associated changes in trade and water demands caused by shifts in production to less water-scarce regions (Kim et al., 2016, Chapter 4). Water supplies are maintained at historical levels throughout the study period in order to isolate the impacts of technological change.

Since the introduction of the Shared Socioeconomic Pathways, several studies have assessed such assumptions (cf. Wada et al., 2016; Hanasaki et al., 2013a, b; Fujimori et al., 2016; Bijl et al., 2016; Mouratiadou et al., 2016). However, these studies have largely focused on individual sectors, predate the introduction of the SSP scenarios to the IAM community, and/or lack the ability to endogenously calculate water demands based upon cost and availability of water supplies. As a result, comparisons to other SSP studies of global water demands are difficult, although some sector-by-sector comparisons can be made. Agricultural sector withdrawals are on the lower side of existing projections (Figure 2.3). For example, values provided by Hanasaki et al. (2013b) range from about 3100 bcm to 8400 bcm in 2085, depending on the scenario, while our study calculated withdrawals of less than 6248 bcm in 2085 when technological advances are considered, or a range of 5350 bcm to

6622 bcm in 2085 without technological change. Such comparisons are affected by important differences between studies, including differences in the extent of irrigated land and cropping intensity, which have been determined endogenously in this study, while prescribed differences exist in Hanasaki et al. (2013b) and should be considered in future comparisons (Figure 2.2). Municipal demand in 2100 in this study ranges from 604 bcm to 811 bcm. These values are also within the lower range of previous studies' values of 450 bcm to 1400 bcm (Figure 2.8). Finally, industrial (electricity generation + manufacturing) demand values in 2100 range from about 450 bcm to 1177 bcm in this study. These values are comparable with previous estimates, which range from 250 bcm to 1500 bcm – although note that mid-century values have a higher range (Figure 2.7).

The assumptions in this study represent different degrees of technological change within a single model (GCAM). The degree to which a given assumption affects the results is variable and each sector has different levels of uncertainty in future projections. However, based on the differences in agricultural water demand reductions across SSP scenarios, irrigation efficiency is the source of the largest uncertainty for future demand projections. In this study, regional irrigation efficiency values in 2100 vary from below 50% for cases without technological change, up to 83% under the most ambitious technological change. The implications of this spread are clear in the 2100 values for agricultural water demands in Table 2.6. As discussed in Section 2.2.2, a comparison of percentage reductions in agricultural water withdrawals – that reflect the varying degrees of technological change implemented – can provide insight into the uncertainty across SSP scenarios and its connection to the chosen application efficiency. Reductions range from <1% in SSP3 to 32% in SSP5, providing upper and lower limits on the effects of irrigation efficiency changes on future withdrawals. While each of the other sectors show significant changes in global water demand based on the assumed degree of technological change, both the impacts and uncertainties of these other sectors are far smaller when compared to the agricultural changes. Further analysis is needed to determine the multi-model spread of possible results.

This study highlights the importance of technological advancement in the water sector across various future global change scenarios, particularly when considering a limited supply of water. It is important to note that with these results we have found that across the SSP scenarios, differing assumptions made outside of the water sector can result in significant changes in future water demands (i.e. agricultural productivity growth and change). Although socio-economic scenarios tend to play a more important role than the climate scenarios in global water resources assessments (e.g. Vörösmarty et al. 2000; Hanasaki et al. 2013b), future SSP studies should consider effects of climate change on water supplies, energy, and land systems and how they may alter global and regional demands. This study maintains historical water supply levels which may miss key changes in accessible water caused by climate change in the individual SSP scenarios. The absence of climate-change-driven water supply in this study has the potential to misrepresent water availability in future scenarios that experience significant warming; therefore, such changes will be considered in Chapter 3. Future studies should incorporate a broader set of water sector dynamics. For example, climate-induced changes to the crop-water intensity of plants, changes in crop breeding to produce more water-efficient plants, and global shifts to more water-efficient crop mixes have the potential to change agricultural water demands but have not been considered in this study. Water savings may also result from changes in water supply through expansion of desalination facilities and reservoirs, and water reuse. These factors also warrant future consideration to broaden the scope of water research in the SSP scenarios.

2.5 Conclusions

This study has focused on the development and implementation of a complete set of future water sector assumptions for the Shared Socioeconomic Pathways. It began with the development of assumptions for future technological change in the agricultural, electricity, manufacturing, and municipal sectors. These assumptions follow the storylines of each of the SSP scenarios and are added to GCAM to analyze global water demands through the end of the century. This work represents the first comprehensive set of water sector assumptions that have been applied to the SSP scenarios and have been run with an Integrated Assessment Model while including water constraints. The study has provided four key results.

First, while water constraints act to decrease water demands, future infrastructure changes in the water sector can increase water savings by up to 32% in 2100 in the SSP scenarios, resulting in large potential changes in regional and global water scarcity.

Second, in SSP1, the focus on sustainability and the ability to invest in future water-efficiency improvements has the potential to lead to end-of-century water demands lower than present day demands despite a higher standard of living and similar global population.

Third, future water-demand changes in the SSPs depend strongly on adoption and implementation of water saving technologies in low-income regions. In SSPs 1, 2, and 5, more than half of the global water demand reductions result from adoption of more efficient technologies in low-income regions.

Fourth, when assumptions for the SSPs are broken down into their various components, there tend to be significant and differing impacts on water demands across SSP scenarios as a result of non-water sector assumptions (i.e. agricultural productivity changes and energy demands), proving that their inclusion is a necessity when analyzing future water demands in the SSPs.

Chapter 3: Humans drive future water scarcity across all Shared Socioeconomic Pathways (Graham et al., 2019 – submitted)

3.1 Introduction

Although climate and socioeconomic systems affect water resources simultaneously, the individual contributions of these systems, and how they will change into the future is relatively unknown at global scales. Previous studies have generally attributed future changes in water scarcity to population changes, economic growth, and resultant demand increases more so than to climate system impacts (Vörösmarty et al., 2000; Arnell, 2004; Alcamo et al., 2007; Hanasaki et al., 2013b; Arnell and Lloyd-Hughes, 2014; Schewe et al., 2014; Schlosser et al., 2014; Shen et al., 2014; Wada et al., 2014; Kiguchi et al., 2015). Studies have also quantified the relative impacts of socioeconomic and climate changes and how they contribute to water scarcity at global and regional scales (Wada et al. 2011; Schewe et al., 2014; Veldkamp et al., 2015). Recent combinations of changing socioeconomic conditions and climatic change have brought to light the importance of the coevolution of human and climate systems on water scarcity estimates at sub-regional scales (Veldkamp et al., 2016; Rant et al., 2016). Despite recent advances, water scarcity attribution assessments often lack the representation of alternative sources of freshwater, constraints on water resources, alternative demand scenarios, and feedback linkages between hydrological and socioeconomic systems (Ligtvoet et al., 2018).

This study aims to address this research gap by attributing the simultaneous relative contributions of both human and climate systems on water scarcity changes through the lens of GCAM. This analysis makes use of a wide range of socioeconomic and climate futures that are placed under constraints on sources of freshwater, including nonrenewable groundwater, surface runoff, and desalinated seawater (Kim et al., 2016; Graham et al., 2018; Turner et al., 2019a). We use GCAM to quantify the relative effects of both systems on water scarcity at global and basin scales across 15 global futures that include five different socioeconomic conditions (the Shared Socioeconomic Pathways, SSPs) and four different climatic conditions (the Representative Concentration Pathways, RCPs). We use these 15 scenarios to first analyze a 'Human Alone' component to isolate the human impact on future scarcity and then apply general circulation model (GCM) derived climate impacts from five models to establish 75 'Human and Climate' scenarios which allow for the quantification of climate impacts (Figure 3.1). The use of models that link energy, water, land, and climate in water scarcity assessments allows for the explicit representation of how climate-induced changes in water availability alter energy and land systems. The results are a novel analysis of how, with limited availability of water resources, humans and climate may drive future water scarcity across a range of socioeconomic and climate futures. Future spatial and temporal representations of human and climate system contributions to water scarcity changes are provided while considering the feedbacks between the human, energy, and land systems.

3.2 Methods

This analysis uses GCAM to make deterministic classifications of how, under water resource constraints, the human and climate systems interact to alter water scarcity across 15 socioeconomic and climate futures. Using GCAM 5.0 with inclusions of water constraints to both renewable and nonrenewable sources of water, we evaluate the drivers of future water scarcity by isolating the impacts that both humans and climate have while accounting for feedbacks between humans, energy, and land. Secondly, we analyze the simultaneous impacts that human and climate systems have on water scarcity by determining whether each system is increasing or decreasing scarcity in all of GCAM's 235 water basins. We begin with the 15 SSP-RCP scenarios that are attainable in GCAM (see Figure 3.1) and then we derive how the human system alone change water scarcity towards 2100 by holding all climate variables to their 2005 levels while altering socioeconomic growth and technological change. Next, we analyze the same 15 scenarios while accounting for GCM derived climate impacts on 4 different sectors, water supply, agricultural productivity and change, hydropower expansion, and building energy expenditures. These impacts come from 5 different bias-corrected GCMs to make a suite of 75 climate runs. By subtracting the human derived impacts of the 'Human Alone' scenarios (Figure 3.1) from the 'Human and Climate' scenarios we isolate the impact that we define as the climate impact. Below we describe the GCAM model, the scenario components, climate derived impacts, and the calculations of scarcity changes and attribution.

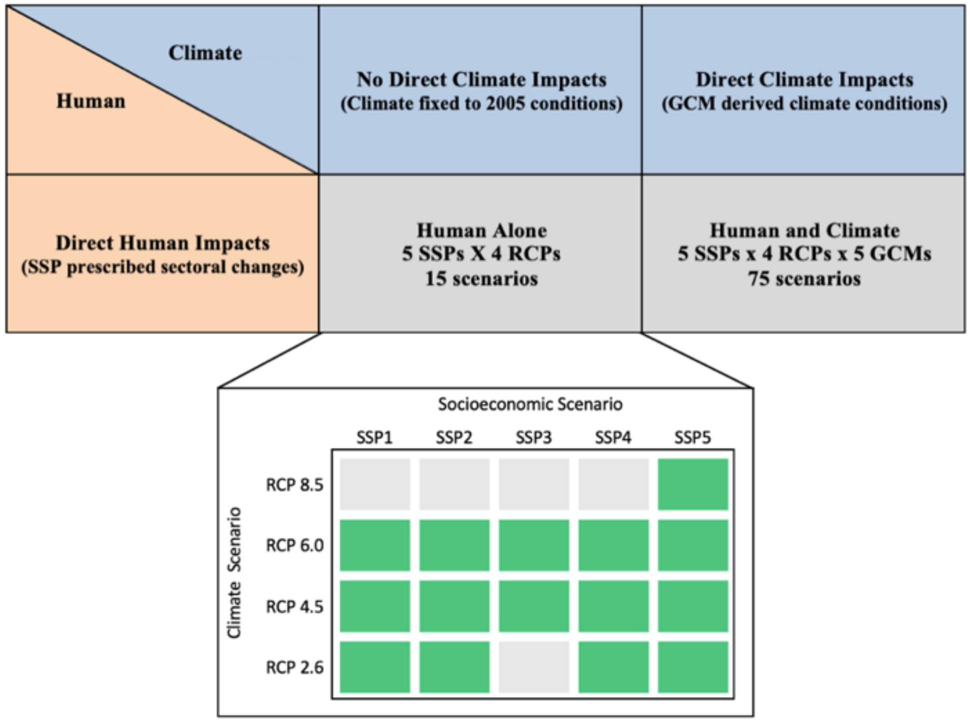

Figure 3.1 Scenario breakdown of 90 total scenarios and the SSP-RCP scenario matrix depicting the set of 15 scenarios (green shading) in which plausible solutions exist in GCAM and for which CMIP5 climate datasets are available.

3.2.1 Scenario Components

We use temporally varying socioeconomics and climate systems. These systems are represented by the Shared Socioeconomic Pathways (SSP), for socioeconomic change, in combination with the Representative Concentration Pathways (RCPs), for climatic change. The SSPs are a set of five future scenarios with varying changes to global population, the economy (Riahi et al., 2017), and land use (Popp et al., 2017), which were designed to explore varying degrees of challenges to climate change adaptation and mitigation (O'Neill et al. 2017). These scenarios have been defined, both qualitatively and quantitatively, using a set of global integrated human-Earth systems models, in which individual models have been used to produce a marker scenario (Riahi et al., 2017) for singular SSPs (Calvin et al., 2017; Fricko et al., 2017; Fujimori et al., 2017; Kriegler et al., 2017; van Vuuren et al., 2017) and provide uncertainty ranges across all other SSPs. The IAM results provide alternative projections of the evolution of the economy, energy systems, land systems, emissions, and climate. Within GCAM, quantitative assumptions of the SSPs have been made for the economy, energy sector, land use, agricultural sector (Calvin et al., 2017), and for the water sector (Graham et al., 2018). The RCPs are a set of four future climate scenarios in which end-of-century radiative forcing approaches four-levels by altering future greenhouse gas emissions and by changing underlying socioeconomic projections (van Vuuren et al., 2011).

The SSPs and RCPs are combined to form a set of future global change scenarios which allows comprehensive socioeconomic assumptions to be matched with future radiative forcing pathways to achieve future global warming targets, creating the next set of scenarios that will provide the basis for future Intergovernmental Panel on Climate Change (IPCC) assessments (O'Neill et al., 2016; Eyring et al., 2016, Section 1.1.5). Each is then matched with their individual Shared Policy Assumptions (SPAs) in order to account for differences in adaptation and mitigation strategies across the SSPs (Kriegler et al., 2014; Calvin et al., 2017). These combinations create a set of 15 potential global futures which are varied six times, for five GCMs and one set in which climate impacts across all sectors are neglected to produce 90 total scenarios.

3.2.3 Climate Derived Impacts from General Circulation Models

This study accounts for four different general circulation model (GCM) derived climatic impacts to water supply, agricultural productivity, hydropower expansion, and building energy expenditures. We calculate the impact on each aspect at four different radiative forcing levels and apply these to the appropriate scenarios within the SSP-RCP scenario matrix. Future water supply is calculated by using bias-corrected hydrologic data derived for four RCPs from five GCMs as part of the Inter-Sectoral Impact Model Intercomparison Project [ISI-MIP; Warszawski et al. (2014)]. These values are entered into the global hydrologic model Xanthos (Li et al. 2017, Liu et al., 2018; Vernon et al. 2019), which calculates accessible water at the GCAM 235-basin scale at five-year time steps. Climate derived impacts to crop yield changes (Rosenzweig et al. 2014), hydropower expansion (Turner et al., 2018), and building energy expenditures (Clarke et al., 2018) are calculated from the same set of ISI-MIP models and the climate varying impacts are added to their respective RCP scenarios. By including scenarios that both include and exclude climate impacts we can account for the compounding effects of changing hydrologic conditions, hydropower availability, crop yields, and energy demands on water scarcity, while also separating the impact of human activities from that of the climate system, which include changing water demands for agriculture, power generation, industry, and public supply.

3.2.4 Human and Climate Contributions to Water Scarcity

Water scarcity analyses can contain several different aspects of water use. For the purpose of this study, we will consider the water scarcity index, noted below as S, by comparing the amount of total water withdrawals, W_d from all sources (renewable surface runoff, nonrenewable groundwater extraction, and desalination) to the total GCM derived accessible surface runoff, Q_R, shown in Equation 3.1, where we calculate scarcity in time period, t, basin, b, and SSP-RCP-GCM scenario, s.

$$S_{t,b,s} = \frac{W_d}{Q_R} \tag{3.1}$$

The change in scarcity, for the 'Human Alone', S_H, and 'Human and Climate', S_X scenarios, is calculated in Equation 3.2a and b respectively, as we use 2005 as the base year of water scarcity and calculate changes throughout the century at any time period t. To isolate the effect of climate alone, S_C, we subtract the change in water scarcity found in the 'Human Alone' scenarios from the 'Human and Climate' scenarios in Equation 3.2c. The 'Human and Climate' scenarios likely contain changes to the human system that are not captured by subtracting the 'Human Alone', however these changes are assumed to be a result of the climate impacts and therefore are classified as a climate impact in this study.

$$\Delta S_H(t) = S_{H_t} - S_{H_{2005}} \tag{3.2A}$$

$$\Delta S_X(t) = S_{X_t} - S_{X_{2005}} \tag{3.2B}$$

$$\Delta S_C(t) = \Delta S_X(t) - \Delta S_H(t) \tag{3.2C}$$

In order to calculate the impact that humans and climate have on water scarcity we adopt and modify Equations S1 and S2 from Veldkamp et al. (2015), which are shown as Equations 3.3a and b below.

$$I_H(t) = \frac{\Delta S_H(t)}{|\Delta S_C(t)| + |\Delta S_H(t)|} \tag{3.3A}$$

$$I_C(t) = \frac{\Delta S_C(t)}{|\Delta S_C(t)| + |\Delta S_H(t)|} \tag{3.3B}$$

I_H, (human impact) and I_C, (climate impact) represent the relative impact on water scarcity due to human or climate influences resulting from the change in water scarcity from 2005 values. In order to find the main driver of water scarcity we compare the two impacts as in Equations 3.4b and c.

$$|I_H| + |I_C| = 1 \tag{3.4A}$$

$$\text{Human Driven: } |I_C| < |I_H| \tag{3.4B}$$

$$\text{Climate Driven: } |I_C| > |I_H| \tag{3.4C}$$

The sign of human and climate impacts allows for the classification of increasing or decreasing scarcity.

3.3 Results

Assessing the relative contributions of socioeconomic and climatic systems to the evolution of water scarcity allows for a deterministic classification of the main driver behind changes in scarcity. We quantify water scarcity using the water scarcity index (WSI), which is the ratio of water withdrawals to water availability. Water scarcity changes in extremely wet regions and regions with minimal demands are likely to produce minimal changes in WSI. To account for this, the lowest quartile of ΔWSI values are determined to be negligible in each scenario. Basins with negligible scarcity changes are left unclassified and are referred to as ‘Negligible’ throughout the remainder of this study.

3.3.1 Main Driver Behind Water Scarcity Changes

Across all scenarios it is found that a majority of the basins that have negligible changes in water scarcity are located in the Northern Hemisphere high latitudes, Amazonian Rainforest, and parts of Australia, regardless of time period or scenario (Figure 3.3, Figure 3.5). In the basins which have a defined change in water scarcity, 78% experience water scarcity changes dominated by humans (red shading and Figure 3.4). This is true for SSP1, SSP2, and SSP4. Whereas in SSP3, extremely high population growth results in 90% of basins with water scarcity changes driven by humans, and SSP5, where only 71% are driven by humans due to the contributions from reaching RCP8.5 conditions (Figure 3.4).

Throughout the century, the number of nonnegligible basins experiencing human driven water scarcity changes typically increases up to the year 2100. Human-dominated water scarcity increases (H+) occur in 51% of basins while 27% of basins have decreasing scarcity due to humans (H-). Significant differences arise across SSPs as socioeconomic differences drive efficiency improvements, demand changes, and altered water dependency (Graham et al., 2018; Calvin et al., 2017). SSP1 experiences a shift from H+ to H- in a large number of basins throughout the century, leading to just 26% of basins classified as H+ in 2100, while humans act to decrease water scarcity in 52% of basins. While not as extreme, similar shifts from H+ and H- occur in SSP4 and SSP5, whereas in SSP2 and SSP3 more than 65% of basins are H+. Although differences exist across each SSP scenario, the three scenarios that shift from H+ to H- experience global or regional GDP growth that allows for the adoption of efficient water use technologies. Additional storyline features such as sustainability focus, fuel preference, and universal adoption rates also influence cross-SSP differences.

Fig 3.3 shows a spatial representation of water scarcity drivers across the average of all future scenarios. Although socioeconomic scenario assumptions diverge in the second half of the century, the main driver remains humans in most basins. The robustness of the results decreases, and uncertainty increases by 2100 (Figure 3.3), consistent with Fig 3.2. Basins in sub-Saharan Africa have significant agreement across scenarios of human driven scarcity changes in both 2050 and 2100 riven by population growth increases throughout the century.

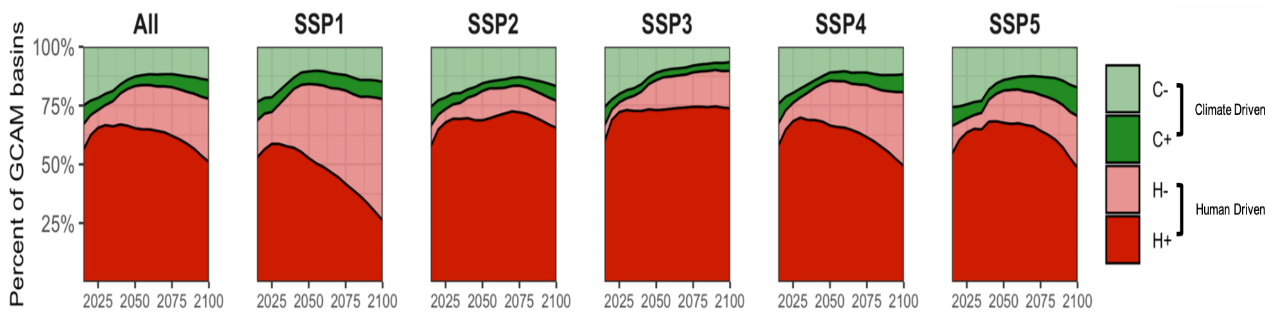

Figure 3.2 Spatial and temporal changes in the percentage of GCAM's water basins in which the main drivers of water scarcity changes are attributed to humans (H) or climate (C) and whether the changes increase (+), decrease (-), or have negligible changes in water scarcity. Each scenario is aggregated into individual SSP scenarios and values are calculated from the total number of nonnegligible ΔWSI basins and total number of scenarios in each aggregation. The 'All' scenario represents the total of all basins in the suite of SSP-RCP-GCM scenarios

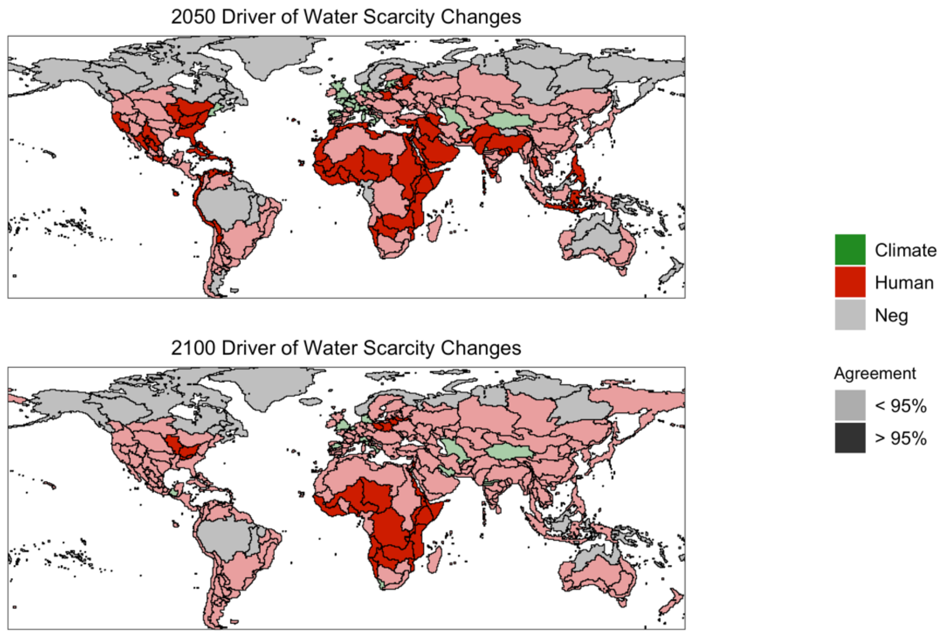

Figure 3.3 Main driver of water scarcity changes due to climate (green) or humans (red) in 2050 (top) and 2100 (bottom). Robustness of results shown as the degree of shading in which there is greater than (darker) or less than (lighter) 95% agreement across all 75 SSP-RCP GCM scenarios. Basins which observed negligible, ‘Neg’, water scarcity changes are shaded as such if at least 95% of the scenarios agree for that particular basin, all basins with less confidence are shaded according to their main driver in the nonnegligible scenarios.

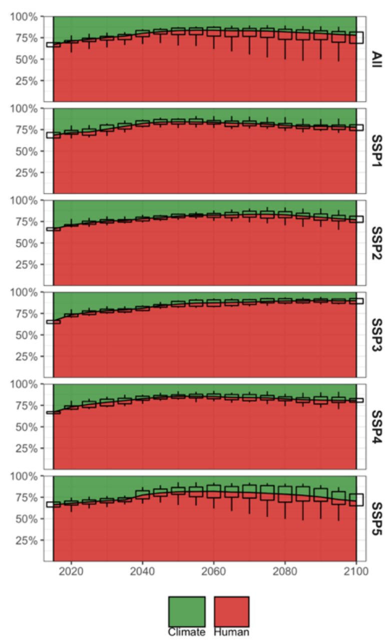

Figure 3 4 Percentage of basins with climate (green) or humans (red) as main driver of water scarcity changes. All negligible basins have been removed and values represent the percent of remaining 75% of basins in which humans or climate dominated water scarcity changes. Box and whisker plots represent the uncertainty spread among GCM and RCP combinations.

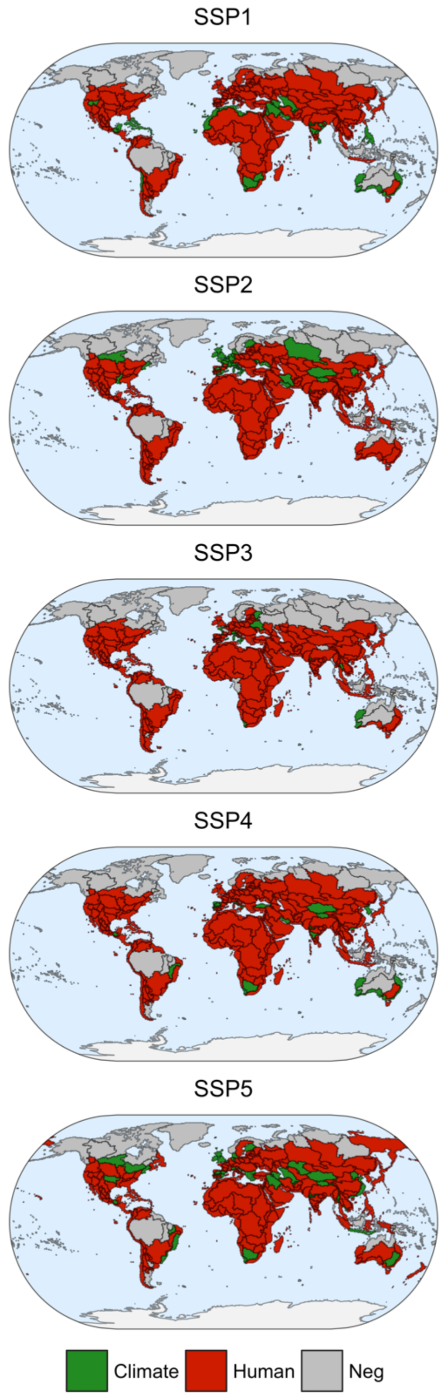

Figure 3.5 Main driver for water scarcity changes by SSP scenarios in 2100, as in Figure 3.2B. Classification is determined by the percentage of occurrence in each SSP scenario. SSP-based basins where water scarcity changes are deemed negligible are highlighted in gray.

3.3.2 Co-Influence of Main and Secondary Drivers

Although the previous section focused on the dominant driver of water scarcity, the impacts by the secondary driver must be accounted. These impacts provide either compounding, where both systems change scarcity by the same sign, or counteracting, where human and climate systems have opposing signs, effects on water scarcity changes. To account for this, Figure 3.6 introduces four distinct water scarcity change categories to define how human (H) and climate (C) systems individually, yet simultaneously, increase (+) or decrease (-) water scarcity within a basin.

Expanding on the notion of differing signs of change and considering the simultaneous impacts of human and climate systems on future water scarcity. Figure 3.6 shows the combination across all scenarios. When considering all scenarios (Figure 3.6, left), 52% of nonnegligible basins show a compounding effect (green and red) by the end of the century, whereas 48% of basins have counteracting effects (orange and blue). An increasing dependence on socioeconomic future arises throughout the century as SSP1 produces compounding effects in 60% of basins. This is due to a significant increase in H-C- basins and a shift away from H+C- conditions in parts of Africa and Eurasia (areas of decreasing robustness in Figure 3.7 and Figure 3.8). SSP2 on the other hand has only 45% of basins with compounding impacts driven by 51% of global basins falling into the H+C- category.

Figure 3.5B represents how water scarcity changes depend on geographic location, as distinct areas of H- and H+ arise while much of the world experiences climate induced scarcity decreases (C-, green and orange). Nearly all of Africa experiences counteracting water scarcity effects as population driven increases in demand lead to increases in scarcity, while climate-driven increases in precipitation increase water supply and thus lower scarcity (Figure 3.8). As in Figure 3.2B, the robustness of the classification is again shown to decrease by the end of the century (right). This is due to differences in efficiency and the sustainability focus of the socioeconomic scenarios driving the evolution of water scarcity categories, particularly in central Eurasia and Africa where population change projections and GDP vary by SSP (Graham et al., 2018; Calvin et al., 2017). Areas of negligible changes remain the same as in Figure 3.3, by definition.

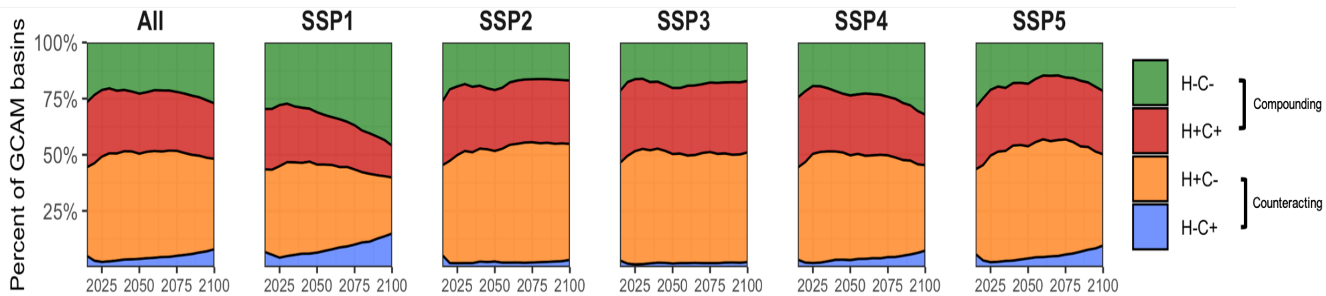

Figure 3.6 Temporal changes in the percentage of GCAM's water basins in which the simultaneous impact of human and climate systems on water scarcity changes are shown by component and sign of change. Each scenario is aggregated into individual SSP scenarios and values are calculated from the total number of nonnegligible ΔWSI basins and total number of scenarios in each aggregation. The 'All' scenario represents the total of all basins in the suite of SSP-RCP-GCM scenarios.

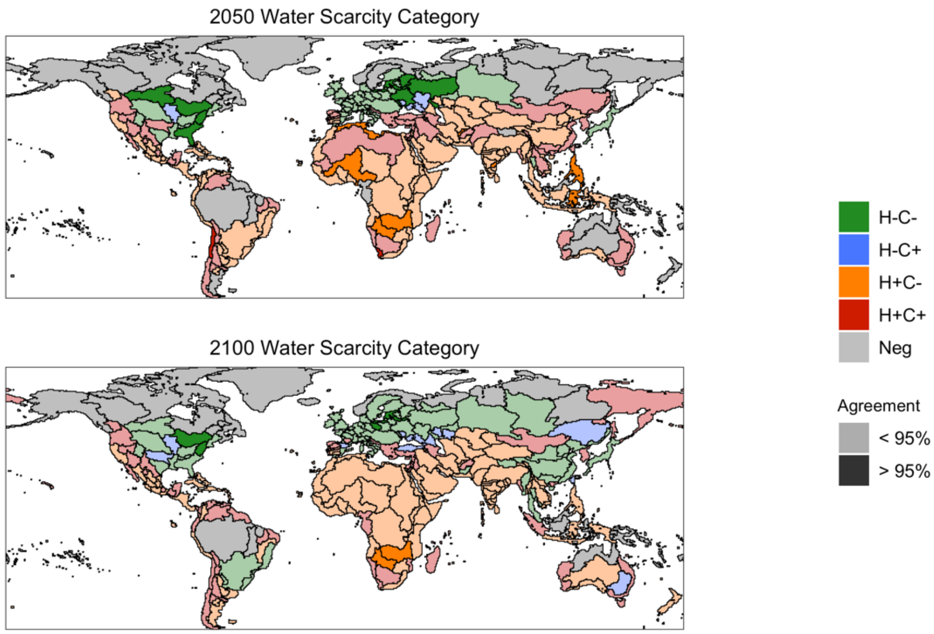

Figure 3.7 Water scarcity category in 2050 (top) and 2100 (bottom). Notation shown as (+) representing either human (H) or climate (C) *increasing* water scarcity and (-) *decreasing* water scarcity. (ex. H+C+ humans and climate both act to increase water scarcity in given basin. 95% agreement across all 75 SSP-RCP GCM scenarios. Basins which observed negligible water scarcity changes are shaded as such if at least 95% of the scenarios agree for that particular basin, all basins with less confidence are shaded according to their scarcity category in the nonnegligible scenarios.

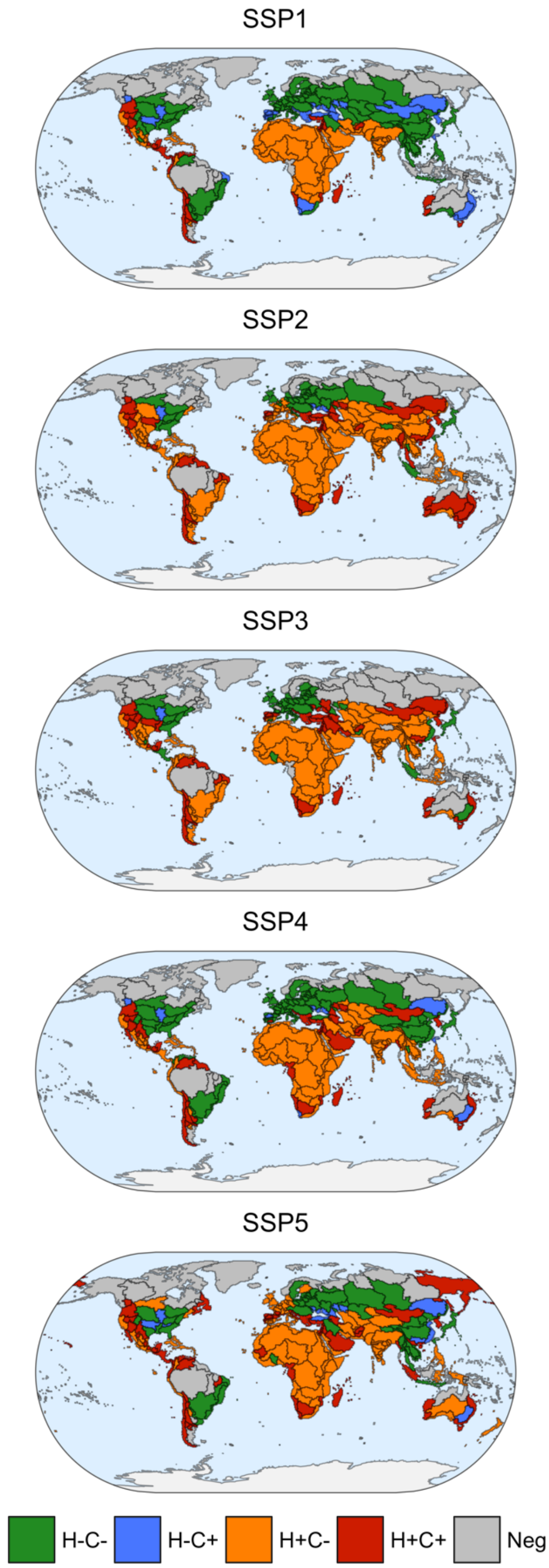

Figure 3.8 Water scarcity change category by SSP scenarios in 2100, as in Figure 3.5B. Classification is determined by the percentage of occurrence in each SSP scenario. SSP-based basins where water scarcity changes are deemed negligible are highlighted in gray.

3.3.3 Representation Across the SSP-RCP framework

Results thus far have focused on differences across SSPs while aggregating all climate futures, but it is important to distinguish between impacts at multiple radiative forcing levels. The end of century distribution of human and climate impacts in a basin by scenario are displayed in Fig. 3.9B, where the size of each point represents the WSI of its basin in 2100. Applying Equations 3.3A and 3.3B, the human and climate impacts will fall on the drawn diamond. However, as each SSP-RCP scenario is made up of five different GCM runs, the robustness of the relative contributions towards water scarcity changes of both human and climate for each basin can be captured. As points move towards the center of the diamond, the GCM agreement on human and climate impacts decreases.

The distribution of human impacts is shown in Figure 3.9A with clear bimodal patterns across all SSPs. The peaks of all distributions fall where ($-0.5 > I_H > 0.5$), where I_H is the human impact, justifying the notion that humans are having a larger impact than climate on water scarcity in most basins globally independent of socioeconomic scenario. However, the distribution of these impacts vary greatly by SSP. Specifically, SSP1 is largely negatively favored (decreasing scarcity), whereas SSP2 and SSP3 lean significantly more positive. The spreads for SSP4 and SSP5 are much closer to a uniform bimodal distribution with close to equal numbers of basins with positive and negative human impacts.

The distribution of climate impacts is shown in Figure 3.9C across each of the RCP radiative forcing levels. Independent of radiative forcing future, the relative impact of climate is slightly negative, shown as the peak frequency is below the zero line in each distribution. The magnitude of this impact provides additional evidence for the relatively low impact of climate compared to humans across all SSP-RCP scenarios. The spread of climate impacts decreases as the end of century radiative forcing target decreases, leading to the conclusion that at lower radiative forcing futures, climate systems are likely to have smaller impacts on scarcity than humans in an increasing number of basins. The opposite result occurs in the RCP8.5 scenario as the distribution is more uniform across climate impacts, which emphasizes the important notion that at higher radiative forcings, water scarcity will likely be more susceptible to climate impacts. As RCP8.5 is currently only attainable under the SSP5 scenario, additional research is needed to understand how different socioeconomic conditions alter future water scarcity at high radiative forcing levels.

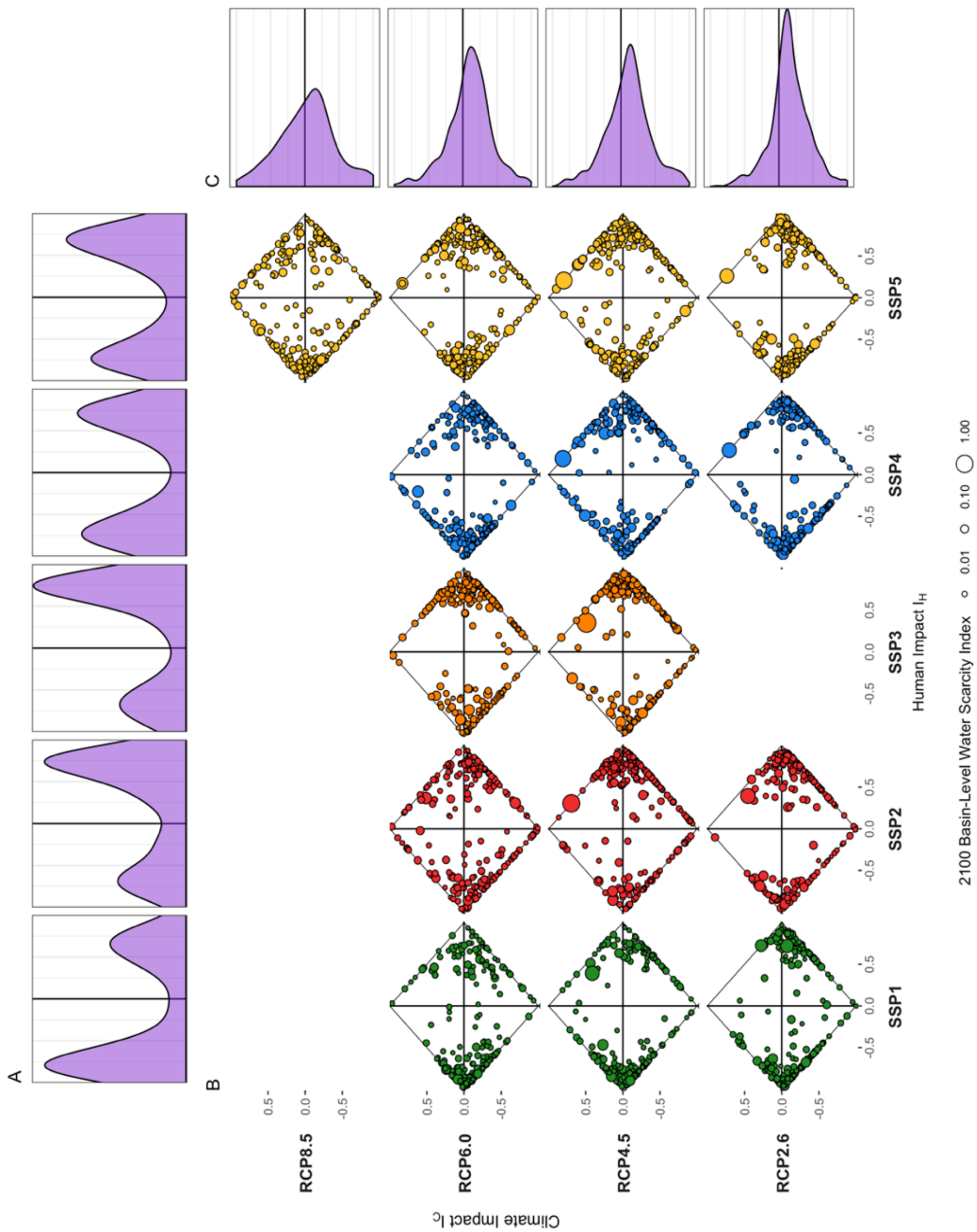

Figure 3.9 Human and climate impact quantifications across the 15 SSP-RCP scenarios in 2100. A, B, C, Numerical quantification of the relative human (I_H, x-axis) and climate (I_C, y-axis) impacts on water scarcity in 2100 across each of GCAM's 235 water basins. SSP-RCP combinations shown with no plots represent scenarios unattainable either through mitigation (i.e. SSP3-RCP2.6) or baseline assumptions fail to reach 2100 forcing levels (i.e. SSP1-4-RCP8.5). A, Probability distribution function of the human impact across each SSP scenario including the aggregates of all RCP combinations. B, Numerical representation of the 5 GCM mean human and climate relative impact across each basin (points). The WSI of each basin in 2100 is shown as the size of points. As GCM uncertainty increases, points move inwards from the mathematical limits of equations 3A and 3B. C, Probability distribution function of the climate impact across each RCP scenario including the aggregates of all SSP combinations.

3.4 Discussion

Understanding the impact that human and climate systems have on water scarcity in the future is extremely important for policymakers to understand. We have expanded upon previous estimates of water scarcity drivers by quantifying how the coevolution of a dynamic socioeconomic system and changing climate system may alter water scarcity into the future. This has been done by using evolving and differing socioeconomic assumptions that account for changes across all sectors (Calvin et al., 2017; Graham et al., 2018), in combination with considerations for climate impacts to water availability, hydropower expansion (Turner et al. 2017), agricultural productivity changes (Rosenzweig et al. 2014), and building energy expenditures (Clarke et al., 2018). The use of these socioeconomic and climate assumptions in GCAM allow for feedback linkages between these systems, enabling price adjustments and resultant demand changes across sectors when supplies become increasingly depleted.

While in line with previous estimates of the influence of human systems on water scarcity (Vörösmarty et al., 2000; Arnell, 2004; Alcamo et al., 2007; Hanasaki et al., 2013b; Arnell and Lloyd-Hughes, 2014; Schewe et al., 2014; Schlosser et al., 2014; Shen et al., 2014; Wada et al., 2014; Kiguchi et al., 2015, Veldkamp et al., 2015; Veldkamp et al., 2016), this study has also quantified the relative impacts across a wide range of potential futures and included combined variations to both the socioeconomic (SSP scenario assumptions) and climate (RCPs and GCM derived impacts) systems which have previously been unexplored. In addition, we have included the ability to not only withdraw, but constrain, local runoff and alternative (groundwater and desalination) water sources (Kim et al., 2016; Graham et al., 2018; Turner et al., 2019a).

These results have shown that human activities drive water scarcity changes through 2100 in 78% of basins that observed nonnegligible changes in water scarcity, and that these impacts may be increasing or decreasing dependent upon socioeconomic scenario and geographic location (Figures 3.2, 3.9A, and 3.9B). For example, throughout the century, SSP1 scenarios cause water scarcity to consistently move from H+ to H- (Figures 3.3 and 3.7), showing that increases in efficient water technologies (Graham et al., 2018), future GDP increases, and a focus on sustainability may help to alleviate some future water stresses particularly in Eurasia and the eastern United States (Figures 3.5 and 3.8). The counteracting impacts of human and climate systems are shown to depend on each socioeconomic scenario, since increases in basin numbers with counteracting impacts occur in SSP2, SSP3, and SSP5, while a shift to H-C- decreases the counteracting impacts in SSP1.
We also find that when population growth continues at or exceeds present day values, GDP growth slows (Calvin et al., 2017), and there exists an inability to invest in efficient futures (Graham et al., 2018), increases in water demands lead to increases in human driven scarcity. The geographic location of water scarcity is also shown to have consistent locations, as the Amazon River basin and much of the Northern high latitudes experience negligible changes in WSI independent of future, while basins in the southwestern United States and much of Africa experience worsening water scarcity due to human activities, independent of socioeconomic or climate future (Figs 3.3 and 3.7).

3.4.1 Limitations

This study quantified the relative impacts of both evolving human and climate systems on water scarcity. Future classifications of climate or human driven water scarcity changes would benefit from a distinct look into how the human components change between "Human Alone" and "Human and Climate" scenarios. This analysis assumes that the human system in both sets of scenarios are comparable. However, human-driven adaptation measures needed to address climate impacts in the "Human and Climate" scenarios may result in differing econometric responses and slightly different human systems. We have included climate derived impacts for four distinct areas, but these results do not fully represent the impacts that a changing climate might have on the suite of energy-water-land sectors and thus the impact for the climate system may not be complete in select basins or scenarios. In addition, water sector technological advances have been prescribed across each SSP at scenario-dependent rates, regardless of investment cost or cooperation (Graham et al., 2018). This may result in overestimations of potential water savings in SSP1 and SSP5 and therefore the results presented in this study should be taken as an initial analysis of potential water scarcity changes.

3.4.2 Future Recommendations

This study highlights the basins in which water scarcity is projected to change as climate and human systems evolve dynamically to 2100, and in particular identifies basins in which human activities may counteract climate to outweigh potential decreases due in large part to population driven demand increases. Future studies that account for the direction of water scarcity impacts may provide an opportunity to analyze where human intervention may act to reduce future water stress and can in turn work together with the climate system to decrease water stress.

3.5 Conclusions

This study has focused on the assessment of how human and climate systems will change basin level water scarcity under various socioeconomic and climate scenarios. This work represents the first analysis of water scarcity drivers in the SSP-RCP modeling framework while using an Integrated Assessment Model to account for cross-sectoral feedbacks while also including water constraints. The study has provided three key results.

First, global water scarcity is, on average, driven by human activities in 78% of non-negligible basins by 2100. This magnitude varies by socioeconomic scenario dependent upon the underlying storylines from O'Neill et al. (2017) providing the ability to decrease water use through technological improvements or increase through population growth.

Second, in more than half of global water basins human and climate activities compounding effects on water scarcity by 2100. The interaction between primary and secondary drivers show that under specific socioeconomic and climate storylines, the human and climate systems can work together to decrease water scarcity as seen in SSP1.

Third, the impact from climate change is shown to become increasingly concentrated as being minimally impactful, yet acting to decreasing water scarcity, as the radiative forcing target decreases. At higher radiative forcing levels, climate change is shown to have larger impacts and drive water scarcity changes in an increased number of global water basins by 2100.

Chapter 4: Future changes in the flows of virtual water (Graham et al., *in prep*)

4.1 Introduction

This study provides, for the first time, a future VWT analysis to account for changing socioeconomic conditions and general circulation model derived climate conditions. We use GCAM in the analysis of future VWT to allow for prices to respond to both the availability and profitability of growing and trading rainfed and irrigated agricultural goods across regional boundaries. This study also provides for the first time an estimate for future evolutions of the nonrenewable groundwater embedded in global virtual water trade. We provide global, regional, and basin level estimations of virtual water exports for all green and blue water and for nonrenewable groundwater, while also tracking the exported crops contributing to the VWT analysis. To better represent the availability of all water sources, we incorporate constraints to both renewable surface and groundwater recharge as well as to nonrenewable groundwater (Kim et al., 2016; Graham et al., 2018; Turner et al., 2019a). This analysis utilizes the Shared Socioeconomic Pathways – Representative Concentration Pathways framework by considering the evolution of VWT in the "middle of the road", SSP2-RCP6.0 scenario. This study provides a novel estimation of the future evolution of the VWT network and the necessary contributions of nonrenewable groundwater to meet international agricultural demands.

4.2 Methods

This analysis uses GCAM to quantify how much water is embedded in the global trading of agricultural goods. This water, called virtual water (Allan 1996), is calculated based upon how much water is consumed by the individual exported crop in the region where it was grown. In order to account for an evolving market and changing production conditions we use a defined future socioeconomic scenario, SSP2, under the set of Shared Socioeconomic Pathways (O'Neill et al., 2017; Calvin et al., 2017) matched with one global climate scenario RCP6.0, under the Representative Concentration Pathways (van Vuuren et al., 2011). A single future is utilized in order to gain an introductory analysis of a business-as-usual scenario without major deviations from present day trends. This combination represents one example of the SSP-RCP framework (O'Neill et al., 2016), but can be extended to additional SSP-RCP combinations to analyze a wider range of potential socioenvironmental futures. We introduced climate derived impacts to allow for changing water needs based upon five general circulation models (GCMs). These impacts included water supply, crop yields, changes in hydropower availability, and building energy expenditures. We analyze the amount of green and blue water consumption that is embedded in global trade and differentiate between renewable surface and groundwater recharge, as well as nonrenewable groundwater to provide global estimates, regional contributions, and basin-level usage. Below we describe the GCAM model, scenario components, virtual water calculations in GCAM, and assumptions for the downscaling of exports and estimations of virtual water imports.

This study uses the GCAM version 5.0 to investigate the relative contributions of climate and human systems on water scarcity regionally and globally under a wide range of scenarios. GCAM is a model that links energy, water, land, and climate systems to allow for the explicit representation of how climate-induced changes in water availability alter energy and land systems. GCAM is a market-equilibrium model that allows for prices to be adjusted within each time step to ensure that the supply and demand of goods and services remains equilibrated at each time step allowing for simultaneous market clearing across sectors. This study accounts for a limited supply of water by employing cost resource curves across all 235 basins that follow a logit formulation to determine the share of each water source (renewable surface water, nonrenewable groundwater, and desalinated water) needed to meet the water demands within all basins (Kim et al., 2016; Turner et al., 2019a). As depletion of various water sources increases the extraction price increases, which leads to compounding price increases on the goods and services that require higher-priced water sources.

4.2.1 Scenario Components

We use a single temporally varying socioeconomic system represented by the Shared Socioeconomic Pathways (SSP), in particular SSP2, in combination with the Representative Concentration Pathways (RCPs), RCP6.0, for future climatic changes. The SSPs provide a set of five future scenarios with varying changes to global population, the economy (Riahi et al., 2017), and land use (Popp et al., 2017), which were designed to explore varying degrees of challenges to climate change adaptation and mitigation (O'Neill et al. 2017). This scenario uses SSP2, a "middle of the road" scenario that has had qualitative and quantitative assumptions implemented into GCAM based upon the storylines outlined in O'Neill et al. 2017 (Calvin et al., 2017; Graham et al., 2018). SSP2 represents a world with steady population growth through the middle of the century, at which time the global population begins to equilibrate towards a 2100 value of 9 billion people. Economic growth continues at present-day values, and thus fuel and energy preferences remain very similar to what they are today. For these reasons, this scenario represents one with medium challenges to both climate mitigation and adaptation (O'Neill et al., 2017). Combining these socioeconomic features with future climatic changes, we implement a future RCP6.0 trajectory that results in end of century climate forcing of 6.0 W/m^2.

This study accounts for four different general circulation model (GCM) derived climatic impacts to water supply, agricultural productivity, hydropower expansion, and building energy expenditures. We calculate the impact on each aspect at four different radiative forcing levels and apply these to the appropriate scenarios within the SSP-RCP scenario matrix. Future water supply is calculated by using bias-corrected hydrologic data derived for four RCPs from five GCMs as part of the Inter-Sectoral Impact Model Intercomparison Project [ISI-MIP; Warszawski et al. (2014)]. These values are entered into the global hydrologic model Xanthos (Li et al. 2017, Liu et al., 2018; Vernon et al. 2019), which calculates accessible water at the GCAM 235-basin scale at five-year time steps. Climate derived impacts to crop yield changes (Rosenzweig et al. 2014), hydropower expansion (Turner et al., 2018), and building energy expenditures (Clarke et al., 2018) are calculated from the same set of ISI-MIP models and the climate varying impacts are added to their respective RCP scenarios.

4.2.2. Calculation of virtual water components in GCAM

Virtual water calculations in GCAM require several assumptions to account for the fact that trading is done across 32 regions. Demands are calculated at the regional level while production occurs at the basin level, and the origin of importing goods is not traceable once exports are placed in the global market. In order to calculate the different components of virtual water trade, we must first calculate the regional and basin level trade. For this, it is impossible to calculate basin level imports (Section 4.2.3), but all exports are trackable to the basin level, using the proportion of production as a proxy. The following calculations make use of agricultural production, demands, and water use of various sources as calculated by GCAM. These values are highly scenario dependent and are driven by socioeconomic and climate influences, as discussed in Chapters 1 and 2. By using the SSP2-RCP6.0 scenario, we assume only one population trajectory along with one potential climate change outcome. The changes to either the human (SSPs) or climate (RCPs) system will have implications on all values and analyses.

The trade, *T*, of any crop, *c*, from any basin, *b*, using growth type, *g*, is calculated using the production of that crop in the basin, *P*, the regional demands *D*, and the proportion of basin level production to the total regional production. Growth types are classified as either rainfed, *RFD*, or irrigated, *IRR*. Positive values of *T*, represent exports, *E*, whereas negative values represent the need for imports, *I*.

$$T_{b,c,g}(t) = P_{b,c,g} - \left[D_C * \left(\frac{P_{b,c,g}}{\sum_{i=1}^{b} P_{b,c,g}}\right)\right] \tag{4.1}$$

Virtual green water exports, VGE, are calculated by considering the green water consumption, *GWC*, the basin level rainfed crop production, and the rainfed exports, *E*. Virtual green imports, VGI, must consider the amount of virtual green water that is in the global market, VGE, the ratio of imports in a region, *r*, and total global imports of each crop, *I*. Finally, the total virtual green water trade (VGT) is calculated at the regional level as the combination of the exports and imports of virtual green water.

$$VGE_{b,c}(t) = \frac{GWC_{b,c}}{\left(\frac{P_{b,c,RFD}}{\sum_{i=1}^{b} P_{b,c,RFD}}\right)} * E_{b,c,RFD} \tag{4.2A}$$

$$VGI_{r,c}(t) = \left(\sum_{i=1}^{b_r} VGE_{b,c}\right) * \frac{I_{r,c,RFD}}{\sum_{i=1}^{r} I_{r,c,RFD}} \tag{4.2B}$$

$$VGT_{r,c}(t) = \left(\sum_{i=1}^{b_r} VGE_{b,c}\right) + VGI_{r,c}(t) \tag{4.2C}$$

Virtual blue water analysis follows the same process as for green water, with the slight adjustment of accounting for irrigated production and trade, as well as the blue water consumption, BWC. Here virtual blue water exports (VBE), virtual blue water imports (VBI), and virtual blue water trade (VBT) require the production of irrigated agriculture.

$$VBE_{b,c}(t) = \frac{BWC_{b,c}}{\left(\frac{P_{b,c,IRR}}{\sum_{i=1}^{b} P_{b,c,IRR}}\right)} * E_{b,c,IRR} \tag{4.3A}$$

$$VBI_{r,c}(t) = \left(\sum_{i=1}^{b_r} VBE_{b,c}\right) * \frac{I_{r,c,IRR}}{\sum_{i=1}^{r} I_{r,c,IRR}} \tag{4.3B}$$

$$VBT_{r,c}(t) = \left(\sum_{i=1}^{b_r} VBE_{b,c}\right) + VBI_{r,c}(t) \tag{4.3C}$$

Finally, the calculation of virtual groundwater exports (VGWE) considers the ratio of groundwater depletion in a basin, GWD, to the total blue water withdrawals in the basin, BWW. Multiplying this proportion by the virtual blue water exports, yields the amount of the blue water exports that is from nonrenewable groundwater sources.

$$VGWE_{b,c}(t) = VBE_{b,c}(t) * \frac{GWD_b}{BWW_b} \tag{4.4}$$

Total virtual groundwater trade (VGWT) and virtual groundwater imports (VGWI) are calculated in the same manner as 4.4, by considering the blue water imports and total trade as the first term on the right-hand side of the equation.

4.2.3 Virtual water assumptions for GCAM

Several assumptions must be made in order to analyze virtual water trade and differentiate between water sources being traded within GCAM. First, GCAM consists of 32 energy-economy regions between which trading can occur. This results in far fewer trade partners than there are when analyzing country-level data. There also exists an inability to track trading within each of the GCAM regions. Intraregional trade is aggregated in the calibration years to assess the trade between the 32 energy-economy regions, after which trade remains aggregated in future years due to spatial limitations within GCAM. This will lead to VWT values that are lower than analysis done at the country level but provide a valuable first approximation. Demands of goods in GCAM are determined at the regional level while production is calculated at the basin level, therefore in order to assess the basin-level trading of goods, we assume that regional exports come from each basin proportionate to the amount of production of that good in the basin (Equation 4.1). This simplified downscaling measure likely results in some misrepresentations but is one of the best first-order downscaling methods to account for the lack of basin level demands. Additional assumptions must be made when considering the importing goods and virtual water in a region. After being exported, crops enter a global market and are distributed to regions based upon unmet demands, however there is no tracking to determine where these crops are coming from. The global market distributes crops based upon unmet regional demands, but does not keep track of source region. In order to attempt to estimate the virtual water imports, we assume that regions import crops and virtual water proportionate to the amount coming from exporting regions. For example, if 80% of the exports of corn come from the United States, any importing region will receive 80% of their imports of corn from the United States (Equation 4.3B). Finally, when differentiating between renewable water and nonrenewable water contained in the virtual water trade, we assume that the proportion of surface runoff withdrawals to nonrenewable withdrawals remain consistent for agricultural purposes. We use this to estimate the VGWT as a proportion of the VBE (Equation 4.4).

4.3 Results

4.3.1 Global estimates of all sources of virtual water

Virtual water trade, for the purpose of this study, is the amount of water, green, blue, or nonrenewable groundwater, that is consumed in the production of an agricultural good that is then traded in the international market. The amount of virtual water, from all sources, that is traded globally increases throughout the century (Figure 4.1). By definition, VWT, or (VWI + VWE), must equal zero globally, therefore we focus on the exports to assess the absolute amount of virtual water within the global market. Uncertainty of virtual water exports (VWE) increases due to differences in GCM-derived climate impacts for the RCP6.0 scenario. In total, VBE and VGE at least triple by the end of the century in response to both increases in population and resultant demand increases. While population increases drive initial increases in VWE, the export per capita experiences a more significant increase after 2050 as global population begins to equilibrate (Figure 4.2). Throughout the century, a significant reliance emerges on trading from water-rich regions of North and South America or from regions that experience significant population dynamic changes such as China, to water scarce regions of India, the Middle East, and Pakistan. Nonrenewable groundwater is increasingly used in agricultural trade throughout the century with an observed doubling of VGWE by the end of the century, but with a definitive peak mid-century.

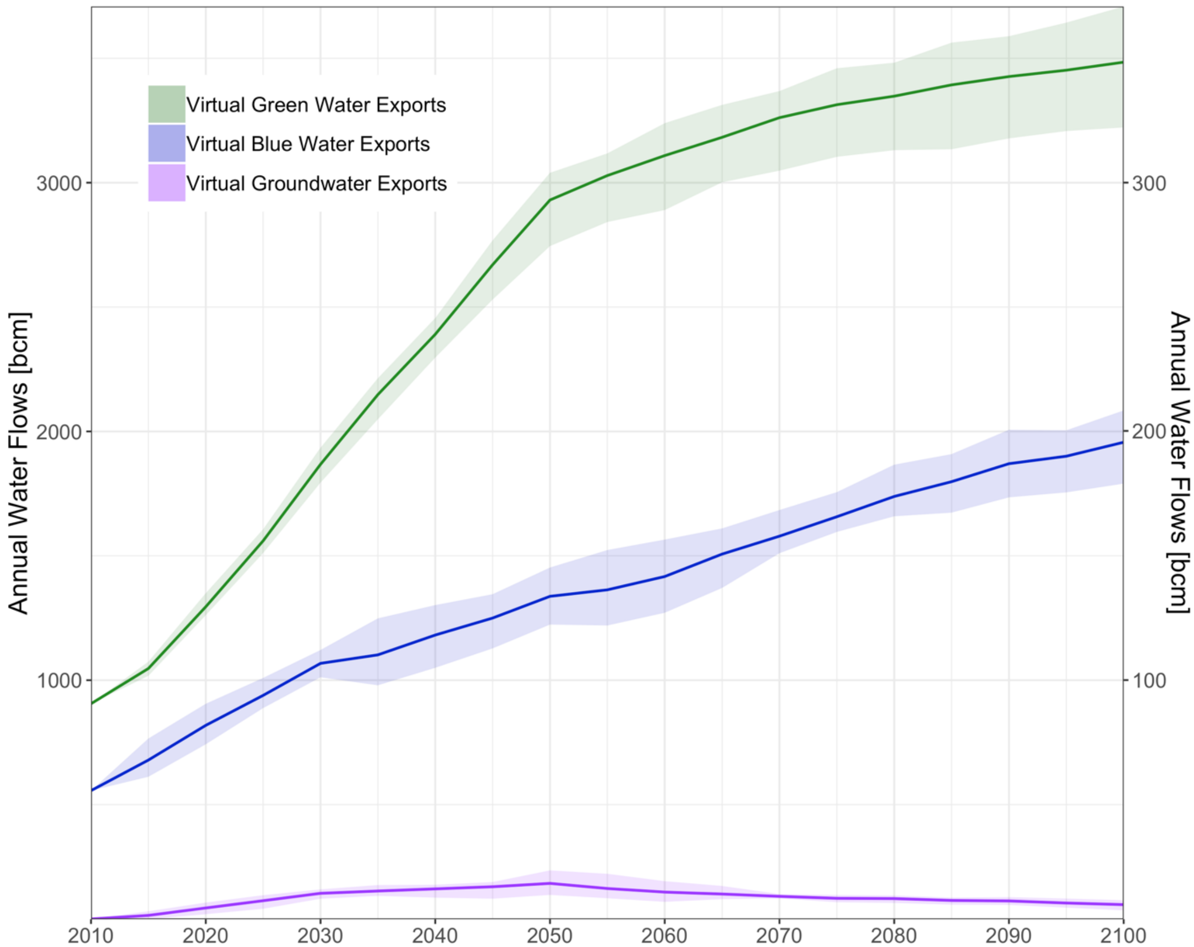

Figure 4.1 Annual water flows of green, blue, and groundwater embedded in agricultural trade for SSP2-RCP6.0. Range of virtual green and blue water exports and the amount of nonrenewable groundwater depletion embedded in agricultural trade for all SSP2-RCP6.0 scenarios including GCM uncertainty. VGE is shown on primary y-axis (left) while VBE and VGWE are represented on secondary y-axis (right). Solid lines represent the average for each water flow in SSP2-RCP6.0. Virtual green and blue water exports are shown to at least triple from starting 2010 values with increases due to population changes and global production shifts. VGE show steep increases towards 2050, with gains much smaller thereafter, reflective of the SSP2 population trajectory. VBE has a much steadier gain throughout the century with nearly consistent per-year increases. VGWE (purple) undergo a five-fold increase towards 2050 and gradual decreasing thereafter.

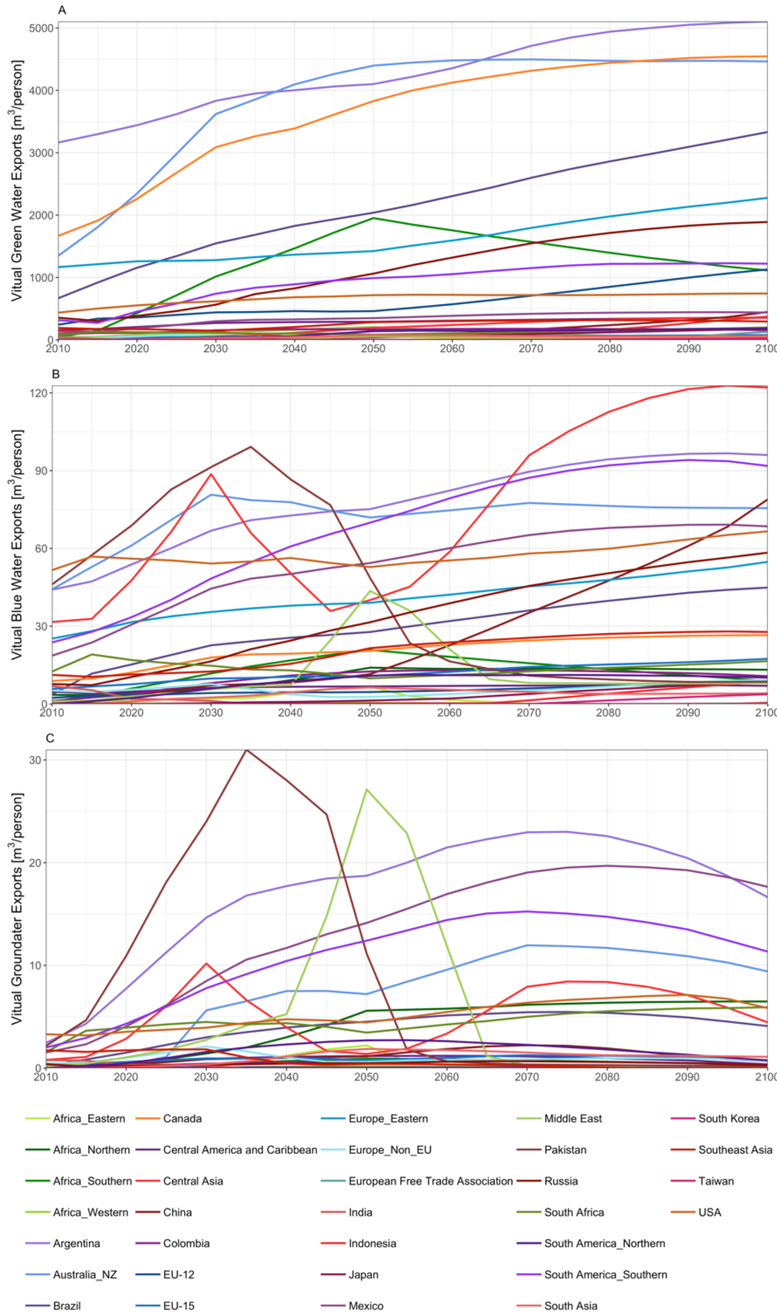

Figure 4.2 Per capita exports of each virtual water trade component by region. A, Virtual green water exports per capita. Argentina, Australia, and Canada represent the three highest per capita exporters of green water with general upwards trends throughout the century. B, Virtual blue water exports per capita. Significant upwards trends are shown in China and Southeast Asia, while declines occur in Pakistan and the Middle East after 2050. C, Virtual groundwater exports per capita. Peaks are observed in Pakistan and the Middle East as groundwater is extracted early in the century as the depletion lessens after 2050, the per capita values drop to zero. Increases are observed in Australia, Argentina, and Mexico.

Previous studies have reconstructed of historical VWT and are compared to the values found in this study along with future projections in Table 4.1. This study has used two methodologies to determine the VWT. We find when using export values and trade across all countries provided by FAO historical data (FAO, 2017), estimates of VWE, particularly VGE, are very similar to previous estimates. However, GCAM traces trade across 32 regions and therefore values provided in this study are likely to be lower than other studies due to the inability to track trade within a GCAM region. The same comparison between country level and GCAM regional level trade is completed for nonrenewable groundwater with similar comparisons to previous estimates of nonrenewable groundwater embedded in agricultural trade (Dalin et al., 2017). However, here, we consider the consumptive nonrenewable groundwater rather than just the extracted volume. While lower than previous estimates of nonrenewable water in trade, groundwater depletion values found in this study are in line with previous historical and future analyses (Table 4.2).

Table 4.1 Global physical water flows

Water Flows	Annual flows (km^3/year)				Source
	1996-2005	2010	2050	2100	
VGE	1352				Hoekstra and Mekonnen 2012
		1239			This Study[1]
		905	2745-3040[3]	3222-3708[3]	This Study – SSP2-RCP6.0[2]
VBE	255				Hoekstra and Mekonnen 2012
		101			This Study[1]
		56	122-145[3]	179-208[3]	This Study – SSP2-RCP6.0[2]
VGWE		25			Dalin et al. (2017)[4]
		17			This Study[1]
		4	13.5-23.5[3]	7.5-11.5[3]	This Study – SSP2-RCP6.0[2]

[1]Calculated using trade between each country from 2010 FAO country-level crop export data.
[2]Calculated using trade between each of the 32 regions in GCAM. Does not include intraregional trade.
[3]Range across the five GCM suite of SSP2-RCP6.0 model runs.
[4]Calculated using groundwater depletion rather than groundwater consumption

Table 4.2 Comparison of nonrenewable and blue water withdrawals. Comparison to historical and future projected water withdrawals and nonrenewable groundwater depletion through the end of the century across various future socioeconomic analyses.

Water Flows	Annual flows (km^3/year)			Source
	2000-2010	2050	2100	
Nonrenewable Groundwater Depletion	280			Wada et al. (2010)
	140			Konnikow (2011)
	292			Dalin et al. (2017)
	332	775		Yoshikawa et al. (2014)
	550	150-1750	60-1500	Kim et al. (2016)
	300		510-680	Wada and Bierkens (2014)
		320-910	110-480	Turner et al. (2019b)
	218	520-873	314-401	This Study – SSP2-RCP6.0
Blue Water Withdrawals	3853			FAO (2016)
	4000	5750	6000	Wada and Bierkens (2014)
	3710	6195-8690	4869-12693	Hejazi et al. (2014b)
	3250	3700-4200		Bijl et al. (2018)
	3594	4931-5125		Alcamo et al. (2007)
	3860	4875-5120	4490-4820	This Study – SSP2-RCP6.0

4.3.2. Regional total virtual water trade

Changes to the components of the VWT network between 2010 and 2100 are shown in Figure 4.3. A large intensification of VGT is observed as the trading of oil crops represents a large proportion of initial trading in 2010 (Fig 4.3A). Increases in corn, oil crops, and wheat lead to significant VGE increases in 2100 (4.3B). The imports of VGE are concentrated in much of Africa, Europe, and India. VBT shows significant differences arising in China, Pakistan, India, and the Middle East as the availability of water for irrigation decreases and population changes throughout the century (Figure 4.3C and D). In 2100, China represents a large source of virtual water embedded in the exports of wheat and rice products. China represents a unique case of shifting from importer to exporter into the future, and this is due to steep declines in total population after 2030. Reduced demands allow for all excess production to be used to meet international agricultural demands. The United States represents another main source of future VBE by exporting several crops while needing to import miscellaneous crops (MiscCrops, e.g. fruits, vegetables, nuts) as parts of southwestern United States shifts production away from MiscCrops towards the end of the century. An important note is that virtual water trading does not necessarily mean that the trading of agricultural goods is actually increasing, rather it determines the amount of water required to grow the crops that are then traded globally. If the originating exports are extremely water intensive in a particular region, an intensification of VWT will be observed if this region is then trading these crops globally. We have found that this intensification does occur in the early part of the century as the Middle East and Pakistan contribute to the global market, while towards the end of the century, exports come from water-rich areas that require less water to grow (Figure 4.6).

VGWE concentrate in several main regions, the United States, Mexico, western South America and Northern Africa. Following the same methodology of total virtual blue water trade, it is found that once again the water scarce regions of Pakistan, Middle East, and India represent some of the largest importers of nonrenewable groundwater in the form of agricultural goods. On a temporal scale, the water scarce regions are found to export nonrenewable groundwater early in the century but cease to do so after mid-century as climate induced water scarcity begins to hinder this ability (Figure 4.6).

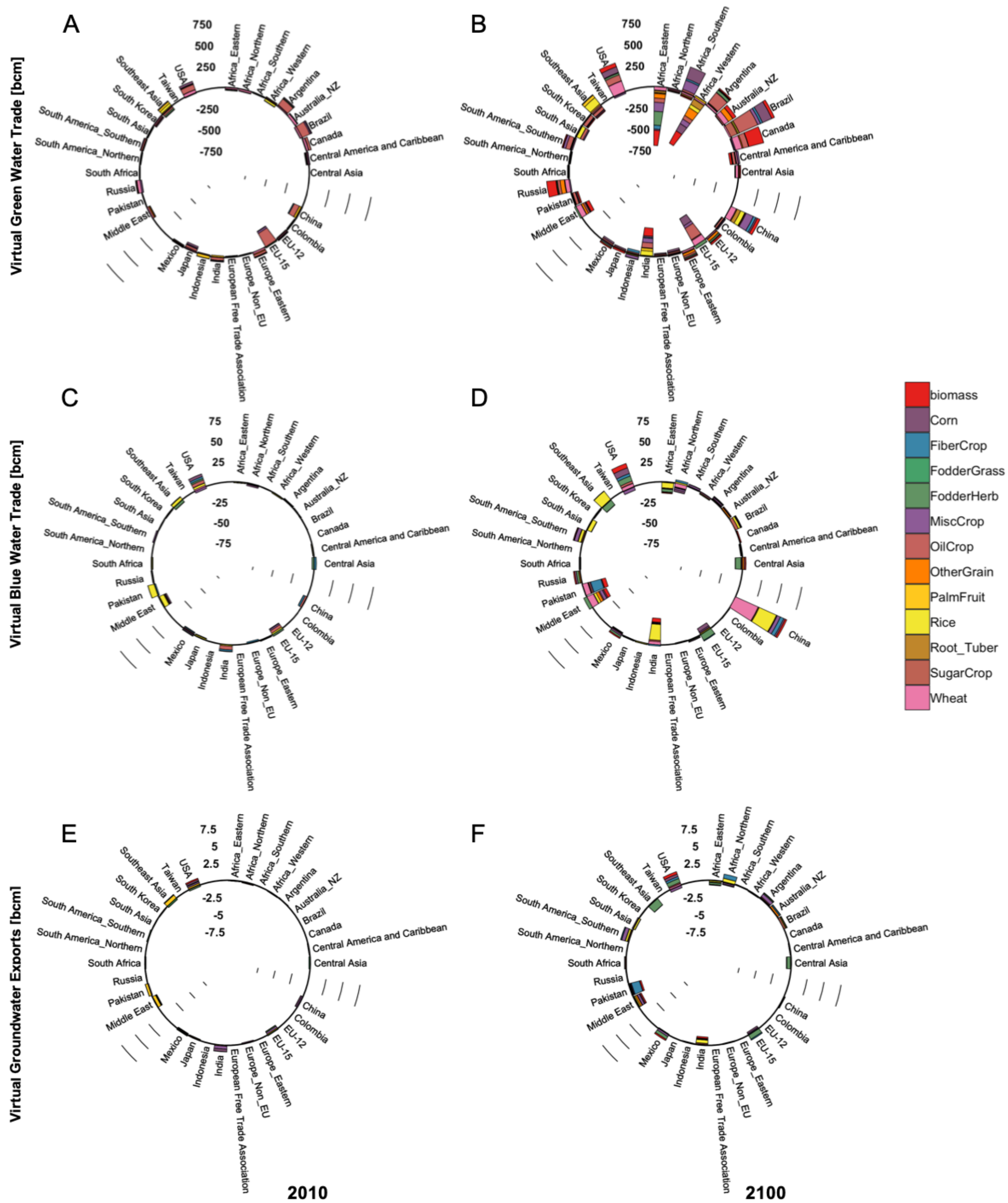

Figure 4.3 Virtual water trade fluxes by region and crop in 2010 and 2100. A, B, Global virtual green water trade (bcm) by crop and aggregate GCAM region in 2010, A, and 2100 for SSP2-RCP6.0, B. All green water traded is from rainfall that grows crops viable for consumption. Imports (negative values) are assumed to come proportionately from exporting regions dependent upon total regional exports of a crop type. Water intensities for these imports are then scaled dependent upon the proportionality of exporting region intensities. C, D, Global virtual blue water trade (bcm) by crop and aggregate GCAM region in 2010, C, and 2100 for SSP2-RCP6.0, D. Scaling of imports follows the same methods for green water. E, F, Global virtual groundwater trade (bcm) by crop and aggregate GCAM region in 2010, C, and 2100, D. Values for imports follow same logic as was used for VWT, with exporting regional nonrenewable to renewable water use calculated and applied.

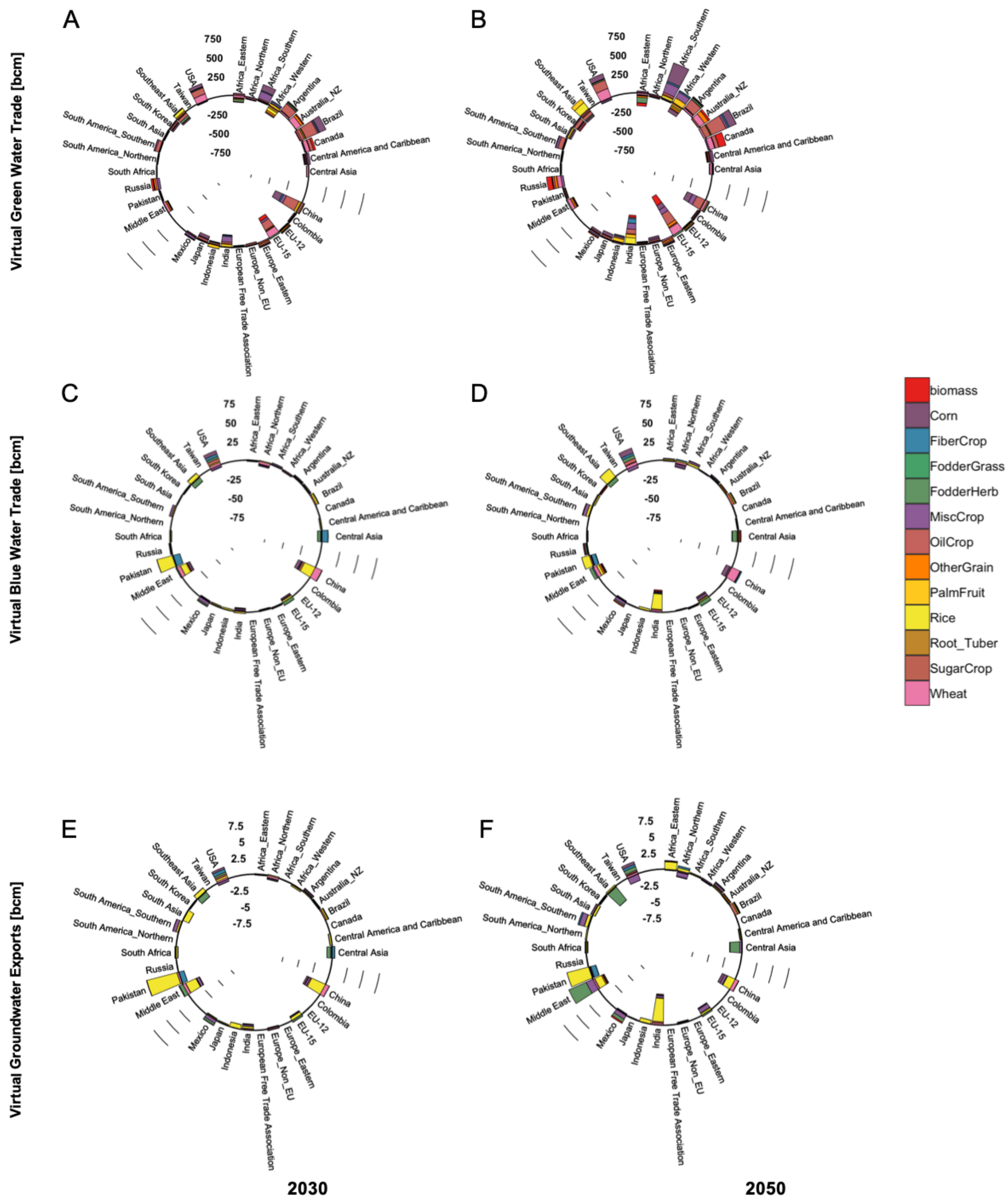

Figure 4.4 Virtual water trade fluxes by region and crop in 2030 and 2050. A, B, Global virtual green water trade (bcm) by crop and aggregate GCAM region in 2030, A, and 2050 for SSP2-RCP6.0, B. All green water traded is from rainfall that grows crops viable for consumption. Imports (negative values) are assumed to come proportionately from exporting regions dependent upon total regional exports of a crop type. Water intensities for these imports are then scaled dependent upon the proportionality of exporting region intensities. C, D, Global virtual blue water trade (bcm) by crop and aggregate GCAM region in 2030, C, and 2100 for SSP2-RCP6.0, D. Scaling of imports follows the same methods for green water. E, F, Global virtual groundwater trade (bcm) by crop and aggregate GCAM region in 2030, C, and 2050, D. Values for imports follow same logic as was used for VWT, with exporting regional nonrenewable to renewable water use calculated and applied.

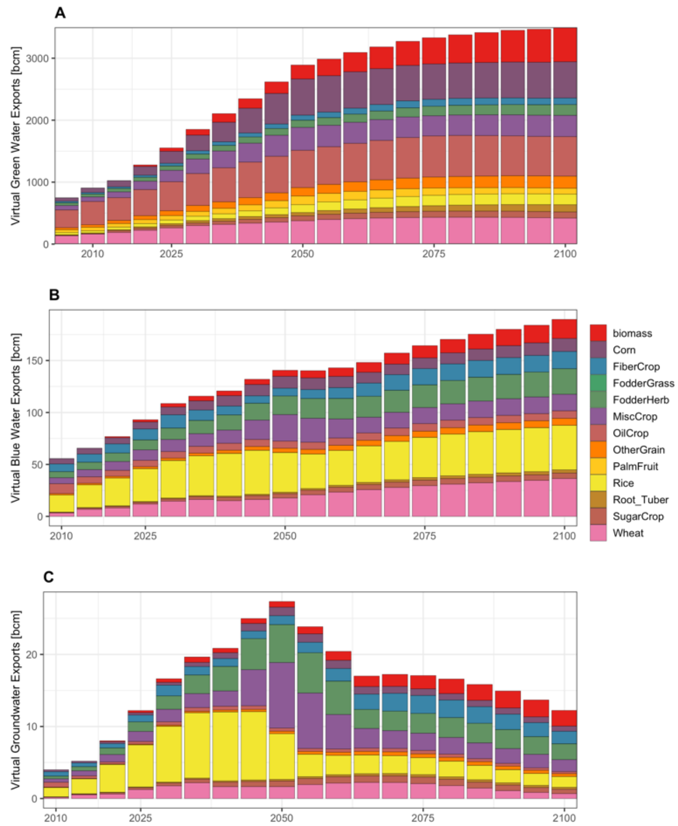

Figure 4.5 Crop breakdown of each virtual water trade component. A, Virtual green water exports by crop, from 2010 to 2100. An intensification of every crop type is seen throughout the century. B, Virtual blue water exports by crop and region. Increases in wheat and rice make up the largest portion of virtual blue water exports. C, Virtual groundwater exports by crop. Quick increases in rice and miscellaneous crop trade is observed through 2050.

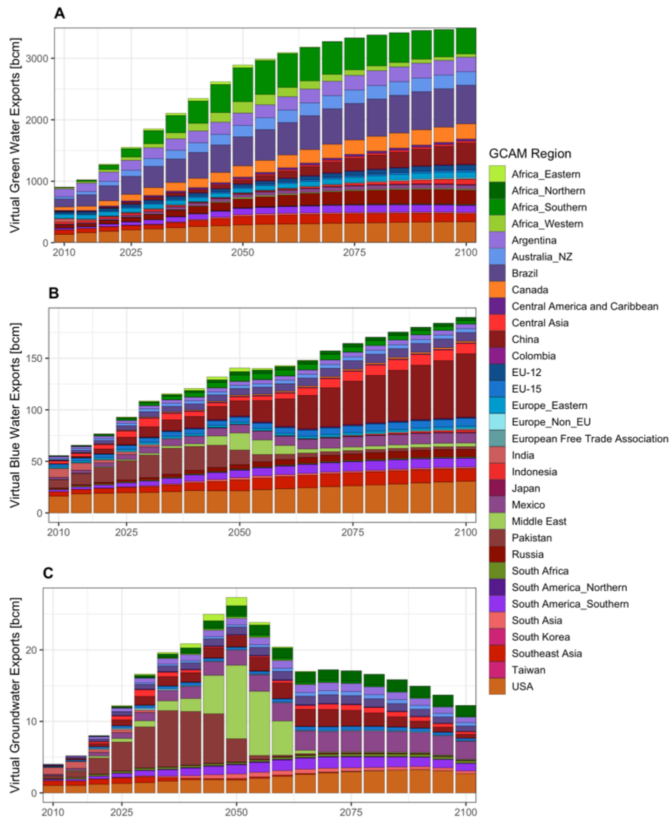

Figure 4.6 GCAM region breakdown of each virtual water export component. A, Virtual green water exports and from GCAM regions, from 2010 to 2100. Brazil and Northern Africa observe the largest increases in net exports. B, Virtual blue water exports by region. An intensification of exports from China is observed. C, Virtual groundwater exports by region. An intensification of exports from Pakistan and the Middle East prior to 2050. After 2060, the groundwater resources become increasing exhausted and more expensive, therefore the exports from these regions cease.

4.3.3. Basin level virtual water exports

While it is important to understand both global and regional changes to the components of VWT, expanding this to understand how specific basins contribute to the observed increases in exports of all virtual water variations provides an important localized analysis. Downscaling to the GCAM 235 water basin scale yields specific locations in which VGE and VBE originate. When comparing the 2050 to 2100 values of VGE and VBE (Fig 4.7A-D), the intensification of exports is evident in much of the water basins in China. Blue and green exports also concentrate in the Missouri River basin, the La Plata basin in South America, and the Murray-Darling basin in Australia. Each of these basins have large amounts of agricultural production and will be relied upon heavily to meet future demands.

Tracing the VGWE show a significant time evolution as basins in Saudi Arabia and the Indus River basin have large amounts of exported water in 2050, but do not contribute to the global VGWE in 2100. This is due to extraction in the first half of the century from the large underground aquifers in Saudi Arabia and India (Al Alawi,1994), causing additional pumping to become too expensive in these regions. Additionally, high amounts of VGWE come from the California River basin, the Arkansas River basin, and northwestern Mexican coast in North America, the Nile River, the La Plata basins, and the Murray-Darling basin in Australia. The Arkansas River basins resides on top of the southern portion of the Ogallala aquifer, which has the largest groundwater reserves in the United States. Exports are not shown from the Missouri River basin, on top of the deepest portion of this aquifer as groundwater extraction calibration (Turner et al. 2019a), has shown that groundwater recharge is greater than nonrenewable extraction in this basin (Scanlon et al., 2018), therefore the groundwater withdrawn in the Missouri River basin is classified as renewable and captured in the VBE. The Nile and La Plata basins are shown to be using nonrenewable groundwater for the production of rice, fibers, and corn that is demanded outside of regional boundaries (Fig 4.3E).

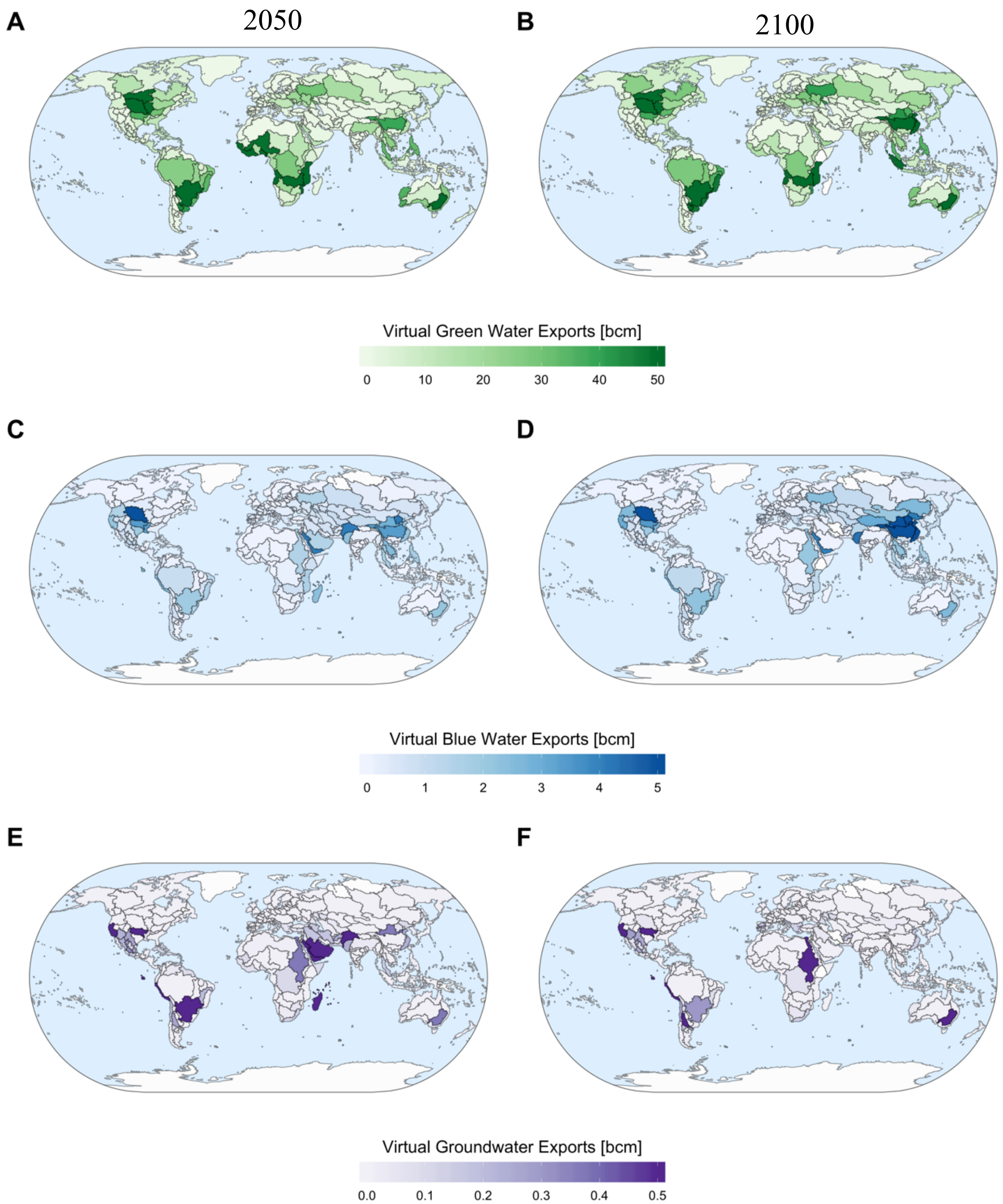

Figure 4.7 Basin level virtual water exports in 2050 and 2100 for all sources, Virtual green water exports (bcm) A and B, and blue water exports (bcm), C and D, in 2050 and 2100 respectively for the average of five GCM runs for SSP2-RCP6.0. Virtual groundwater exports (bcm) in 2050 and 2100 for the same averaged GCM runs for SSP2-RCP.6.0 is shown in E and F. All values are considering the exports of agricultural crops only with additional, potentially necessary virtual water imports not considered. VGE are concentrated in much of China, central North America, and eastern South America. Exports of blue water come mainly from China, and the Missouri River basin in the United States. Virtual groundwater extraction in agricultural trade is largest in the California River basin, the Arkansas River basin, southwestern North America, the Nile River basin, western South America, and the Murray-Darling basin in Australia.

4.4. Discussion

Using GCAM to account for the future evolutions of the global trade market dependent upon changing socioeconomic and climate conditions has allowed for a first look at how virtual water trade may evolve over the century. In this analysis, we have built upon previous advances in the reconstruction of the historical global virtual water trade network (Dalin et al. 2012, Mekennon and Hoekstra, 2012, Dalin et al., 2017) by allowing future socioeconomic and climatic changes to alter the production of agricultural goods that causes resulting price fluctuations in the global trade market and potential restructuring of global agricultural trading. We find that as a result of changing socio-environmental conditions, the amount of virtual green and blue water in the global trade market will increase throughout the century from 905 bcm and 56 bcm in 2010 to more than 3200 bcm and 170 bcm, respectively, by the end of the century. This time-forward look at virtual water trade has also provided the first analysis of how much nonrenewable groundwater is extracted from aquifers around the world to meet the international crop demand. An initial 500% increase in this extraction towards 2030 eventually levels off in the second half of the century as Middle Eastern regions move away from groundwater pumping. This results in a general doubling of nonrenewable groundwater in the global market by 2100, much of which originates from southwestern North America, the Murray-Darling and the Nile River basins.

4.4.1 Limitations

This first analysis of the evolution of virtual water trade and nonrenewable groundwater trade has yielded an initial set of results that can be used to understand the dependency upon rainfall, renewable, and nonrenewable water usage in external regions to meet future global demands under evolving socioeconomic and climate conditions. However, future analysis of the virtual water trade network should expand upon the intraregional trade which was not captured in this study. Trading between all countries is likely to increase the VWT values shown and therefore a more extensive trade network is needed to fully understand how both renewable and nonrenewable water may be traded into the future. Along these lines, it is also important to better understand the virtual water flows into importing countries. Exports are able to be tracked explicitly in GCAM, however, once in the global market, the originating region of an imported good cannot be traced. It is important to understand where the imported virtual water is coming from to better understand interregional dependencies.

4.4.2. Looking forward

This study has focused only on water used to grow agricultural crops, and while nearly 90% of blue water consumption is used for agricultural purposes (Falkenmark and Rockström, 2006), energy and industrial goods are extensively traded in the global market and it is important to understand international dependency on these different sectors and how this may change into the future. Understanding how trade changes into the future is not a trivial task, but obtaining estimates based upon differing climate and socioeconomic conditions can allow for a wide range of potential trade evolutions. This study has focused on one socioeconomic scenario (SSP2) and one climate scenario (RCP6.0), however, to obtain this range of potential outcomes it is important to analyze how the VWT network develops under different socioeconomic and climate conditions.

4.5 Conclusions

This study has provided, for the first time, a projection of future virtual water trade. Using the trade feedbacks embedded in an Integrated Assessment Model, trade responses to price and availability of agricultural goods are possible. This work considers the amount of green, blue, and nonrenewable groundwater that must be used to meet international agricultural demands. The inclusion of water constraints and a consistent socioenvironmental scenario have allowed for the first estimations on the reliance on external sources of water to meet domestic demands. This work has provided three key results.

First, global virtual water trading is projected to increase by at least three times present day values by 2100. This includes at least a tripling of green water trade, and a doubling of blue water and nonrenewable groundwater trading.

Second, population dynamics allow for China to represent a main source of blue water exports in the future as population declines after 2030 create a surplus of production to demands. Slight changes to this specific projection would cause large changes in the current projections for the SSP2-RCP6.0 scenario.

Third, the contributions from nonrenewable groundwater show that continued extraction from California, the Nile River Basin, and the Murray-Darling basin will be needed to meet international agricultural demands.

Chapter 5: Conclusions and Future Work

This thesis has provided a look at how the use and dependency of water resources might change in the future, dependent on changing socioeconomic and climate conditions. The use of an Integrated Assessment Model accounts for feedback linkages between the human, energy, and land systems while also placing constraints on the water resources accessible for use. Several key conclusions have emerged from this work and are presented in Section 5.1. Future investigative directions are provided in Section 5.2, with notes on how these studies can be improved and how they can be extended in the future. Finally, some concluding remarks about how the results here may be interpreted and potential uses for the integrated assessment of future water resources use in the future are provided in Section 5.3.

5.1 Addressing Research Questions Posed

In Section 1.4, three research questions were posed. The conclusions that these studies have yielded are presented below, with appropriate references to journal article submissions and sections of this text.

5.1.1. Water sector assumptions for the SSPs

What are the implications of quantitative assumptions for the water sector across the five Shared Socioeconomic Pathways scenarios on global water demands in a water constrained world?

In Chapter 2 and as published in Graham et al. (2018), quantitative water sector assumptions for each of the five SSPs were implemented into GCAM to analyze how their inclusion would alter the water demands across six demanding sectors. Consistency with the framework laid out, first by O'Neill et al. (2017) and enhanced for GCAM by Calvin et al. (2017), was imperative. As the SSPs provide a wide range of potential socioeconomic futures, the impact of global water demands was highly dependent upon individual SSP assumptions. It was found that future infrastructure changes in the water sector in SSP5, due to significant increases to GDP across all regions, can decrease water demands by up to 32% in 2100. Additionally, in SSP1, the focus on sustainability and the ability to invest in future water-efficiency improvements has the potential to lead to end-of-century water demands lower than present day demands despite a higher standard of living and similar global population. SSP3 is the only scenario that does not decrease water demands, as several sectors maintain 2010 efficiency values and technological improvements are slowed in the municipal sector. As population growth is highest in this scenario, the lack of water demand reductions is likely to cause increased stresses on water resources in an effort to meet the increased global demands for goods and services.

Individual sector impacts of water technology inclusions have been analyzed and compared to previous studies. The results have shown that water demands from the five SSP scenarios run with socioeconomically viable water sector technology changes are within the range of previous sector assessments (Figures 2.4, 2.7, and 2.8).

While cross-SSP reductions are shown to have a high dependency on the quantitative assumptions, the income level of regions in which the reductions occur is also shown to have a high dependency across the SSPs. Future water-demand changes in the SSPs depend strongly on adoption and implementation of efficient water technologies in low-income regions (as defined in Calvin et al., 2017). In SSPs 1, 2, and 5, more than half of the global water demand reductions result from the adoption of more efficient technologies in low-income regions. These reductions stem from significant increases in irrigation technologies improving from crop flooding to universal drip irrigation by the end of the century. Sector specific reductions are also shown to have income level dependency as high-income regions observe reductions to the electricity and manufacturing sectors due to the highly industrialized state of these regions, whereas middle- and low-income regions see larger reductions with irrigation technology improvements (Figure 2.10).

Finally, it is shown that while the addition of water constraints is expected to decrease water demands due to limited supplies (Kim et al., 2016), the reductions with water technology improvements result in nearly an order of magnitude greater reduction (Figure 2.12).

This work has provided the first comprehensive analysis of water sector assumptions across the SSPs while accounting for limited supplies of water across global basins. This first-step IAM analysis of the various impacts that technological change can have on water demands across a range of socioeconomic futures provides a starting point for the analysis of future water savings brought upon by human interventions.

5.1.2. Water scarcity drivers across the SSP-RCP scenario matrix

How does the coevolution of human-energy-water-land-climate systems affect the driver of water scarcity changes and how do human and climate

systems interact to alter water scarcity attributions both spatially and temporally?

In Chapter 3 and Graham et al. *submitted*, the water sector technological assumptions from Chapter 2 are used in combination with climate impacts to four different sectors to analyze how the human and climate systems may act to alter water scarcity across a wide set of global futures. The use of various socioeconomic and climate futures allows for water use to be exposed to differing supply and demand scenarios. After accounting for basins which are deemed to have negligible changes in water scarcity, it was found that, across all scenarios, 78% of global basins have water scarcity changes that are driven by human systems. This value is in line with previous estimates of water scarcity drivers. However, dependent upon socioeconomic future, these changes may reduce water scarcity or enhance it. Throughout the century, SSP1 scenarios cause water scarcity to consistently move from human-driven increases to decreases (Figures 3.3 and 3.7), showing that with the sustainability focus and necessary means to do so, certain socioeconomic conditions can lead to up to 52% of basins experiencing human-driven water scarcity reductions from 2005 values. Counteracting water scarcity impacts are also found to have a scenario dependence, as SSP2, SSP3, and SSP5 all show increases throughout the century, however SSP1 experiences reductions due to human and climate driven reductions to water scarcity.

When determining the relative impacts of human and climate systems on changes to water scarcity, it is found that regardless of SSP-RCP combination, the human system is likely to have a greater impact than the climate system. As radiative forcing target decreases, there is increasing agreement that the climate system will act to decrease water scarcity around the world, whereas, this determination becomes less certain at higher radiative forcing levels (Figure 3.9C). Independent of socioeconomic and climate future, the human system is found to have a higher impact on water scarcity changes in a majority of basins around the world.

This work has expanded upon previous estimates of water scarcity drivers by quantifying how the coevolution of socioeconomic and climate systems may alter water scarcity into the future. The use of socioeconomic and climate assumptions in GCAM allow for feedback linkages between these systems, enabling price adjustments and resultant demand changes across sectors. It also allows, for the first time, the consideration of limited supplies of water, and alternative water sources to be included in an integrated assessment of water scarcity drivers.

5.1.3. Future virtual water trade analysis

How will future changes in socioeconomics and climate affect the amount of water embedded in international agricultural trade and what are the implications for nonrenewable groundwater extraction?

Chapter 4 and Graham et al. *in prep* analyze socioeconomic and climate impacts on the future of water and the drivers behind water scarcity changes, and the dependency upon the trading of and for water intensive agricultural goods. Water scarcity is shown to increase in over 60% of basins in SSP2 (Figure 3.2). Due to this increase in scarcity, domestically grown food may not meet the increased future demands in some regions. Therefore, understanding the reliance on water intensive trade provides a unique analysis of regional dependencies in the future. Historical reconstructions of virtual water trade networks have yielded several gross virtual water trade values. These values have been compared with two calculation methodologies (Section 4.2 and Table 4.1). It is shown that green water exports are comparable to previous studies while blue water export values are found to be lower than previous estimates. This is likely due to the aggregation of crop water intensities across regions in GCAM limiting the amount of water used for particularly intensive crops.

Under SSP2-RCP6.0 conditions, it is found that the amount of green, blue, and nonrenewable groundwater used for the growth of internationally traded agricultural goods increases throughout the century. As climate change alters the future water availability around the world, regions in the Middle East become increasingly reliant on imports from water-rich regions. Regions in Africa also observe large increases of virtual imported water due to significant increases in demand from an ever-growing population. The reliance on China and the United States to meet international demands through blue water use is only possible if China follows the currently implemented SSP2 population growth projection. Outside of this projected population decrease in China, the global trade market may continue to shift to meeting evolving demands, specifically if the population dynamics do not occur as prescribed in SSP2.

Nonrenewable groundwater use for internationally traded agricultural goods is shown to also increase throughout the century. Areas of the southwestern United States, the Nile River basin, and the Murray-Darling basin in Australia use high amounts of groundwater to grow internationally traded agricultural goods. The notion of this potential reliance is an important note for policymakers.

This analysis provides, for the first time, a projection of how reliant regions around the world will be on the trade of water intensive crops under a single socioeconomic and climate scenario. The quantification of the virtual green, blue, and nonrenewable groundwater trade provide a novel look at the water necessary to grow and trade the agricultural goods needed to meet global demands through the end of the century.

5.2 Future Work

The results presented here represent a look at how water usage may change across various socioeconomic and climate futures while accounting for interactions between the human, energy, and land systems. This thesis has focuses on demands, scarcity, and the water embedded in global agricultural trade. However, there are several additional considerations that are worthy of exploration in the future. Throughout this work, no consideration for water quality was given and this is a limitation of GCAM as the modeling capability is currently not available. It is important to understand, not only the quantity of water that is need under various futures, but how the quality of water changes with implemented technological changes, socioeconomic evolution, and climate change.

Chapter 2 provided an analysis of water sector assumptions across the SSPs; however, it was assumed that all technological advancements would be implemented, independent of cost. An analysis of the attainability, between cost and cooperation, would provide an important update to these assumptions. The cost of moving from crop flooding to drip irrigation may not allow these implementations to take place in certain regions and resultant water demand reductions may not be as great as presented. These assumptions are continued in each chapter of this work and therefore the lack of cost consideration will be a limiting factor in future analyses until addressed.

The virtual water trade analysis provided in Chapter 4 has limited the breadth of scenarios to just SSP2-RCP6.0. This scenario results in limited climate mitigation and provides one potential socioeconomic future. Analysis of the suite of SSP-RCP scenarios will provide a valuable assessment of how socioeconomic conditions, climate change mitigation, and the extensiveness of the global trade network might alter the dependencies of international trade to meet domestic demands. Additionally, the ability to account for intraregional trading in GCAM into the future will lead to increased accuracy in any virtual water assessment as current estimates are based on trade between 32 regions, rather than the over 200 countries that are tracked by the FAO.

The analyses conducted in this thesis have utilized GCAM to investigate human and climate impacts on water usage in the future. However, this is not the only model that can be used in this type of study and the assumptions used for the SSP-RCP modeling framework are not the only potential socioeconomic and climate futures. Using additional IAMs that can account for human-climate feedback linkages can help provide uncertainty ranges for each of the analyses from this thesis. Varying individual parameters in the SSP-RCP framework can also assist in the uncertainty analysis of these studies, similar to Lamontagne et al. (2018). While O'Neill et al. (2017) defined the storylines for the SSPs, the evolution of future socioeconomics is very much unknown. Therefore, it must be noted that a limiting factor of this research is brought upon by the lack of knowledge about the future evolution of the human and climate systems (Chapter 1).

Finally, the work compiled here has utilized the CMIP5 database for climate change impacts across the four previously mentioned RCPs. In the sixth installment of the CMIP, additional radiative forcing levels are being explored with inputs from IAMs (as described in Chapter 1). Expanding the climate impacts to additional radiative forcing levels to better match with the trajectories of the SSPs will improve this analysis. As shown in Figure 1.3, the baseline radiative forcing for SSP2, SSP3, and SSP4 is 7.0 W/m^2, therefore the implementation of more appropriate baseline impacts will provide a more accurate representation of some of the SSP scenarios.

5.3. Concluding Remarks

Wada et al. (2017) has stated that one of the key shortcomings of current water resource assessments, particularly in the future, is the necessity of modeling the co-evolution of human and systems while accounting for land use and climate interactions. Additionally, the Sustainable Development Goals have included in them, ambitious improvement to the water sector. Understanding both the positive and negative consequences of attaining these goals by 2030 are extremely important. In order to accomplish this, considerations for both human interventions and climate change must be taken into account. This body of work has included in it, not only the human-water interactions through and integrated modeling framework but has accounted for land use changes and climatic system evolution. This, by no means, is the final piece of this puzzle, and the necessity to further our understanding of the human-earth system interactions cannot be emphasized enough. Unfortunately, the uncertainty surrounding water use, availability, and the response to socioeconomic and climate forcings is unlikely to decrease significantly in the coming years. With the wide-ranging scenario base for the SSPs and RCPs, the ambiguity of projections will remain high at long time scales. For these reasons, it will remain important to explore these “what-if” scenarios in an IAM framework to explore how the human and climate systems will alter water on global and local scales. Projections, scenarios, and conditions will change and evolve over time, and it is important to react to these to understand the evolving consequences. Water availability is declining in many parts of the world, and the continued overuse will have lasting impacts in the future. Understanding how and why the use and availability of water may change in the future will allow for societies to take proper steps to avoid running out of water. Water sector analyses, particularly ones that include human interactions, need to continue and become increasingly sophisticated by including higher temporal resolution, increased spatial resolution, and accounting for the most up-to-date changes and projections in socioeconomic and climate systems in order to provide the most accurate projections to planners and policymakers.

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